Appraisal of water quality indices for service reservoirs in water distribution networks

M. S. Nyirenda and T. T. Tanyimboh

ABSTRACT

The use of water quality indices to aggregate pollution loads in rivers has been widely studied, with researchers using various sub-indices and aggregation methods. These have been used to combine various quality variables at a sampling point in a river into an overall water quality index to compare the state of water quality in different river reaches. Service reservoirs in a water distribution network, like rivers, have complex mixing mechanisms, are subjected to various water quality variables and are variably sized and sited. Water quality indices and the relevant sub-indices are formulated here and applied to service reservoirs within a water distribution network. This is in an attempt to compare holistically the performance of service reservoirs in solutions of optimisation algorithms with regards to water quality.

Key words | optimisation algorithms, service reservoirs, water distribution networks, water quality index

M. S. Nyirenda (corresponding author)
T. T. Tanyimboh
School of Civil and Environmental Engineering,
University of the Witwatersrand,
Johannesburg,
South Africa
E-mail: *nyirenda.mercy@yahoo.com*

M. S. Nyirenda
GIBB (PTY) Ltd,
Woodmead North Office Park, 54 Maxwell Drive,
Woodmead,
South Africa

INTRODUCTION

Water quality indices are widely used to quantify pollution loads in streams and rivers and have been used to describe the state of water quality at different points within rivers using a single aggregated value (CCME 2001; Cude 2001; Madalina & Gabriela 2014; Rathnayake & Tanyimboh 2015). Service reservoirs or tanks in a water distribution network, similar to points in a river, are variably located and sized as well as subjected to complex mixing mechanisms and multiple water quality variables. To describe the state of water quality in a service reservoir at a point in time, it would be appropriate to apply the idea of the water quality index by aggregating the measured or calculated value of each water quality variable. This is useful for cases when different water distribution network designs for a water distribution network are presented and have to be weighed against each other. The water quality index can also be particularly useful in optimisation algorithms to assess the suitability of the service reservoirs at every step during the optimisation process. Otherwise, a disproportionate number of candidate solutions become non-dominated too early in the optimization process as the number of water quality criteria increases, thus increasing the computational complexity and likelihood of premature convergence (Saxena *et al.* 2013; Sinha *et al.* 2013; Saleh & Tanyimboh 2014, 2016).

doi: 10.2166/wst.2020.215

Three water quality indices previously presented in the literature have been evaluated and used here for the first time to assess the water quality of service reservoir designs optimised by different methods. A set of sub-indices has been developed for three common water quality variables while the three different indices are used to aggregate the sub-indices to quantify the water quality for each reservoir. This formulation aims to provide a first estimate of the overall quality within a reservoir. The aim of this research is to enable designers to compare designs of service reservoirs that vary spatially and in size with regards to water quality performance and during optimisation procedures.

METHODOLOGY

Dojildo *et al.* (1994) proposed an unweighted harmonic square mean formula and Cude (2001) applied it to improve the Oregon Water Quality Index (OWQI), which was previously presented by Dunette (1979). The improved OWQI provided the Oregon Department of Environmental Quality with a means to compare temporal and spatial conditions of water quality between different reaches of river. The OWQI includes aggregation of nine sub-index values informed by sub-index charts developed by the department. The aggregation allows a value between 10 and 100 to be calculated for each river reach depending on the actual measured water quality variables. The unweighted harmonic square mean formula is given by the equation below:

$$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n} s_i^{-2}}} \quad (1)$$

where WQI is the water quality index, n is the number of water quality variables and s_i is the sub-index value.

The classification proposed by Cude (2001) considers 10–59 to be very poor, while 90–100 is considered to be excellent. This indicates a score of 10 to be the lowest possible score and 100 to be the highest possible score.

Swamee & Tyagi (2000) proposed an ambiguity and eclipsicity free aggregation method which, like the OWQI, makes use of sub-indices to describe a river reach according to nine measured water parameters. The authors of this aggregation method have described this method as one free from ambiguity and eclipsicity. This is done by removing the influence of an acceptable water quality variable while ensuring the bias of the aggregation towards a poor water quality variable.

The sub-indices are aggregated as follows:

$$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-1/k}\right]^{-k} \quad (2)$$

where the variables are described as in Equation (1), with k being equal to 0.4.

Swamee & Tyagi (2007) further proposed an improved water quality index similar to Equation (2). This index was claimed to be free from rigidity due to the replacement of the constant exponent parameter value k of 0.4 in Equation (2) by a function based on the number of water quality variables n. The improved index is as follows:

$$WQI = \left[1 - n + \sum_{i=1}^{n} s_i^{-\log_2(n-1)}\right]^{-1/\log_2(n-1)} \quad (3)$$

where the variables are described the same as in Equation (2).

The interpretation of Equations (2) and (3) is based on the National Sanitation Foundation–Water Quality Index (NSFWQI) (Brown *et al.* 1970), which uses a scale of 0 to 100, with 100 being the highest and 0 being the lowest possible score. The indices are further broken down into the five ranges in Table 1.

Formulation of sub-indices

The sub-indices charts proposed here represent a first step in the formulation of the sub-indices for each of the water quality variables analysed. A set of sub-index charts are formulated for the most common water quality indicators of water distribution networks, i.e. water age, chlorine and tri-halomethanes (THM). To the authors' knowledge, the formulation of these sub-indices has not been done before for use in service reservoirs. To ensure that no division by zero occurs in the aggregation, the minimum in all of the sub-indices is 0.1 in Figures 1–3.

Table 1 | Qualitative interpretation of WQI value

WQI range	Qualitative descriptor of WQI
0–25	Poor water quality
26–50	Fair water quality
51–70	Medium or average water quality
71–90	Good water quality
91–100	Excellent water quality

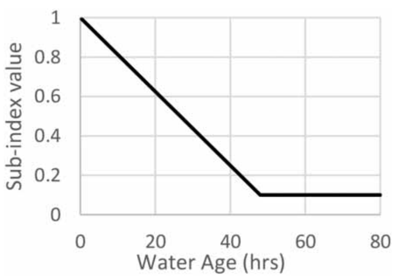

Figure 1 | Water age sub-index.

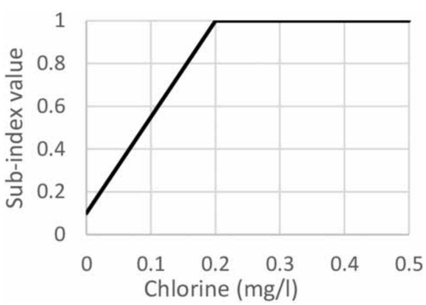

Figure 2 | Chlorine sub-index.

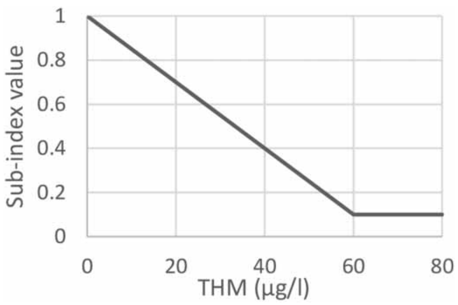

Figure 3 | THM sub-index.

The water age sub-index describes a measured water age of more than 48 hours to be long and is assigned the minimum value of 0.1. The 48-hour restriction is selected as a conservative estimate of water age; a water age of longer than three days is recommended as long by the United States Environmental Protection Agency (AWWA 2002). However, no consensus has been reached in specifying what a long or desirable water age range is because water age is essentially a surrogate water quality indicator. The water age sub-index is described in Figure 1.

The chlorine sub-index (Figure 2) describes a concentration of 0.2 mg/l (World Health Organization 2017) as the minimum required by giving a measured chlorine value greater than or equal to this value the maximum sub-index value of 1. High values of chlorine concentration are also thought to have negative effects such as increasing the formation of disinfection by-products (Centers for Disease Control and Prevention 2018). However, this has not been considered here because the chlorine levels are restricted by the chlorine concentration at the source water treatment plant.

The THM sub-index (Figure 3) indicates a maximum acceptable value of 60 μg/l (World Health Organization 2017) by assigning a calculated value over this threshold the minimum value of 0.1. A THM concentration of zero would be ideal in a water distribution network. This is taken into account in the sub-index by giving a concentration of 0 μg/l a value of 1.

Analysis

Siew *et al.* (2016), Vamvakeridou-Lyroudia *et al.* (2005) and Prasad (2010) have proposed optimisation algorithms for water distribution networks that have multiple pumps and service reservoirs. They have applied their algorithms to the benchmark Anytown Network Problem (Figure 4), first presented by Walski *et al.* (1987). The network requires upgrading and has multiple hydraulic and cost minimisation variables, including siting and sizing of new tanks/service reservoirs to provide for five demand scenarios. The Anytown Network includes a treatment plant, a pump house with three

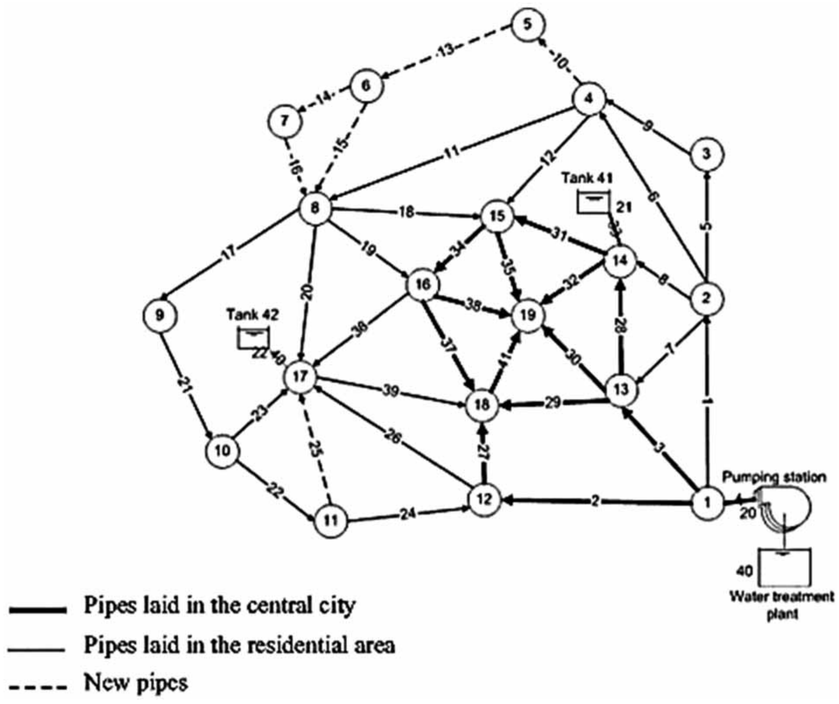

Figure 4 | Anytown Network Problem.

existing pumps and two existing reservoirs located centrally in the network.

Siew *et al.* (2016) presented multiple feasible solutions to the problem; however, only two of the cheapest solutions (Solution 1 and Solution 2) were considered here (Figures 5 and 6). Both solutions presented one new tank located in the far north of the network. Both Vamvakeridou-Lyroudia *et al.* (2005) and Prasad (2010) proposed similar solutions, with both solutions proposing two new tanks located close to the existing tanks (Figure 7). Neither the original problem nor the proposed solutions included water quality as an objective. Water quality considerations unavoidably introduce an extra layer of complexity, hence the need for the aggregation procedures under investigation herein. Nevertheless, the solutions to the Anytown Network were analysed here for chlorine, water age and THM in EPANET 2 (Rossman 2000) based on first-order reaction dynamics. Alternative water quality simulation models (e.g. Seyoum & Tanyimboh 2017) could be substituted readily if required.

Hydraulic and water quality time steps of 1 minute were assumed, while bulk and wall coefficients of 0.5/day and 0.1 m/day (Seyoum *et al.* 2014), respectively, were used based on a first-order kinetics model (Figueiredo 2014). Initial concentrations of chlorine were assumed to be zero, except for the treatment plant which was assumed to have a constant concentration of 0.6 mg/l (Seyoum *et al.* 2014). THM and water age variables were assumed to be zero at the start of the simulation. The simulation was run over 72 hours, allowing the water quality variables to stabilise and establish a pattern and thus only the results for the last 24 hours are presented. The simulated water quality values at each hour were assigned values according to the applicable sub-index. The sub-indices for each hour were aggregated using each method as described in Equations (1)–(3). Because the index will vary at each point in time, only the minimum aggregation value for each method over the last 24 hours for each reservoir is presented in the results to compare the reservoirs with the worst water quality. A total of 14 reservoirs were analysed among the four solutions presented by the optimisation algorithms.

RESULTS AND DISCUSSION

Table 2 shows a summary of the worst water quality results as obtained from the hydraulic and water quality analyses for the service reservoirs. It can be seen that the worst

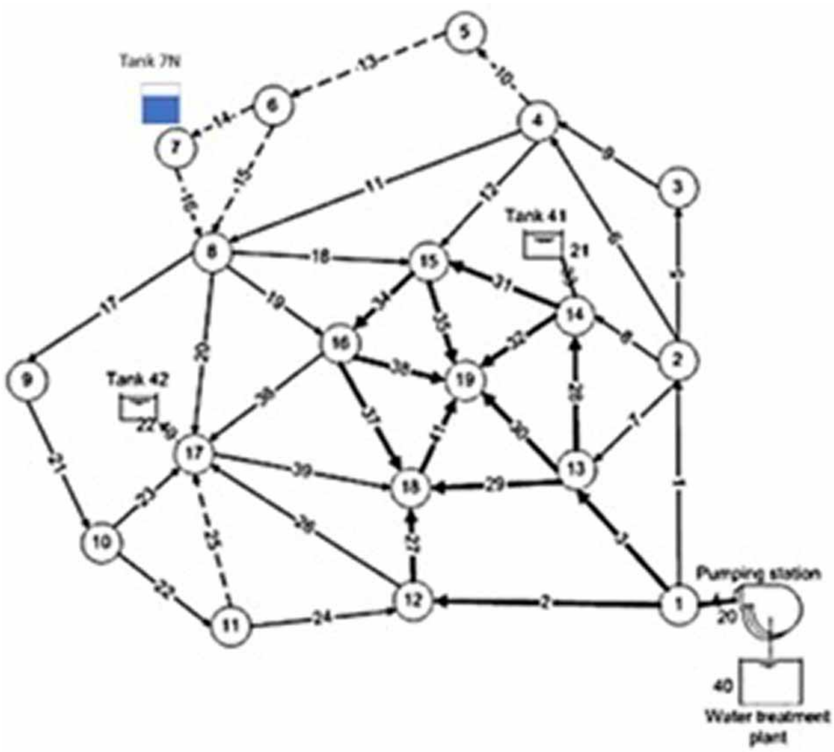

Figure 5 | Siew *et al.* (2016) Solution 1.

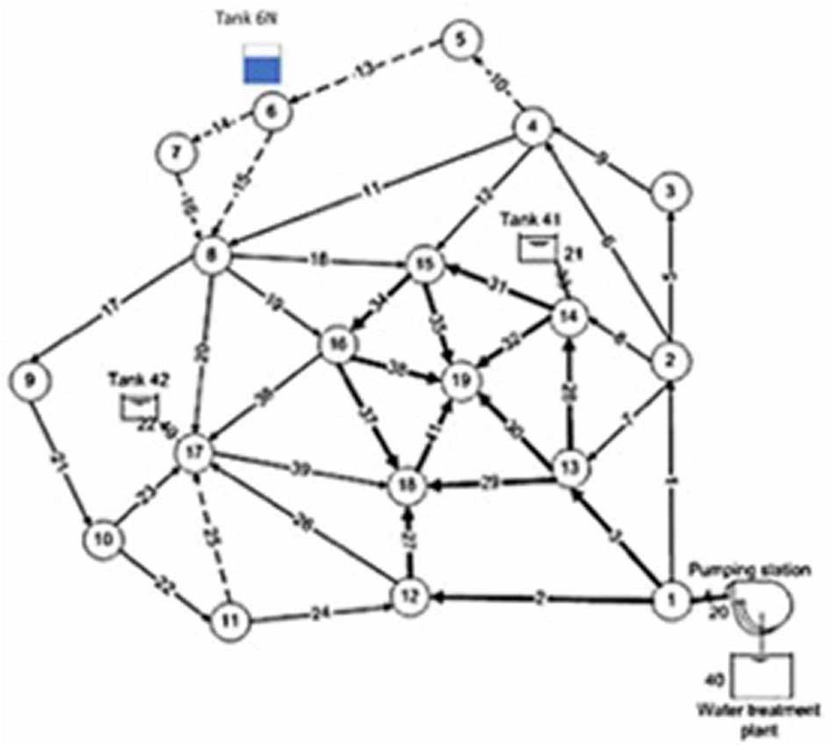

Figure 6 | Siew *et al.* (2016) Solution 2.

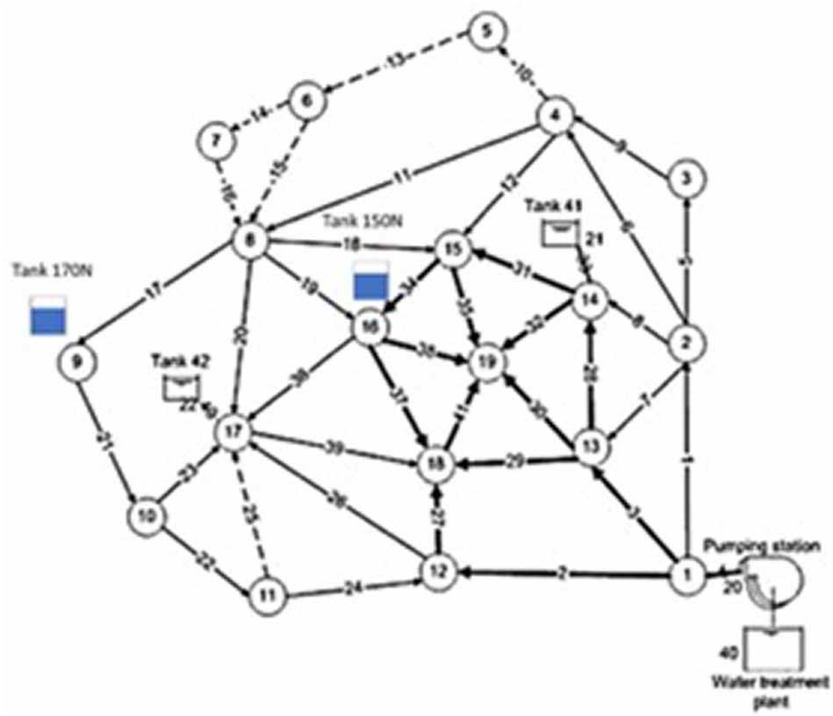

Figure 7 | Vamvakeridou-Lyroudia *et al.* (2005) and Prasad (2010) solutions. The new tank sizes vary.

Table 2 | Summary of water quality results for the reservoirs

	Siew *et al.* (2016) Solution 1	Siew *et al.* (2016) Solution 2	Vamvakeridou-Lyroudia *et al.* (2005)	Prasad (2010)
Maximum water age (hours) (and location)	37.53 (7N)[a]	39.32 (6N)	54.02 (41E)[b]	46.57 (150N)
Time of occurrence	18:00	15:00	00:00	18:00
Time period over 48 hours (hrs)	0	0	0.98	0
Minimum chlorine conc. (mg/l) (and location)	0.25 (7N)	0 (41E)	0 (41E)	0.17 (150N)
Time of occurrence	14:00	20:00	00:00	18:00
Time period under 0.2 mg/l (hours)	0	1.1	24.0	5.0
Maximum THM conc. (μg/l) (and location)	50.59 (7N)	53.1 (6N)	67.59 (41E)	59.74 (150N)
Time of occurrence	16:00	15:00	00:00	18:00
Time period over 60 μg/l (hours)	0	0	10.0	0

[a]N refers to a new tank.
[b]E refers to an existing tank.

performing service reservoirs are the new tanks and one of the existing tanks (41E). The Vamvakeridou-Lyroudia *et al.* (2005) solution is the worst performing solution because it has the longest water age and highest THM concentration in existing Tank 41E, while the same tank and solution has a chlorine concentration of 0 mg/l over the entire 24-hour period. Tank 41E in Solution 2 also experiences a 0 mg/l concentration; however, this was over a 1-hour, 18-minute period only. Tank 150N could be of concern in the Prasad solution because it has a chlorine concentration of less than 0.2 mg/l; however, this occurs over a period of 5 hours, which is marginally less than the tank in the Vamvakeridou-Lyroudia solution.

Figures 8–10 summarise the minimum water quality indices as applied to the service reservoirs using Equations (1)–(3), respectively.

From the results in Figure 8, the results are as expected, with service reservoirs that have been shown to experience problems (Table 1) having the lowest indices. Existing reservoir 41E obtained the lowest indices in Solution 2 and the Vamvakeridou-Lyroudia *et al.* (2005) solution, while Tank 150N obtained the lowest score in the Prasad solution. Existing reservoir 41E also has the highest indices in Solution 1 and the Prasad solution, while existing reservoir 42E achieves consistently high indices across all solutions. These results are consistent with the results presented in

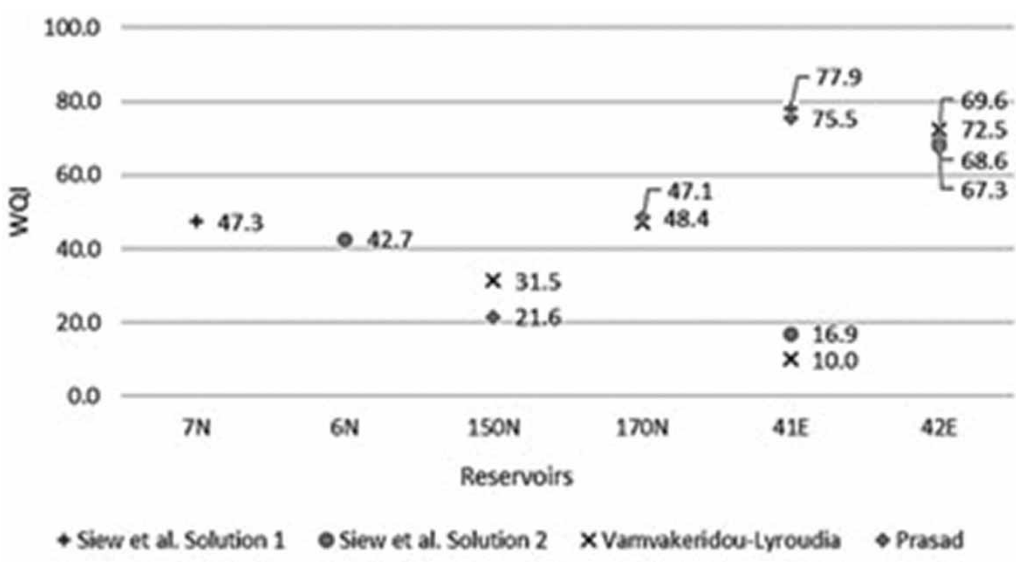

Figure 8 | Minimum water quality index results for the reservoirs based on Equation (1).

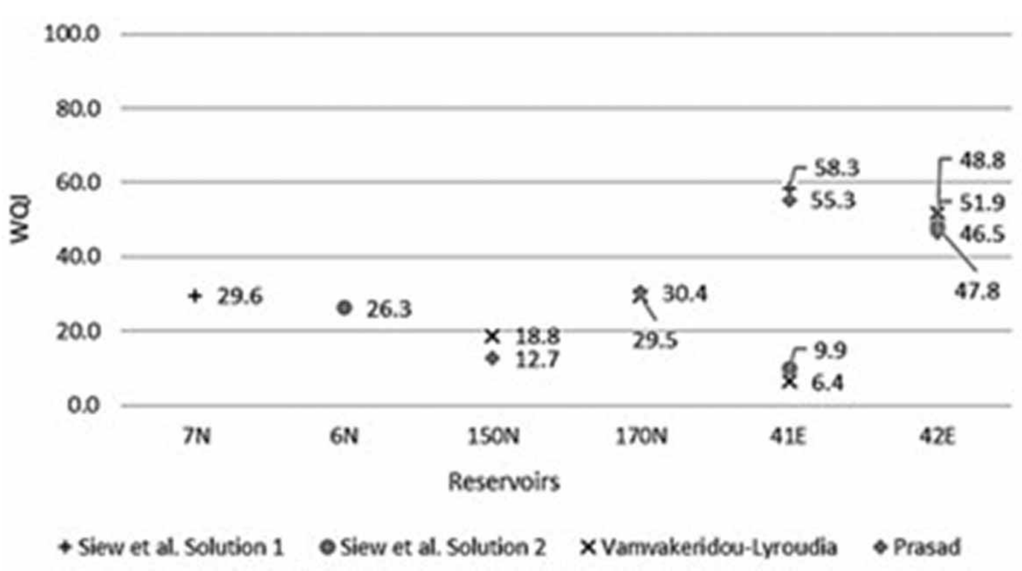

Figure 9 | Minimum water quality index results for the reservoirs based on Equation (2).

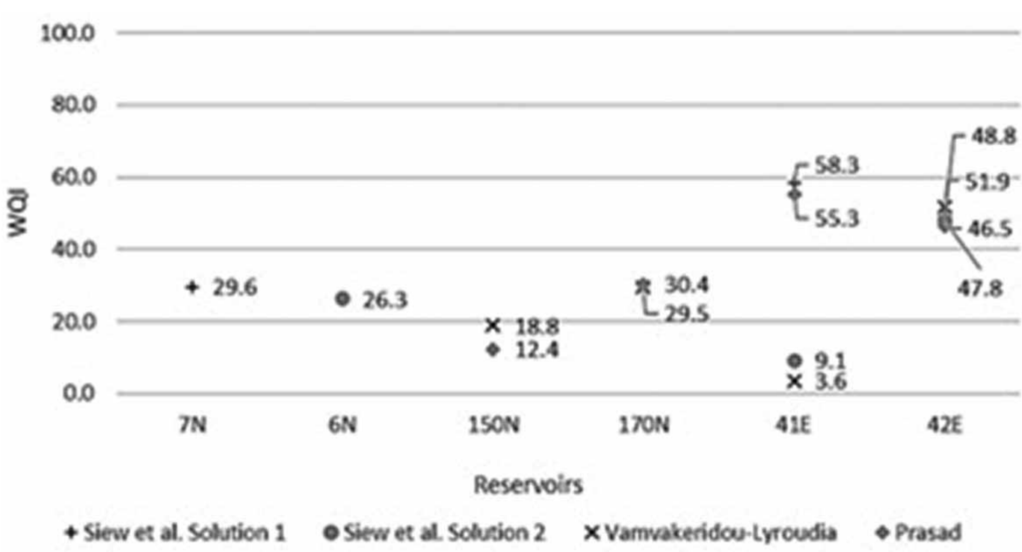

Figure 10 | Minimum water quality index results for the reservoirs based on Equation (3).

Table 2. It is interesting to note that Tank 41E would indicate good water quality for the Siew *et al.* Solution 1, although it indicates poor water quality for Siew *et al.* Solution 2 and Vamvakeridou-Lyroudia *et al.* Solution according to Table 1.

Figure 9 represents the water quality index results according to Equation (2). Similar to Figure 8, existing reservoirs 41E and new reservoir 150N have the lowest indices, indicating poor water quality states. Unlike the first method, however, all of the reservoirs are scored much lower, with the highest score for reservoir 41E being 58.3 compared to 77.9 in Figure 8. This indicates that none of the tanks have good water quality according to the qualitative interpretation in Table 1.

Figure 10 represents the water quality index results according to Equation (3). The numbers shown in Figure 10 are the same as those shown in Figure 9. The indices produced by Equations (2) and (3) do not vary significantly, and hence, the minimum water quality indices from the overall results produced by Equation (3) are identical to those in Equation (2). Again, the same trend is repeated, with reservoirs 41E and 150N having the lowest indices.

By comparing Figures 8–10, it can be seen that the graphs are similar with regards to the placement of the indices in the graph space. The difference comes when comparing the values of the indices. Figure 8 has higher values compared to Figures 9 and 10. Despite the differences in terms of the numerical values, all of the indices still give essentially the same indication of the water quality state within the reservoirs relative to one another. On the other hand, the qualitative interpretation shows major deviations between the equations. It is noted, however, that the qualitative interpretation was developed for use with Equation (1) OWQI only. A new definition for the qualitative interpretation of the indices would have to be developed if one of the other equations is used or if the end-user requires more lax or stringent definitions for the state of water quality in the tanks.

CONCLUSIONS

Three water quality indices have been formulated here to describe the water quality in service reservoirs in water distribution networks. The indices require the development of sub-indices, as demonstrated here for water age, chlorine and tri-halomethanes. The sub-indices are a first estimate and will likely require refinement. The indices have proved useful in comparing various designs for service reservoirs, and are consistent in their results and the underlying water quality analyses results from which they were derived.

The concept of the water quality index is seemingly befitting to be used in service reservoir and water distribution network designs. The water quality index results herein indicate consistency in describing the water quality within a reservoir regardless of its size or location. It was also seen that comparable results were obtained from the various indices and sample network considered.

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First received 24 November 2019; accepted in revised form 23 April 2020. Available online 5 May 2020