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Application of Water Quality Index Models to an Irish Estuary

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ABSTRACT: The paper investigates the application of different Water Quality Index (WQI) models for to estuarine waters. WQI models are aggregation based mathematical models that convert extensive water quality data into a single value. They typically contain four crucial components with the functions of (1) selecting parameters, (2) developing sub-index rules, (3) generating weighting values, and (4) aggregating the sub-indices. They are attractive because of their relative simplicity and ease of application. However, there is a level of uncertainty in the final aggregated indices due to the potentially large spatial and temporal variations in the input water parameter values. Here we apply seven different WQI models to Cork Harbour, an estuary on the southwest coast of Ireland. The water quality data input data included measurements of nine water quality monitoring parameters from 31 monitoring sites in Cork Harbour. The spatial uncertainty of the WQI models was estimated based on the standard deviation of the computed indices. The spatial uncertainty of the input water quality data was also determined and compared with that of the WQIs for any correlation.

KEY WORDS: Water Quality Index; WQI model; estuary; uncertainty

1 INTRODUCTION

Water is a crucial component of the biosphere since it is essential for living organisms. Surface water quality has gradually been deteriorated by both natural and anthropogenic processes in the last number of decades. In recent times, the global community has been faced with a significant challenge to maintain good water quality status. Management of water quality requires effective water quality assessment tools and techniques.

The Water Quality Index (WQI) model has become a popular method for assessing water quality since it was first developed by Horton in 1965. It is a relatively simple tool which allows one to convert extensive water quality data into a single numerical value which describes the water quality. Since it is relatively easy to use by professionals and the output is easy to understand, particularly for non-professionals, it is widely used around the world.

Many countries/agencies have developed different WQI models to evaluate different types of waterbodies (Fig. 1). A review of 107 studies of WQI applications determined more than 35 different WQI models with 80% of the applications to rivers, 10% to lakes and 10% to estuaries. Of the 35 different WQIs, many are variations of earlier models.

Due to the many variations between models and the nature of their basic function (i.e. converting large amounts of temporally- and spatially-varying data into single values), the resulting WQI model index values have differing levels of uncertainty. This uncertainty is mainly associated with the formulations of the WQI model components [1]. Most WQI models have four components including: (1) selection of parameters to be included in the model, (2) development of sub-indices for each water quality parameter, (3) generation of weightings for each parameter and (4) aggregation of the sub-indices.

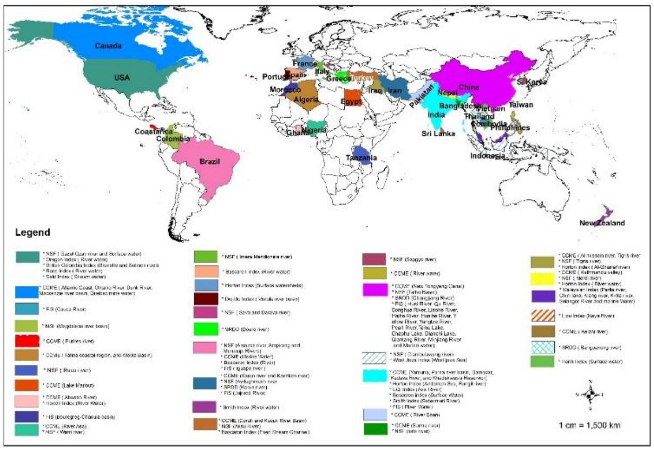

Figure 1: Global applications of WQI models.

Some researchers have shown that most of the model uncertainty is contributed by the sub-indexing and parameter weighting components [2, 3] but, more recently, other researchers have reported that the aggregation function is the primary source of the uncertainty [4].

The present research applies seven of the most commonly used WQI models to an Irish estuary – Cork Harbour – and assesses the levels of uncertainty in the computed water quality indices. Cork Harbour was chosen for the study as a broader research aim is to explore the viability of using WQI models for assessment of water quality in estuaries; there is currently a dearth of literature in this area.

Section 2 of this paper presents a description of Cork Harbour and the monitoring stations. Section 3 describes the materials and methods and Section 4 presents the results of the WQI applications and the uncertainty assessment. Section 5 presents some conclusions based on the research.

2 THE STUDY AREA – CORK HARBOUR

Cork Harbour is a macro-tidal estuary on the southwest coast of Ireland. It has a typical spring tide range of 4.2 m at the entrance to the harbour [5]. Water depths are generally relatively shallow with much of the estuary having a depth of less than 5 meters on spring tides. At low water, a major portion of the harbour area is exposed with mud-flats and sand-flats (Fig 2). The harbor deepens towards the mouth in the main Channel to depths of about 30 m.

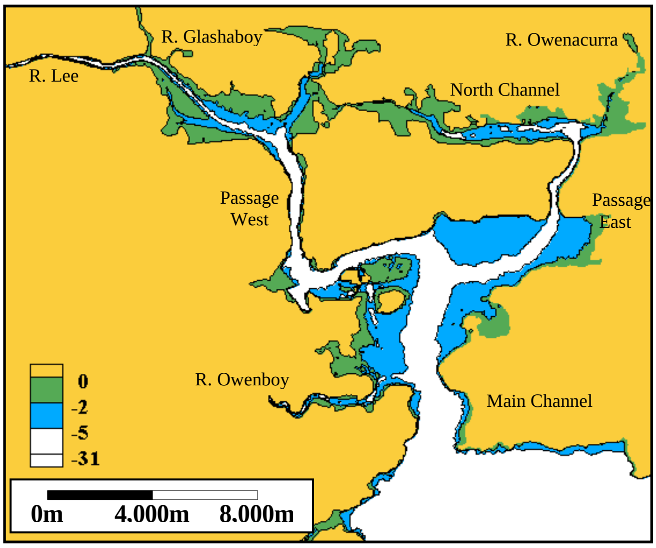

Figure 2: Plan view of Cork Harbour showing mean water depths. Green areas are inter-tidal.

Cork Harbour is the largest natural harbor in Ireland and it is heavily populated and industrialised. A number of rivers flow into the estuary, the largest being the River Lee which flows through Cork City and accounts for approximately 75% of the freshwater delivered to the estuary [5]. Cork city on the River Lee is home to a population of approximately 125,000. When its immediate suburbs are included, the population rises to approximately 200,000. The city is the industrial centre of the Irish southwest region. It is home to a number of large multinationals in the pharmaceutical (e.g. Boston Scientific and Pfeizzer) and ICT (e.g. Apple and Logitec) sectors as well as having a strong domestic industry base. In addition, the surrounding hinterland is subject to relatively intense agricultural activity. As part of the water quality framework, water quality is monitored by the Irish Environmental Protection Agency at 31 monitoring stations in the harbour (Fig 3).

3 MATERIALS AND METHODS

Seven WQI models were applied to Cork Harbour for the study area extents shown in Fig 3. Brief descriptions of the WQIs and the input water quality data follow.

3.1 Water Quality Index (WQI) Models

A review of WQI models used in the literature, identified seven basic models which are evaluated in this research [6]. These are:

- The Horton Index model
- The National Sanitation Foundation (NSF) model
- The Scottish Research Development Department (SRDD) model
- The Canadian Council of Ministers of the Environment (CCME) model
- The West-Java (WJ) model
- The Bascaron model
- The Hanh model.

Details of the model structures, mathematical approaches and their applications can be found in [6].

3.2 Water quality Input Data

In total, nine water quality parameters were used in the WQI models, namely:

- Salinity
- Temperature (0 c)
- pH
- Dissolved oxygen (DO)
- Total organic nitrogen (TON)
- Ammoniacal nitrogen (NH_3^+)
- Nitrate (NO_3^-)
- Orthophosphate (PO_4^{3-})
- Chlorophyll-a (Chl-a) (as a measure of algae)

Water quality parameters were selected based on the WQI model's requirements and monitoring guidelines of surface water quality. Data from the 31 EPA monitoring locations in Cork Harbour shown in Fig 3 were used. 2007 was selected as the test year as the data were available from another research project. EPA generally take measurements at each location at approximately high and low tide on the same day in winter and summer conditions, although the months of collection vary from year to year.

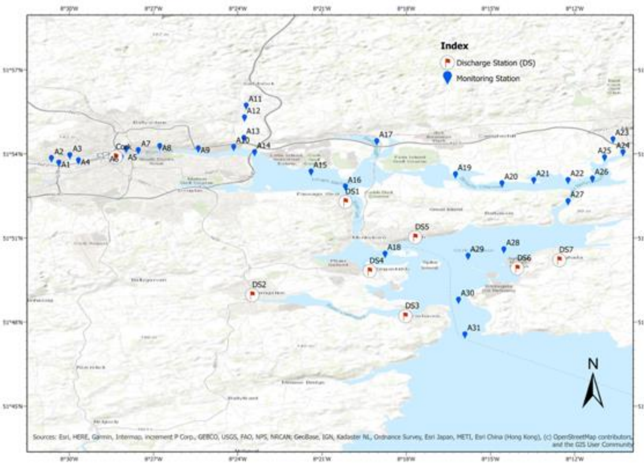

Figure 3: Water quality monitoring locations used in study.

3.3 WQI Application Procedure

The water quality data at each location were depth- and time-averaged at to give an average annual value. The same input water quality data were then supplied to all seven WQI models. The parameter weighting values for the models were produced by applying the Analytical Hierarchy Process (AHP) technique. Final WQI scores were obtained according to the aggregation functions of each WQI model. The different WQI model aggregation functions are defined in equations (1)-(7).

$$\text{Horton index} = \left[\frac{W_1S_1+W_2S_2+W_3S_3+\cdots+W_nS_n}{W_1+W_2+W_3\ldots\ldots+W_n}\right] m_1 m_2 \qquad (1)$$

where s_i and w_i are the sub-index and weight values of water quality parameter i, n is the number of parameters, and m_1 correction factors of temperature and m_2 is the correction factor for pollution respectively; both are ranges between 0.5 to 1.0.

$$NSF\ index = \sum_{i=1}^{n} w_i s_i \qquad (2)$$

$$SRDD\ index = \frac{1}{100}\left(\sum_{i=1}^{n} S_i W_i\right)^2 \qquad (3)$$

$$CCME = \frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732} \qquad (4)$$

where F_1 is the percentage of failed parameters that do not meet with regarding their guideline value; F_2 is the percentage of individual test cases these do not meet with the guideline value and F_3 is the variation percentage of the failed test parameters that do not meet their objectives; and 1.732 is a divisor that is applied for normalization [7].

$$West\ Java\ Index = \prod_{i=1}^{n} {S_i}^{w_i} \qquad (5)$$

$$Bascaron\ Index = \frac{\sum C_i P_i}{\sum P_i} \qquad (6)$$

$$Hanh\ Index = \left[\frac{1}{6}\sum_{i=1}^{6} q_i \times \frac{1}{2}\sum_{i=1}^{2} q_j \times q_k\right]^{1/3} \qquad (7)$$

where q_i is the sub-index value of the organic and nutrients group including pH, DO, NH_4^+ NO_3^-, PO_4^{3-}, TON; q_j is the sub-index value of the particulates group, including temperature and salinity; and q_k is the sub-index value of the biological group containing only *Chlorophyll-a*.

3.4 Uncertainty analysis

Each WQI model produced 31 index values, one for each monitoring station. For each WQI model, the standard deviation of the 31 indices was used as the measure of spatial uncertainty. The spatial uncertainty of the water quality input data was also determined in the same way for each water quality parameter. All statistical parameters were calculated using SPSS.

4 RESULTS AND DISCUSSION

3.1 WQI Index Values

The model indices computed at each monitoring location are presented in figure (4) – (10) for each of the WQI models. Each station is attributed a ranking using the model ranking scales. The ranking systems used are shown in Table 1.

Unlike the other models, for the Horton model a lower score indicates better water quality. The lowest index obtained was 18 while the highest index was 24 (Fig. 4). According to the ranking system, excellent water quality was observed at all stations. The NSF indices ranged from 68 to 98 and 15 of the 31 stations (48%) in Cork harbour were attributed excellent water quality status. Around 23 % of monitoring locations water quality was evaluated with good status, while the remaining locations were attributed medium quality status (Fig. 5). The SRDD model indices ranged from 55 to 98 and gave excellent water quality in 15 of the 31 stations (Fig. 6). For the CCME model, indices ranged from 93-100 and excellent water quality was therefore observed at 17 locations (Fig. 7).

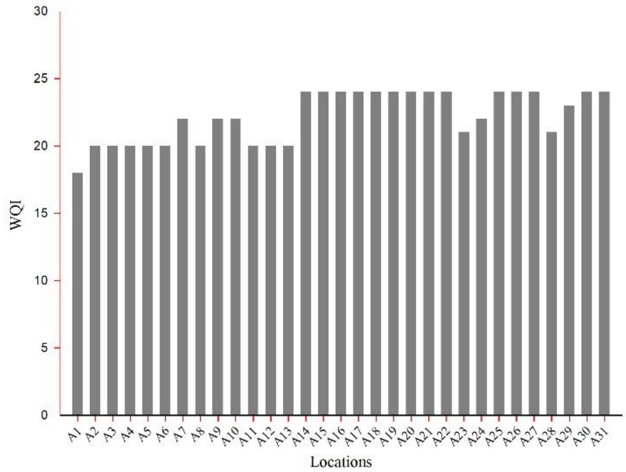

Figure 4: Horton WQI scores

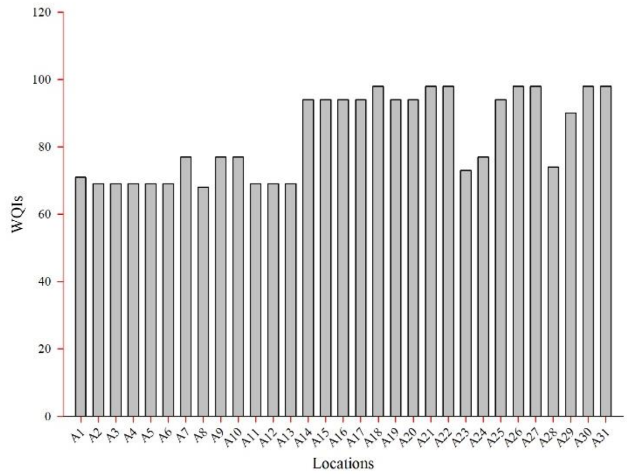

Figure 5: NSF WQI scores

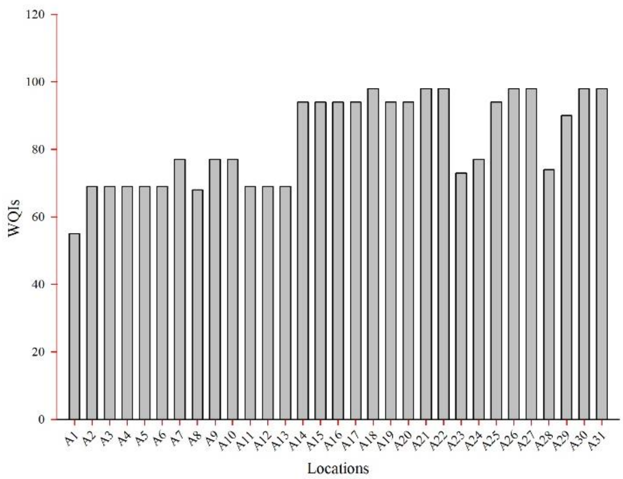

Figure 6: SRDD WQI scores

Approximately 41% of monitoring locations were ranked excellent quality by the West Java model for which indices ranged from 0-55 (Fig. 8). The other locations water quality was determined “good” to “fair”. Comparatively, the poorest water quality status was estimated by the Hanh model. Approximately, 16 locations water quality were ranked in the marginal category that ranges between 26 – 50 (Fig. 10).

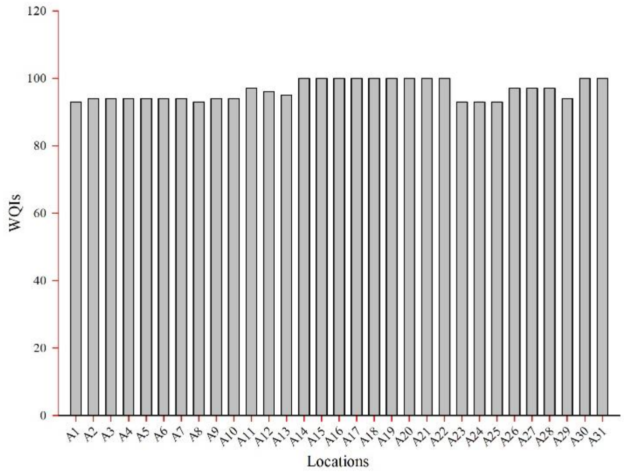

Figure 7: CCME WQI scores

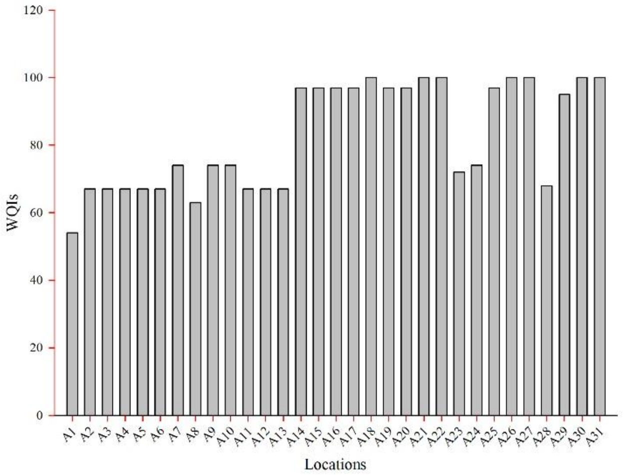

Figure 8: West Java WQI scores

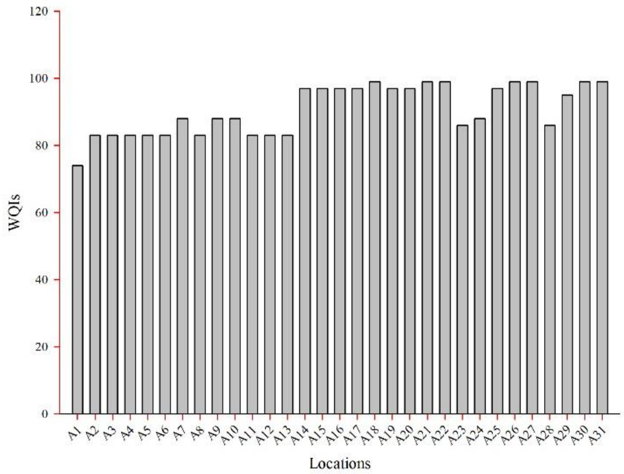

Figure 9: Bascaron WQI scores

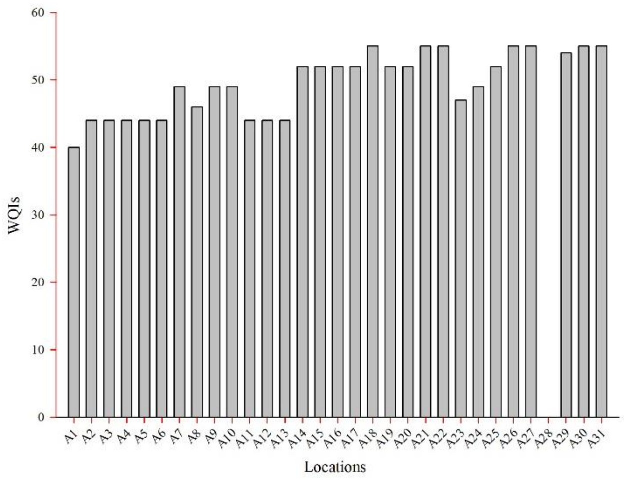

Figure 10: Hanh WQI scores

In general, looking across all the models, with the exception of the Horton model water quality status was poorer in stations A1-A13 relative to the rest of the harbour. These stations lie in the River Lee and are thus subject to agricultural run-off from the Lee catchment and combined sewer overflow discharges from Cork city which straddles the river.

Table 1 Water quality ranking scales of different WQI model

WQI model	Ranking scales	WQ status
Horton	0 – 25	Excellent
	25 – 50	Good
	51 – 75	Fair
	101 – 150	Very poor
NSF	90 – 100	Excellent
	70 – 89	Good
	50 – 69	Medium
	25 – 49	Bad
	0 – 24	Very bad
SRDD	90 – 100	Excellent
	70 – 89	Good
	40 – 69	Tolerable
	30 – 39	Polluted
	0 – 29	Severely polluted
CCME	95 – 100	Excellent
	80 – 94	Good
	65 – 79	Fair
	45 – 64	Marginal
	0 – 44	Poor
West Java	90 – 100	Excellent
	75 – 89	Good
	50 – 74	Fair
	25 – 49	Marginal
	0 – 24	Poor
Bascarón	91 – 100	Good
	61 – 90	Acceptable
	31 – 60	Regular
	16 – 30	Bad
	0 – 15	Very bad
Hanh	91 – 100	Excellent
	76 – 90	Good
	51 – 75	Fair
	26 – 50	Marginal
	<25	Poor

3.2 Uncertainty analysis of WQI Indices

Uncertainty is a fundamental inherent feature in any hydrological model that is associated with different components of the model [1]. Its quantification is crucial for assessing the model reliability [8]. A number of studies have used SD to evaluate uncertainty of WQI models. [3] and [4] used the SD for estimating the model uncertainty of the sustainability index model and the West-Java WQI model, respectively. The smallest SD value indicates the final outputs does not propagate by the model input components [7]. However, the standard deviation must be assessed in relation to the mean value. The spatial uncertainty of the WQI models was therefore apprised using the coefficient of variation (CoV) calculated as the ratio of the standard deviation (SD) of the indices to the mean across all 31 stations. These values are given in Table 2 along with the maximum and minimum values recorded across all stations. The CoV was lowest for the CCME model (0.03) followed by the Bascaron and Horton models (0.08, 0.09) respectively. The spatial uncertainties of the other models were significantly higher with CoV values ranging from 0.15 to 0.21.

Table 2. Analysis of the spatial uncertainty of measured WQI models.

WQI Models	Minimum	Maximum	Mean	SD	CoV
Horton	18	24	22.16	1.92	0.09
NSF	68	98	83.23	12.56	0.15
SRDD	55	98	82.71	13.38	0.16
CCME	93	100	96.45	2.92	0.03
WJ	54	100	82.68	15.81	0.19
Bascaron	74	99	90.71	7.45	0.08
Hanh	0	55	47.87	9.99	0.21

3.3 Uncertainty analysis of WQI Input Data

Some of the spatial uncertainty of the indices calculated by the various model undoubtedly comes from the spatial variation of the input water quality parameters. Many researchers have determined input entities are one of the main sources of uncertainty in WQI models [1, 8]. The uncertainty of the model input parameters was also evaluated using CoV values of the measured time-averaged water quality data at each station. Water quality parameters statistics are presented in Table 2. The highest levels of spatial uncertainty were recorded for TON, NO_3^- and Chl-a where CoV was greater than 1. Significant levels of spatial uncertainty were also observed for salinity, NH_3^+ and PO_4^{3-}; while the lowest CoV was calculated for DO, pH and water temperature, respectively (Table 3).

Table 3. Spatial uncertainty analysis of WQI models inputs.

WQ Parameters	Min	Max	Mean	SD	CoV
Salinity (g/Kg)	.25	34.68	19.45	13.69	0.70
Temp (0 C)	12.45	16.46	14.83	0.99	0.07
pH	7.66	8.21	8.01	0.17	0.02
DO (mg/l)	5.05	10.55	8.59	1.07	0.12
TON (mg/l)	.02	8.05	1.73	1.99	1.15
NH_3^+(mg/l)	.02	.32	0.08	0.07	0.88
NO_3^-(mg/l)	.02	8.05	1.73	1.99	1.15
PO_4^{3-} (µg/l)	9.90	68.50	25.75	13.03	0.51
Chl a (µg/l)	.65	76.90	6.13	13.27	2.16

In the WQI models, weightings are attributed to the various water quality parameters when the parameter sub-indices are combined into the overall index using the aggregation functions in equations (1)-(7). The same parameter weight values were used in each model. One of the highest weight values is attributed to Chl a given that is a result of eutrophication and thus an indicator of heavily polluted waters. Since Chl-a also had the highest CoV of all the input parameters, it is likely that spatial variations in chlorophyll-a are one of the main sources of the spatial uncertainty in the computed water quality indices.

4. Conclusion

Water Quality Index (WQI) models are a useful method to assess water quality. Worldwide it has become a popular tool due to its simplicity, ease-of-use and low computational cost. However, there have been relatively few applications of WQIs to estuarine waters. The present study was conducted firstly to determine the ease of application of a number of WQI index models to an estuarine system. Seven WQI models were successfully adapted for application to estuaries and indices were successfully calculated. Water quality was assessed mostly in the “fair” to “excellent” classes in Cork harbour but water quality in the River Lee was consistently assessed as poorer quality than the rest of the harbour. A second objective was to assess the level of spatial uncertainty in the computed indices across the 31 monitoring stations used in the study. The lowest uncertainty was found in the CCME, Bascaron and Horton models while the highest uncertainty was found in the Hanh model. Given that chl-a had the highest spatial variation of all of the input water quality parameters and one of the highest parameter weight values, it therefore contributes strongly to some of the observed model uncertainty.

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