DEVELOPMENT OF A DRINKING WATER QUALITY INDEX FOR DRY ZONE OF SRI LANKA: APPLICATION TO KALA-OYA BASIN

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Thesis submitted in partial fulfillment of the requirements for the
degree of Master of Science in Environmental Engineering and Management

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October 2015

DECLARATION

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ABSTRACT

Water Quality Indices have been developed to assess the suitability of water sources for its intended uses which give the status of water quality in water sources. Over past few decades, deterioration of water sources in Sri Lanka is getting critical. Ground water plays a significant role as a drinking water source in rural communities of dry zone while surface water is not that vital. In such circumstances, feasibility of use of water from traditional village irrigation tanks for drinking is utmost importance. To assess the surface water in dry zone, Drinking Water Quality Index was developed following four steps; (1) Selection of parameters considering their importance to the assessment study and availability of data. (2) Development of sub-indices by converting different units and rangers of water quality measurements for selected parameters into common scale, (3) Assigning weighting to the selected parameters considering their contribution to final index, (4) Aggregation of sub-indices and weightings using aggregation equations producing final index. Drinking Water Quality Index was then applied to Kala-oya basin in order to characterize the spatial and temporal variability of surface water quality in the basin. Kala-oya basin, located in the north-western dry zone of Sri Lanka is irrigational watershed which supplies water to agriculture, recreation and domestic purposes including drinking. Drinking Water Quality Index was calculated from ten physicochemical parameters; pH, Conductivity, Total Dissolved Solids, Turbidity, Hardness, Nitrate, Phosphate, Sulfate, Fluoride, Biochemical Oxygen Demand, Chemical Oxygen Demand, Total Coliform and Faecal Coliform periodically measured at 16 sampling sites in three reservoirs in Kala-oya basin; Kalawewa, Dambulu-oya and Bowathenna, from January to December 2014. The results revealed that Drinking Water Quality Index scores varied between 38 to 80 indicating deterioration of water quality. It was observed that surface water samples from 78% of sampling locations were categorized as ‘Marginal’ water quality. Results of remaining locations showed ‘Fair’ and ‘Poor’ water quality. In none of the locations, the score of the DWQI was determined as ‘Good’ or ‘Very Poor’. Water quality analysis done for assessing the level of treatment showed all the locations need advanced water treatment. The Drinking Water Quality Index shows an overall suitability of water bodies for drinking with level of treatments. Proposed Drinking Water Quality Index can be applied for watersheds in other parts of the country.

Key Words: Drinking Water Quality Index, Water Quality, Water Quality Parameters, Kala-oya basin

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LIST OF ABBREVIATIONS

BOD_5	Biochemical Oxygen Demand
CCME WQI	Canadian Council of Ministers of the Environment Water Quality Index
CKDu	Chronic Kidney Disease of unknown etiology
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
DWQI	Drinking Water Quality Index
MASL	Mahaweli Authority of Sri Lanka
NSF WQI	National Science Foundation Water Quality Index
OWQI	Oregon Water Quality Index
TDS	Total Dissolved Solids
WHO	World Health Organization
WQI	Water Quality Index
WQIs	Water Quality Indices
SLS	Sri Lankan Standards

1. INTRODUCTION

1.1 Global concern on water quality

Water is the most important natural resources of the ecosystem, having an important role for both drinking as well economic sectors. In the last century the availability and quality of inland freshwaters has been affected, mainly due to urbanization, industrialization, agriculture, etc. The water quality in any water resource influences the way in which the water is used for such as drinking, recreation, irrigation and industrial purposes. There is global concern that water resources are unable to maintain their fitness for intended use.

1.2 Assessment of Water Quality

The quality of water source can be assessed using physical, chemical and biological parameters and determining the quality is important before its intended use. It is possible to show different level of contamination relating to different parameters tested. To identify the contaminants and variations in water quality, relevant physical, chemical and biological parameters are periodically measured and analyzed in monitoring programs. In general, this gives indications about situation of the water quality for a given time frame and particular objectives.

In water quality monitoring programs, constituents in water samples are regularly analyzed against the water quality standards. This is the traditional approach to assess the water quality of the water source. Water quality guidelines and standards are ensured the provision of clean and safe water for human consumption, recreational activities, industrial uses and agriculture, etc, thereby protecting human health and the environment. In many cases, the use of this method allows for a proper identification of contaminated sources and may be essential for checking legal compliances. However, this method is not adequate for understanding the overall situation of the water source and it does not indicate variations of water quality spatially and temporally (Debels, et al., 2005).

According to Fredrick et al., 2007, the usefulness of traditional method is limited for several reasons. They are; ‘’ 1) it detects water quality standards violation but does not describe water quality conditions (water body is how good or how bad) 2) it does not perform a simultaneous, multi parameter, composite evaluation 3) it does not provide a single composite station evaluation that can assess temporal and spatial variation in water quality 4) it does not priority rank all sampling stations according to level of degradation 5)the analytical data does not provide a logical concise and composite summery of meaningful information that can be used by the water resource professionals for water quality management purposes 6) the analytical data is not easily understood by the non-experts and the public’’ (Fredrick et al., 2007).

There is a need for a scientific approach to give a composite evaluation to water quality and provide spatial and temporal variation of the water source. And this product should be useful to water resource managers and easily understood by the public (Ballance et al., 1996). During the years, several water quality evaluating methods and approaches have been developed by national and international organizations to assess the quality of water bodies

1.3 Importance of Water Quality Index

Water Quality Indices have been introduced by the several researchers as a method to obtain a numerical expression for the quality of water source (Bordalo et al., 2001; Cude 2001; Hallock 2002; Saeedi 2010). According to Abbasi, 2012, ‘’Water Quality indices aim at giving a single value to the water quality of a source on the basis of water quality standards which translates the list of constituents and their concentrations present in a sample into a single value at a particular time’’ (Abbasi et al., 2012). Then it can be used to compare different samples of water quality with respect to index value obtained for water samples. It gives easy to understand information about the water source than the long list of numerical values for a large selection of parameters.

Due to its simple and readily understandable nature, Water Quality Indices are used by the managers and decision makers to express the possible use of the water body.

Also it can be easily understood and used by the public as it turns complex water quality data into simple number. Water Quality Indices provide information to general public about the condition of the water quality of a water body; whether it is acceptable or not for an intended use.

Water Quality Indices were initially introduced by Horton (1965) and Brown et al. (1970) (Abbasi et al., 2012). Over the past few decades, different methods of calculating Water Quality Indices have been proposed by several researchers and organizations. (UNEP GEMS 2007; Abbasi et al., 2012; Cude 2001; Khan 2004) Fitness of water quality for different uses has been evaluated using Water Quality Indices. Since first introduced, water quality indices have been used to assess the status of water quality in water resources worldwide (Khan et al., 2003; Bonanno 2010; Akkoyunlu 2012; Prasanna 2012; Lermontov 2009: Lee et al., 2014: Debels et al., 2005). Authorities responsible for water quality monitoring and pollution control strongly recommend development and use of Water Quality Indices (Abbasi, 2012).

1.4 Sri Lankan Context

In Sri Lanka, inland freshwaters which appear in the form of rivers, streams and reservoirs play a vital role, as a source of drinking water. Though clean water is basic human need, the health impacts due to deterioration of water sources is becoming a growing problem in the country. This situation is getting critical due to endemic occurrence of Chronic Kidney Disease of unknown etiology (CKDu) reported in certain parts of the dry zone among farming community of Sri Lanka. It is a new and emerging health issue and is being attributed to consumption of water with undesirable constituents (Chandrajith et al, 2011).

Poor water quality not only spreads disease and causes death, it also hold back socio-economic progress of the country. According to World Health Organization (WHO) Communicable Disease Epidemiological Profile, 2010 (WHO, 2010) morbidity is very high due to water-borne diseases in Sri Lanka. In addition to morbidity on individuals, loss of man hours and productivity, cost of treatment and wage losses has an enormous impact on household and national economy. Therefore it is necessary to provide safe water to increase nation's health and productivity. Still 29% of population in Sri Lanka is provided with piped borne water (WHO/UNICEF, 2013). Majority of population who has no access to safe drinking water are rural population live in dry zones of the country.

Ground water plays a significant role in rural water supplies in dry zone however it has been reported that in many areas, the quality of groundwater has deteriorated to an extent that it is not possible to adopt conventional treatment methods. Even though many ground water resources thought not safe enough for direct consumption, is still being used by many as no other alternative is available (Herath & Ratnayake, 2010). In contrast, due to growing number of patients of CKDu, rural communities in affected areas in dry zone are reluctant to consume groundwater where the groundwater contains high level of hardness and fluoride (Chandrajith et al., 2011; Jayasumana et al, 2014). Compared to ground water, surface water as a source of drinking water is not a popular option among rural communities in dry zone. However many people in dry zone still use water from irrigation tanks and canals where water is often contaminated and therefore not suitable for human consumption. In this context, feasibility of use of water from irrigation tank and canals for drinking is important.

1.5 Kala-oya Basin

Kala Oya, is one of the 103 river basins in the country, situated in the North western dry zone of Sri Lanka. It lies across North Western, North Central and Central Provinces of the country. Kala-oya basin spreads over a long and narrow strip, having an average width of about 25 km and a length of 150km and area around 2,870 sq km. It has unique characteristics in terms of bio diversity, wetlands, water bodies and other natural resources. Kala-oya basin has about 600 irrigation tanks including abandoned tanks. In addition to playing a major role by providing irrigation water it provides many more services for the farming community. As it is an intensely irrigated agricultural watershed, about 99% of regulated water in the lower valley of the basin is used for agriculture. The total annual domestic demand is about 4.8 MCM. Contents of this chapter on Kala-oya basin have been drawn mostly from the Interim Reports prepared by River Basin Management and Planning Unit of Mahaweli Authority of Sri Lanka in 2002 – 2003 (MASL 2003; MASL 2002).

The basin area is about 2,870 sq. km. where 76% of land is in dry zone and the rest is within the intermediate zone. The basin consists of a population of over 0.411 million, which is expected to increase up to 0.467 by the year 2016 with a 90% rural population. The majority of them engaged in farming as their main occupation.

The highest land uses are scrub jungles (21%), home gardens (17%), forest (24%) and paddy cultivation (21%). Functional tanks occupy approximately 7% of the total basin area. The three provinces representing the Kala-oya basin area are North Central (52%), North Western (30%) and Central (18%). It represents four districts viz. Anuradhapura, Kurunegala, Puttalum and Matale and 20 District Secretariat Divisions.

The average annual rainfalls in Kala-oya basin vary from 1128 mm to 1725 mm. The lowest occurrence of rainfall has been during the period of June to August while highest occurrence during October to December. The basin receives about 480 MCM water annually as trans-basin diversion while about 343 MCM receives as runoff from rainfall. Annually about 40, 000 hectares of agricultural land are cultivated using about 1,100 MCM of water including drainage water.

Under the Mahaweli Development Project, up to 2000 cubic seconds of water of Mahaweli river is diverted at Polgolla diversion and this water is regulated through Bowathenna reservoir of which 1000 cubic seconds of water is diverted to Kala-oya basin. The major reservoirs are Kalawewa/Balaluwewa and Rajanganaya while there are many medium scale reservoirs that are in operation namely, Devahuwa, Dambuluoya, Kandalama and Mahailluppallama. There are about 680 of small tanks exist within the basin of which of 473 are functioning. Schematic representation of stream network of Kala-oya basin was shown in Appendix B (MASL 2003; MASL 2002).

As part of the transformation process of Mahaweli Authority of Sri Lanka to include river basin management, Kala-oya basin has been earmarked as a pilot basin to implement river basin management concepts through a comprehensive planning process. Accordingly water quality studies were carried out to assess and implement measures to improve water quality of surface and ground water of Kala-oya basin. As a result, Kala-oya basin has comprehensive collection of water quality monitoring data covering the majority of water bodies in the basin.

1.6 Water Quality Problems in Kala-oya Basin

Kala-oya basin is considered as one of the most fertile areas in dry zone with a diverse range of flora and fauna. It experiences severe problems of degradation of its watershed, water scarcity, water pollution and bio diversity reduction. Due to little or no attention being paid to water quality of tanks and canals, water quality issues have started to surface indicating the degradation of water quality in basin area. High incidence of water borne diseases in the basin area has been reported. Health problems are arising in drinking water as well as recreational facilities.

At present, Kala-oya basin is identified as one of the CKDu prone area where the occurrence of CKDu is thought to be caused by the consumption of polluted water (Chandrajith et al., 2011). There is a serious concern regarding the presence of high concentrations of pesticides and herbicides in waters of the Kala-oya basin.

It is also reported that water in certain tanks and canals are unsuitable even for recreational activities such as bathing during some months of the year due to skin ailments and odour. Most of the minor and medium capacity tanks have shown eutrophication effects due to accumulation of nutrients.

The analytical results of previous water quality monitoring studies of Kala-oya basin indicated the deterioration of water quality. The turbidity level has been quite high with respect to WHO acceptability level of 5 NTU. Total hardness has been exceeded in drainage and irrigation water with respect to desirable limits of 250 mg/l of Sri Lankan Standards. Water samples collected from Kalawewa and Kala-oya have shown higher concentration of total phosphate than the recommended Sri Lankan Standards (SLS) of 2 mg/l for potable water during certain month of the year. Water samples collected from Dambulu-oya and Kala-oya have shown higher concentration of nitrates than the recommended SLS of 10 mg/l for drinking during certain month of the year.

Therefore if due attention is not paid to manage the water quality, serious degradation of the water in Kala-oya basin is unavoidable. In the long run, if these situations continue there will be a serious shortage of water for drinking purposes. Even water is available in quantity; it will become unavailable for drinking due to low quality.

1.7 Water Quality Index for Kala-oya Basin

Assessment of water quality is often a difficult issue in multiple land use watersheds like Kala-oya basin. Because water bodies within the basin are closely inter connected through cascade irrigation tank network system and may influence each other directly or through intermediate stages; flood plains and marshes (Chapman, 1996). Identification of causes for the water quality behavior needs better understanding of the watershed and more investigations. Water quality measurements over a spatial and temporal distribution are of enormous value for such investigations.

The difficulty of assessing water quality always links to the non-point source pollution. As being intensely irrigated agricultural watershed, waters of Kala-oya basin indicate symptoms of typical non-point source water pollution (MASL, 2002; MASL, 2003). Control of such problems needs a careful understanding of the relationships between state of the water source and anthropogenic and natural activities. Therefore characterization of spatial and temporal variability in water quality of cascade tank system in Kala-oya basin is essential to understand the situation and prevent the pollution. In this context, it is suggested that use of Water Quality Index as an assessment tool.

There are several water quality monitoring programs conducted by different governmental and non-governmental organizations to assess the quality of surface and ground water in Sri Lanka. As water quality monitoring is now being recognized an important part of the government programs, several agencies have legal responsibility in monitoring water quality. In most of these programs, ambient water quality of the water source is compared against WHO Guidelines/ Sri Lankan Standards. Though there were some attempt to develop Water Quality Index in selected water sources in Sri Lanka, basin research relate to Water Quality Index are not generally available.

1.8 Objectives of the Study

The primary objective of this study is to develop a Water Quality Index to assess the suitability of surface water in dry zone of Sri Lanka for drinking and level of treatment and apply the proposed Water Quality Index to reservoirs in Kala-oya basin. The second objective is to characterize the spatial and temporal variability of surface water quality and analyze overall water quality of Kala-oya basin from its pollution point of view. The third objective is to discuss possibilities and limitations of the application of proposed method to watersheds in other parts of the country.

In order to fulfill the objectives of the study, literature that is published on water quality indices were reviewed and analyzed. Available long-term water quality monitoring data for Kala-oya basin were collected and analysed to develop Water Quality Index. Using developed Water Quality Index, pollution of Kala-oya basin was analysed based on geographical locations, anthropogenic and natural activities, and time.

Retrospective data is being used in this study and the scope was restricted as some of the parameters commonly used in developing water quality indices are not available in Sri Lankan context.

2. LITERATURE REVIEW

Water quality indices are commonly defined and used to evaluate the level of quality or pollution of a water body and for temporal and spatial trends. The literature reveals that a great number of different water quality indices have been published over the past few decades. Over hundreds of water quality indices predominantly based on physico-chemical parameters have been published and a many indices based on bio assessment also have been developed and appeared in literature. These indices greatly differ in terms of the number and types of parameters included, mathematical structures, scales and overall index range. Since first introduced in 150 years ago, most of the countries have developed and applied water quality indices to classify water within their regions. However, there is no globally accepted water quality index (GEMS, 2007). Rather than evolving towards a uniform structure, each published index often shows little or direct relationship to previous published indices (Otte, 1978).

2.1 Historical Background

2.1.1 Horton’s Index (1965)

The concept of formulating a water quality index in its basic form was first introduced in 1848 in Germany which uses the presence and absence of certain organisms in water to state the fitness of water (Lumb et al., 2011). The use of numerical scale to represent gradation in water quality levels were first began with Horton’s index in 1965.

Horton (1965) developed the first Water Quality Index as a means for comparative evaluation of water quality conditions and pollution abatement programmes by selecting and weighting water quality parameters and introducing an aggregation function. He set following criteria including ‘’1) the number of variables to be handled by the index should be limited to avoid making the index unwieldy, 2) the variables should be of significant in most areas, 3) only such variables of which reliable data are available should be included’’ (Horton, 1965).

In Horton’s index, 10 mostly measured water quality parameters were included. They were dissolved oxygen, pH, coliforms, specific conductance, alkalinity and chloride. Total Dissolved Solids were represented by Specific conductance and influence of Organic matters was replicated by carbon chloroforms extract. One of the variables was sewage treatment (percentage of population served) which was included to represent the effectiveness of abatement activities on the premises. Any toxic chemicals were not included in the index. The index weightings range from 1 to 4.

The sub-indices and weightings were combined using a linear sum aggregation function. The sub-indices were calculated using a table of specific sub-index values corresponding to ranges of each variable. Aggregation function is as follows;

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} wiqi}{\sum_{n=1}^{n} wi} M1M2$$

Where; qi is the sub indes value of the ith parameter and wi is the weighting assigned to ith parameter. M1 and M2 reflect the temperature and obvious pollution.

Horton’s index was considered as highly subjective as the selection of parameters, development of sub-indices and assigning of weightings were based on the judgment of the Horton and few of his associates. Since then several researchers has followed the Horton’s index and made an effort to develop water quality indices with less subjectivity and more sensitivity (Abbasi et al., 2012).

2.1.2 National Sanitation Foundation Index (1970)

Following the Horton’s index, with the help of National Sanitation Foundation of USA, Brown et al. (1970) developed an index for water quality. This new index is well-known as National Sanitation Foundation Water Quality Index (NSFWQI) and it has wider scope than Horton’s index in selecting parameters, developing rating scales and assigning weights. The NSF WQI provides a standardized method for comparing the water quality of various water bodies. It has been widely used all over the world.

To develop NSF WQI, a panel of experts in water quality management asked to consider 35 water quality parameters for possible selection in a water quality index. A list of nine parameters was finalized. They were also asked to give an important rating for each parameter on a scale of 1-5 where 1 corresponded to the highest significance while 5 corresponded to the lowest significance. With the judgment of the panelists, concentration – value relationship of each parameter was obtained in the form of a graph (rating curves) and their weighting factors. The selected water quality parameters and their weighting factors (in parentheses) are dissolved oxygen (0.17), fecal coliforms (0.16), pH (0.11), biochemical oxygen demand (0.11), nitrate (0.10), total phosphate (0.10), temperature change (0.10), turbidity (0.08), and total solids (0.07). In rating curves which is in range of 0–100; a score of 100 represents the best quality, while score of zero represents the worst quality.

Final Index is expressed mathematically in additive aggregation form as;

$$\mathrm{WQI} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{wiqi}$$

Where: qi is the standardized water quality value of ith parameter obtaining from respective rating curve and wi is the relative weight of ith parameter where $\sum_{i=1}^{n} wi = 1$ and n is number of parameters.

The scores of NSFWQI classifies water bodies as poor (0–25), fair (25–50), medium (50–70), good (70–90) or excellent (90–100). Even with widespread application, NSF WQI has been criticized for its inflexible structure, inadequate input of water quality parameters and subjective rating curves. In order to overcome lacked of sensitivity towards extreme values of single parameter, Brown et al. (1973) proposed a variation of NSF WQI in the following multiplicative aggregation form (Lumb et al, 2011):

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{qi}^{\mathrm{wi}}$$

To compare the indices of additive aggregation to the multiplicative aggregation, McClelland (1974) obtained survey responses from over 100 water quality experts—

with 30 of them having participated in the original Brown et al. (1970) survey. Following Delphi procedure, experts were given data from actual stream samples and asked to rate them. When compared to the experts' ratings of water sources, it showed that multiplicative formulation agreed better with expert opinion than did the additive one. Using a similar process, Landwehr and Deininger (1976) also found that the indices formed on multiplicative aggregation matched experts' ratings better than indices formed in additive aggregation. However, both of aggregation functions continued to be in use and considerable advances on development of the composite indices have been made based on them (Cude, 2001; Liou et al., 2004).

2.1.3 Canadian Council of Ministers of the Environment Index (2001)

One of the successful attempts for development of an efficient Water Quality Index was performed by the Canadian Council of Ministers of the Environment in the late 1990's (CCME, 2001). Contrary to most of the previous water quality indices, the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) compares observed levels of water quality parameters to guideline or standard values as benchmarks instead of standardizing observations by subjective rating curves (CCME, 2001; Khan et al., 2003; Lumb et al., 2006). The purpose of developing the CCME WQI is to reduce the multivariate nature of water quality data and report the results in understandable way.

It provides a flexible index structure adaptable to the site specificity and treatment considerations of drinking source water. The CCME WQI is an objective-based index that compares measured water quality values to guidelines to produce a score ranging from 0, representing worst quality, to 100, representing best quality. Practitioners are free to select appropriate parameters and guidelines for their purposes therefore accommodating the site specific and treatment considerations associated with assessing drinking source water. The Canadian Council of Ministers of the Environment provides detailed information regarding index calculation and application (CCME, 2001 a, CCME, 2001 b).

Index scores are calculated as follows:

$$\text{WQI} = 100 - \frac{(F1+F2+F3)}{1.732}$$

Where:

F1 (scope) represents the percentage of the selected variables that do not meet their respective guidelines at least once during the time period considered,

F2 (frequency) represents the percentage of individual sample measurements (tests) that do not meet their respective guideline in the time period considered, and

F3 (amplitude) represents the amount by which failed measurements do not meet their respective guideline, calculated in 3 steps and scaled to a value between 0 and 100.

CCME WQI is also being used by many countries all over the world (Lumb et al., 2011) and has also been allowed by United Nations Environmental Program in 2007 as a model for Global Drinking Water Quality Index (UNEP GEMS, 2007).

2.1.4 Oregon Water Quality Index (2001)

The Oregon Water Quality Index (OWQI) is a single number that expresses water quality by integrating measurements of eight water quality variables; temperature, dissolved oxygen, biochemical oxygen demand, pH, ammonia nitrate nitrogen, total phosphorus, total solids, and fecal coliform. Purpose of developing the index is to provide simple and summarizing method to evaluate the ambient water quality of Oregon's streams for general recreational use, including fishing and swimming. First OWQI was developed in the 1970s. After that it has been updating based on improved understanding about water quality behavior (Cude, 2001).

OWQI aggregates sub index values using un-weighted harmonic square mean aggregation function. The aggregation function is given by;

$$\text{WQI} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{qi}}}$$

Where n is the number of sub-indices and qi is Sub-index i.

This aggregation function allows the most impaired variable to impart the greatest influence on the water quality index. It acknowledges that different water quality variables will create differing significance to overall water quality at different times and locations. In methods that assign fixed weightings to parameters, the parameter given the greatest statistical weight always has the greatest influence on water quality index scores regardless of the degree of impairment of that variable (Cude, 2001). As there is no weighting in OWQI aggregation function, it is free from this influence.

2.2 Water quality indices based on physico-chemical parameters

As per literature review, water quality indices based on physical and chemical parameters can be classified into four main categories;

(1) Indices of general water quality

(2) Indices for specific water uses

(3) Indices for planning

(4) Indices through statistical approaches

All of these indices have one or more ‘biological’ parameters but they are all predominantly based on physico-chemical parameters. Next section will review and summarize 13 articles to evaluate methodology, purposes and validity of the indices in above categorizations.

2.2.1 Water quality indices of general water quality

The indices for general purpose water quality are probably the most familiar and provide the clearest examples of the difficulties associated with environmental indexing. General water quality indices aggregate a variety of water quality attributes that describes characteristics such as potable, recreational, visual and aesthetic and aquatic.

Prati et al., (1971) calculated an index of pollution to evaluate the surface water quality in the Province of Ferrara in Italy for two year period from 1967 to 1969. First they classified the thirteen surface water quality parameters as Excellent, Acceptable, Slightly Polluted, Polluted, and Heavily Polluted according to existing standards. Then one pollutant was selected as the basis for reference and its actual values was considered directly as reference value. Finally, series of mathematical expressions for each of the values of the parameters were transformed into indices following the principle established above. The index was calculated as mean value of sub-indices. As this method lacks of objectivity, authors recommended using it to compare degree of pollution present in rivers (Prati et al., 1971).

Sharma et al., (2011) applied CCME WQI to River Yamuna, India (within the territory of Delhi) to study the after effects of the projects implemented within the river to rejuvenate it. River had been faced the deterioration of water quality during past few decades. Pollution was occurred due to large amount of wastewater enter into the river. The aim of this study was to assess the pollution level of the river for a period of 10 years using a water quality index. It also identified the contaminants which affect the quality of river water when it passed along the city limits. Different indices were calculated for three different seasons at four locations of the river. These seasons were pre-monsoon, monsoon and post-monsoon season. Results of the study revealed that water quality is in poor category except for one location. In that location, water quality varied from good to marginal category (Sharma et al., 2011).

Barceló-Quintal et al., (2013) evaluated the water quality in the Upper Lerma River Basin in Mexico using NSF WQI. Results obtained were compared with the similar studies of National Water Commission of Mexico. In this study, dissolved oxygen, pH, DOB_5, temperature change, total phosphates, nitrates, and total solids were used which were measured during 2005, 2006 and 2012. High levels of BOD_5, nitrates and phosphates were found in the Upper Lerma River indicating quality of water was bad. These results were similar to the studies carried out by the National Water Commission of Mexico showing that water quality was unacceptable (Barceló-Quintal et al., 2013).

Lee et al., (2014) developed the ‘Lake Water Quality Index’ for lakes and reservoirs in Korea as an integrated easy-to understand index that provides information about the relative status of each lake which is useful for ecosystem management. Water quality and phytoplankton were examined in 36 lakes, two natural lakes and 34 artificial lakes for period of 6 years. The study lakes were selected to represent the range geographic regions and lake morphology in Korea. After investigating the interrelationships among water quality parameters, four parameters (total organic carbon, chlorophyll-a, total phosphorus, and turbidity) were selected as representative indicators of overall water quality. A relative evaluation system was developed by adopting a logistic function index that describes a cumulative distribution function and reflects the relative position of each parameter among the study lakes. The cumulative distribution probability ranging from 0 to 1 was multiplied by 100 and then transformed into the water quality index ranging from 0 to 100. A score of 50 was assigned to the median value of the dataset, 0 to the highest concentration value and 100 to the lowest concentration value (Lee et al., 2014).

2.2.2 Water quality Indices for specific water uses

A common problem encountered in general purpose indexing is establishing criteria levels that are mutually appropriate to two or more uses. For example, high phosphate levels may be beneficial in irrigation water but detrimental in a reservoir. Similarly, saturation with dissolved oxygen may be crucial to fish habitat but undesirable in boiler feed water. To address this problem, indices are developed for selecting different criteria values for specific water uses.

Khan et al., (2003) applied the concept of CCME WQI to three selected watersheds of Atlantic region in Canada. They estimated water quality index for three different water uses: drinking, aquatic, and agriculture. The results revealed the water is not of optimal quality for aquatic and drinking uses, while it is excellent for agricultural use. A trend analysis was indicated that there is a deteriorating trend in drinking water quality (prior to treatment) of two sites. Study showed that limited number of records of the parameters significantly affected the trend analysis by producing higher WQI score (suggesting a better water quality). They stated the reason for it as less data reduces the probability and proportion of exceeding with respect to the CCME WQI (Khan et al., 2003).

Boyacioglu, (2007) developed the ‘’Universal Water Quality Index’’ to provide a simpler method for describing the quality of the surface water used for drinking water supply. Based on standards set by Council of European Communities, Turkish water pollution control regulations and other reported scientific information, three classification schemes for water quality were proposed for surface water quality assessment. To represent the drinking water quality, 12 water quality parameters were selected. They were cadmium, cyanide, mercury, selenium, arsenic, fluoride, nitrate-nitrogen, dissolved oxygen, biochemical oxygen demand, total phosphorus, pH and total coliform. Sub-indices developed using rating curves with the contribution of expert opinion. High weightings were assigned to health related parameters and lower weighting for chemical parameters than microbiological parameters considering the health impacts caused by them. Weighted additive aggregation function was used for aggregating sub-indices and weightings. Universal Water Quality Index was applied to Tahtali Reservoir in Turkey. Results of the study revealed that overall quality of the surface water falls under the ‘excellent’ class and water quality was strongly affected by agricultural and domestic uses (Boyacioglu, 2007).

Ramesh et al., (2010) developed the Drinking Water Quality Indexing system for ground waters of Southern Tamil Nadu, India. The aim of this study is to minimize the uncertainty and imprecision in the decision-making process of selecting ground water sources. Ground water samples were collected from 24 number of selected bore wells on monthly intervals for one year. These boreholes were already identified by respective authorities for drinking purposes. Twenty two water quality parameters were categorized into five groups on the basis of experts’ opinion and having their importance with respect to drinking water quality assessment to eliminate problem of ambiguity. Problem of eclipsing was eliminated by Min–Max operator with weighted multiplicative aggregation function (Ramesh et al., 2010).

Verlicchi et al., (2011) developed the ‘Wastewater Polishing Index’ to assess the quality achieved by different polishing treatments for water discharged into surface water bodies. The index was defined by a weighted average of six parameters including suspended solids, BOD_5 COD, ammonia, total phosphorus, and Escherichia coli, each transformed onto a sub-index scaled from 0 to 100. The index is equal to 0 if none of the six pollutants are present in the effluent and to 100 when all six parameters equal their corresponding Italian legal limits for discharge into surface water bodies. The index has been validated and tested on a pilot plant including a rapid sand filtration, a slow filtration through a horizontal subsurface flow system and a lagoon. The experimental investigation showed that the index is good tools for rapid indicate of how much the achieved effluent quality is satisfy the effluent standard because for an adequately treated wastewater, the index value should be less than 100. Sensitivity analysis revealed that Escherichia coli is the most influential parameter (Verlicchi et al. 2011).

2.2.3 Water quality indices for planning

Even each and every water quality index is a planning or decision making tool, Ott (1978) separated planning indices on the basis that they contain variables not associated with water quality. These include sub-indices such as stream miles affected by pollution, gross national product, and population in a drainage basin, as well as subjective indices involving aesthetic appeal and other values dependent on user preference.

Inhaber, (1974) developed an Environmental Quality Index for Canada. It combined four indices which are air, water, land and other miscellaneous aspects of environmental quality. The air quality index consists of three sub-indices; air quality in urban, air quality around these areas and air quality outside major urban areas. The water quality index consist of two major sectors including industrial and municipal discharges of wastes into water and the actual measured water quality and some secondary aspects of it. In the land quality index, six sub-indices were combined. These included characteristics of forests, overcrowding in cities, erosion, access to parkland, strip mining, and sedimentation. In the index for miscellaneous aspects of environmental quality, sub-indices on pesticides and radioactivity were combined. Some of the sub-indices were again broke down into sub-indices. To combine indices or sub-indices, the root-mean-square method was used. Weightings were used because some parts of the environment are more important than others. These weights were assigned on the advice of experts. A second type of weighting was used with respect to population. Since air, water, and land are all important components of environmental quality, and no data were available to assess the relative importance of each, they were weighted equally giving 0.3 per each. Index for miscellaneous aspects of environmental quality was received a lower weight of 0.1. The author pointed out that final value received as Environmental Quality index is not represent 'the state of the Environmental quality of Canada' but rather 'a measure' based on many assumption made (Inhaber, 1974).

Debels et al., (2005) compared the performance of several water quality indices for Chilblain river watershed in Central Chilie, in order to characterize the special and temporal variability of surface water quality in the watershed. An original WQI was calculated from nine physico-chemical parameters, periodically measured at 18 sampling sites in 11 months period. On the basis of the results from a Principal Component Analysis, modifications were introduced into the original WQI to reduce cost associated with its implementation. Two of the versions of WQI, which are both based on one laboratory analysis (chemical oxygen demand) and four field measurements (pH, temperature, conductivity and dissolved oxygen) were developed and seen to adequately reproduce the most important spatial and temporal variations observed with the original index. They were proposed as useful tool for monitoring global water quality trends in similar agricultural watersheds to Chilean Central Valley. Inclusion of additional parameters especially microbial data was recommended (Debels et al., 2005).

2.2.4 Water quality indices through statistical approaches

In order to reduce various uncertainties associated with index development, number of indices have been developed using statistical techniques such as multivariate analysis, principal component analysis, and factor analysis. However, the indices based on statistical analysis are more complex and more difficult to apply than conventional indices (Abbasi et al., 2012).

Liou et al., (2004) developed ‘River Pollution Index’ for Taiwan employing aggregation method with different aspects. Purpose of developing a WQI is to provide vital and usable information about water quality of Taiwan. WQI consisted of additive and multiplicative aggregations as moderated by scaling coefficients. Thirteen variables were aggregated to develop the WQI, which were DO, BOD_5, ammonia nitrogen, fecal coliforms, turbidity, suspended solids, temperature, pH, cadmium, lead, chromium, copper and zinc. Measurements for each variable were converted to values on an interval scale ranging from 0 to 100, in accordance with the degree of water quality from worst to highest. The criteria for the sub-indices referred to the classification of national water, source water criteria adopted by other countries, the background data of water quality, the legislated standards of Taiwan, etc. The Principal Component Analysis was proposed for categorizing the employed variables in accordance with common features. The proposed WQI applied in the Keya River in Taiwan showed that the quality, affected by industrial activities, causing water quality problems in Taiwan, did not significant represent the existing index (Liou et al., 2004).

Sedeño-Díaz et al., (2007) assessed spatial and long temporal variations in water quality of Río Lerma river basin from 1975 to 1999 with two approaches: the use of a weighted multiplicative water quality index and a Principal Component Analysis. Twelve parameters enter into the formulation of the WQI: dissolved oxygen, biochemical oxygen demand, total and fecal coliforms, alkalinity, hardness, chloride, conductivity, pH, nitrate, color and water temperatures. The mean annual values of each parameter were used to calculate sub-index functions from which the WQI was then derived. Principal Component Analysis was applied to assess the significance of parameters that explain the patterns of the monitoring stations.

WQI scores was denoted Rio Lerma water is not fit for drinking, requires treatment for most industrial and crop uses, and is suitable for coarse fish only (Sedeño-Díaz et al., 2007).

Mostafaei, (2014) was developed a WQI to assess the spatial and long temporal variations of surface water quality of the Kashkan River in Iran based on measured chemical ions. CCME WQI methodology was applied to 10 sampling stations during a period of 36 years. The measured parameters were cations (Na^+, K^+, Ca^{+2}, Mg^{+2}), anions ($HCO3^-$, Cl^-, $SO4^{-2}$), pH and electrical conductivity. In order to identify which parameter to be included in the WQI, Principal Component Analysis was performed. In addition, Kashkan River water quality was evaluated for its suitability for drinking and irrigation purposes using conventional methods. Results of the study revealed that ability of CCME WQI to evaluate Kashkan River water quality as fair for general consumption and suitable to be considered for most industries or irrigation without much treatment (Mostafaei, 2014).

2.3 Water quality indices based on biological assessments

According to the literature, WQIs are most often based on analysis of physical and chemical parameters. Some of them are pH, dissolved oxygen, temperature, turbidity, hardness, total solids, nitrogen, phosphorus, some metals and some pesticides. It is quite unlikely, biological parameters are attributed in the WQIs. Only fecal coliforms and BOD_5 are frequently used (Abbasi et al., 2012). This has been a common feature of the frequently used indices such as NSF WQI and CCME WQI. During recent years, attention has been paid over neglect of biological parameters. Therefore water quality indices based on biological assessments has been introduced.

2.4 Calculation of WQI

According to literature review, there are several number of water quality indices have been published. They vary from each other due to their basic structure and different types of parameters composite to develop the final product (Al-Shujair, 2014). However general procedure to calculate WQIs depends on following four common steps (Abbasi et al., 2012; Cude 2001; CCME 2001).

1. Selection of parameters
2. Development of subindices
3. Assignment of weightings
4. Formulating final index

Among these steps, most of the indices have been developed following steps 1, 2 and 4. Some of the indices have been developed without using the step 3 (Abbasi et al., 2012).

2.4.1 Selection of parameters

A water sample consists of several constituents including anions and cations, organics and non- organics, suspended and dissolved particles, colour and odour. If all of these constituent are taken into account, development of the water quality index is impractical. Therefore it is necessary to include parameters to represent the overall water quality for the intended use. Usefulness of any index depends on the parameter included in the index. Therefore selection of parameters is a crucial step when formulating an index. Enormous care, experience and expertise are required to ensure the most representative parameters are included in the index.

Browns et al., 1970; Smith, 1990 and Cude, 2001 used Delphi method for parameters selection which generates results from convergence of expert opinion. Indices developed by Ramesh, 2010; Abdul Hameed, 2010; Mohsen Nasirian, 2007; Kaurish, 2007 parameters were selected based on information developed from the literature. However parameter selection based on Delphi method or using parameters preferred by the index developer are subjective. Researchers have used statistical methods to overcome this form of selection bias. Ana Célia Maia Meireles (2010); Liou (2004) and Debels et al. (2005) used Principal Component Analysis / Factor Analysis for parameter selection.

2.4.2 Development of sub-indices

Water quality parameters in water vary in different ranges and units. Also they have different behavior in terms of concentration impact relationship. Second step of development of Water Quality Index, all the parameters are converted into single scale. In general, this scale varies from 0 to 100 where 0 implies the worst water quality while 100 implies the excellent water quality (Abbasi et al., 2012). To formulate sub-indices, different mathematical equations are used for different parameter variables. Over the last few decades, various methods are applied in the context of sub-indices development (Swamee and Tyagi, 2000). Among those approaches, Liou et al, 2003, Ramesh et al., 2010 and Song and Kim (2009) used segmented linear mathematical equations and Walski and Parker (1974), Bhargava (1985) used an exponential function. Dinius (1987) used power function for most of the sub-indices.

2.4.3 Assignment of weightings

All parameters short listed in step 1 are not always equally important. Some parameters are more important than others as indicators of water quality. Therefore different weightings are assigned to the different parameters. Assigning weighting is depending on expert opinions.

2.4.4 Formulating final index

As the final step, all the sub-indices specified in the step 2 and weightings assigned for parameters in the step 3 are combined together using an aggregation function. There are two most commonly used aggregation functions; the additive aggregation function and the multiplicative aggregation function.

Earlier researchers have used the weighted additive form (Horton 1965; Brown et al. 1970; Prati et al. 1971; Dinius 1972; Ott 1978) for aggregation:

$$\mathrm{WQI} = \sum_{\mathrm{i}=1}^{n} \mathrm{wiqi} \qquad \mathrm{Eq.\,(1)}$$

Later researchers have employed a weighted multiplicative form (Landwehr et al. 1974; Walski and Parker 1974; Bhargava 1985; Dinius 1987) for aggregation:

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{qi}^{\mathrm{wi}} \qquad \mathrm{Eq.\,(2)}$$

When comparing these two aggregation functions, Ott (1978), Landwehr and Deininger (1976), Walski and Parker (1974) suggested that multiplicative indices are behaving better in extreme values of the water quality. It is less affected by the extreme values than an additive aggregation functions.

Except these commonly used two aggregation functions, some researchers also suggested some other aggregation techniques. Some of them are minimum operators (Smith, 1990), hybrid methods (Dojlido et al., 1994; Swamee and Tyagi, 2000) and mixed aggregation function (Liou et al., 2004) (Ramesh, et al., 2010).

The three primary concerns surrounding any aggregation procedure are eclipsing, ambiguity, and rigidity (Swamee and Tyagi, 2000; Swamee and Tyagi, 2007). Eclipsing occurs when final index is insensitive to a single variable. Therefore, eclipsing can result in an acceptable index score despite one variable having extremely poor quality (Ott, 1978; Swamee and Tyagi, 2000). Ambiguity is somewhat of the opposite problem in which the overall index is reflective of poor quality conditions despite no single sub-index having a poor score (Ott, 1978). Both eclipsing and ambiguity tend to increase with increasing numbers of parameters (Swamee and Tyagi, 2000). Rigidity is the direct result of adding parameters to an index formulation. According to Swamee and Tyagi, 2007 ‘’rigidity arises when additional parameters are included in an index to address quality concerns and due to the index formulation, artificially reduce the resulting score’’ (Swamee and Tyagi, 2007). Table 2.1 outlines some important issues that must be taken into account when selecting an appropriate index aggregation technique.

Table 2.1: Characteristics of index aggregation formulas

Aggregation Function	Mathematical Formulation	Quality Index Attributes
weighted additive	$\mathrm{WQI} = \sum_{i=1}^{n} wiqi$	eclipsing no ambiguity rigidity

Aggregation Function	Mathematical Formulation	Quality Index Attributes
		(Ott, 1978)
weighted multiplicative	$WQI = \prod_{i=1}^{n} qi^{wi}$	potential eclipsing rigidity (Ott,1978; Swamee and Tyagi, 2000)
Minimum Operator Maximum Operator	WQI = min (q1, q2, q3...qn) WQI = max (q1, q2, q3...qn)	no eclipsing no ambiguity but does not provide a composite measure of quality rigidity (Ott, 1978; Swamee and Tyagi, 2000)

2.5 Sensitivity Analysis

Sensitivity analysis are carried out to find the most sensitive parameter and its impact on variation of WQI. It is assessed the impact of sensitive parameter or parameters on water quality. Findings of the sensitivity analysis is utilized to recognize the most sensitive parameter and the main concerned issues for deterioration in water quality in dry zone river basin. That will helpful for the selection of appropriate treatment technique to meet the concerned issues for drinking water. These findings will also help to suggest recommendations for legislative decision makers in for river basin management (UNEP GEMS, 2007, Tim et al., 2012).

2.6 Summary of referred WQIs

Table 2.2: Summary of referred WQIs

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
NSF WQI **Brown et al, (1970)**	DO, Fecal coliforms, BOD_5, pH, Temperature change, P, NO_3, Turbidity, TS	142 experts drew curves for raw data and assigned a value ranging from 0 to 100 and final curves were obtained with weighting factors for each parameter	0.17 0.16 0.11 0.11 0.10 0.10 0.10 0.08 0.07	$\sum_{i=1}^{9} \text{Si Wi}$	0.25 = very bad 26-50 = bad 51-70 = regular 71-90 = good 91-100 =excellent	To provide a standardized method for comparing the water quality of various bodies of water
CCME WQI **CCME,**	Not defined	F1 (scope) - percentage of the selected variables that	No weightings in aggregation	$100 - \frac{(F12+F22+F32)}{1.732}$	0 - 44 = Poor 45-64 = Marginal	To reduce the multivariate nature of water quality

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
(2001)		do not meet their respective guidelines at least once F2 (frequency) - percentage of individual sample measurements (tests) that do not meet their respective guideline F3 (amplitude) - amount by which failed measurements do not meet their respective guideline, Calculate in 3 steps and scaled to a value between 0 and 100	function		65-79 =Fair 80-94= Good 95-100 = Excellent	data and report the results to both managers and the general public in understandable way
Oregon WQI **Dunnette, (1979);**	Temperature DO, BOD$_5$,	Using Rating curves and mathematical equations	No weightings in aggregation function	$\sqrt{\frac{n}{\sum_{i=2}^{n}\frac{1}{\mathrm{Si}^2}}}$	10-59 = Very Poor 60-79 = Poor 80-84 =Fair	To provide a simple and concise method for expressing the ambient water quality of Oregon's

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
Cude, (2001)	pH, TS NH_3 NO_3-N Fecal coliform				85-89 = Good 90-100 = Excellent	streams for general recreational use, including fishing and swimming
Prati's Implicit Index of Pollution **Prati et al., (1971)**	pH, DO, BOD_5, COD, SS, NH_3, NO_3, Cl, Fe, Mn	Mathematical equations and rating curves	No weightings in aggregation function	Arithmetic mean of sub -indices	Not mentioned	To classify surface water quality in the Province of Ferrara in Italy
Sharma et al., (2011)	pH, DO, BOD_5, total coliforms, fecal coliforms,	F1: scope F2:Frequency F3:Amplitude	No weightings in aggregation function	$100-\left(\frac{F12+F22+F32}{1.732}\right)$	0–44 = Poor 45–64 = Marginal 65–79 = Fair 80–94 = Good	To study the after effects of the river rejuvenate projects in River Yamuna, India

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
	free ammonia				95–100 = Excellent	
WQI to Lerma River Upper Basin Barceló-Quintal et al., (2013)	DO, pH, DOB$_5$, temperature change, TP NO_3, TS	F1: scope F2:Frequency F3:Amplitude	No weightings in aggregation function	$100\text{-}\left(\frac{F12+F22+F32}{1.732}\right)$	0 - 24 = Very Bad 25 - 49 = Bad 50 – 69 = Medium 70 – 89 = Good 90 – 100 = Excellent	To evaluated the water quality in the Upper Lerma River Basin in Mexico and compare with National WQI
Lake Water Quality Index **Lee et al., (2014)**	TOC chlorophyll-a, TP turbidity	Mathematical equation and rating curves using cumulative distribution	No weightings in aggregation function	Average of sub- indices	Not mentioned	To provide information about the relative status of Korean lakes which is useful for ecosystem management
Khan et al., (2003)	Fe, Mn, Pb, Zn. Al, Cr. Cu. P, As, Se, Ba Hg, Cd, Na, NO_3,	F1: scope F2:Frequency F3:Amplitude	No weightings in aggregation function	$100\text{-}\left(\frac{F12+F22+F32}{1.732}\right)$	0–44 = Poor 45–64 = Marginal 65–79 = Fair 80–94 = Good	To assess the suitability of water for drinking, aquatic, and agriculture for

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
	SO_4,Cl, F DO, pH, Turbidity, Color, Temperature Hardness Specci. Con. Coliforms				95–100 = Excellent	three selected watersheds of Atlantic region
Universal Water Quality Index **Boyacioglu (2007)**	Cd, Hg, Se, As, F NO_3-N DO, BOD_5, TP pH total coliform	Mathematical equation and rating curves	0.086 0.086 0.086 0.086 0.113 0.086 0.086 0.114	Weighted additive	0–24 = Poor 25–49 = Marginal 50–74 = Fair 75–94 = Good 95–100 = Excellent	To provide a simpler method for describing the quality of the surface water used for drinking water supply

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
			0.029 0.057 0.057 0.114			
Ramesh et al. (2010)	(pH, Con., Na, Cl, SO_4) (TA, TH, Ca, Mg, Fe) (Fl, NO3, NO2, Mn, Zn) (Cd, Cr, Pb, Cu, Ni) (Total Coliform, Salmanella)	Rating curves with mathematical equations	0.147 0.132 0.206 0.279 0.235	Weighted multiplicative and Min.-Max. Operator	< 60 = Very Poor 60-75 = Poor 75 –85 = Marginal 85 – 92.5 = Fair 92.5-97.5= Good 97.5 -100 = Excellent	To minimize the uncertainty and imprecision in the decision-making in ground water source quality, Southern Tamil Nadu, India
Wastewater Polishing Index	SS, BOD_5 COD, NH_3, total P, E.	Rating curves	Wi is equal to 1 for all parameters except 1.4 for E.	$\frac{\sum_{i=1}^{n} Si^{wi} * 100}{\sum_{i=1}^{n} 100^{wi}}$	Not mentioned	To assess the quality achieved by different polishing treatments for

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
Verlicchi et al. (2011)	coli		coli			water discharged. into surface water bodies
Debels et al., (2005)	NH_4 BOD_5 Conductivity COD DO NO_3 NO_2 pH Ortho-phosphate Temperature	Assigning scores for different ranges of parameter values	0.13 0.17 0.06 0.17 0.18 0.07 0.12 0.10 0.12 0.10	$\frac{\sum_{i=1}^{n} Si * Wi}{\sum_{i=1}^{n} Wi}$	0 – 19 = very bad 20-39 = bad 40-59 = deteriorated 60-79 = reasonably good 80-100 = good	To characterize the special and temporal variability of surface water quality in the Chilblain river watershed in Central Chilie

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
Sedeño-Díaz et al., (2007)	Temperature pH DO DOB_5 NO_3 PO_4 TDS	Not mentioned	Not mentioned	$\sum_{i=1}^{n} \mathrm{Si} * \mathrm{Wi}$	0-24 = Vey Bad 24-49 = Bad 50-69 = Medium 70-89 = Good 90-100 = Excellent	To assess spatial and long temporal variations in water quality of Río Lerma river basin
Liou et al., (2004)	DO BOD_5 NH_3-N faecal coliforms turbidity SS temperature pH	Rating curves for non-toxic parameters and equation $\mathrm{ri}=\frac{\mathrm{Ci}}{\mathrm{Si}}$ for toxic parameters Where; ri = concentration ratio of i substance, Ci = substance with concentration and Si = maximum permissible concentration	Not mentioned	$Ctem * CpH * Ctox$ $\left[\begin{matrix}\left(\sum_{i=1}^{3} SiWi\right)\left(\sum_{j=1}^{2} SjWj\right) \\ \left(\sum_{k=1}^{1} Sk\right)\end{matrix}\right]^{1/3}$ Where; Si = sub-index values for DO, BOD_5 and ammonia nitrogen Sj = the sub-index	Not mentioned	To provide vital and usable information about water quality of Taiwan

Index	Parameters	Sub-index (Si)	Weighting Factors (Wi)	Aggregation Function	Range of WQI	Applicability
	Cd Pb Cr Cu Zn			values for the suspended solids and turbidity Sk = the measurement of faecal coliform *C*tem, *C*pH, *C*tox three scaling coefficients for temperature, pH and toxicity substances		
Mostafaei, (2014)	cations (Na^+, K^+, Ca^{+2}, Mg^{+2}), anions (HCO_3^-, Cl^-, $SO4^{-2}$), pH, electrical conductivity	F1: scope F2:Frequency F3:Amplitude	No weightings in aggregation function	$100\text{-}\left(\frac{F12+F22+F32}{1.732}\right)$	0–44 = Poor 45–64 = Marginal 65–79 = Fair 80–94 = Good 95–100 = Excellent	To assess the spatial and long temporal variations of surface water quality of the Kashkan River in Iran based on measured chemical ions

2.7 WQIs developed in Sri Lanka

There are few number of WQIs developed in Sri Lanka to evaluate water sources in the country. Some of those studies are given below.

Central Environmental Authority has been carried out water quality monitoring programmes at Keleni River, Ma-oya and Dadugam-oya from 2010 to 2012 and water quality of these water bodies were evaluated using CCME WQI. Parameters tested were pH, Electrical conductivity, Turbidity, Temperature, DO, BOD_5, COD, Lead, Chromium and Nutrients. As microbiological testing was not carried out periodically, it was not considered for the evaluation. For Kelani River, it was observed that fecal coliforms and turbidity were always exceeding the proposed CEA's inland water quality standards. Anthropogenic activities such as mining of gems and sand in the river and uncontrollable urban runoff cause to erode the river banks eventually cause the increased levels of turbidity. Results of the CCME WQI revealed that out of 12 sampling locations, the highest WQI score in the Kelani River was detected at the middle of the river located at Welivita (68) and the lowest score was detected at the sampling site at Thalduwa (46) and Seethawake (51). Some locations are showed good water quality as they were located in far reach of the river and in upstream. For Ma-oya, out of 8 locations, the highest WQI score was detected at the most upstream site, located at Mawanella Bridge (74) and the lowest score was detected at the most down-stream site located at the Kochchikade Bridge (53). Domestic use of water for bathing and washing are sources of contaminants of Ma-oya at up-steams. As being intensely agricultural water shed, pollution in down-stream of M-oya is due to runoff from agricultural activities. For Dadugam-oya, WQI score was between 45 - 58 indicating poor water quality for all 6 sampling locations. In mid-stream to down-stream, evidence of industrial pollution was indicated (CEA, 2012).

Wijetunge & Hewage (2001) developed a WQI for Bolgoda Lake-Weras Ganga area using physical, chemical and microbiological water quality parameters measured in ten different locations of the lake over a period of eight months. The objective of the study was to identify the pollution levels of the Lake. WQI was developed using weighted additive aggregation function. For sub index development, rating curves were used. Weighting factors were obtained referring to literature. Results of the study revealed that quality of water was bad concluding that water was relatively polluted. For proposed intended uses of aquatic life, irrigation and drinking and bathing, water should be improved (Wijetunge & Hewage, 2001).

3. METHODOLOGY

3.1 Development of Drinking Water Quality Index

3.1.1 Drinking Water Quality Index

In this study, ‘’Drinking Water Quality Index (DWQI)’’ was developed to provide a simple method to evaluate the quality of the water for the purpose of drinking and to investigate spatial and temporal variations of a water resource. It was developed in four steps; (1) Selection of parameters considering their importance to the assessment study (2) Development of sub-indices by converting different units and ranges of water quality measurements for selected parameters into common scale (3) Assigning weighting to the selected parameters considering their contribution to final index (4) Aggregation of sub-indices and weightings using aggregation equations producing final index. Extant research has been conducted in this domain, adopted for the development of this index.

3.1.2 Selection of parameters

The WHO (2011) guidelines divide water quality parameters into two categories:

1. Health related parameters which have potential to direct adverse impact on health
2. Acceptability related parameters that may not have any direct health effects but result in objectionable taste or odor in the water.

Considering above, parameters with health related aspects and consumer acceptability aspects were given priority during selection of parameters. Constituents present in significant concentrations in the water source were also considered as important.

3.1.3 Development of sub-indices

Sub-indices are used to convert different units and magnitude of water quality parameters into common scale. This step is the most important step in developing DWQI. During sub-index development, each parameter had been assigned a rating value between 0 and 100 depending on its limits of water quality criteria used.

Following water quality standards and literature were used to develop DWQI. Water quality standards used for the study are shown separately in Table 3.1.

1. Council Directive 75/440/EEC concerning the quality required of surface water intended for the abstraction of drinking water in the Member States set by the Council of the European Communities (EEC, 1975)
2. Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by Central Environmental Authority of Sri Lanka (CEA, 2001)
3. World Health Organization's Guidelines for Drinking Water Quality (WHO, 2011)
4. Sri Lankan standards for potable water (SLS 614, 2013)

According to Council Directive 75/440/EEC, surface water intended for the abstraction of drinking water is divided into three categories according to limiting values. For each category, standard method of treatment for transforming surface water into drinking water is assigned and is summarized as:

- Class I: Simple physical treatment and disinfection, e.g. rapid filtration and disinfection
- Class II: Normal physical treatment, chemical treatment and disinfection, e.g. pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination)
- Class III: Intensive physical and chemical treatment, extended treatment and disinfection, e.g. chlorination to break-point, coagulation, flocculation, decantation, filtration, adsorption (activated carbon), disinfection (ozone, final chlorination) (EC, 1991).

Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by CEA of Sri Lanka also has a similar categorization scheme.

- Class I: Drinking water with simple treatment
- Class II: Drinking water with conventional treatment

Table 3.1: Water Quality Standards used for the study

Parameter	**Council Directive 75/440/EEC quality required of surface water intended for the abstraction of drinking water in the Member States set by the Council of the European Communities (1975)**			**Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by CEA of Sri Lanka (2001)**		**Drinking Water Quality Standard/ Guideline**	
	Class I (excellent)	Class II (acceptable)	Class III (polluted)	Drinking water with		**WHO (2011)**	**SLS 614 (2013)**
				simple treatment	conventional treatment		
pH (at 25^{0}C +2^{0}C)	6.5-8.5	5.5-6.5	5.5-6.5	6.0-8.5	6.0-8.5	6.5-8.5	6.5-8.5
		8.5-9.0	8.5-9.0				
Conductivity / (ms/cm)	1	1	1	0.75	1	-	-
Total Dissolved Solids/ (mg/l)	-	-	-	-	-	500	500
Turbidity /(NTU)	-	-	-	5	-	5	2 (max.)
Hardness (as CaCO3)/ (mg/l)	-	-	-	250 (desirable) 600 (maximum)	-	200	250

Parameter	**Council Directive 75/440/EEC quality required of surface water intended for the abstraction of drinking water in the Member States set by the Council of the European Communities (1975)**			**Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by CEA of Sri Lanka (2001)**		**Drinking Water Quality Standard/ Guideline**	
	Class I (excellent)	Class II (acceptable)	Class III (polluted)	Drinking water with			
				simple treatment	conventional treatment	**WHO (2011)**	**SLS 614 (2013)**
Nitrate (as NO3-N)/ (mg/l)	25 (as $NO3^-$)	-	-	5	5	50	50
Phosphate (as PO4-P)/ (mg/l)	0.4	0.7	0.7	0.7	0.7	-	2
Sulfate ($SO4^{-2}$) / (mg/l)	150	150	150	250	250	250	250
Fluoride (F^-)/ (mg/l)	1.5	-	-	1.5	1.5	1.5	1.0
BOD_5 / (mg/l)	<3	<5	<7	3	5	-	-
COD / (mg/l)	-	-	30	15	20	-	10

Parameter	**Council Directive 75/440/EEC quality required of surface water intended for the abstraction of drinking water in the Member States set by the Council of the European Communities (1975)**			**Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by CEA of Sri Lanka (2001)**		**Drinking Water Quality Standard/ Guideline**	
	Class I (excellent)	Class II (acceptable)	Class III (polluted)	Drinking water with		**WHO (2011)**	**SLS 614 (2013)**
				simple treatment	conventional treatment		
Total Coliform/ (/100 ml)	50	5,000	50,000	5,000	2,000	0	3
Faecal Coliform/ (/100 ml)	20	2,000	20,000	250 (desirable) 600 (maximum)	-	0	-

Considering the required level of treatment, three classes of water is defined and each class is categorized as:

- Class I: Drinking water with simple treatment e.g. rapid filtration and disinfection
- Class II: Drinking water with conventional treatment e.g. coagulation, flocculation, sedimentation, filtration, disinfection
- Class III: Drinking water with advanced treatment e.g. coagulation, flocculation, sedimentation, filtration, softening, ion exchange, adsorption, disinfection

Proposed water quality criteria used to develop DWQI along with ranges of concentrations of selected parameters based on above standards and other literature are given in Table 4.1 in Results and Discussion.

To develop the sub-index rating curves, sub-index equal to 100 is assigned to limit of Class I water while sub-index equal to 50 is assigned to limit of Class II water. Similarly for the parameters that exceed the limit for Class III, the rating of sub-index was equaled to 1. In sub-index rating curves, concentration of parameters are in X-axis and corresponding sub-index values are in Y-axis. Sub-index rating curves for selected parameters are shown in Figure 4.1 to 4.11 in in Results and Discussion.

Regression analysis was used to calculate other sub-indices in between 0 and 100. Goodness of best-fit (R^2) was used to analyze best fit of a sub-index rating curves. Values of R^2 is in the range of 0 to 1, and R^2 of 1.0 indicates that the regression line perfectly fits the data, while an R^2 closer to 0 indicates a regression line does not fit. Mathematical equations for sub index development are presented in Table 4.2 in Results and Discussion.

3.1.4 Assignment of Weightings

Considering importance of water quality parameters to drinking water quality evaluation, temporary weighting factors (Wt) were assigned to each water quality parameters. Then final weighting factor (Wi) was calculated by dividing individual temporary weighting factor by total of the temporary weighting factors.

$$Wi = \frac{\mathrm{Wt}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{wt}} \qquad \text{Eq. (3)}$$

where; Wi is weight factor of the parameter where $\sum_{i=1}^{n} \mathrm{wi} = 1$; Wt is the temporary weight of that parameter; n is total number of the parameters.

To develop the DWQI successfully, it is necessary to assign appropriate weighting factors to water quality parameters. This step was carried out using a Questionnaire Survey distributed among water quality experts and referring to literature. Respective Questionnaire is given in Appendix A. Response rate to Questionnaire Survey is 35%. The assigned temporary weighting factors and final weighting factors for each parameter are given in Table 4.3 in Results and Discussion.

3.1.5 Formulating Final Index

Aggregation is the final step of developing the DWQI. As the final step, sub-indices developed in step 2 and weighting factors calculated in step 3 are aggregated using an aggregation function. Most commonly used aggregation function is additive aggregation function. However several researchers showed that multiplicative indices are better than additive indices as multiplicative aggregation functions is less affected by extreme values than an additive aggregation functions.

Considering above, in the present study, weighted multiplicative aggregation was applied to aggregate the index (Eq. 2).

$$\mathrm{WQI} = \prod_{i=1}^{n} \mathrm{qi}^{\mathrm{wi}} \qquad \text{Eq. (2)}$$

where: qi is the standardized water quality value of i^{th} parameter obtained from respective rating curve and Wi is the relative weight of i^{th} parameter where

$\sum_{\mathrm{i=1}}^{10} \mathrm{wi} = 1$ and n is number of parameters.

The aggregation equation generates a number between 0 and 100, with 0 indicating worst water quality and 100 indicating excellent water qualities. Table 3.2 presents the classification of water quality using the Drinking Water Quality Index. As given in Table 3.2, the DWQI classifies the water quality in five categories as good, fair, marginal, poor and very poor respectively. The number of locations categorized as good, fair, marginal, poor and very poor was shown in Figure 4.4 in Chapter 4: Results and Discussion.

Table 3.2: Classification of DWQI Scores

Category	Range of index scores	Remarks
Good	95-100	Class I limits occasionally exceeded, but usually by small amounts. ‘Good Quality’.
Fair	75-94	Class I limits often exceeded, quality departs from Class II limits by small amounts. ‘Acceptable Quality’.
Marginal	50-74	Class II limits often exceeded. ‘Threatened Quality’.
Poor	25-49	Class III limits occasionally exceeded. ‘Poor Quality’
Very poor	0-24	Class III limits often exceeded. ‘ Worst Quality’

3.2 Selection of Level of Treatment

Following method was adopted to evaluate level of treatment required for reservoirs in Kala-oya basin by individually considering the health impacts of water quality parameters. Water Quality Index formulated to assess the level of treatment was calculated using following equation.

$$WQI_i = \begin{matrix}\text{Probability of being Class I}\\ \text{of the } i^{th} \text{ parameter}\end{matrix} = \begin{matrix}\text{Health Risk Factor}\\ \text{for the } i^{th} \text{ parameter}\end{matrix} \times \begin{matrix}\text{Occurrence of the}\\ i^{th} \text{ parameter}\end{matrix}$$

Health Risk Factor of an individual parameter gives either value of 0 or 1 where 0 indicates 95% confidence that a health risk is evident and 1 indicates that there is no health risk. To assess the health risks, adverse health impacts due to selected water quality parameters were studied. Health risks of selected parameters for different ranges are shown in Table 4.5 in Results and Discussion.

Occurrence of the parameter is calculated as a percentage of the threshold limits of respective parameter to the measurement of that parameter. If occurrence of the parameter exceeds 1, it was not satisfied the Class I limit.

The Water Quality Index of each sampling location is calculated as,

$\mathrm{WQI}_{\mathrm{Total}} = \frac{\sum_{i=1}^{n} \mathrm{WQI}_{\mathrm{i}}}{n}$, where n is number of parameters.

If $\mathrm{WQI}_{\mathrm{i}}$ for one parameter becomes 0, $\mathrm{WQI}_{\mathrm{Total}}$ was considered as 0 and water quality sample is not satisfied for Class I.

If $\mathrm{WQI}_{\mathrm{Total}} < 0.95$, it was considered that sample had within the Class I limit and drinking water with simple treatment is recommended.

If $\mathrm{WQI}_{\mathrm{Total}} > 0.95$, sample is not within the Class I category. Similar check for Class II is to be followed. If it is satisfied, drinking water with conventional treatment is recommended. If not, similar check for Class III to be carried out.

3.3 The Study Area

The proposed scheme of water quality classification and the methodology presented for estimation of DWQI was applied to assess the water quality status at 16 sampling locations of three reservoirs in Kala-oya basin.

3.4 Data Collection

Mahaweli Authority of Sri Lanka is conducting water quality assessment studies in certain reservoirs of the Kala-oya basin which was used for this study. Historical water quality data of Kalawewa, Dambulu-oya and Bowathenna reservoirs in 16 sampling locations on monthly intervals from January, 2014 to December, 2014 were considered. Map showing study area with three reservoirs considered was presented in Figure 3.1. Locations of the sampling points and statistical summary of water quality measurements for each location are given in Appendix C and D.

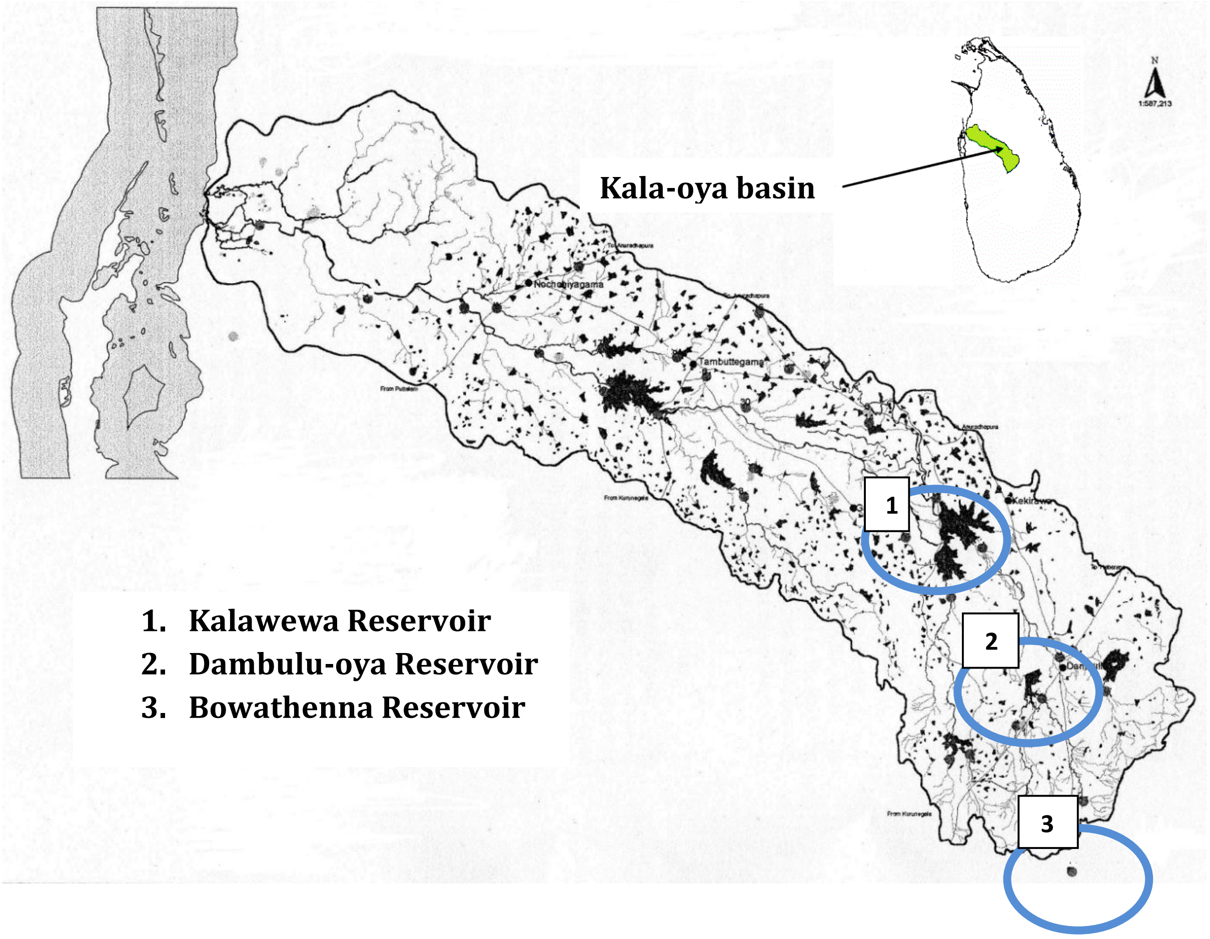

Figure 3.1: Map showing study area with three reservoirs considered

3.5 Sensitivity Analysis

A sensitivity analysis was carried out to assess the influence of input parameters on the results of the WQI. This task was achieved by removing the each of the significant parameters from the original index and recalculating a reduced index. Figure 4.23 to 4.29 in Chapter 4: Results and Discussion shows the results of sensitivity analysis.

4. RESULTS AND DISCUSSION

4.1 Development of Drinking Water Quality Index

4.1.1 Selection of Parameters

The proposed DWQI was developed using eleven physico-chemical water quality parameters. They are pH, Conductivity, TDS, Turbidity, Hardness, Nitrate, Phosphate, Sulfate, Fluoride, BOD_5, COD, Faecal Coliforms and Total Coliforms. Parameters were selected considering following data.

pH is one of the most important operational water quality parameter which helps for effective disinfection and clarification in all stage of treatment work (WHO, 2011). Conductivity and TDS are associated with dissolved solids present in the water. The presence of high levels of TDS may also be objectionable to consumers which associated with staining, taste, or precipitation (WHO, 2011). Higher level of turbidity prevents disinfection by protecting microorganisms and is unpleasant to drinking due to cloudiness. High concentration of hardness is a common problem in Kala-oya basin (MASL, 2003). It causes bad taste and forms soap scum. Water with hardness may cause scale deposition in the treatment works, distribution system and pipe work and tanks within buildings (WHO, 2011). Literature indicates that there is a relationship between CKDu and hardness in water (Chandrajith et al., 2011; Jayasumana et al., 2014). Presence of sulfate in drinking-water can cause noticeable taste and higher level links with laxative effects in consumers (WHO, 2004). Short term exposure to higher level of Nitrates causes blue-baby syndrome (methaemoglobinaemia) in bottle-fed infants (WHO, 2011) and higher levels of Nitrate is an indication of Nitrate pollution. High concentration of phosphorus cause nutrient pollution in water which eventually cause eutrophication in water resources. Even if there is no direct health impact due to phosphorus, nutrient pollution has impacted the water resources, resulting in serious environmental and human health issues. The presence of high BOD_5 may indicate faecal contamination or increases in particulate and dissolved organic carbon from sources of plant and animal which eventually indicate organic pollution in water. Presence of high COD is an indication of chemically polluted water source.

Considering the importance as a drinking water quality parameter, Fluoride was incorporated into index calculation by using historical data of 2003 of Kala-oya basin. This helps to give a more meaningful evaluation to the water quality as Fluoride is readily available in the Kala-oya basin. Fluoride varied in the range of 0.5 to 0.8 mg/l. Low concentrations of Fluoride provide protection against dental caries, both in children and in adults but elevated fluoride intakes can have more serious effects on skeletal tissues (WHO, 2011). According to Chandrajith et al., (2011), inorganic fluoride intake can cause a considerable nephrotoxic effect on human but this toxicity depends strongly on Na+ and Ca2+ activities where higher Ca2+ activity aggravates the damage caused by fluoride.

Available historical data in Kala-oya basin for Fecal Coliforms and Total Coliform were used to assess the level of microbial contamination. This helped to get an understanding during categorizing water quality into different Classes. Fecal Coliform varied in the range of 20 to 800 /100 ml. Total Coliforms varied in the range of 100-5050 /100 ml.

Due to unavailability of data, important drinking water quality parameters such as pesticides and heavy metals were not considered for this study. During development of water quality index for drinking, Boyacioglu (2007) and Ramesh et al. (2010) have been incorporated fecal coliforms, heavy metals and fluoride to their indices. They assigned higher weightings to Fecal coliforms considering its importance to health. Khan et al., (2003), Mostafaei, (2014) have been assessed surface water quality for consumption without microbiological parameters.

4.1.2 Development of Sub-indices

Water quality criteria and rating curves developed for the study are shown in Table 4.1and Figure 4.1 to 4.11.

Table 4.1: Water quality criteria used for the study

Parameter	Class I	Class II	Class III
pH	6.5-8.5	5.5-6.5 8.5-9.0	<5.5 >9.0
Conductivity /(mS/cm)	0.75	1	3.5
Total Dissolved Solids/ (mg/l)	500	800	1000
Turbidity /(NTU)	5	8	10
Hardness (as CaCO3)/ (mg/l)	100	250	600
Nitrate (as NO_3-N)/ (mg/l)	5	-	10
Phosphate / (mg/l)	0.4	-	0.7
Sulfate / (mg/l)	150	250	400
Fluoride (F^-) / (mg/l)	1.0	-	1.5
BOD_5 / (mg/l)	3	5	7
COD / (mg/l)	15	20	30
Total Coliform/ (/100 ml)	50	5000	50000
Faecal Coliform/ (/100 ml)	20	2000	20000

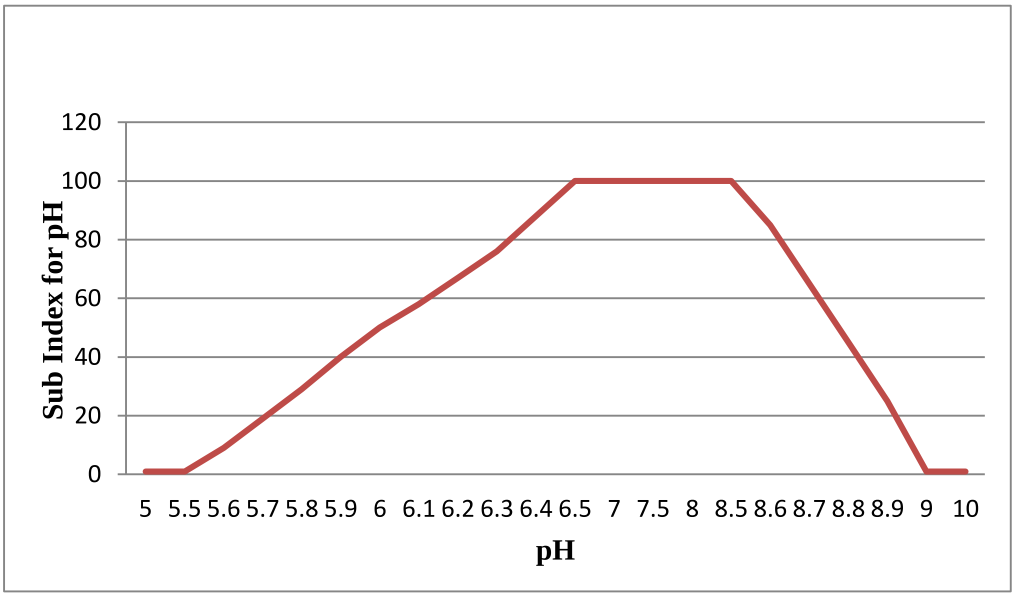

Figure 4.1: Rating Curve for pH

Controlling of pH is essential in water treatment works as it is one of the most important operational water quality parameter. It helps for effective disinfection and clarification in all stage of treatment work (WHO, 2011). Limits for Class I and II were taken from 75/440/EEC. Extreme values of pH cause skin and eye irritation. It also has indirect effect to health because extreme pH levels cause corrosion in metals and prevent effective disinfection (WHO, 2003 a). Therefore pH levels in water less than 5.5 and greater than 9.0 was considered as polluted and was taken as limit of the Class III.

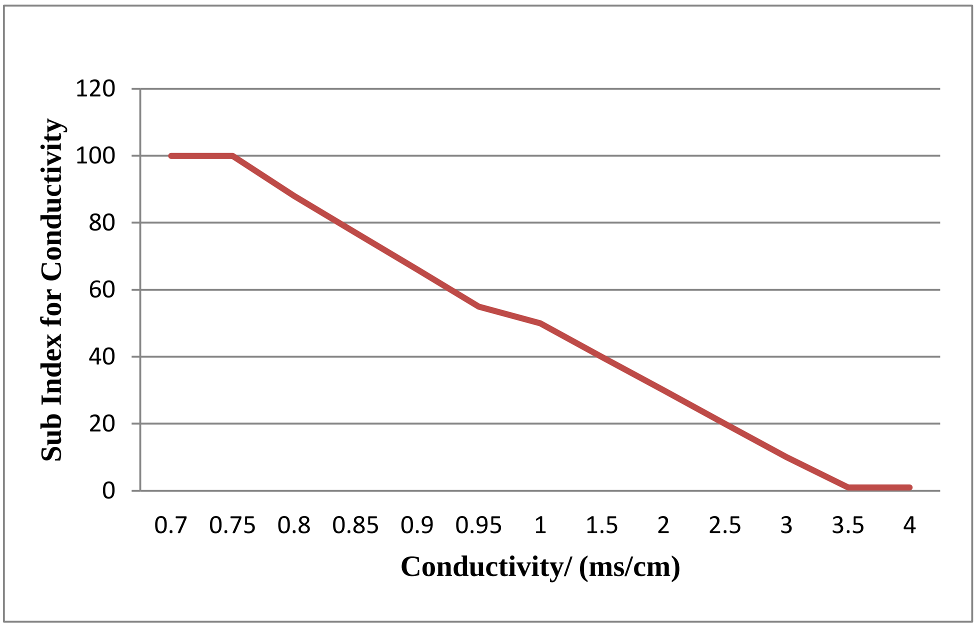

Figure 4.2: Rating Curve for Conductivity

Limits for Class I and II were taken from Proposed Ambient Water Quality Standards for Inland Waters of Sri Lanka by Central Environmental Authority of Sri Lanka. Based on literature, limit of Class III was taken.

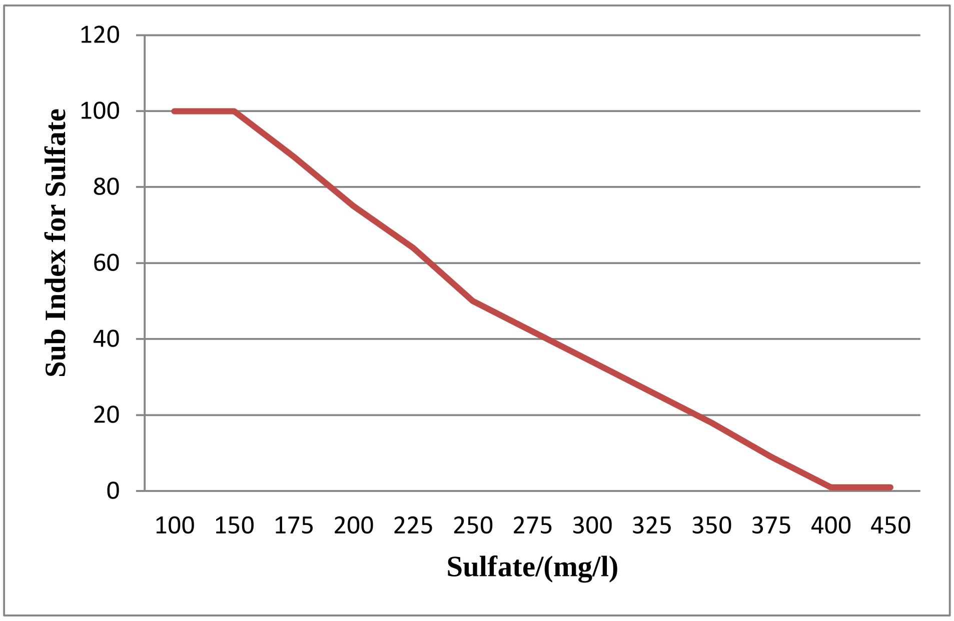

Figure 4.3: Rating Curve for Sulfate

The drinking water which contains Sulfate can cause noticeable unpleasant taste to consumers. When Sulfate levels are less than 250 mg/l, taste impairment is minimal (WHO, 2011). According to WHO, 2004, drinking water containing Sulfate level greater than of 750 mg/l is linked with a self-reported laxative effect, whereas water containing Sulfate level less than 600 mg/l is not (WHO, 2004). However US EPA, 1999 reported that most people experienced a laxative effect when they drank water containing Sulfate levels greater than 1000 mg/l. Considering above facts, limits for Class II water was taken as 250 mg/l and Class III was taken as 400 mg/l.

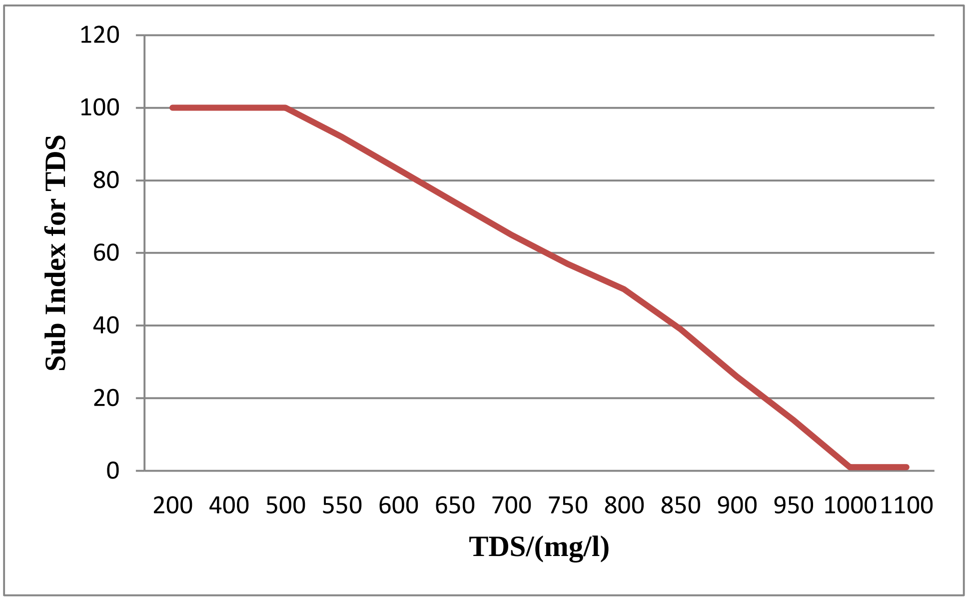

Figure 4.4: Rating Curve for Total Dissolved Solids

No health impact due to TDS in water but a high concentration of TDS will make drinking water unpalatable. Presence of high levels of TDS may also be objectionable to consumers which associated with staining, taste, or precipitation.

According to WHO, 2011, the palatability of water with a TDS level of less than 600 mg/l is considered to be acceptable; drinking-water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/l. Therefore for Class I water, limit of TDS was taken as 500 mg/l. 800 mg/l and 1000 mg/l were assigned respectively for Class II and Class III water.

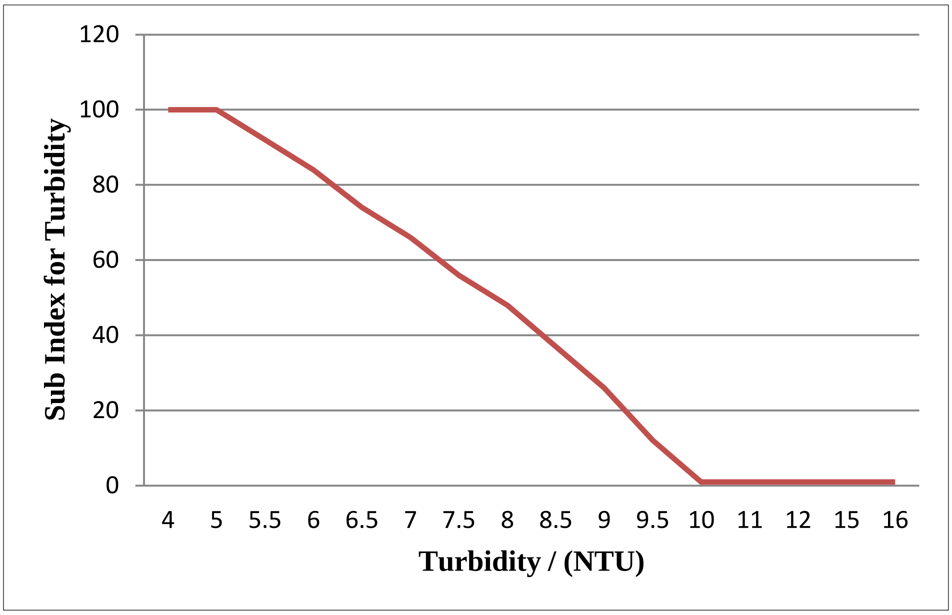

Figure 4.5: Rating Curve for Turbidity

High concentration of Turbidity will make drinking water unpalatable. In water treatment process, for effective disinfection, median turbidity should be below 0.1 NTU as turbidity prevents disinfection by protecting microorganisms (WHO, 2011). The appearance of water with a turbidity of less than 5 NTU is generally acceptable to consumers (WHO, 2011). Therefore for Class I water, limit of Turbidity was taken as 5 NTU. As Turbidity can be removed by conventional water treatment, limits for Class II and III water was taken as 8 NTU and 10 NTU respectively.

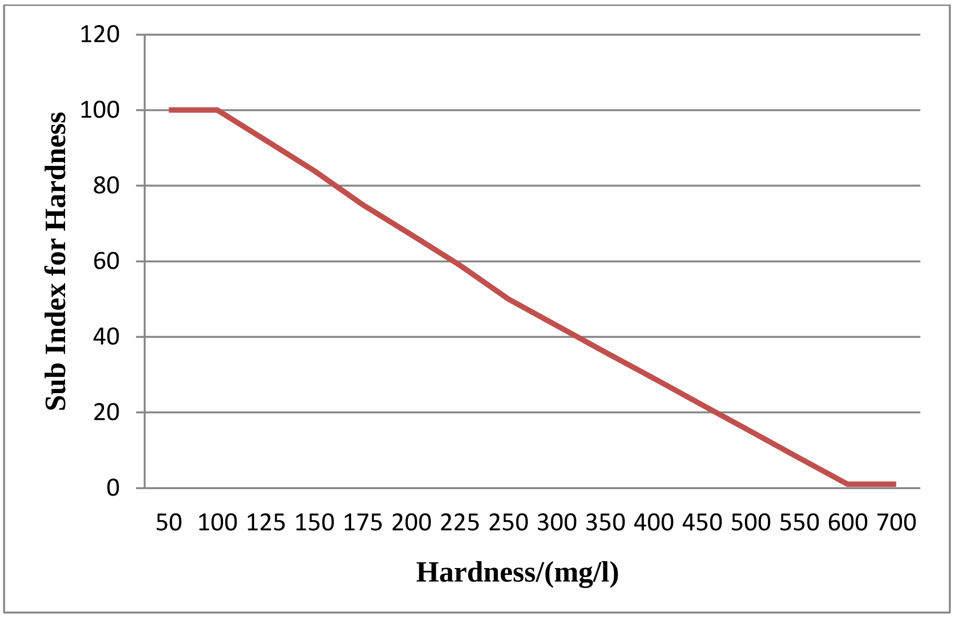

Figure 4.6: Rating Curve for Hardness

High concentration of hardness causes bad taste and forms soap scum. Consumers become aware of changers in hardness. Scales deposit in the treatment works, distribution system and pipe work and tanks within buildings, when hardness of water is higher than 200 mg/l. Table 4.2 shows the classification of hardness in water adopted by Mackenzie, 2010.

Table 4.2: Hard water classification (Mackenzie, 2010)

Hardness range (mg/l as $CaCO_3$)	Description	Comment
0–50	Extremely soft	
50–100	Very soft	
100–150	Soft to moderately hard	Acceptable to most users
150–300	Hard	
> 300	Very hard	

As hardness level of 100 mg/l is acceptable to most users, limit for Class I water was taken as 100 mg/l. During conventional water treatment, hardness cannot be removed. According to SLS 614 (2013), 250 mg/l of hardness level is acceptable for portable water. Therefore limit for Class II water was taken as 250 mg/l. As Class III water will be undergone to advances water treatment, limit for Class III water was taken as 600 mg/l.

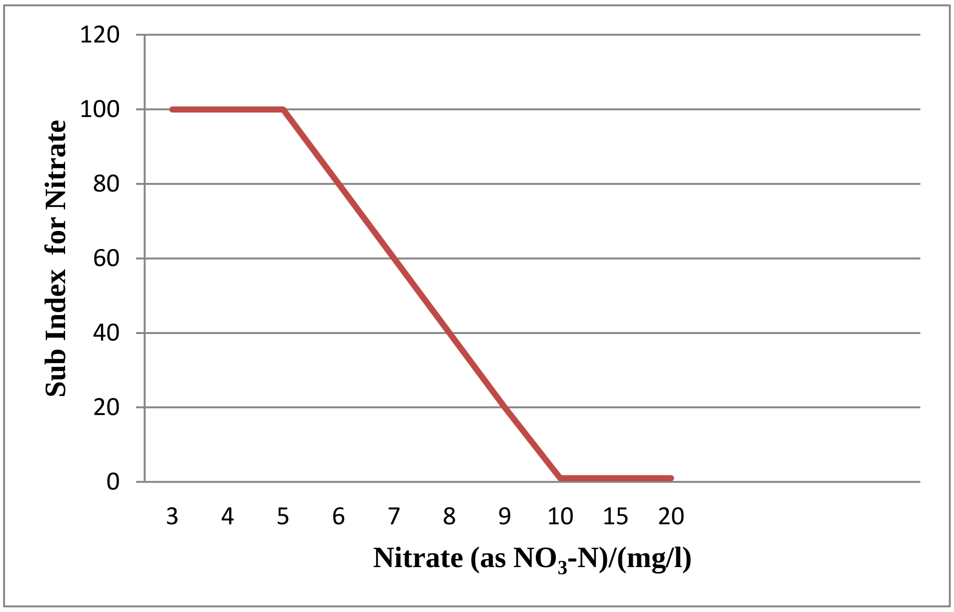

Figure 4.7: Rating Curve for Nitrate

Nitrates add into surface water and ground water as a result of agricultural activities (Excessive use of inorganic nitrogenous fertilizers and unconventional manures by farmers). Wastewater discharges and oxidation of nitrogenous waste products in human and animal excreta, including septic tanks have also been identified as main contributing factors. Nitrate in surface water or ground water is an indication of Nitrate pollution.

Nitrate has a health based guideline value proposed by WHO (2011) of 50 mg/l (as NO_3) to protect against methhaemoglobinaemia in bottle-fed infants (short-term exposure). SLS (2013) requirement is also 50 mg/l (as NO_3). According to proposed ambient water quality standards of Sri Lanka, both drinking water with simple treatment and conventional treatment has Nitrate (as NO_3-N) level of 5 mg/l. Environmental Protection Agency (EPA) has set Nitrate (as NO3) level as 10 mg/l for drinking water to prevent potential health problems.

Therefore limits for Class I and Class III were taken as 5 mg/l and 10 mg/l. Limit for Class II was not set as nitrate cannot be treated using conventional water treatment.

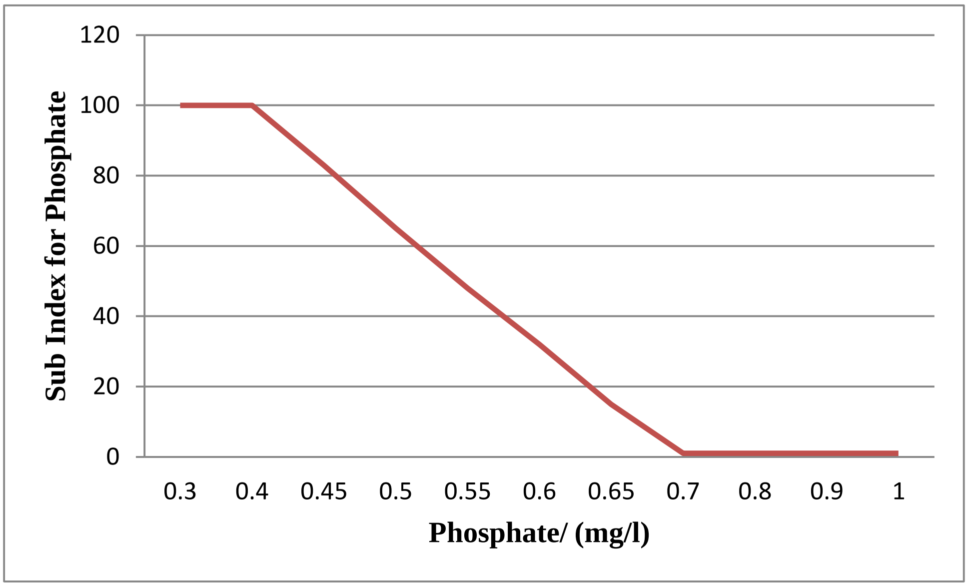

Figure 4.8: Rating Curve for Phosphate

High concentration of phosphorus cause nutrient pollution in water which eventually cause to eutrophication in water resources. Even if there is no direct health impact due to phosphorus, nutrient pollution has impacted the water resources, resulting in serious environmental and human health issues. Phosphorus has no either health based or acceptability guideline proposed by the WHO (2011). However SLS (2003) set 2 mg/l as total phosphate requirement. Limits for Class I and Class III were taken as 0.4 mg/l and 0.7 mg/l considering proposed ambient water quality standards of Sri Lanka and 75/440/EEC. Limit for Class II was not set as phosphate cannot be treated using conventional water treatment.

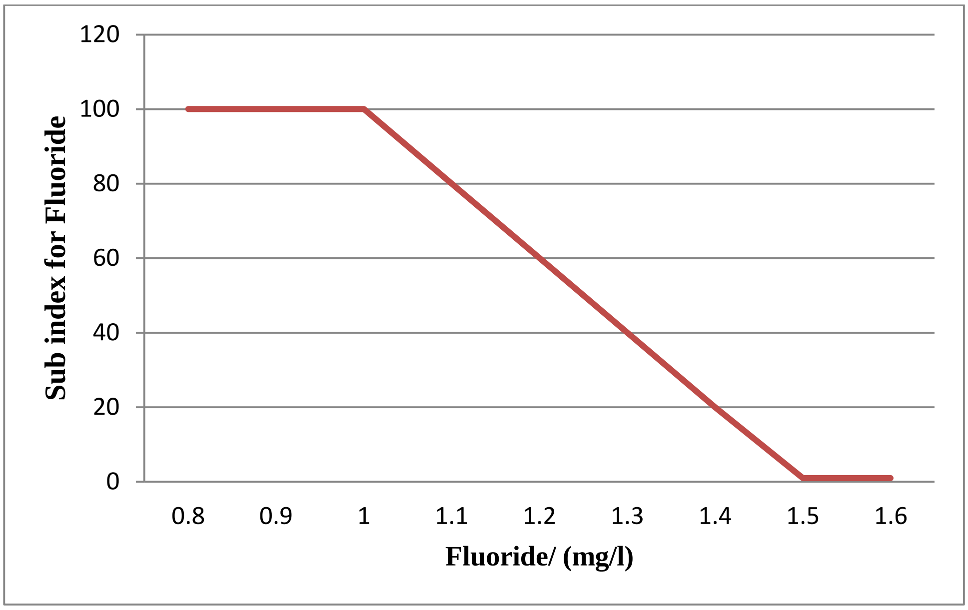

Figure 4.9: Rating Curve for Fluoride

High concentrations of Fluoride carry an increasing risk of dental fluorosis and that progressively higher concentrations lead to increasing risks of skeletal fluorosis. Fluoride has a health based guideline value proposed by WHO (2011) of 1.5 mg/l for drinking water to prevent potential health problems. SLS 614:2013 requirement is 1.0 mg/l. According to proposed ambient water quality standards of Sri Lanka, both drinking water with simple treatment and conventional treatment has Fluoride level of 1.5 mg/l. Therefore limits for Class I and Class II were taken as 1.0 mg/l and 1.5 mg/l. Limit for Class II was not set as Fluoride cannot be treated using conventional water treatment

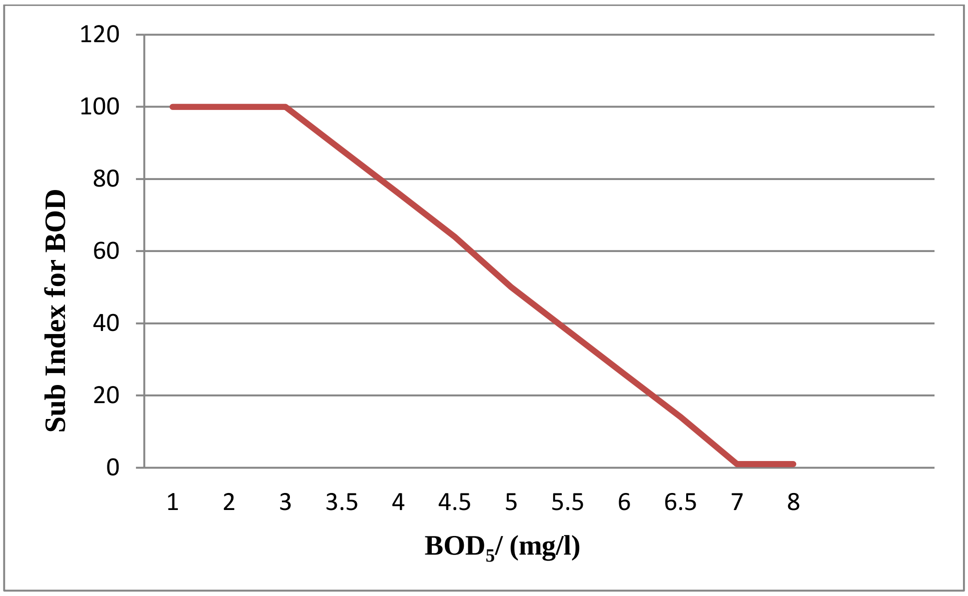

Figure 4.10: Rating Curve for BOD5

There is no direct health impact due to BOD_5 in drinking water. The presence of high BOD_5 may indicate faecal contamination or increases in particulate and dissolved organic carbon from sources of plant and animal. This will cause to restrict water use, necessitate expensive treatment and impair ecosystem health. Limits were taken from proposed Ambient Water Quality Standards of Sri Lanka and EC Directive 75/440/EEC.

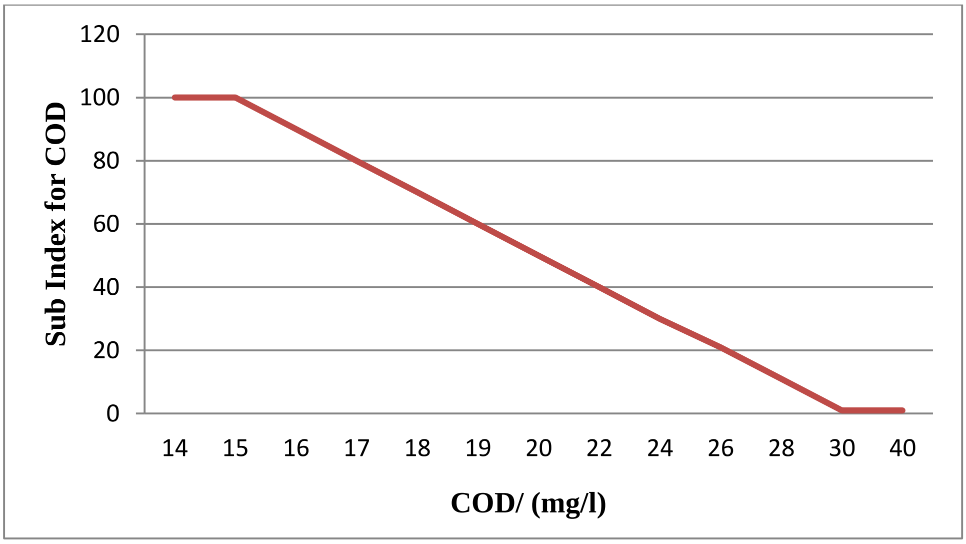

Figure 4.11: Rating Curve for COD

Similar to BOD_5, there is no direct health impact due to COD in drinking water. But presence of high COD is an indication of chemically polluted water source. Limits were taken from proposed Ambient Water Quality Standards of Sri Lanka and 75/440/EEC.

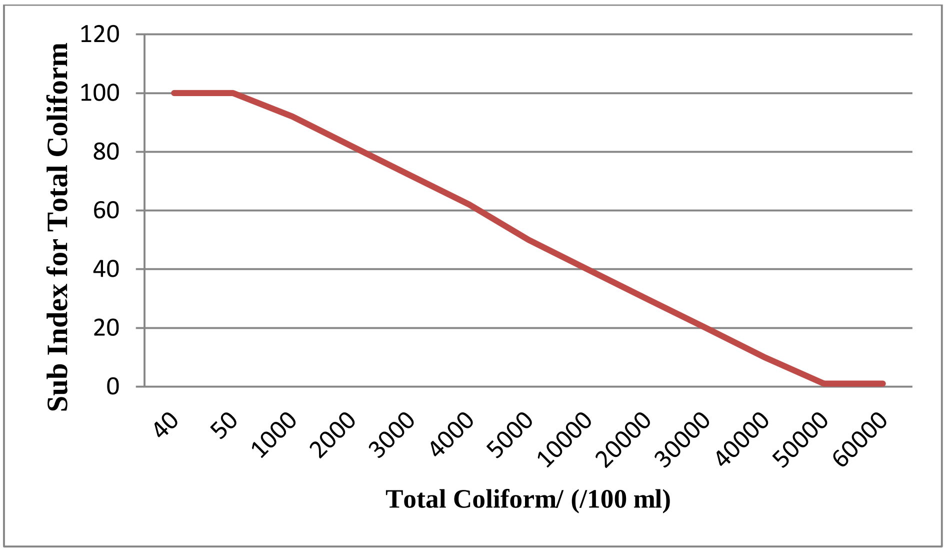

Figure 4.12: Rating Curve for Total Coliform

Limits for Class I, Class II and Class III were taken from EC Directive 75/440/EEC.

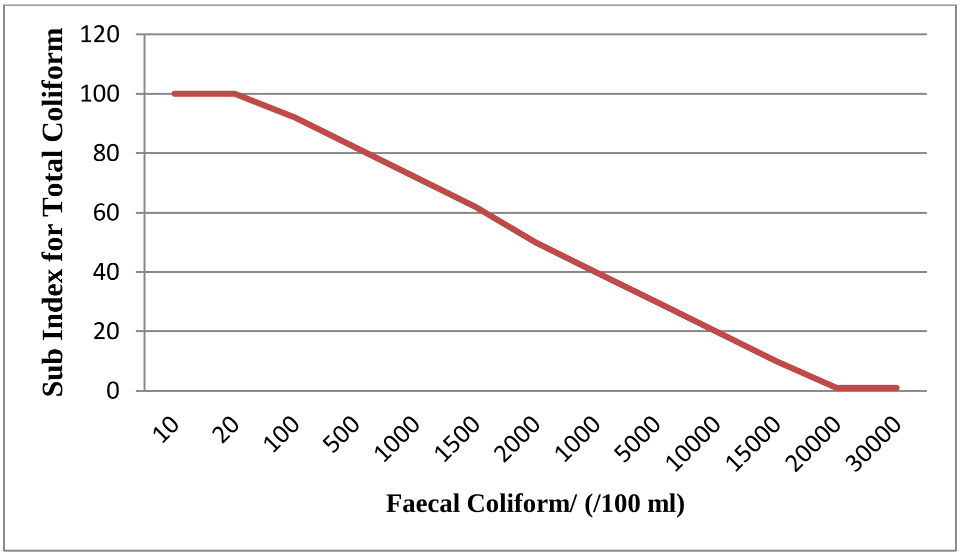

Figure 4.13: Rating Curve for Faecal Coliform

Limits for Class I, Class II and Class III were taken from EC Directive 75/440/EEC.

Using Regression Analysis, different mathematical equations were derived for different ranges of the water quality. Mathematical equations for sub index development are presented in Table 4.3.

Table 4.3: Mathematical equations for sub index development

Parameter	Unit	Range	Sub-Index Equation	R^2
pH		$pH<5.5$	$SI_{pH} = 1$	
		$5.5<pH<6.5$	$SI_{pH} = 96.24\ pH - 529.04$	0.9991
		$6.5\leq pH\leq 8.5$	$SI_{pH} = 100$	
		$8.5<pH\leq 9.0$	$SI_{pH} = (-198.57)\ pH + 1791$	0.9961
		$pH>9.0$	$SI_{pH} = 1$	
Conductivity	mS/cm	$EC\leq 0.75$	$SI_{EC} = 100$	
		$0.75<EC\leq 1.0$	$SI_{EC} = (-205.71)\ EC + 252.67$	0.9894
		$1.0<EC\leq 3.5$	$SI_{EC} = (-19.71)\ EC + 69.52$	0.9997
		$EC\geq 3.5$	$SI_{EC} = 1$	
Sulfate	mg/l	$SO4\leq 150$	$SI_{SO4} = 100$	
		$150<SO4\leq 250$	$SI_{SO4} = (-0.49)\ SO4 + 174.6$	0.9989
		$250<SO4\leq 400$	$SI_{SO4} = (-0.33)\ SO4 + 132.04$	0.9997
		$SO4>400$	$SI_{SO4} = 1$	
Total Dissolved Solids	mg/l	$TDS\leq 500$	$SI_{TDS} = 100$	
		$500<TDS\leq 800$	$SI_{TDS} = (-0.17)\ TDS + 184.92$	0.9987
		$800<TDS\leq 1000$	$SI_{TDS} = (-0.25)\ TDS + 247.4$	0.9993
		$TDS>1000$	$SI_{TDS} = 1$	
Turbidity	NTU	$TB\leq 5$	$SI_{TB} = 100$	
		$5<TB\leq 8$	$SI_{TB} = (-17)\ TB + 185.21$	0.9988
		$8<TB\leq 10$	$SI_{TB} = (-24.6)\ TB + 246.6$	0.9987
		$TB>10$	$SI_{TB} = 1$	
Hardness	mg/l	$TH\leq 100$	$SI_{TH} = 100$	
		$100<TH\leq 250$	$SI_{TH} = (-0.333)\ TH + 133.54$	0.9997
		$250<TH\leq 600$	$SI_{TH} = (-.14)\ TH + 85$	1
		$TH>600$	$SI_{TH} = 1$	
Nitrate (as NO_3-N)	mg/l	$NO_3\leq 5$	$SI_{NO3} = 100$	
		$5<NO3\leq 10$	$SI_{NO3} = (-19.85)\ NO3 + 199.09$	0.9999
		$NO3>10$	$SI_{NO3} = 1$	

Parameter	**Unit**	**Range**	**Sub-Index Equation**	**R^2**
Phosphate	mg/l	PO4 ≤0.4	$SI_{PO4} = 100$	
		0.4<PO4 ≤0.7	$SI_{PO4} = (-332.86)\ PO4 + 232.21$	0.9991
		PO4>0.7	$SI_{PO4} = 1$	
Fluoride	mg/l	F< 1	$S_F = 100$	
		1< F< 1.5	$S_F = (-198.57)\ F + 298.38$	1
		F>1.5	$S_F = 1$	
BOD$_5$	mg/l	BOD <3	$SI_{DD} = 100$	
		3<BOD≤5	$SI_{DO} = (-24.8)\ DO + 174.8$	0.9989
		5<BOD≤7	$SI_{DO} = (-24.4)\ DO + 172.2$	0.9997
		BOD>7	$SI_{BOD} = 1$	
COD	mg/l	COD<15	$SI_{COD} = 100$	
		15<COD≤20	$SI_{COD} = (-10)\ COD + 250$	1
		20<COD≤30	$SI_{COD} = (-4.87)\ COD + 147.28$	0.9997
		COD>30	$SI_{COD} = 1$	
Total Coliform	/100 ml	50< TC	$SI_{TC} = 100$	
		50< TC < 5000	$SI_{TC} = (-0.010)\ TC + 101.60$	0.9976
		5000 <TC < 50000	$SI_{TC} = (-0.001)\ TC + 52.36$	0.9907
		TC > 50000	$SI_{TC} = 1$	
Faecal Coliform	/ 100 ml	20 > FC	$SI_{FC} = 100$	
		20 < FC < 2000	$SI_{FC} = (-0.023)\ FC + 96.31$	0.9831
		2000 FC < 20000	$SI_{FC} = (-0.002)\ FC + 45.92$	0.9307
		FC > 20000	$SI_{FC} = 1$	

During sub index development, rating curves and mathematical equations were developed following concentration – value relationship of the water quality parameters using water quality standards and literature. In NSF WQI, they used expert opinion for the development of rating curves. Similarly, rating curves and mathematical equations were used by Prati et al., (1971), Lee et al., (2014), Boyacioglu (2007), Ramesh et al., (2010), Verlicchi et al. (2011) and Liou et al., (2004) for their sub index development.

4.1.3 Assignment of Weightings

Considering importance of water quality parameters to drinking water quality evaluation, temporary weighting factors were assigned to each water quality parameters. This step was carried out using a Questionnaire Survey distributed among water quality experts and referring to the literature. In the present study, parameters related to health scored higher weighting factors than parameters with acceptability aspects. Weighting factors assigned to individual parameters are present in Table 4.4.

Table 4.4: Temporary Weightings and Weighting Factors of each parameter

Parameter	Unit	Temporary Weightings (Wt)	Weighting Factors (W)
pH		7	0.0700
Conductivity	mS/cm	10	0.1000
Sulfate	mg/l	5	0.0500
Total Dissolved Solids	mg/l	10	0.1000
Turbidity	NTU	7	0.0700
Hardness	mg/l	10	0.1000
Nitrate (as NO_3-N)	mg/l	10	0.1000
Phosphate	mg/l	7	0.0700
Fluoride	mg/l	10	0.1000
BOD_5	mg/l	5	0.0500
COD	mg/l	5	0.0500
Total Coliform	/ml	7	0.0700
Faecal Coliform	/ ml	7	0.0700
		TOTAL	1

Based on responses received to the Questionnaire Survey distributed among water quality experts and literature, higher weightings were assigned to Nitrate, Hardness, TDS, Conductivity and Fluoride. Nitrate causes health impacts on infants if present in high concentrations. Hardness also present in higher concentration in Kala-oya basin. According to hypothesis of Jayasumana et al., (2014), "a strong association between the consumption of hard water and the occurrence of the CKDu has been observed, but the relationship has not been explained consistently". TDS and Conductivity indicate possible presence of dissolved solids in the water. Turbidity, Faecal Colifoms and Total Coaliforms did not received higher weighing as it can remove during water treatment. Due to less significance, BOD_5 and COD were assigned lower weightings. In similar research, Boyacioglu (2007) assigned higher weighting to Arsenic, DO and Total coliform and lower weighting to BOD_5 and COD. In contrast, Ramesh et al. (2010) assigned lower weightings to Hardness and Conductivity.

4.1.4 Formulating a Final Index

To develop the DWQI, sub-indices and weighting factors were aggregated using multiplicative aggregation function. Most commonly used aggregation function is additive aggregation function. However several researchers showed that multiplicative indices are better than additive indices as multiplicative aggregation functions is less affected by extreme values than an additive aggregation functions. Brown et al., (1970), Boyacioglu (2007), Debels et al., (2005) and Sedeño-Díaz et al., (2007) used additive aggregation function while Ramesh et al., (2010) and Verlicchi et al., (2011) used multiplicative aggregation functions.

4.2 Selection of Level of Treatment

During development of water quality index to assess the level of treatment required, each water quality parameter had been thoroughly scrutinized to identify health impacts on consumers. At different ranges, water quality parameters shows different health impacts. Table 4.5 shows the health risks of selected parameters for different ranges.

Table 4.5: Health risks of water quality parameters

Parameter	Range	Health Risk
pH	$6.0<pH<6.5$	No health effects (WHO, 2011)
	$6.5 \le pH \le 8.5$	
	$8.5<pH \le 9.0$	
Conductivity/ (mS/cm)	$EC \le 0.75$	No known health effects
	$0.75<EC \le 1.0$	
TDS/ (mg/l)	$TDS \le 500$	No health effects (WHO, 2011)
	$500<TDS \le 1000$	TDS is an indicator of aesthetics effects of water. An elevated level of TDS, by itself, does not indicate that the water presents a health risk. However, elevated levels of specific ions included in the TDS measurement, such as nitrate, arsenic, aluminum, copper, or lead could present health risks. There are negative health impacts in ingestion of water with low levels of TDS. Therefor it is considered no health impacts due to TDS within this range.
Turbidity/ (NTU)	$TB \le 5$	No health effects (WHO, 2011)
	$5<TB \le 10$	Turbidity indicates that potentially harmful constituents may present in water. Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses and some bacteria.

Parameter	Range	Health Risk
		Therefore it may have adverse health effects due to turbidity within this range.
Hardness/ (mg/l)	TH≤100	No health effects (WHO, 2011)
	100<TH≤250	
	TH> 250	According to hypothesis of Jayasumana et al., (2014), a strong association between the consumption of hard water and the occurrence of the CKDu has been observed, but the relationship has not been explained consistently. The health effects of hard water are mainly due to the effects of the ions dissolved in it, primarily calcium and magnesium (WHO, 2011). Therefore it may have adverse health effects due to hardness.
Nitrate/ (mg/l)	$NO_3 \leq 5$	No health effects (WHO, 2011)
	5<NO3≤10	
	NO3>10	Short-term exposure to nitrate cause methaemoglobinaemia in bottle-fed infants (WHO, 2011).
Phosphate/ (mg/l)	PO4 ≤0.4	No known health effects. (Epidemiological studies have indicated a casual relationship between glyphosate and CKDu (Jayasumana et al., 2014) where glyphosate is degraded in the environment
	0.4<PO4 ≤0.7	
	PO4> 0.7	

Parameter	Range	Health Risk
		into inorganic phosphate. However evidence on the effect of phosphate on CKDu remains poor to date.)
Sulfate/ (mg/l)	SO4≤150	No health effects (WHO, 2011)
	150<SO4≤250	
	SO4>250	Sulfate level greater than of 750 mg/l is linked with a self-reported laxative effect (WHO, 2004).
Fluoride/ (mg/l)	F≤1	No health effects (WHO, 2011)
	1< F≤1.5	
	F>1.5	High Fluoride levels cause dental fluorosis and skeletal fluorosis. According to Chandrajith et al., (2011), inorganic fluoride intake can cause a considerable nephrotoxic effect on human but this toxicity depends strongly on Na+ and Ca2+ activities where higher Ca2+ activity aggravates the damage caused by fluoride.
BOD_5/ (mg/l)	$BOD_5 \leq 3$	No known health effects
	$3 < BOD_5 \leq 5$	
COD/ (mg/l)	COD≤15	No known health effects
	15<COD≤20	
Total Coliform	-	Total Coliforms indicates possible presence of pathogenic organisms in water and may

Parameter	Range	Health Risk
		have health risks.
Faecal Coliform	-	Faecal Coliform indicates possible presence of pathogenic organisms in water and may have health risks.

Some water quality parameters have no direct health impact to the consumers. In that instance, it was assumed that there are no known health effects due to that parameter.

4.2.1 Water Quality Analysis

This specimen calculation shows how water quality sample is categorised to respective Class of water. Table 4.6 shows the water quality analysis for month of January for location 1.

Table 4.6: Water quality analysis for Location 1

Parameter	Value (a)	Class I Threshold limit (b)	Health Risk Factor (0 or 1) (c)	Occurrence of the individual parameter (d)=(a)/(b)* 100%	WQI_i (e)=(c)*(d)
pH	8.3	8.5	1	0.92	0.92
Conductivity/(mS/cm)	0.245	0.75	1	0.32	0.32
TDS/ (mg/l)	122	500	1	0.24	0.34
Turbidity/ (NTU)	13.11	5	0	2.62	0
Hardness/ (mg/l)	362	100	0	3.52	0
Nitrate/ (mg/l)	0.72	5	1	0.14	0.14

Parameter	**Value**	**Class I Threshold limit**	**Health Risk Factor (0 or 1)**	**Occurrence of the individual parameter**	**WQI $_i$**
Phosphate/ (mg/l)	0.62	0.4	1	1.55	1.55
Sulfate/ (mg/l)	6.7	150	1	0.04	0.04
Fluoride/ (mg/l)	0.51	1	1	0.51	0.51
BOD_5/ (mg/l)	8.2	3	1	2.72	2.72
COD/ (mg/l)	16	15	1	1.07	1.07
Total Coliforms	1000	50	0	>1	0
Faecal Coliforms	450	20	0	>1	0
WQI $_{Total}$					0

Water Quality Index for location 1, WQI $_{Total} = \frac{\sum_{i=1}^{11} WQI_i}{11}$

There are health risks when Turbidity is 13.11 and Hardness is 362. And Faecal Coliforms and Total Coliforms are not in the desirable range.

Therefore $WQI_{Turbidity} = 0$, $WQI_{Hardness} = 0$, $WQI_{Faecal\ Coli.} = 0$ and $WQI_{Total\ Coli.} = 0$. Hence WQI $_{Total} = 0$

Therefore water quality of location 1 is not satisfied for Class I water. To find the respective category of water quality, similar procedure should be followed for Class II and Class III water.

4.3 Evaluation of the drinking water quality status in the study area

The proposed WQI to assess level of treatment was calculated for 16 locations in three reservoirs of Kala-oya basin. It categorises sampling locations in to three categories; Class I, Class II and Class III. It was observed that all the sampling locations were categorized as Class III of water quality which requires advanced water treatment. None of the locations were categorised as Class I or Class II water quality which need simple treatment or conventional treatment.

Drinking water, regardless of its source, may be subjected to one or more of a variety of treatment processes aimed at improving its safety and/or aesthetic quality. These processes are selected in each case according to the source water and the constituents and contaminants that require removal. Results of this study indicated that prior to use of water for drinking; different levels of water treatments are required. As none of the locations has Class I category, simple treatment such as boiling and filtration is not recommended. In conventional treatment, surface water often undergo coagulation, flocculation, sedimentation, filtration, stabilization and disinfection for turbidity removal and microbial quality control. According to the results, only conventional water treatment is not adequate for removing constituent present in water in the study area. Further to remove hardness and other undesirable constituents from source water, advanced water treatment is recommended. Some of the advanced water treatment technologies are softening, iron exchange and adsorption.

According to the results, reservoirs in Kala-oya basin are not in a position to provide safe drinking water without appropriate treatment. All the sampling locations need advanced water treatment. Similar situation may prevail throughout the dry zone. This indicates that water resources of Kala-oya basin are polluted to an alarming level where low- cost treatment methods are no longer effective.

4.4 Evaluation of spatial and temporal variability of water quality in study area

The proposed DWQI was calculated for 16 locations in three reservoirs of Kala-oya basin. The spatial and temporal variability of surface water of three reservoirs are graphically presented in Figure 4.14 to 4.16.

The results revealed that DWQI scores varied between 38 to 80. The number of locations categorized as 'Good', 'Fair', 'Marginal', 'Poor' and 'Very Poor' was shown in Figure 4.17. It was observed that surface water samples from 78% of sampling locations were categorized as ‘Marginal’ water quality. Results of remaining locations showed ‘Fair’ and ‘Poor’ water quality. In none of the locations, the score of the DWQI was determined as ‘Good’ or ‘Very Poor’.

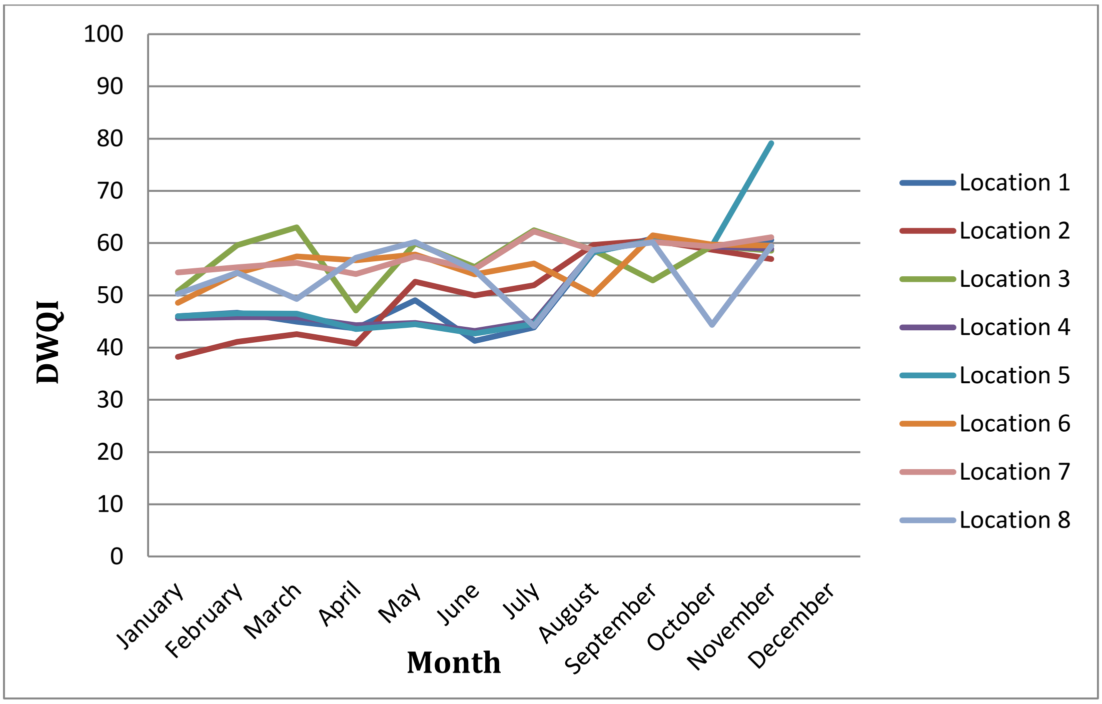

Figure 4.14: DWQI for Kalawewa Reservoir

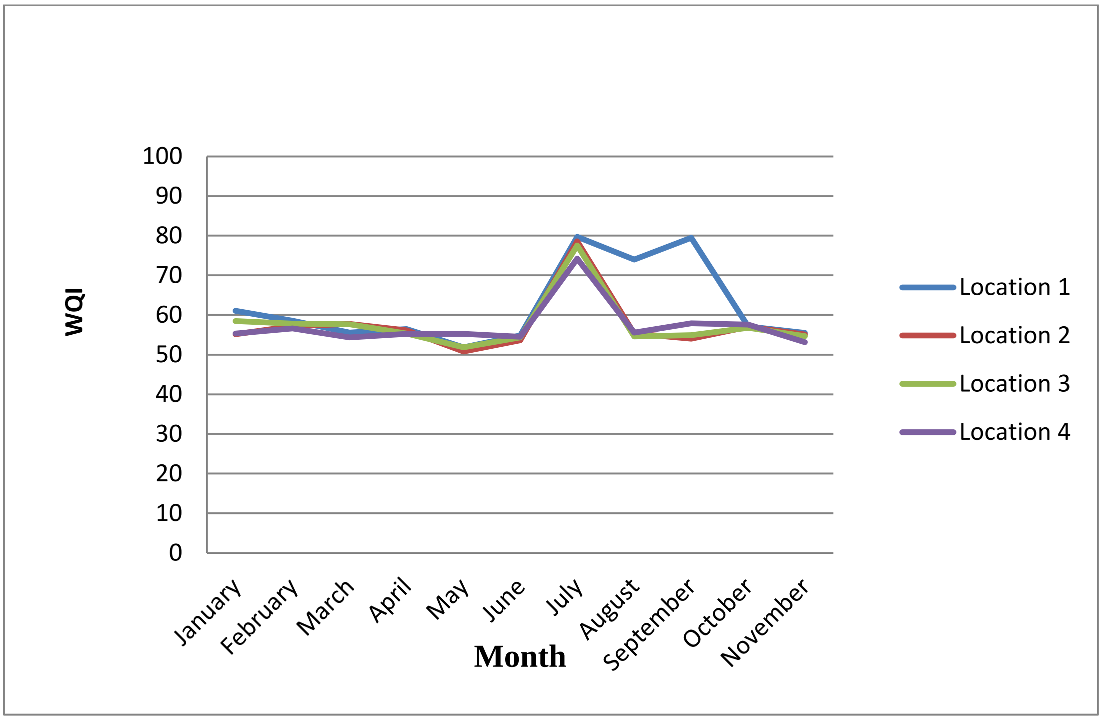

Figure 4.15: DWQI for Dambulu-oya Reservoir

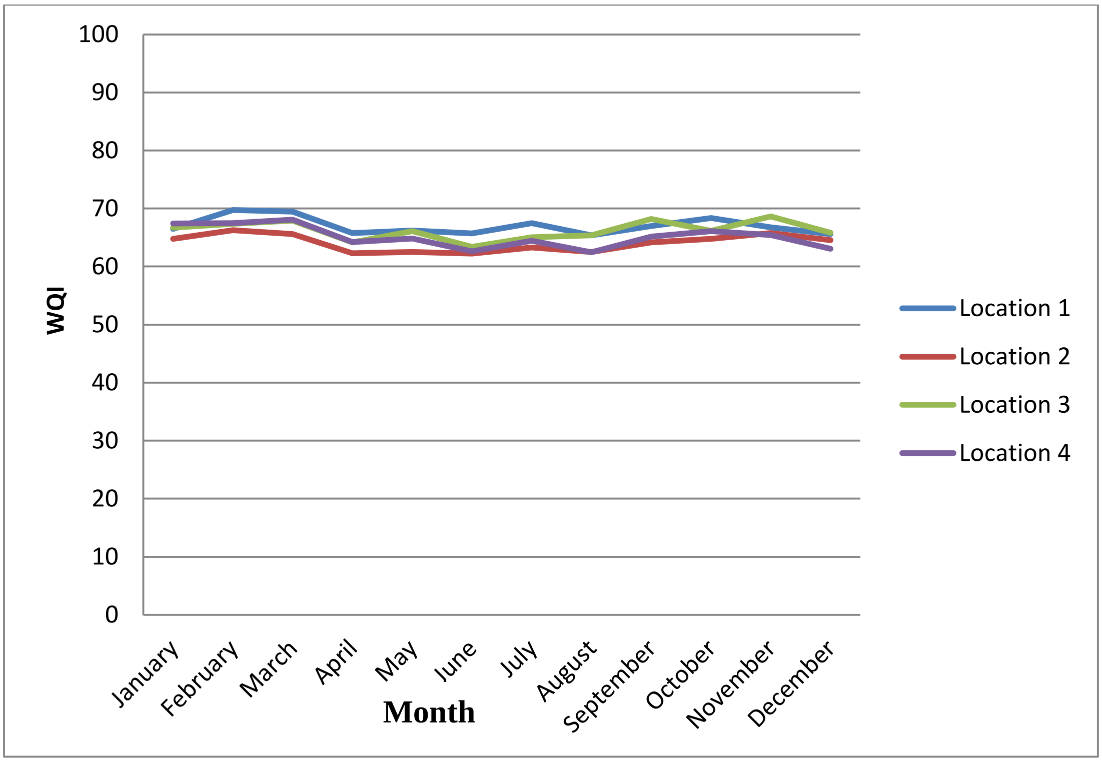

Figure 4.16: DWQI for Bowathenna Reservoir

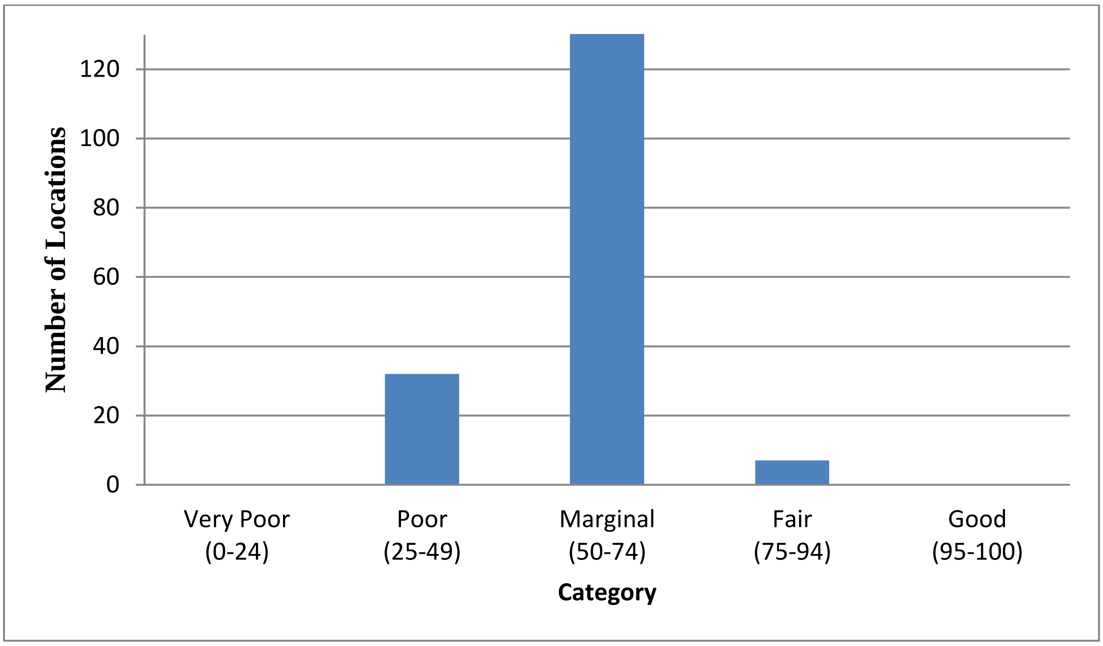

Figure 4.17: Categorizing of Locations using DWQI

The overall situation of surface water of three reservoirs according to the proposed DWQI is shown in Figure 4.18 to 4.20. For all three reservoirs, DWQI varies between 50 to 67. Therefore water quality can be described as 'Marginal'.

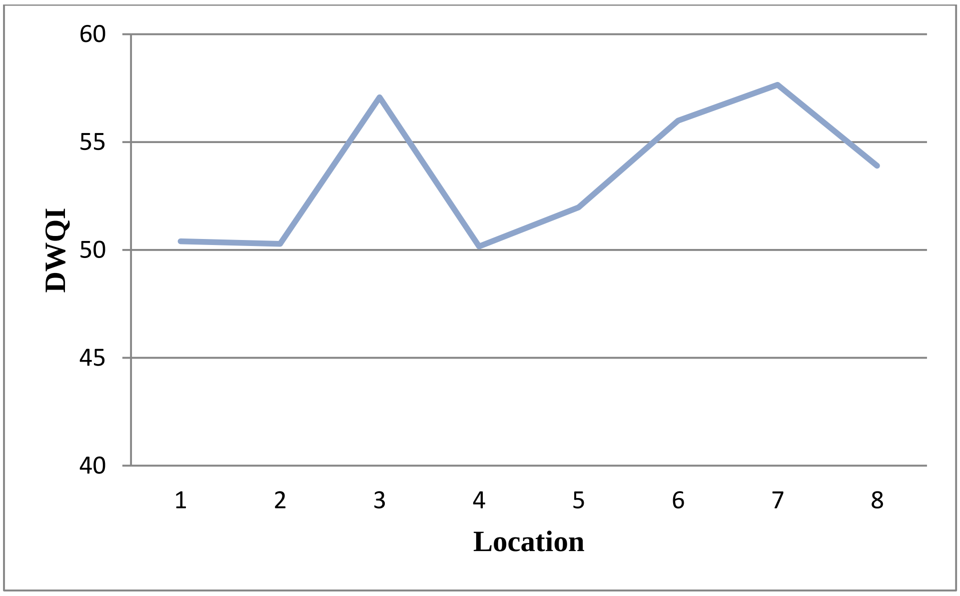

Figure 4.18: Spatial variation of annual average DWQI for Kalawewa Reservoir

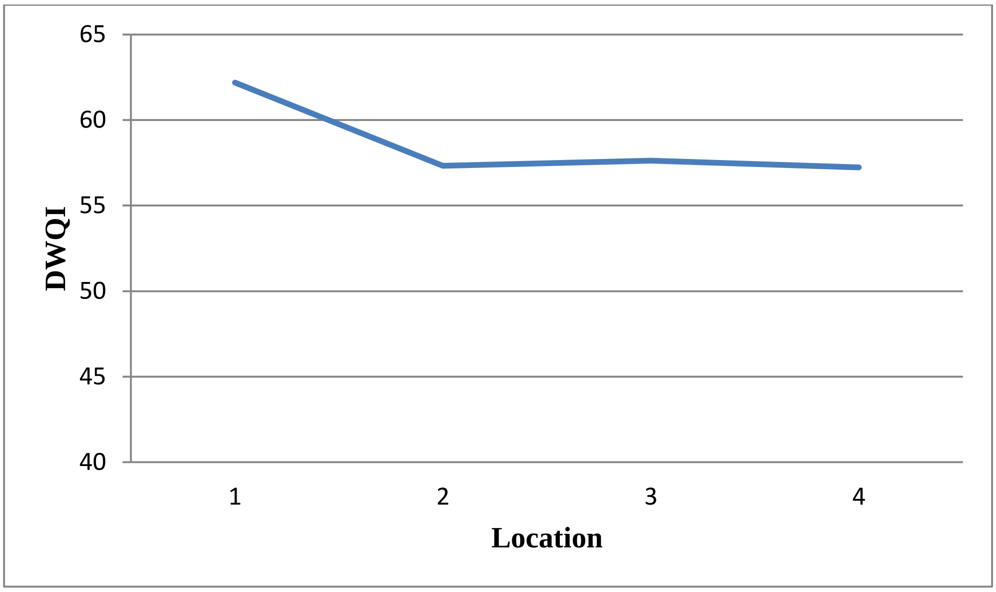

Figure 4.19: Spatial variation of annual average DWQI for Dambulu-oya Reservoir

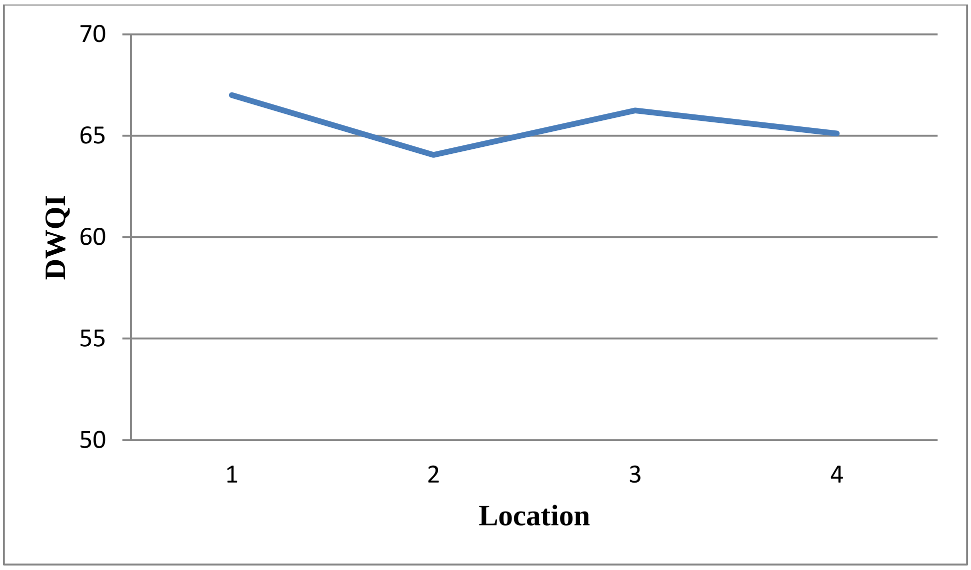

Figure 4.20: Spatial variation of annual average DWQI for Bowathenna Reservoir

The Temporal variation of DWQI at three reservoirs in the Kala-oya basin from January to December, 2014 was shown in Figure 4.21 to 4.23 which indicate higher scores during the October to December. According to monthly average rainfall figures, lowest occurrence of rainfall has been during the period of June to August while highest figures are recorded during October to December where monsoon occurs (MASL, 2003). During monsoon season, increase of water capacity of reservoirs causes to dilute the concentrations of water contaminants which give better water quality. Sharma et al., (2011) calculated different indices for different seasons; for River Yamuna and revealed that the pre-monsoon season is worst affected with WQI falling largely into poor category throughout the study period with slight improvement seen in both monsoon and post-monsoon seasons. Similar findings have been discussed in Barceló-Quintal et al., (2013). This confirms the research finding of this study of better water quality indices in monsoon season.

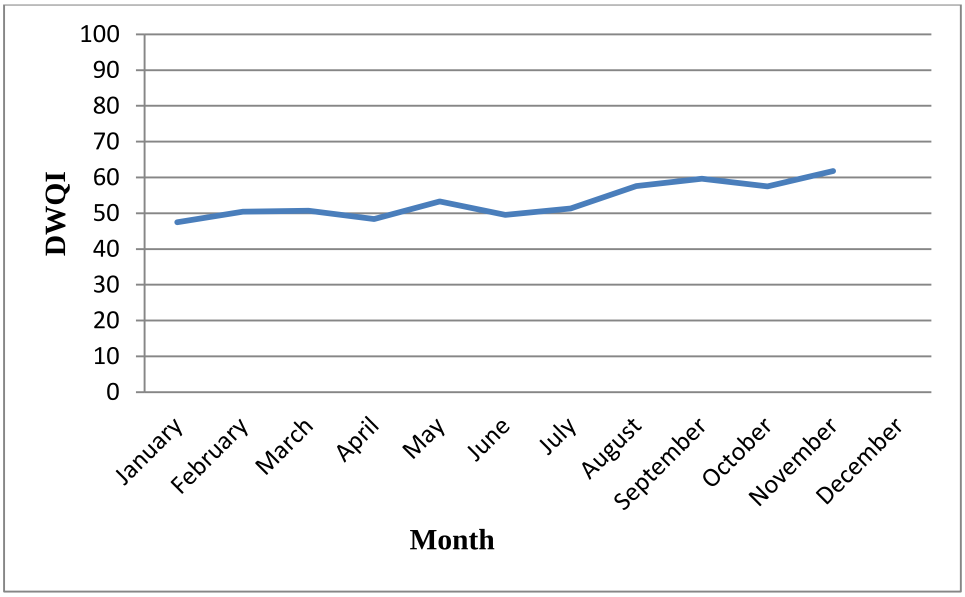

Figure 4.21: Temporal variation of DWQI for Kalawewa Reservoir

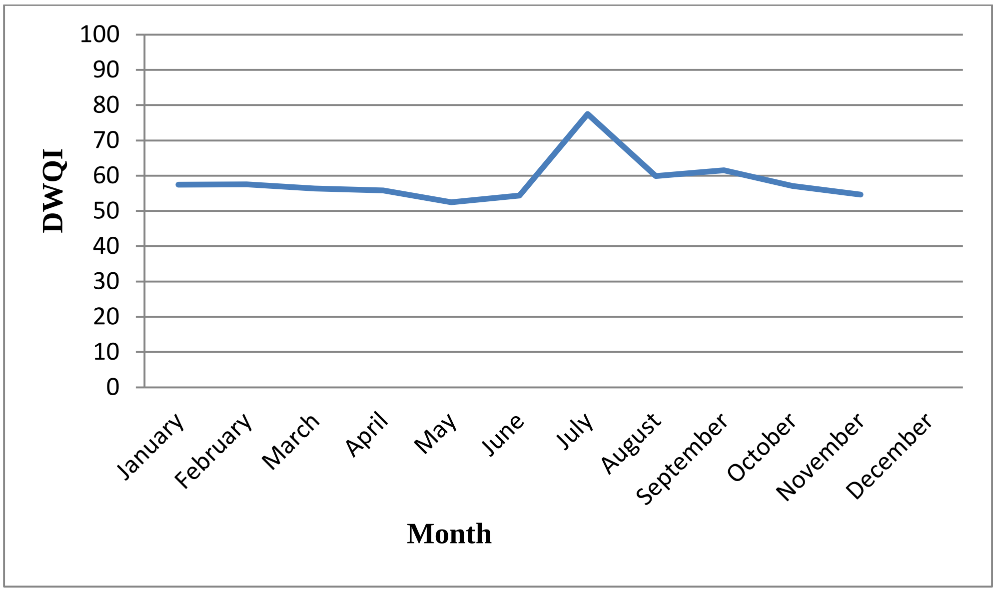

Figure 4.22: Temporal variation of WQI for Dambulu-oya Reservoir

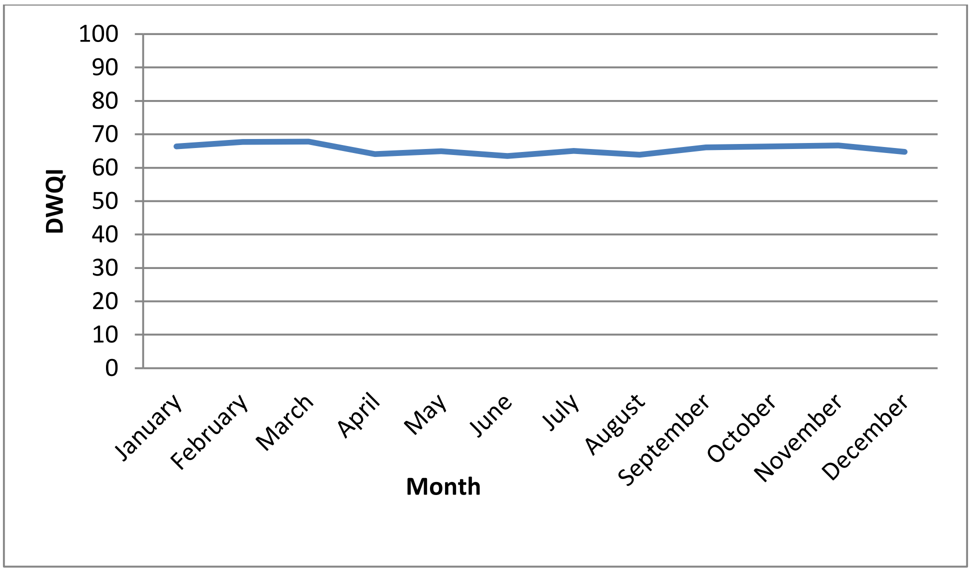

Figure 4.23: Temporal variation of DWQI for Bowathenna Reservoir

4.5 Pollution at Kala-oya basin

Results of the study revealed that surface water of Kala-oya basin is polluted. It is not suitable for drinking after simple treatment such as filtering and boiling or conventional treatment. To use the water for drinking, it needs to undergo advanced water treatment.

Water is considered to be polluted when it contains enough foreign material to make it unfit for a specific beneficial use. However, the term pollution usually implies that human activity is the cause of the poor water quality. Some of the examples of human practice which are source for contaminations of water in Kala-oya basin are agricultural activities such as applications of fertilizers, manure, and pesticides. Surface erosion washes chemical residues into streams which eventually cause surface water pollution. Dumping of waste to water ways is another main reason for water pollution.

Surface water can become contaminated due to both point sources and non-point sources. Examples of point source pollution are discharges from sewage treatment plants, municipal and industrial wastewater effluent, runoff and leachates from waste discharge sites. Non-point source pollution include runoff of excess fertilizers, herbicides and pesticides from agricultural land and residential areas, oil, grease and toxic chemicals from urban runoff and sediment from improperly managed construction sites, crop and forest lands and eroding stream banks (EPA,2015). In Kala-oya basin, most of the pollution is due to non-point sources.

Previous water quality monitoring studies at Kala-oya basin has been reported that most of the minor and medium capacity tanks have shown eutrophication effects due to accumulation of nutrients (MASL, 2003). According to EPA, the critical level for Phosphate for occurrence of eutrophication in reservoir is 0.08 mg/l (EPA, 1988). At present study, higher Phosphate levels which are greater than the EPA standard were observed in Kalawewa and Dambulu-oya reservoirs throughout the year 2014. As most of the reservoirs in Kala-oya basin are interconnected through cascade irrigation systems, there is a possibility for occurrence of eutrophication in the future due to the enrichment of Phosphate in waters of Kala-oya basin.

Elevated concentration of BOD_5 is observed in all three reservoirs compared to Proposed Ambient Water Quality Standards of Sri Lanka of 3 mg/l with simple treatment. The presence of high BOD_5 may indicate faecal contamination or increases in particulate and dissolved organic carbon from sources of plant and animal in waters of Kala-oya basin. High concentrations of COD also observed in

Dambulu-oya and Bowathenna reservoirs. This indicates chemically pollution of water.

4.6 Sensitivity Analysis of the proposed DWQI

DWQI scores calculated using water quality monitoring data were used to examine the relative contribution of parameter to resulting scores. Spatial and temporal variation of DWQI calculated without mostly violated parameters for three reservoirs are shown in Figure 4.24 to 4.26. Results of the sensitivity analysis revealed that Phosphate was the most significant parameter for Kalawewa reservoir. For Dambulu-oya reservoir, Turbidity, Hardness and Phosphate were the mostly violated parameters but Turbidity is the most significant parameter. For Bowathenna reservoir, BOD_5, COD and Turbidity are the mostly violated parameters but Turbidity was identified as significant parameter.

Turbidity, Hardness and Phosphate are the mostly significant parameters in the Kala-oya basin. They often violated legal limits of Proposed Ambient Water Quality Standards of Sri Lanka.

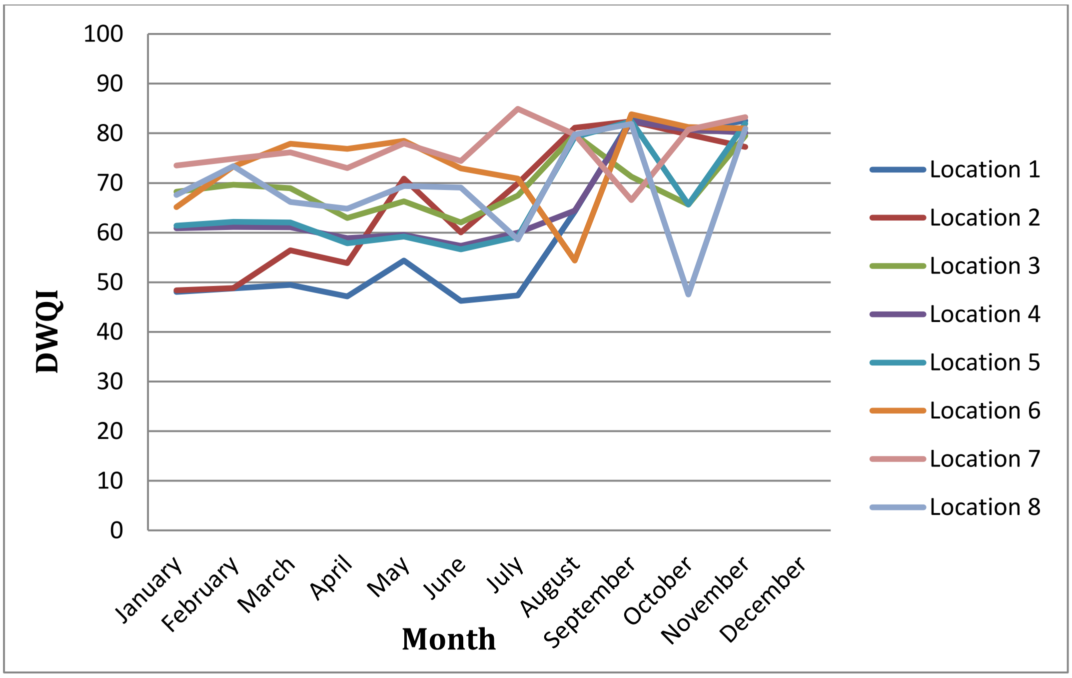

Figure 4.24: Variation of DWQI without Phosphate for Kalawewa Reservoir

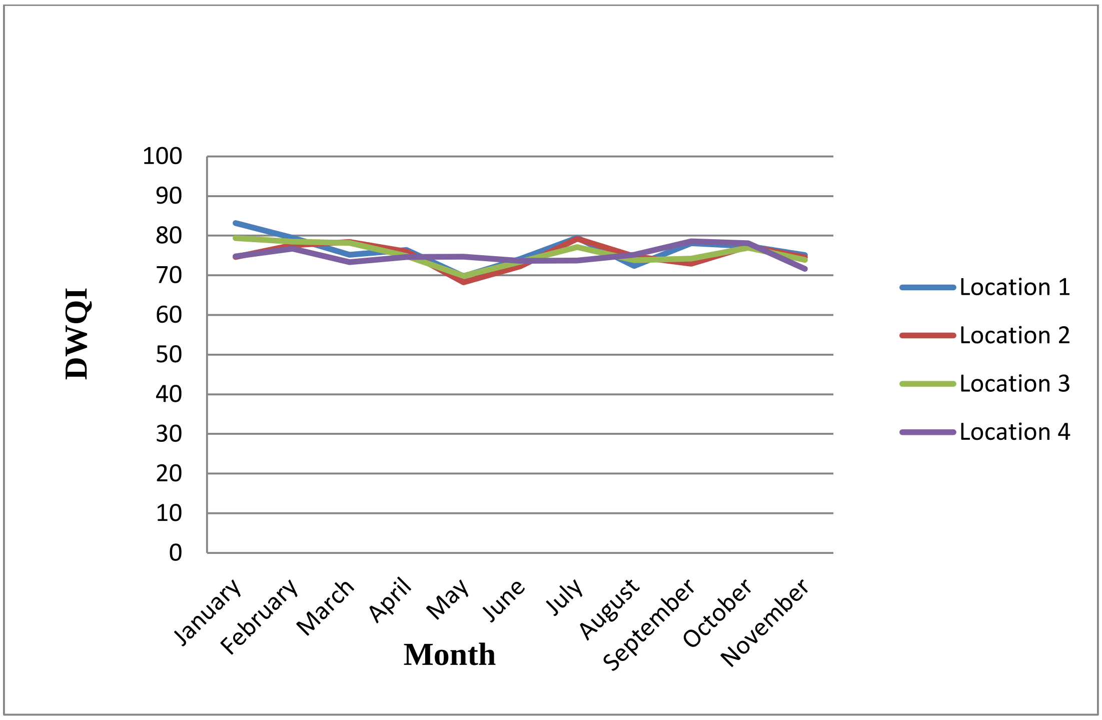

Figure 4.25: Variation of DWQI without Turbidity for Dambulu-oya Reservoir

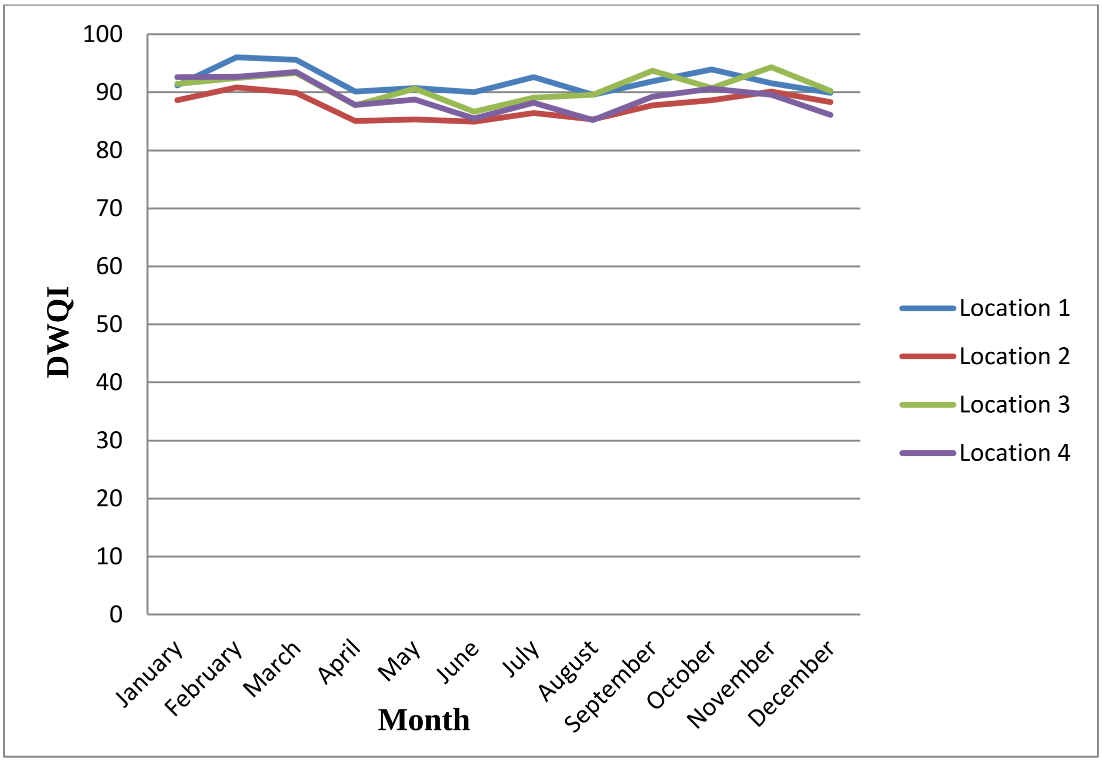

Figure 4.26: Variation of DWQI without Turbidity for Bowathenna Reservoir

The reason for Turbidity in water is due to presence of suspended matters such as clay, silt, colloidal organic particles, viruses, bacteria, algae, planktons and other microscopic organisms. This affects the acceptability of water to consumers (WHO, 2011). And also it gives an indication of possible presence of contamination that would be a concern for quality of water. Analytical results of raw water quality data revealed that detected values of turbidity of three reservoirs are high through-out the year 2014 with respect to the Proposed Ambient Water Quality Standards of Sri Lanka of 5 NTU with simple treatment. This may associated with the heavy rainfall reported in the area during October to December and man-made activities. For safe drinking water, Turbidity is removed by coagulation, sedimentation and filtration.

According to Mackenzie, 2010, Hardness in natural waters comes from the dissolution of minerals from geologic formations that contain calcium and magnesium. Water of Kalawewa and Dambulu oya reservoirs are hard which always exceed the desirable limit of Proposed Ambient Water Quality Standards of Sri Lanka of 250 mg/l. High concentration of hardness causes bad taste and forms soap scum. Consumers become aware of changers in hardness. Scales deposit in the treatment works, distribution system and pipe work and tanks within buildings, when hardness of water is higher than 200 mg/l. High concentration of hardness in drinking water is a common problem in Kala-oya basin (Vidange et al., 2005). According to hypothesis of Jayasumana et al., (2014), a strong association between the consumption of hard water and the occurrence of the CKDu has been observed, but the relationship has not been explained consistently. Therefore removal of hardness prior to drinking of water from irrigation tanks will be mandatory in future. The conventional method to remove hardness from water is lime-soda softening. Other benefits of lime-soda softening include removal of heavy metals, Natural Organic Matter, turbidity, and pathogens. Due to lime soda softening, quality of water is improved which cause to reduce the cost for corrosion of distribution system. Added advantage of lime soda softening is removal of heavy metals such as arsenic, chromium, iron, lead, manganese, and mercury (Mackenzie, 2010).

Elevated concentration of Phosphate is observed in both Kalawewa and Dambulu-oya reservoirs compared to Proposed Ambient Water Quality Standards of Sri Lanka which is 0.7 mg/l with simple treatment. With the intense rainfall, applied fertilizers, crop residues, animal excreta along with the soil sediments are being transported through the surface run off and accumulated in the tanks resulting in increased concentrations of Phosphate in reservoir water (Wijesundara, et. al, 2012) As being an intensely irrigated watershed, Phosphate is more likely to be occurring from agricultural run-off of fertilizers applied to the paddy in Kala-oya basin. High concentration of phosphorus cause nutrient pollution in water which eventually cause to eutrophication in water resources. Even if there is no direct health impact due to phosphorus in drinking water, nutrient pollution has impacted the water resources, resulting in serious environmental and human health issues. Therefore, it is necessary to take mitigation action to reduce the non-point pollution due to Phosphate in Kala-oya basin.

4.7 Possibilities and Limitations of the application of proposed DWQI

4.7.1 Possibilities

The DWQI can be used to assess the suitability of water bodies for drinking with level of treatments. It successfully composite water quality parameters and gives an overall status of the water body. Possibilities of use of the DWQI is widening because it is easy to calculate and flexible in selecting parameters, evaluating criteria, assigning weighting factors and classification of status of water quality.

The DWQI shows an overall suitability of water bodies for drinking with level of treatments. Due to its simple and readily understandable nature, it can be used by the managers and decision makers to express the possible use of the water body. Also it can be easily understood and used by the public as it turns complex water quality data into simple number. DWQI provide information to general public about the condition of the water quality of a water body; whether it is acceptable or not for drinking. Therefore proposed DWQI can be applied for watersheds in other parts of the country.

4.7.2 Limitations

Selection of parameters, development of rating curves and assigning weighting factors are highly subjective and which needs expertise and experience in water quality. Lack of objectivity is a major limitation of the proposed methodology. In order to reduce the subjectivity associated with development of water quality indices, Sedeño-Díaz et al., (2007), Liou et al., (2004) and Mostafaei , (2014) and other several researchers suggested statistical approaches. However, based on literature, indices developed following statistical methods are more complex to apply than the conventional indices. For future development of indices with less subjectivity, statistical approaches are recommended.

In this study, some important water quality parameters such as Pesticides and Heavy metals were not entered into the index due to unavailability of data. Boyacioglu (2007) and Ramesh et al. (2010) incorporated fecal coliforms, heavy metals and fluoride to their indices which were developed for assessing drinking water quality. Khan et al., (2003) applied CCME WQI to assess drinking water quality without microbiological parameters. It is more reliable if it can include physical, chemical and biological parameters to the index instead of only physico-chemical parameters. However in other situations, any additional parameters can be added to the existing DWQI due to its flexible structure.

In Sensitivity Analysis, it was observed that the parameter given the greatest weightings always has the greatest influence on water quality index scores regardless of the degree of impairment of that variable. In order to eliminate this influence, Cude, 2001 and Al-Shujair, 2014 has used un-weighted harmonic square mean aggregation function. This formula allows the most impaired variable to report the greatest influence on the water quality index. For future development of Water Quality Indices, un-weighted aggregation functions can be incorporated.

Though the DWQI can be used to quantify composite water quality conditions, it should not be substituted for a more detailed intensive assessment.

5. CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

Water Quality Indices have been developed to assess the suitability of water sources for its intended uses which give the status of water quality in water sources. Over past few decades, deterioration of water sources in Sri Lanka is getting critical. It is worsen due to endemic occurrence of Chronic Kidney Disease of unknown etiology reported in certain parts of the dry zone as a new and emerging health issue and is being attributed to consumption of water with undesirable constituents. Ground water plays a significant role as a drinking water source in rural communities of dry zone while surface water is not that vital. In such circumstances, feasibility of use of water from traditional village irrigation tanks for drinking is utmost importance.

To assess the surface water in dry zone, DWQI was developed following four steps; (1) Selection of parameters considering their importance to the assessment study and availability of data. They were pH, Conductivity, TDS, Turbidity, Hardness, Nitrate, Phosphate, Sulfate, BOD_5 and COD, (2) Development of sub-indices by converting different units and rangers of water quality measurements for selected parameters into common scale, (3) Assigning weighting to the selected parameters considering their contribution to final index. This step was carried out using a Questionnaire Survey distributed among water quality experts, (4) Aggregation of sub-indices and weightings using aggregation equations producing final index. DWQI was then applied to Kala-oya basin in order to characterize the spatial and temporal variability of surface water quality in the basin. DWQI was calculated from ten physicochemical parameters, periodically measured at 16 sampling sites in three reservoirs; Kalawewa, Dambulu-oya and Bowathenna, from January to December 2014.

Results of this study concluded that prior to use of water for drinking; different levels of water treatments are required. As none of the locations has Class I water quality, simple treatment is not recommended. Conventional water treatment is also not adequate. Further to remove Hardness, Nitrate, Fluoride and Sulfate from water, advanced water treatment is recommended.

The developed drinking water quality index provides an effective tool for communicating quality data to the public, policy makers and other stakeholders. The index can also be used as a means of examining trends in quality. The DWQI shows an overall suitability of water bodies for drinking with level of treatments. It can be also applied for watersheds in other parts of the country.

Results of the sensitivity analysis revealed that relative contribution of parameter to resulting scores. Phosphate was the most significant parameter for Kalawewa reservoir. For Dambulu-oya reservoir, Turbidity, Hardness and Phosphate are the mostly violated parameters but there were no significant changes in the index scores. Turbidity was identified as significant parameter for Bowathenna reservoir.

Results of this study concluded that prior to use of water for drinking; different levels of water treatment are required. As none of the locations has ‘Good’ water quality, simple treatment is not recommended. According to calculated DWQI, conventional water treatment is recommended for ‘Marginal’ to ‘Fair’ water quality. Further to remove Hardness, TDS, Nitrate, Phosphate and Sulfate from water, conventional water treatment with advanced water treatment is recommended.

The DWQI shows an overall suitability of water bodies for drinking with level of treatments. Proposed DWQI can be applied for watersheds in other parts of the country.

5.2 Recommendations

Following areas are recommended in order to upgrade the proposed DWQI and to improve the water quality of Kala-oya basin.

- It is not very practical and economical to measure all the defined water quality parameters for assessment of water recourses. However to get a more reliable DWQI score, it is necessary measure some important water quality parameters and incorporated into DWQI. Therefore it is recommended to measure and incorporate some drinking water quality parameters such as Faecal coliforms, Fluoride and Heavy metals in future development of WQIs.

- Selection of parameters, development of rating curves and assigning weighting factors are highly subjective and which needs expertise and experience in water quality. Subjectivity associated with index development can be reduced by following statistical approaches. It is recommended to adopt statistical methods in future development of WQIs.
- Results of the study revealed that surface water of Kala-oya basin is polluted. It was observed that concentration of Phosphate and Turbidity always exceed the respective guidelines. To prevent pollution in water resources in Kala-oya basin, necessary mitigatory actions should be implemented.
- Results of this study indicated that prior to use of water for drinking; different levels of water treatment are required. It is not advisory to use simple treatment such as boiling and filtration. Conventional water treatment is also not adequate. In order to use water for the purpose of drinking, it is recommended advanced water treatment.

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Appendix A: Questionnaire Survey

Questionnaire Survey

Thank you for your participation in this survey intended to develop a **Water Quality Index** to assess the suitability of surface water of dry zone of Sri Lanka. Through this Water Quality Index we plan to transform large quantities of WQ data into a single number which represents the status of overall water quality that allow to assess changes in water quality spatially and temporally.

Over past few decades, deterioration of water sources in the country is getting critical due to endemic occurrence of Chronic Kidney Disease of unknown etiology reported in certain parts of the dry zone as a new and emerging health issue and is being attributed to consumption of water. Ground water plays a significant role as a drinking water source in rural communities of dry zone while surface water is not that vital. In such circumstances, feasibility of use of water from irrigation tanks for drinking is utmost importance. The objective of this study is to develop a Water Quality Index to assess the suitability of water of irrigation tanks for drinking and level of treatment.

Kala-oya basin was selected to represent the dry zone due to availability of past WQ data and that shows the significant deterioration of WQ. Ambient Water Quality Standards for Inland Waters of Sri Lanka proposed by CEA was considered as the benchmark to formulate the Water Quality Index. Relevant acceptability levels of parameters of CLASS I waters with simple treatment are provided for your information.

Attached you will find some water quality parameters which are based on water sampled from surface water source of irrigation tanks in Kala-oya basin. For each parameter, please provide score considering importance of it's as a water quality indicator for drinking (higher scores for more important parameters).

Name:		
Place of Work:		
Category:	Academic/Water Engineer/Chemist/Other	

Parameter	Unit, Type of Limit	Ambient water quality standards (CLASS 1 Waters- Drinking water with simple treatment)	**Weighting Score (out of 10)**	Remarks (if any)
Total Dissolved Solids	mg/l	-		
Conductivity	µS/m	750		
Odour	-	unobjectionable		
Taste	-	unobjectionable		
Turbidity	NTU, max	5		
Total hardness	as $CaCo_3$ mg/l,	250 des., 600 max.		
Alkalinity	mg/l	-		
pH		6.0-8.5		
Dissolved Oxygen at 25^0C	mg/l, min	6		
BOD_5 (5 days at 20^0C)	mg/l, max	3		
COD	mg/l, max	15		
Nitrates (NO3 – N)	mg/l, max	5		
Total phosphate (PO_4-P)	mg/l, max	0.7		
Chlorides (Cl)	mg/l,max	200		
Fluorides (F)	mg/l, max	1.5		
Iron (Fe)	µg/l	300 des., 1000 max.		
Total coliform	MPN/100 ml,	5000		
Faecal coliform	MPN/100 ml,	250 des. 600 max.		

Abbreviations:
des = Desirable highest level
max = Maximum permissible level
min = Minimum permissible level

Appendix B: Schematic representation of stream network of Kala-oya basin

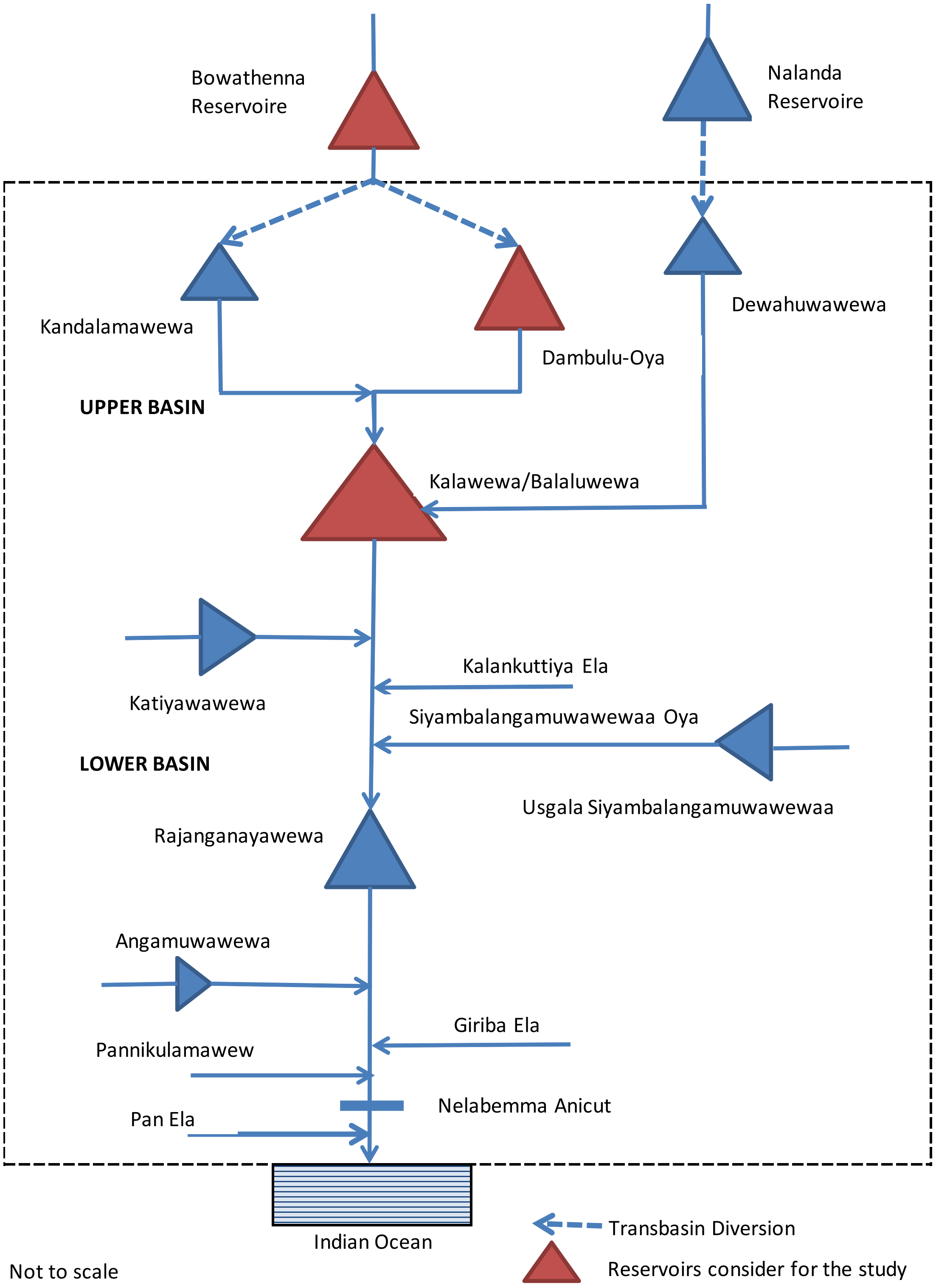

Figure B.1: Schematic representation of stream network of Kala-oya basin

Appendix C: Water quality sampling locations

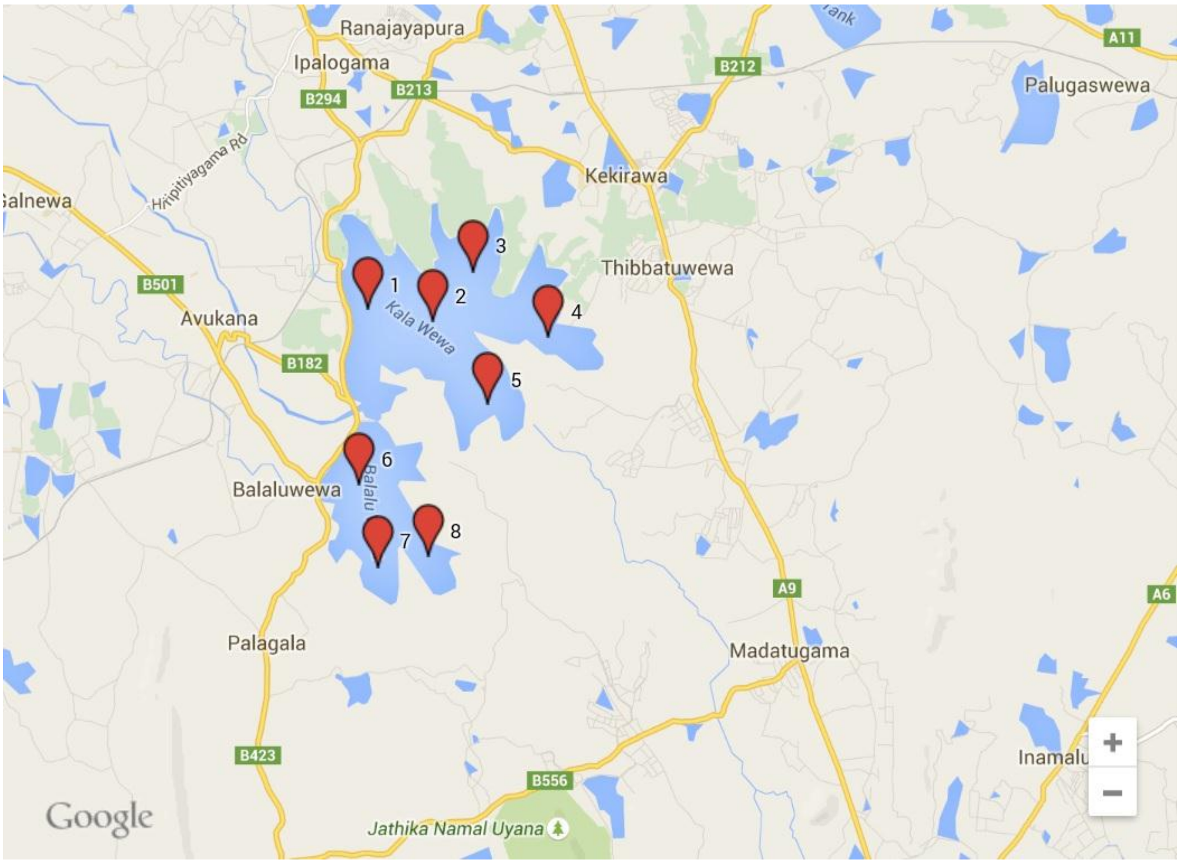

Figure C.1: Water Quality Sampling Locations of Kalawewa Reservoir

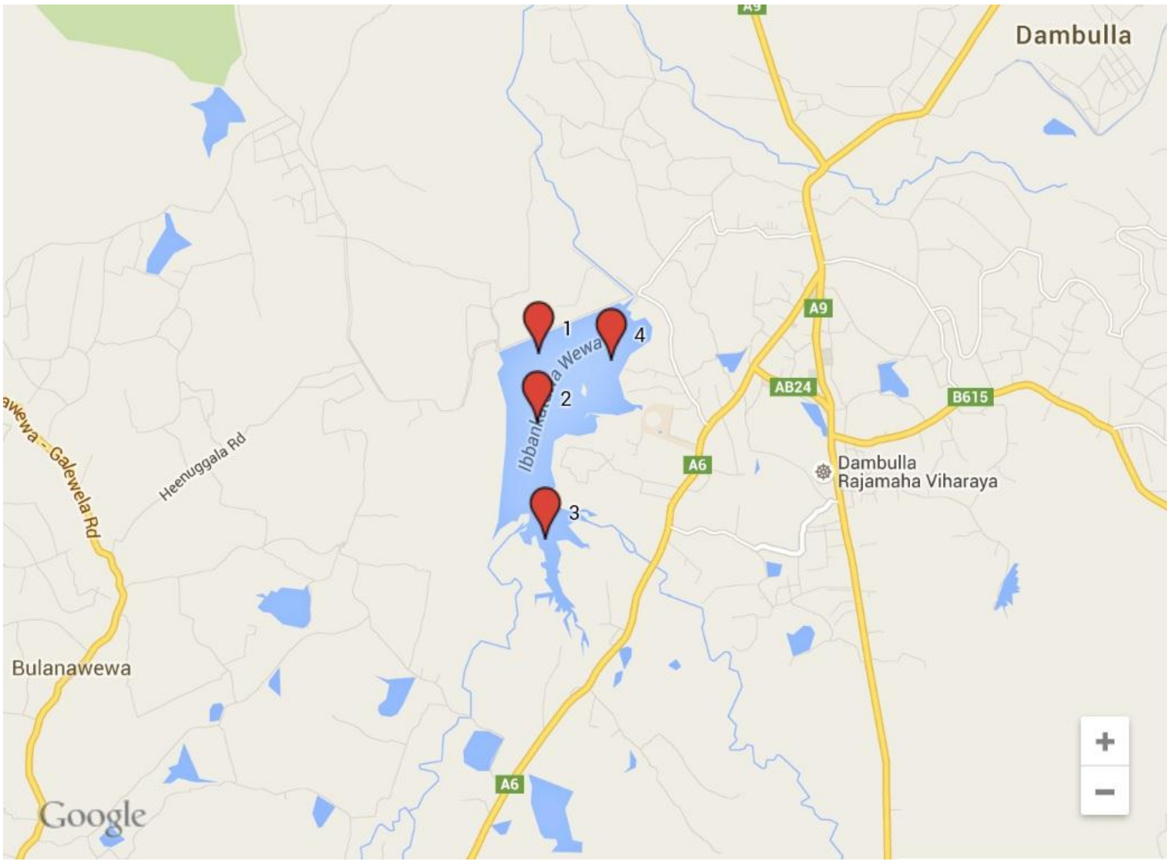

Figure C.2: Water Quality Sampling Locations of Dhambulu-Oya Reservoir

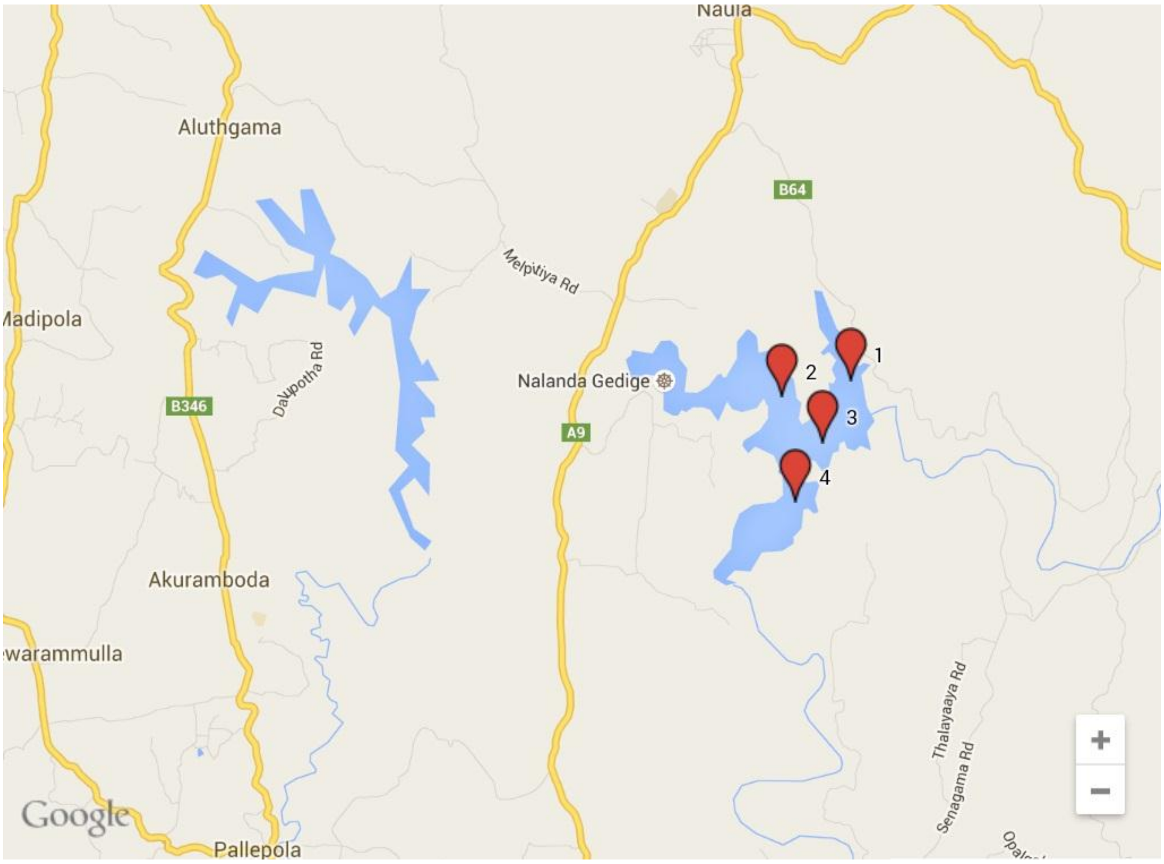

Figure C.3: Water Quality Sampling Locations of Bowathanna Reservoir

Appendix D: Statistical summary of water quality measurements

Table D.1: Statistical summary of water quality measurements of Kalawewa Reservoir

Location		pH	TDS /(mg/l)	Conductivity /(mS/cm	Turbidity /(NTU)	Total Hardness /(mg/l)	NO$_3^-$ as N /(mg/l)	PO$_4^-$ /(mg/l	SO$_4^{2-}$/ (mg/l)	BOD$_5$/ (ppm)	COD/ (ppm)
1	Min	7.01	119.80	0.24	5.09	338.00	0.67	0.62	5.60	3.50	12.10
	Max	8.30	142.50	0.29	13.11	438.00	1.40	1.30	6.70	8.15	16.00
	Mean	7.73	126.20	0.25	10.29	371.92	0.86	0.78	6.12	6.36	13.76
	S.D.	0.39	7.40	0.02	3.26	36.16	0.28	0.24	0.40	1.77	1.21
2	Min	7.01	108.50	0.23	3.70	347.60	0.52	0.68	5.01	4.30	12.00
	Max	8.75	118.00	0.24	11.70	466.00	1.04	1.06	6.55	7.50	14.25
	Mean	8.10	114.38	0.23	8.32	380.04	0.64	0.80	5.64	6.16	12.84
	S.D.	0.58	2.56	0.00	3.00	35.23	0.18	0.12	0.41	1.01	0.65
3	Min	7.01	113.00	0.23	5.09	361.65	0.53	0.63	5.55	4.25	12.45
	Max	8.66	142.50	0.28	9.88	466.00	1.04	0.91	8.98	6.90	14.85
	Mean	8.13	119.05	0.24	8.74	375.37	0.66	0.73	6.63	5.95	13.37
	S.D.	0.59	9.48	0.02	1.55	30.52	0.15	0.10	1.05	0.94	0.79
4	Min	6.90	113.50	0.24	3.62	362.00	0.53	0.65	5.26	3.85	11.90
	Max	7.85	143.50	0.27	12.94	466.00	1.35	1.30	8.98	4.85	14.80
	Mean	7.60	123.20	0.25	9.90	381.16	0.73	0.81	6.24	4.34	13.63
	S.D.	0.29	8.56	0.01	3.22	34.05	0.29	0.18	1.02	0.29	1.01
5	Min	7.01	113.25	0.18	3.70	362.00	0.53	0.55	5.26	3.35	12.05

Location		pH	TDS /(mg/l)	Conductivity /(mS/cm	Turbidity /(NTU)	Total Hardness /(mg/l)	NO_3^- as N /(mg/l)	PO_4^- /(mg/l	SO_4^{2-}/ (mg/l)	BOD_5/ (ppm)	COD/ (ppm)
	Max	8.18	132.50	0.27	14.13	438.00	1.35	1.30	6.65	4.95	15.55
	Mean	7.82	117.94	0.21	11.19	378.62	0.72	0.78	5.88	4.30	14.02
	S.D.	0.43	6.63	0.04	4.11	27.49	0.26	0.19	0.41	0.54	1.14
6	Min	7.01	108.50	0.23	5.09	351.50	0.64	0.65	5.26	4.30	12.45
	Max	8.67	142.50	0.29	12.24	438.00	1.04	0.90	6.65	7.35	15.20
	Mean	8.04	128.10	0.26	7.69	369.44	0.70	0.77	5.85	5.78	13.59
	S.D.	0.51	10.18	0.02	1.89	27.08	0.12	0.07	0.41	0.98	0.84
7	Min	6.90	113.50	0.24	3.62	206.10	0.64	0.65	4.15	3.55	12.05
	Max	7.90	147.00	0.29	9.88	428.00	1.35	1.30	6.65	5.65	16.05
	Mean	7.52	136.87	0.28	8.02	358.10	0.81	0.82	5.43	4.64	14.12
	S.D.	0.27	10.11	0.02	1.99	56.82	0.25	0.21	0.78	0.75	1.49
8	Min	6.96	113.50	0.24	4.94	358.50	0.67	0.65	4.60	3.70	3.27
	Max	8.06	148.45	0.29	12.24	464.00	1.35	1.30	6.25	7.85	14.60
	Mean	7.41	137.81	0.27	8.84	377.56	0.82	0.78	5.58	5.00	12.09
	S.D.	0.40	13.11	0.02	2.26	35.31	0.20	0.19	0.45	1.04	3.12

Table D.2: Statistical summary of water quality measurements of Dambulu-oya Reservoir

Location		pH	TDS /(mg/l)	Conductivity/ (mS/cm)	Turbidity/ (NTU)	Total Hardness/ (mg/l)	NO_3^- as N / (mg/l)	PO_4^- /(mg/l	SO_4^{2-}/ (mg/l)	BOD_5/ (ppm)	COD/ (ppm)
1	Min	7.20	65.50	0.13	4.06	369.00	0.46	0.42	4.30	3.12	12.00
	Max	7.75	105.00	0.21	23.55	478.00	0.72	0.62	5.80	5.54	19.50
	Mean	7.49	77.71	0.16	16.51	463.96	0.60	0.49	4.83	4.24	15.63
	S.D.	0.17	16.35	0.03	8.00	31.61	0.08	0.06	0.41	0.69	2.97
2	Min	7.22	59.50	0.12	6.73	435.00	0.50	0.42	4.25	3.92	12.00
	Max	7.73	111.50	0.22	27.65	510.00	0.71	0.62	5.65	5.50	21.60
	Mean	7.52	82.85	0.16	21.94	461.62	0.60	0.47	4.80	4.85	18.07
	S.D.	0.15	18.19	0.03	6.14	20.75	0.07	0.06	0.40	0.51	3.25
3	Min	7.28	61.50	0.12	6.02	435.00	0.50	0.42	4.25	4.00	12.15
	Max	7.85	132.00	0.27	26.05	510.00	0.71	0.62	5.65	5.50	20.95
	Mean	7.50	77.78	0.15	21.42	461.62	0.60	0.47	4.80	4.82	17.46
	S.D.	0.20	20.30	0.04	5.26	20.75	0.07	0.06	0.40	0.51	2.79
4	Min	7.20	53.50	0.10	6.18	429.50	0.50	0.42	4.25	4.30	12.25
	Max	7.85	112.00	0.23	41.05	528.00	0.72	0.56	5.16	5.59	19.45
	Mean	7.51	71.39	0.14	25.46	469.25	0.59	0.47	4.74	5.10	16.00
	S.D.	0.21	18.36	0.04	11.16	23.25	0.08	0.05	0.33	0.40	2.88

Table D.3: Statistical summary of water quality measurements of Bowathenna Reservoir

Location		pH	TDS /(mg/l)	Conductivity/ (mS/cm)	Turbidity/ (NTU)	Total Hardness/ (mg/l)	NO_3^- as N /(mg/l)	PO_4^- /(mg/l	SO_4^{2-}/ (mg/l)	BOD_5/ (ppm)	COD/ (ppm)
1	Min	6.90	64.60	0.13	20.61	39.00	0.66	0.45	3.65	3.95	11.10
	Max	8.40	79.00	0.17	87.40	45.25	0.94	0.63	5.45	5.59	19.50
	Mean	7.50	68.03	0.14	29.44	41.18	0.82	0.54	4.62	4.74	17.49
	S.D.	0.36	3.71	0.01	19.76	1.74	0.09	0.07	0.67	0.57	2.29
2	Min	7.35	67.35	0.13	21.95	27.00	0.66	0.45	3.49	5.40	16.40
	Max	8.20	99.00	0.19	31.50	43.00	0.94	0.63	5.20	6.30	21.80
	Mean	7.62	86.04	0.17	25.10	32.55	0.82	0.53	4.15	5.88	19.61
	S.D.	0.23	14.03	0.02	2.87	5.58	0.09	0.08	0.48	0.24	2.04
3	Min	7.03	69.90	0.13	21.83	27.80	0.77	0.45	3.90	4.60	17.00
	Max	8.20	99.10	0.19	31.50	42.00	0.93	0.63	5.80	5.65	20.95
	Mean	7.52	77.91	0.16	23.71	33.82	0.86	0.52	4.64	5.14	18.64
	S.D.	0.31	11.29	0.02	3.04	6.01	0.05	0.07	0.65	0.36	1.06
4	Min	7.28	53.50	0.10	21.83	28.00	0.72	0.48	3.85	4.90	17.25
	Max	7.85	97.50	0.19	41.05	40.50	0.93	0.63	5.50	6.03	21.00
	Mean	7.56	66.24	0.13	31.87	32.72	0.83	0.58	4.81	5.56	18.62
	S.D.	0.19	14.18	0.03	8.68	4.20	0.08	0.05	0.51	0.37	1.12