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Application of water quality index to identify deteriorated river sections – A case study for the Hawkesbury Nepean River System in Australia

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Abstract: *The world's water resources are increasingly being threatened with rapid urbanisation. A comprehensive water quality management program is necessary to protect the valuable freshwater resources and to safeguard public health. River water quality assessment mainly involves two components: measurement of water quality variables and comparison of measurements to benchmark with guidelines and water quality objectives to assess the degree of change and its impacts on aquatic environment and human health. Traditionally, water quality data is summarised in technical reports that are valuable to individuals who understand the technical content; however, this information is not always useful to non-technical individuals and community members. A Water Quality Index (WQI) provides a convenient means of summarising complex water quality data and facilitates its communication to a general audience. This paper presents the use of WQI to identify changes in river water quality over time, identify and assess deteriorated river sections and the water quality parameters which contributed to the deterioration and their relative contributions. The Hawkesbury Nepean River System (HNRS), which is the main source of drinking water supply to more than 4.8 million people living in and around Sydney, Australia, was assessed using a Canadian WQI. Water quality data obtained from 9 sampling stations along the HNRS during the last 21 years (1993 to 2013) were used to identify changes in water quality at different sampling stations over time, and to compare water quality parameters among the stations. The results provide an estimate of the overall water quality against the Australian and New Zealand Water Quality guidelines. It has been found that the overall water quality at the HNRS is at marginal to poor state.*

***Keywords**: Water quality index; Hawkesbury Nepean River System; River water quality.*

1. Introduction

Many rivers in world have been highly degraded over the past few decades due to rapid urbanisation (Pinto and Maheshwari, 2011; Edet et al., 201; Zhang et al., 2015). The main reasons for such water quality degradation are discharge of treated sewage into the river system and increased stormwater runoff from urban areas. Rivers that are badly impacted due to anthropogenic activities are said to have suffered from 'Urban stream syndrome' (Walsh et al., 2005). Once a river is deteriorated, it is difficult and costly to purify it to an acceptable level. Algal blooms in Australian rivers cost the country between AUD180 and AUD240 million annually (Atech, 2000). Thus, prediction of water quality is important to prevent possible effects and also it is required by a wide range of river users such as urban water supply authorities, farmers and environmentalists (Pinto et al., 2012; Memarzadeh et al., 2013).

The concept of Water Quality Index (WQI) is based on the comparison of water quality parameters with respective regulatory standards and gives a single value, which can be used to describe the overall quality of a water body (Boyacioglu, 2010). The number of variables with exceedances, frequency of exceedances, and magnitude of exceedances of regulatory standards for specific parameters are reflected in the WQI.

The first studies on WQI were done in 1848 in Germany that developed WQI based on 8 water quality parameters (Sarkar and Abbasi, 2006). Dede et al. (2013) used 5 WQI methods (Oregon WQI, aquatic toxicity index, overall index of pollution, universal WQI, and the Canadian Council of Ministers of the Environment (CCME) WQI) to evaluate surface water quality, and concluded that CCME WQI is the only method that allows utilization of all the available parameters in the calculation of an overall index value. However, it is important to note that the CCME WQI is not a substitute for detailed analysis of water quality data and should not be used as a sole tool for management of water bodies (Al-Janabi et al., 2012). It was simply developed to provide a broad overview of environmental performance (Khan et al., 2004). The objective of this study was to apply WQI for assessing river water quality.

The Hawkesbury Nepean River System (HNRS) provides 97% of the fresh drinking water for more than 4.8 million people living in Greater Sydney and nearby towns; and hence, the water quality of this river is of great importance (Kuruppu and Rahman, 2013).Although there are a number of dams and in-stream structures in the HNRS, it is considered to be an unregulated river (Kuruppu et al., 2012). This river system is characterized by complex land use ranging from agriculture, commerce, industry, urban and forest. The outcomes of this study would provide an insight into the overall water quality of the HNRS that can be used in developing management strategies to improve the water quality of the HNRS.

2. Methodology

This study uses the CCME WQI, which is based on a formula developed by the British Columbia Ministry of Environment, Lands and Parks and modified by Alberta Environment. This WQI incorporates three elements: (a) Scope (F_1) – the number of variables not meeting water quality objectives; (b) Frequency (F_2) – the number of times these objectives are not met; and (c) Amplitude (F_3) - the amount by which the objectives are not met.
Scope (F_1) assesses the extent of water quality guideline non-compliance over the time period of interest, which means the numbers of parameters whose objective limits are not met. F_1 is defined by:

$$F_1 = \frac{Total\ number\ of\ failed\ variables}{Tatal\ number\ of\ variables} \times 100 \quad (1)$$

Where the variables indicate those water quality parameters whose objective values (threshold limits) are specified and observed values at the sampling sites are available for the index calculation.
Frequency (F_2) - the frequency (i.e. how many occasions the tested or observed value are off the acceptable limits) with which the objectives are not met, which represents the percentage of individual tests that does not meet the objectives (failed tests):

$$F_2 = \frac{Number\ of\ failed\ tests}{Total\ number\ of\ variables} \times 100 \quad (2)$$

Amplitude (F_3) is the amount by which the objectives are not met (amplitude) that represents the amount by which the failed test values do not meet their objectives, and is calculated in three steps. The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is termed an "excursion" and is expressed as follows. When the test value must not exceed the objective:

$$excursion_i = \left(\frac{Faild\ test\ value_i}{Objective_j}\right) - 1 \quad (3)$$

For the cases in which the test value must not fall below the objective:

$$excursion_i = \left(\frac{Objective_j}{Faild\ test\ value_i}\right) - 1 \quad (4)$$

The collective amount, by which the individual tests are out of compliance, is calculated summing the excursions of individual tests from their objectives and then dividing the sum by the total number of tests. This variable, referred to as the normalized sum of excursions (nse) is calculated as:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Number\ of\ tests} \quad (5)$$

F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (nse) to yield a value between 0 and 100:

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \quad (6)$$

The CCME WQI is finally calculated as:

$$CCME\ WQI = 100 - \left(\frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732}\right) \quad (7)$$

The factor of 1.732 has been introduced to scale the index from 0 to 100. Since the individual index factors can range as high as 100, it means that the vector length can reach a maximum of 173.2 as shown below:

$$\sqrt{100^2 + 100^2 + 100^2} = \sqrt{30000} = 173.2 \quad (8)$$

The index produces a number between 0 (worst water quality) and 100 (best water quality). These numbers are divided into 5 descriptive categories to simplify presentation, as listed below.

- Excellent: (CCME WQI Value 95-100) – water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.
- Good: (CCME WQI Value 80-94) – water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
- Fair: (CCME WQI Value 65-79) – water quality is usually protected, but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
- Marginal: (CCME WQI Value 45-64) – water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
- Poor: (CCME WQI Value 0-44) – water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

3. Study area and data description

This study uses data from the HNRS in the Australian State, New South Wales (NSW). The Hawkesbury-Nepean catchment is one of the largest coastal basins in NSW. With an area of 21,400 square kilometres, over 70 per cent of the catchment consists of mountainous terrain, with about 10 per cent of flat terrain. The south terrain, around 10 per cent of the total catchment, comprises undulating plateau type country. The maximum elevation is about 1,290 metres. The HNRS supports a $259 million agriculture industry. Major water users in this catchment include Sydney Water

Figure 1. Water quality monitoring stations along the HNRS

Corporation, local councils, the irrigated agriculture, tourism, fishing and oyster industries, and various recreational users. Sydney Water supplies water to most homes and businesses within the Greater Sydney Metropolitan area. Thus, monitoring and assessing the water quality of this river system is of immense importance. Many government organizations, researchers and environmental agencies monitor and collect water quality data along the HNRS; however, the full capacity of the water quality data set has not been well used to draw meaningful conclusions describing the state of the river due to the complexity of analysing the data and summarizing the results in ways that can be easily understood by the general people, water distributors, planners, managers and policy makers. In this study, water quality data obtained from 9 sampling stations along the HNRS during the last 21 years (1993 to 2013) are evaluated for track changes at different stations over time, and for comparisons among the stations. Figure 1 showed the water quality monitoring stations along the HNRS. A schematic diagram of the monitoring stations along the HNRS with the land use details and all the inflows are presented in Figure 2.

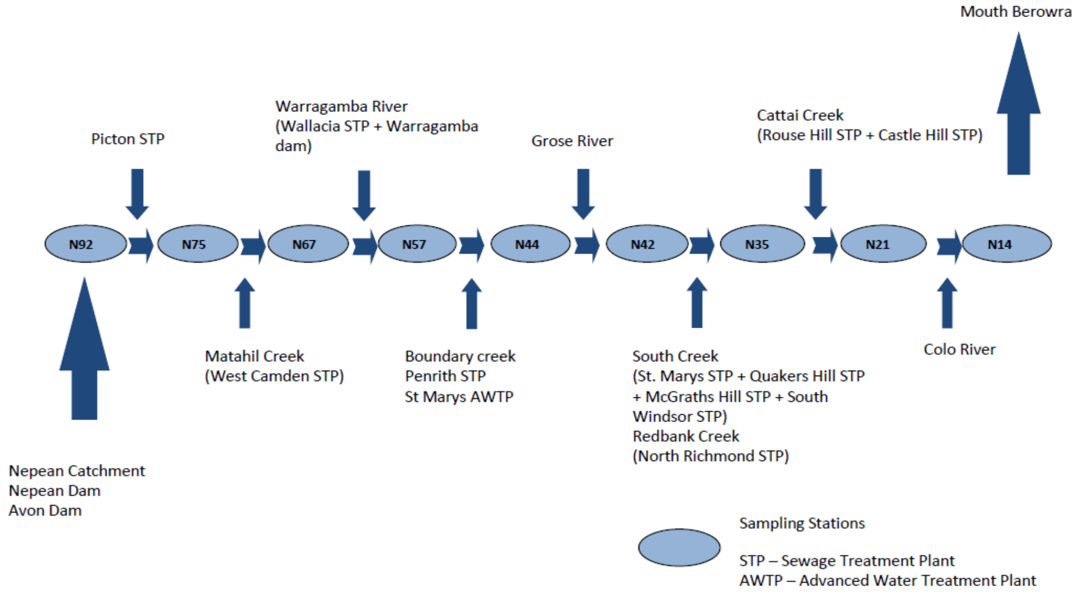

Figure 2. Schematic diagram of the monitoring stations along HNRS with the land use details

Table 1. ANZECC Guidelines for Fresh and Marine Water Quality

Water quality parameter	ANZECC trigger value		Unit
	Maximum	Minimum	
pH	8	6	
Nitrogen Total	0.35		mg/L
Phosphorous Total	0.05		mg/L
Chlorophyll	5		µg/L
Dissolved Oxygen		5	mg/L
Turbidity	20		NTU
Iron Total	0.3		mg/L
Aluminium Total	0.2		mg/L
True Colour	15		
Alkalinity	20		
Suspended Solids	20		
Conductivity	0.35		mS/cm

For the calculation of CCME WQI, 12 water quality parameters were selected based on the importance and the availability of data (Kuruppu and Rahman, 2015). The water quality data was obtained from Water New South Wales who adopted a standard laboratory procedure to test/monitor water quality from the HNRS. These selected water quality parameters and Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC, 2000) are presented in Table 1.

4. Results and Discussion

WQIs were primarily developed for each year between 1993 and 2013 at 9 sampling locations to investigate the water quality changes along the HNRS over time. An improvement of water quality over time was observed at most of the stations (Figure.3). Also, the results shows a marginal water quality with WQI of 45 – 64 at all the stations except N14 and N35, which have WQIs less than 40 over the years.

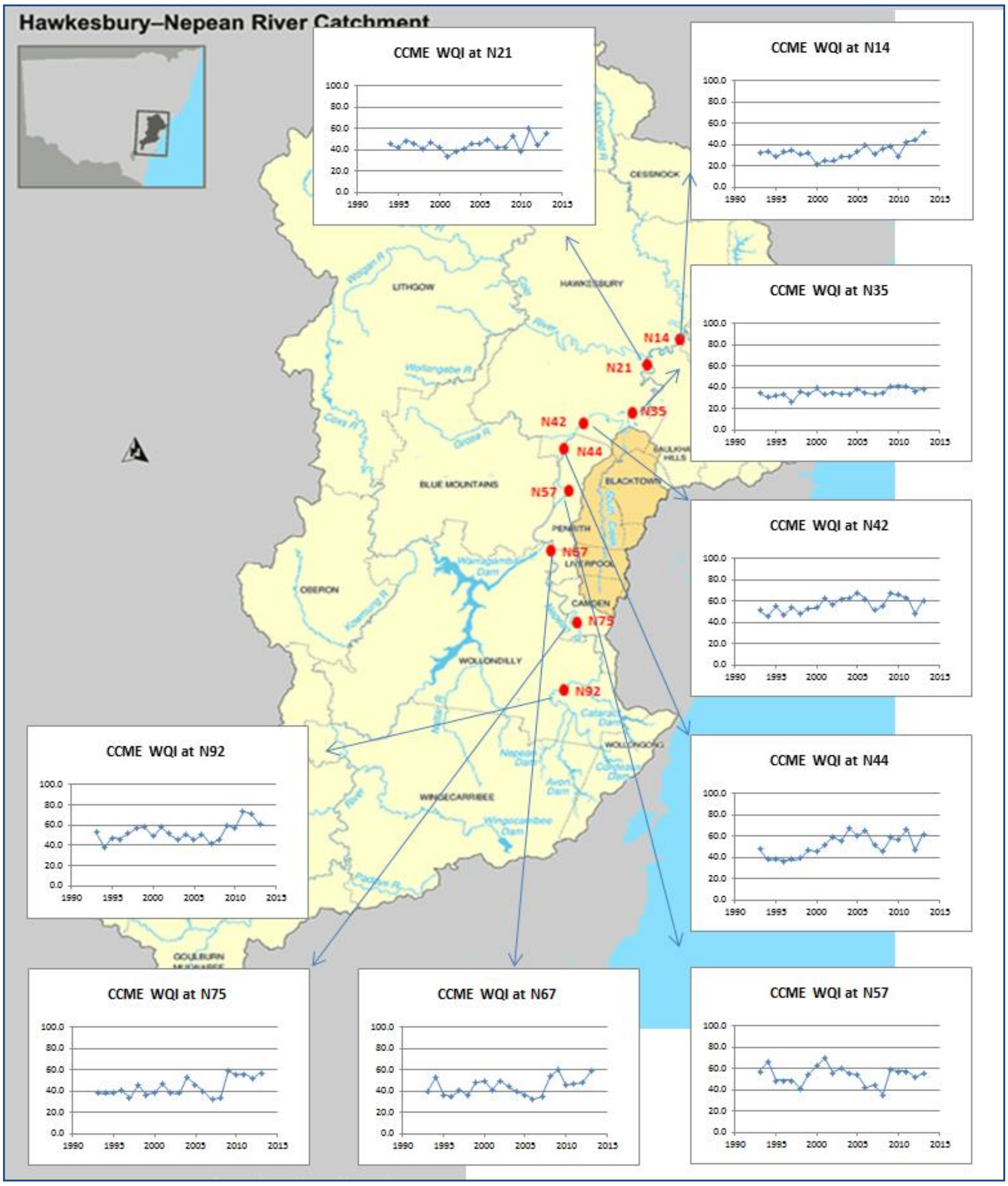

Figure 3. Change in WQI over time for 9 monitoring stations in HNRS

Medians of CCME WQI values over the 21 years range from 33 to 57. All the monitoring stations indicate marginal or poor water quality. Water quality at N21, N42, N44, N57 and N92 is frequently threatened or impaired. WQIs at N14, N35, N67 and N75 are below 40 indicating that water quality at these stations is almost always threatened or impaired (Figure 4).

Scope, frequency, and amplitude values at 9 monitoring stations are presented in Figure 5. At station N35, nearly 90% of water quality values are beyond the ANZECC guideline values. Station N35 shows the highest frequency and highest amplitude (46.3) among 9 monitoring stations. The upstream of N35 is affected by quality and magnitude of flows coming from the South Creek that carries discharges from St. Marys Sewage Treatment Plant (STP), Riverstone STP, Quakers Hill STP, McGraths Hill STP and South Windsor STP and North Richmond STP. The dominant land use in this part of the catchment includes rural use, grazing, commercial gardening, intensive agriculture, and urban and industrial activities. These land uses can be attributed to the low WQI at station N35.

At station N14, 81% of the water quality data is outside the ANZECC guidelines. This station also has an amplitude of 70%. Between 1993 and 2008, amplitudes were greater than 60%. Table 2 presents the amplitudes at 9 stations during 1993 - 2013. The years with higher amplitude (greater than 60%) are indicated in red.

Further data exploration was done at station N14 as it shows the worst WQI among the 9 stations. Table 3 presents details of percentage failed tests for different water quality parameters (the total number of tests, number of failed tests, and percentage failed for each parameter for different years). Total nitrogen, chlorophyll-a (Chl-*a*), total iron, total aluminium, alkalinity, and conductivity exceeded the ANZECC guidelines in many occasions. The water quality at Stations N14 (and N21 and N35) are highly affected by discharges from South Creek and Cattai Creek which receive effluents from 6 STPs as shown in Figure 2.

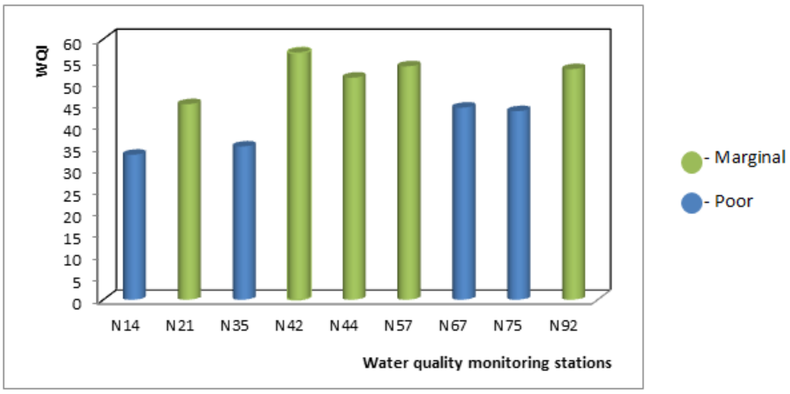

Figure 4. Average WQI along the HNRS

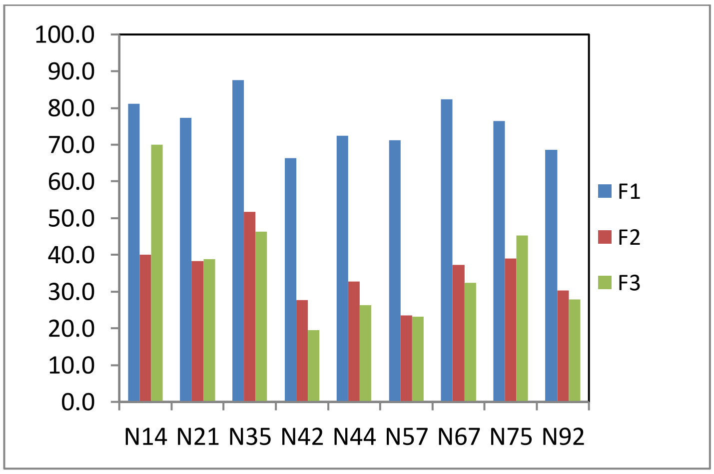

Figure 5. Scope, frequency, and amplitude values at 9 monitoring stations in HNRS

Table 3 indicates that water quality at station N14 is poor with respect to nitrogen, Chl-*a*, iron, aluminium and conductivity. Nitrogen is a nutrient used by plants within natural ecosystems, with minimal leakage into surface or groundwater (Vitousek et al., 2002). Nitrogen concentrations in streams generally increase due to discharge of sewage water, pollutant wash off from urban and agricultural land, and atmospheric deposition. Increased nitrogen may result in an overgrowth of algae, resulting in an increase in eutrophication of the aquatic system and decrease in dissolved oxygen content of the water, thereby harming or killing fish and other aquatic species (USEPA, 2005). Control of nitrogen load in urban river systems is viewed as a priority by many river management authorities as this affects the growth of algae (algal bloom) and other aquatic plants. Harmful algal bloom is considered to be a serious event in regard to water quality as some species of these aquatic organisms can excrete toxic chemicals (e.g. microcystis produced by a blue-green algae

Microcystis aeruginosa). A number of episodes of harmful algal bloom and rapid growth of aquatic weeds were observed in the HNRS in the past causing public concern. For example, the shallow mid Nepean River section was affected heavily by aquatic weed *Egeria densa* (Roberts et al., 1999) and the Berowra Creek estuarine section of the river was infested by toxic dinoflagellate algal blooms (SMEC, 1997).

The long-term persistence of elevated levels of Chl-*a* is a significant concern to water authorities. An excessive growth often leads to poor water quality, noxious odours, oxygen depletion, and human health problems and fish death. It may also be linked to harmful (toxic) algal blooms. Poor water quality associated with high Chl-*a* concentration needs to be distinguished from the natural variation observed with the seasons and those associated with hydrodynamic features (e.g. upwelling). However, there is very little information to make this distinction (Ward et al., 1998). Observed increases in the concentrations of Chl-*a* may be related to increased nutrient concentrations (nitrogen in particular), decreased flow/changed hydrodynamics (increased residence times) and/or decreased turbidity (increased light penetration) (i.e. the increasing eutrophication).

If the alkalinity level is too high, the water can be cloudy, which inhibits the growth of aquatic plants and algae. This may be considered to be a controlling measure of harmful algal bloom; however, a higher alkalinity may raise the pH level, which in turn can harm or kill fish and other aquatic organisms which are very sensitive to higher pH levels. High alkalinity may result from the presence of the bicarbonate ion, which is derived from the dissolution of carbonates by carbonic acids due to factors such as weathering of limestone and dolomite rocks mainly composed of calcite.

Table 2. Amplitudes at 9 stations in different years

Index Period	Stations								
	N14	N21	N35	N42	N44	N57	N67	N75	N92
2013	39.0	31.2	39.9	29.5	34.8	30.1	35.5	24.7	20.2
2012	44.4	32.1	43.4	31.4	35.4	23.0	26.4	20.6	16.8
2011	49.9	24.8	34.7	7.2	14.8	18.8	21.9	15.5	7.5
2010	50.8	40.4	35.7	17.1	18.7	22.9	25.1	24.4	22.3
2009	52.3	33.1	37.4	10.8	22.3	35.4	31.1	36.8	31.3
2008	65.9	32.0	42.6	24.9	30.6	49.7	41.0	53.4	43.5
2007	71.0	38.5	43.6	22.3	33.4	50.5	46.4	57.2	55.8
2006	81.6	43.2	45.3	15.9	22.2	41.5	47.0	60.9	50.7
2005	76.3	43.4	44.7	13.9	23.8	32.3	41.1	53.9	39.3
2004	82.9	45.2	46.6	15.2	26.7	35.3	37.0	55.4	38.9
2003	80.2	39.3	43.7	17	26.7	41.3	37.7	54.8	43.3
2002	78.7	37.7	41.4	19.2	26.3	29.7	30.6	52.8	40.1
2001	78.2	35.3	38.9	16.7	23.4	3.6	29.4	40.0	26.0
2000	87.1	35.2	41.0	16.3	22.0	6.9	25.8	49.3	30.2
1999	65.1	42.7	50.4	22.5	38.2	18.8	35.5	55.6	19.9
1998	75.0	39.9	50.7	19.5	22.8	10.6	30.6	49.2	20.7
1997	81.2	46.4	58.3	21.5	27.0	7.4	34.5	59.1	19.7
1996	69.2	39.0	54.7	20.6	30.4	9.4	33.3	60.1	13.5
1995	80.4	37.7	58.0	18.2	24.3	12.2	27.8	50.3	7.9
1994	85.3	60.1	60.9	20.1	20.7	2.0	18.0	51.4	17.8
1993	74.8		61.5	31.4	29.2	4.1	23.4	24.5	18.9

Table 3. Water quality results at N14 (yellow colour indicates 25% to 49% failure and red colour indicates ≥ 50% failure)

	pH			Nitrogen Total			Phosphorous Total			Chlorophyll			Dissolved Oxygen			Turbidity		
Index Period	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)
2013	4	0		4	3	75.0	4	0		4	4	100.0	4	0		4	0	
2012	13	0		14	11	78.6	14	0		15	12	80.0	13	0		13	2	15.4
2011	13	0		13	7	53.8	13	0		13	13	100.0	13	0		13	3	23.1
2010	12	1	8.3	12	10	83.3	12	1	8.3	12	11	91.7	12	1	8.3	10	4	40.0
2009	13	1	7.7	13	8	61.5	13	0		13	12	92.3	13	0		13	1	7.7
2008	12	0		12	8	66.7	12	0		12	11	91.7	12	0		12	2	16.7
2007	13	0		12	11	91.7	12	1	8.3	13	8	61.5	13	0		13	4	30.8
2006	13	0		13	6	46.2	13	0		13	7	53.8	13	0		13	0	
2005	12	0		12	8	66.7	12	0		12	11	91.7	12	0		12	1	8.3
2004	13	0		13	4	30.8	13	1	7.7	13	7	53.8	13	0		13	2	15.4
2003	13	1	7.7	13	11	84.6	13	1	7.7	13	10	76.9	13	0		12	1	8.3
2002	14	0		14	10	71.4	14	3	21.4	14	9	64.3	14	1	7.1	14	5	35.7
2001	17	0		11	8	72.7	11	1	9.1	17	11	64.7	17	2	11.8	17	5	29.4
2000	21	2	9.5	16	12	75.0	16	1	6.3	27	12	44.4	21	1	4.8	21	2	9.5
1999	12	1	8.3	26	25	96.2	26	7	26.9	26	22	84.6	12	0		0	0	
1998	24	2	8.3	24	20	83.3	24	7	29.2	24	13	54.2	24	0		0	0	
1997	23	0		23	9	39.1	23	3	13.0	23	18	78.3	23	0		0	0	
1996	19	1	5.3	26	16	61.5	26	2	7.7	26	18	69.2	26	0		0	0	
1995	26	1	3.8	26	18	69.2	26	3	11.5	25	11	44.0	25	0		0	0	
1994	25	2	8.0	26	13	50.0	24	0		26	5	19.2	25	0		0	0	
1993	7	1	14.3	8	8	100.0	25	1	4.0	25	9	36.0	24	0		0	0	

	Iron Total			Aluminium Total			True Colour			Alkalinity			Suspended Solids			Conductivity		
Index Period	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)	Number of Tests	Number of Failed Tests	Percent Failed (%)
2013	4	3	75.0	4	2	50.0	4	3	75.0	4	4	100.0	4	0		4	3	75.0
2012	14	10	71.4	14	8	57.1	14	5	35.7	14	11	78.6	14	2	14.3	13	10	76.9
2011	13	9	69.2	13	7	53.8	13	5	38.5	13	9	69.2	13	2	15.4	12	8	66.7
2010	12	9	75.0	12	7	58.3	12	5	41.7	12	11	91.7	12	1	8.3	9	7	77.8
2009	13	8	61.5	13	6	46.2	13	3	23.1	13	13	100.0	13	1	7.7	11	8	72.7
2008	12	9	75.0	12	9	75.0	12	5	41.7	12	12	100.0	12	1	8.3	11	10	90.9
2007	12	9	75.0	12	8	66.7	12	3	25.0	12	11	91.7	12	4	33.3	13	12	92.3
2006	13	5	38.5	13	6	46.2	13	0		13	13	100.0	13	2	15.4	12	11	91.7
2005	12	7	58.3	12	6	50.0	12	2	16.7	12	12	100.0	12	4	33.3	12	12	100.0
2004	13	6	46.2	13	5	38.5	13	2	15.4	13	13	100.0	13	1	7.7	13	13	100.0
2003	13	6	46.2	13	6	46.2	13	0		13	13	100.0	13	4	30.8	12	12	100.0
2002	14	10	71.4	14	11	78.6	14	4	28.6	14	12	85.7	14	8	57.1	14	13	92.9
2001	6	5	83.3	6	5	83.3	6	1	16.7	6	6	100.0	17	8	47.1	17	17	100.0
2000	0	0		0	0		0	0		0	0		27	1	3.7	21	18	85.7
1999	0	0		0	0		0	0		0	0		26	1	3.8	12	11	91.7
1998	0	0		0	0		0	0		0	0		24	7	29.2	24	20	83.3
1997	0	0		0	0		0	0		0	0		23	3	13.0	23	23	100.0
1996	0	0		0	0		0	0		0	0		26	6	23.1	19	19	100.0
1995	0	0		0	0		0	0		0	0		26	4	15.4	26	25	96.2
1994	0	0		0	0		0	0		0	0		23	8	34.8	24	24	100.0
1993	0	0		0	0		0	0		0	0		16	1	6.3	8	8	100.0

There are number of factors that can lead to high conductivity levels in river water. For examples, streams that run through clay catchments may have a higher conductivity level as the presence of clay particles ionize when they enter into the river system (DSEWPC, 2013). Groundwater inflows can have the same effects if it contains clay particles (Tutmez et al., 2006). An underperforming STP could raise the conductivity level because of the presence of chloride, phosphate and nitrate (Morrison et al., 2001).

5. Conclusion

This study applies WQI method to effectively derive information from complex water quality data sets to assess the water quality of the HNRS in NSW, Australia. Water quality data obtained from 9 sampling stations along the HNRS during the last 21 years were evaluated for track changes at different water quality monitoring stations over time, and for comparisons among stations. The CCME WQI method with Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC) have been applied to identify the deteriorated zones of the HNR and identify the water quality parameters which contribute to poor WQI. Among the 9 sampling stations in the HNRS examined here, 5 demonstrate a marginal water quality and 4 demonstrate poor water quality. Stations N14 and N35 are the most polluted stations. These stations are mainly affected by the effluents of six sewage treatment plants. At N14, it has been found that total nitrogen, chlorophyll-a (Chl-*a*), total iron, total aluminium, alkalinity, and conductivity have exceeded the ANZECC guidelines in many occasions. Overall, the water quality in the HNRS is at a marginal to poor state. The findings of this study can be used to devise an intervention program to improve the overall water quality of the HNRS.

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