Assessment of Water Quality Using Water Quality Index (WQI) Models and Advanced Geostatistical technique

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ABSTRACT: Water quality index (WQI) models are popular tools to evaluate the quality of water; as such they have been developed and used by many agencies worldwide. However, the WQI model may generate excessive uncertainties in the aggregation process. This research is focused on the performance of various WQI modes. In this study, seven WQI models (Horton, CCME, NSF, West-Java, SRDD, Baccarin and Hanh) were applied in order to intercompare their performances and results generated by them. The Cork Harbour in the south of Ireland is used as a study case. Six years (2007 - 2012) of water quality monitoring data across the Harbour is used to conduct the analysis. Development of a WQI model involves four consecutive steps: (1) parameters selection, generation of (2) sub-indices, (3) weight values and (4) aggregation function; these were applied in the study. In total, nine crucial water quality parameters from 31 monitoring locations were selected in step (1) of the analysis. The EU Water Framework Directive (WFD) guidelines were applied to create the parameter sub-index rules (step 2). In step (3) the parameters weight values were generated by applying the Analytic Hierarchy Process (AHP). Finally, in step (4) the WQI model aggregation functions were applied to estimate the final WQI score for each of the seven models. Ultimately, the advanced geostatistical Empirical Bayesian Kriging (EBK) technique was used to spatially interpolate WQI calculated at the monitoring stations onto the whole domain of Cork Harbour. A comparison of the cross-validation parameters (ASE, MSE, RMSE, RMSSE and CRPS) was used to select the WQI model for the least uncertainty interpolation. The results show that the lowest uncertainty was generated by the EBK model for WQI generated by the CCME model, while the highest uncertainty obtained for the Hanh and West Java WQIs. Based on the EBK result, a ranked water quality map was proposed to be used for an assessment of surface water quality and its classification. The water quality ranked map proposed in this research can help not only to assess water quality but also to enhance understanding of water quality spatial variability in any waterbody. Based on the analysis of WQI models, it was concluded that the Cork Harbour water quality was of ‘good’ to ‘excellent’ status during the period of analysis 2007-2012.

KEY WORDS: Modified WQI architecture; Empirical Bayesian Kriging (EBK) technique; model prediction uncertainty; Cork Harbour water quality; water quality ranked map

1. INTRODUCTION

Environmental concerns are central to sustainable water resource management and planning. Over many decades, freshwater consumption has been increasing worldwide due to population growth, industrialisation and urbanisation [1]. The surface water quality deteriorates in many basins due to pollution of anthropogenic sources [2, 3]. In this context, a water resources conservation and sustainable management are critically important for achieving at least good surface water quality status.

In recent years, a range of tools and techniques has been developed to evaluate surface water quality and diagnose the health of aquatic ecosystem. The water quality index (WQI) model is one of such tools. It assesses the status of water quality based on a characteristics of water quality parameters [4, 5, 6] by converting extensive water quality data into a single number. This number as the WQI model output can be associated with a simple description of water quality status using a simple terminology such as “excellent”, “good”, “medium”, “bad or acceptable”, “very bad or unfit” [6, 7] . This allows the non-expert communities to easily understood the status of the water quality without an expert knowledge of underlying conditions and processes [2].

Due to its simple structure and application process, the WQI models have gained popularity in recent years. As the number of models and their application increases, more sensitivity and uncertainty analyses have been conducted to reveal shortcomings of the WQI models. A significant contribution of the model uncertainty has been associated with the model aggregation function [4, 8]. The parameter sub-indexing and weighting process are known to generate uncertainty in the WQI models too [9].

The aim of this study is to assess surface water quality in Cork Harbour by apply various WQI models. The assessment is initially made for the monitoring stations and later extended to the whole domain of Cork Harbour using a sophisticated interpolation technique. Also in this study, a comparative analysis of the various WQI models is performed.

2. MATERIALS AND METHODS

2.1 Water quality data

Cork Harbour is designated as the Special Protection Area. Water quality in the harbour is assessed by the Environmental Protection Agency (EPA), Ireland through their monitoring programme which comprises of 31 sampling stations (Fig 1). In total, nine water quality parameters listed in Table 1 are routinely analysed as part of the programme. From this dataset, water quality data for the period 2007-2012 was used to calculate WQI for each year and each station.

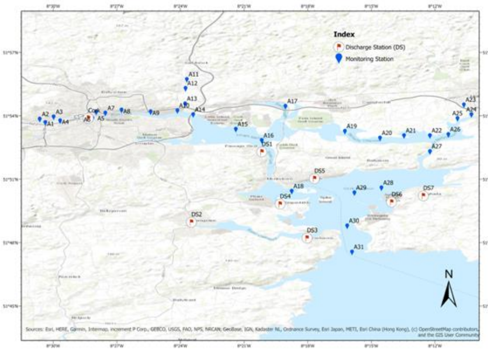

Fig 1. Map of EPA monitoring stations and effluent discharges in Cork Harbour (from EPA report 2016, pp. 135).

2.2 ANALYTICAL PROCEDURES

2.2.1 WQI models

For the purpose of this research, the existing WQI models have been extensively reviewed and their suitability to the current study preliminarily assessed. In total, seven WQI models were ultimately selected for in-depth analysis of their performance. They are (1) the National Sanitation Foundation (NSF WQI), (2) Canadian Council of Ministers of the Environment (CCME WQI), (3) Scottish Research Development Department (SRDD), (4) West Java (WJ WQI), (5) Horton Index, (6) Hanh Index, and (7) Bascaron Index.

2.4.2 WQI model architecture

Commonly, the WQI calculations comprise of four consecutive steps: (1) parameter selection, (2) parameter sub-index selection, (3) parameter weighting, and (4) application of the aggregation function [4, 6]. The WQI model architecture and parameters used are discussed in [2].

The following steps were applied to calculate WQI and to estimate uncertainty for each WQI model:

(a) Acquisition of water quality data for Cork Harbour
(b) Selection of water quality parameters based on the EU water quality monitoring guidelines, WQI model requirements and data availability
(c) Transformation of WQ parameter units and dimensions to a common dimensionless scale using sub-indexing process
(d) Determination of weight values for each WQ parameter using the Analytic Hierarchy Process
(e) Aggregation of sub-indices for each of the WQI model to obtain final WQI scores for each model and dataset.
(f) Implementation of the Empirical Bayesian Kriging (EBK) advanced geostatistical interpolation technique to produce spatial variability maps of WQI and WQ ranks in Cork Harbour, and finally
(g) Assessment of the EBK model uncertainties by utilizing the cross-validation statistical methods.

In this study, a range of WQI models is reviewed and best performance model is utilized to evaluate the surface water quality and its classification in Cork Harbour.

2.3.3 Parameter selection

The parameter selection is based on screening of the water quality parameters in respect of their environmental significance [5]. As such the process is subjective, site specific and lacks universality. Table 1 lists these parameters along with recommended and optional parameters for each WQI model.

Table 1: Developed WQI model parameters

WQ Parameters	WQI models						
	Horton	NSF	CCME	SRDD	WJ	Hanh	Bascaron
Temperature	×[b]	✓[a]	✓	✓[a]	✓[a]	×[b]	✓[a]
Salinity	×[b]	×[b]	✓	×[b]	×[b]	×[b]	×[b]
pH	✓[a]	✓[a]	✓	✓[a]	×[b]	×[b]	✓[a]
DO	✓[a]	✓[a]	✓	✓[a]	✓[a]	✓[a]	✓[a]
T. Ammonia	×[b]	×[b]	✓	✓[a]	✓[a]	✓[a]	✓[a]
T. Phosphate	×[b]	✓[a]	✓	✓[a]	×[b]	✓[a]	✓[a]
Nitrates	×[b]	✓[a]	✓	×[b]	×[b]	×[b]	✓[a]
TON	×[b]	×[b]	✓	✓[a]	✓[a]	×[b]	×[b]
Chl a	×[b]	×[b]	✓	×[b]	×[b]	×[b]	×[b]

✓[a] WQI Model recommended; ✓ optional parameters; ×[b] used in this study;

2.3.4 Parameter sub-indexing

The parameters sub-indexes are established to transform dimensions and units of each parameter to a common scale [5]. Typically, the conversion rates are adopted from legislated water quality standards guidelines for the water quality classification operated in a given country [e.g. 5, 10, 11]. Similarly here, the sub-index rules were developed based on the EPA guidelines for surface water quality assessment [12] with is an implementation of the European Communities regulations for 'Quality of surface water intended for the abstraction of drinking water (1989)'[20], 'Quality of Shellfish waters (2006)' and OECD classification scheme for lake waters (1982). Depending on their values, each parameter is assigned to one of the three categories A1 – A3. Table 2 describes classification criteria for each water quality category.

The conversion of a parameter value to sub-index is based on a reference value for a parameter and rules for each category. Sub-index score normalizes a parameter value into 0-100 range with the value of 100 assigned to A1 class and value of 0 to A3 class. The exception for this rule is West-Java WQI model where for the for computational reasons the lowest sub-index value assigned to 5.

Table 2. Classification of the surface water quality and required actions proposed by the European Communities regulations.

Category	Definitions and required actions
A1	Need to modest physical treatment and disinfection, e.g. rapid filtration and disinfection.
A2	Typical physical treatment, chemical treatment and disinfection, e.g. prechlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination).
A3	Required to 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).

2.3.5 Parameters weighting process

The third step in the determination of WQI involves an assignment of weight values to each parameter to produce a hierarchy of all parameters with respect to their environmental significance and impact on water quality. The Analytic Hierarchy Process (AHP) proposed by [18] was adopted to develop a rank of parameters (or their weight values) based on a multi-criteria analysis of their importance respectively to other parameters. A ranged of water quality guidelines issued by EPA Ireland, EPA USA, the UK as well as the personal experience of the research team and environmental conditions in Cork Harbour were used to establish importance of each parameter on water quality. The AHP ranking scale ranges from 1 – equal importance to 9 – extreme importance, and their assigned values for parameters selected in step 1 are shown in Table 4. The normalized AHP values were used to develop paired comparison of criteria in a pair-wise all-parameter matrix [9x9] to ultimately generate weight values for each parameter (Table 4). Such methodology was previously successfully applied for a range of water quality studies [5].

The second step of the weighting process is to calculate consistency ratio (CR) to evaluate consistency of the set of judgments made in relation to AHP ranking and weights. A true Consistency Ratio (CR) is calculated by dividing the Consistency Index (CI) for the set of judgments by the Random Index (RI) for the corresponding random matrix as follows

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \qquad (1)$$

The RI value is set to 1.45 for 9 as recommended in [24] while the CI value was calculated using the following equation

$$\text{CI} = \frac{\lambda_{max} - n}{\text{n}-1} \qquad \textbf{(2)}$$

where $\boldsymbol{\lambda}_{max}$ is the largest eigenvalue of the matrix and n represents the total associate of the matrix [13]. If the CR exceeds 0.1 the set of judgments may be too inconsistent to be reliable and as such the set of judgments needs to be revised [14]. The CR was found to be close to 0 and as such the consistency of subjective judgment in relation to the derived AHP ranking is satisfied.

Table 3. Water quality parameters, standard values, classes, sub-index rules and their S_i values.

Selected parameters	Units	[a]References values	[b]Water categories	Rules	Sub-index values (S_i)
pH			A1	5.5 – 8.5	100
		6.5 – 9.0	A2 -A3	> 8.5	0 or 5[e]
Temperature	(^{0}C)	25	A1 – A2	= <25	100
			A3	>25	0 or 5[e]
DO	(mg/L)		A1	equal or >6	100
		> 6	A2	> 5	75 <Si ≤ 50
			A3	>3	50 < Si ≤ 25 or 5[e]
NO3	(mg/L)	50	A1 -A2	equal or <50	100
			A3	>50	0 or 5[e]
[c]Salinity	(g/Kg)		A1	equal or <35	100
			A2	> 10	75 < Si ≤ 50
		35	A3	< 10	50 < Si ≤ 25
			A4	0 or >35	0 or 5[e]
[d]Chlorophyll a	(µg/L)		A1	equal or <8	100
		8	A2 -A3	> 8	0 or 5[e]
NH3	mg/L as N)		A1	equal or < 0.2	100
		0.2	A2	equal or < 1.5	50
			A3	equal or > 4	0 or 5[e]
TON	(mg/L)	1	A1	equal or <1	100
			A2	equal or >2	75 < Si ≤ 50
			A3	equal or >3	0 or 5[e]
PO4	(µg/L as P)	500	A1	equal or <500	100
			A2 -A3	equal or > 700	0 or 5[e]

[a]EPA, Ireland (2001), recommended values for the surface water/freshwater/river water/aquatic life.
[b] water categories were defined as per guidelines of the European Communities (Quality of surface water intended for the abstraction of drinking water) regulations, 1989 (S.I. No. 294/1989).
[c] the European communities (Quality of Shellfish waters) regulations, 2006 (S.I. No. 268/2006).
[d]the Organisation for Economic Cooperation and Development (OECD) classification scheme for lake waters, 1982, adopted by (with modifications) EPA, Ireland.
[e]this scale only applied for West Java WQI model when criteria do not meet to the objective values.

2.3.4 The aggregation process

Final step in calculation of WQI scores employs aggregation functions of each WQI model. The different WQI model aggregation functions are defined in equations (1)-(7).

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

where s_i and w_i are the sub-index and weight values of water quality parameter i, n is the number of parameters.

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

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

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

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 [15].

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

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

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

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*.

2.5 EMPIRICAL BAYESIAN KRIGING (EBK) TECHNIQUE

In this study, the water quality indices are produced for geographical locations in Cork Harbour where WQ data are available. In order to better understand horizontal distributions of water quality within the Harbour, WQI were spatially interpolated. From a arrange of interpolation techniques, the Empirical Bayesian Kriging (EBK) was selected to predict WQI at points not included in the monitoring programme. EBK is a geostatistical interpolation method that automatically calculates the kriging model parameters through a process of sub-setting and simulations. Also, the model, when calculates the samivariogram, takes into account the uncertainty of semivariogram estimation and by that reduce underestimation of standard errors of predictions [21]. These are the significant advantages of the method over the other kriging models [16]. The empirical semivariogram was calculated using the following equation

$$\gamma\ (h \pm \delta) = \frac{1}{2|N(h \pm \delta|} \sum_{(i,j)\in N(h\pm\delta)} \left|z_i - z_j\right|^2 \qquad (8)$$

where h is the distance between sampling points, δ is the tolerance range between points, N(h $\pm\ \delta$) is a set of points N(h $\pm\ \delta) \equiv \left\{(S_{i,}\ S_j): \left|S_i S_j\right| = h \pm \delta; i,j = 1,2, \dots, N\right\}$. $\left|z_i - z_j\right|^2$ are the squared variances between observations. The squared variances are added and normalized by the natural number N(h $\pm\ \delta$). The empirical transformation function was employed to predict the probability distribution of the aggregation value of WQI model.

2.6 EBK validation process

The cross-validation of the interpolated data was used to assess the accuracy and uncertainty of the EBK interpolation model [17]. The EBK model uncertainty was estimated using the prediction standard errors parameters. When the average standard error (ASE) is close in value to the root mean squared error (RMSE), then the EBK output exhibits the lowest uncertainty for a given WQI model. ASE values smaller than RMSE indicate an underestimation of variability in interpolated data. Also, the root mean squared standardised errors (RMSSE) close to one suggests that the model prediction standard errors are valid. The RMSSE value larger (smaller) than 1 indicates underestimation (overestimation) of variability in model predictions.

$$ASE = \frac{1}{n}\sum_{i=1}^{n}(p_i - \left(\sum_{i=1}^{n} p_i\right)/n)^2 \quad (4)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(p_i - m_i) \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i - m_i)^2} \quad (6)$$

$$RMSSE = \sqrt{\frac{1}{n}[\sum_{i=1}^{n}(ps_i - ms_i)\Big/\sigma s_i]^2} \quad (7)$$

where *n* is the number of measured sampling locations; *p* is the predicted value at *i^th^* sampling locations (I = 1, 2,.. …n); *m* is the calculated value; *ps* is the standardized predicted value; *ms* is the standardized measured value and σs standardized deviation.

The average Continuous Ranked Probability Score (CRPS) is used to estimate uncertainty of EBK predictions [5]. CRPS measures the deviation of cumulative distribution function [9].

$$CRPS = \frac{1}{n-1}\sum_{j=1}^{n}\left(\sum_{j=1}^{n} p_j - \sum_{j=1}^{n} m_j\right)^2 \quad (8)$$

where n is the number of outputs, p_j is the predicted probability of output j^{th} location, and m_j is the measured probability of output j^{th} location. Usually, the CRPS score lies between 0 to 1. The smaller CRPS score is the better the fit of EBK model to data.

4. RESULTS

In this study the accuracy and usability of existing water quality index models were evaluated. In total 7 WQI models were used to generate WQIs. Cork Harbour, a hydrologically compound estuary characterised by complex ecosystem dynamics and dependencies was used as a case study. The water quality dataset consists of 9 parameters collated annually at 31 locations within the study domain during the period 2007-2012. This dataset was used to produce WQI maps and ultimately to selected best-performance WQI model.

4.1. GENERATION OF WQI

For each of the 7 WQI models, the generation of WQIs consist of four consecutive steps: (1) parameters selection, generation of (2) sub-indices, (3) weight values and (4) aggregation function. Steps (1) – (3) are identical for each model. Outputs of these steps are discussed below.

With regards to the parameter selection, nine parameters were selected to determine WQI. The selection was based on recommendations given by each model developer, data availability, parameter cross-correlation and EPA recommendations. The list of parameters is shown in Table 1.

The generation of sub-indices in step (2) allows to convert dimensions and units of each parameters to a universal scale so the parameters can be intercompared. The process is described in section 2.3.4; sub-index values were determined for each parameter based on rules and criteria summarised in Table 3. In step (3) parameter weights are generated to rank an importance and contribution of induvial parameters to the overall water quality score. The rank of parameters on AHP scale of 1 to 9 is shown in Table 4. The numbers were assigned with respect to impact of a parameter on water quality and hence environmental conditions and ecosystem. From the assigned AHP ranks, the weights were calculated and are presented in Table 4. As the process of assignments of AHP sores is based on a set of subjective judgments in relation to a significance of the parameter, consistency of the set of judgments was evaluated using the Consistency Ratio, which was found to be close to 0 (< 0.1). This confirms that the judgments made are consistent throughout the dataset and there are no conflicts between assigned values. Consequently, the derived weights are consistently assigned and can be used in step (4).

Table 4: Estimated parameters weight values.

WQ Parameters	Weight values
DO	0.16
Temperature	0.16
Chl a	0.13
pH	0.13
Salinity	0.09
TP	0.09
Nitrate	0.09
TON	0.09
TA	0.05
Sum	1

Finally, in step (4) WQI are calculated for given sub-index and weight values using the aggregation function defined in section 2.3.4. Each model applies different aggregation function so the differences in WQI values obtained for various WQI models are directly related to the aggregation method used. Table 5 shows WQI values (AMV) averaged spatially over 31 datasets (locations in Figure 1). All models (except Horton) operate on 0-100 scale; the higher the number is the better water quality. The Horton WQI model with value of 0 describes excellent water quality status while WQI >100 represents very poor conditions[19]. The WQIs are ultimately used to categorize water quality into classes. From the analysis of WQI it is apparent that for a given dataset the water quality is good to excellent depending on the applied model. Such discrepancies may lead to erroneous interpretations of the water quality status and result in inappropriate management decisions and actions.

Table 5: WQI values generated by WQI models (AMV) and interpolated using EBK model (APV) with average statistical error (ASE).

WQI Models	2007			2008			2009			2010			2011			2012		
	AMV	APV	ASE	AMV	APV	ASE	AMV	APV	ASE	AMV	APV	ASE	AMV	APV	ASE	AMV	APV	ASE
Horton	88.68	88.77	3.74	86.81	86.61	4.49	86.58	86.10	5.89	83.55	83.52	4.66	88.90	88.88	5.11	84.71	84.49	14.41
Bascaron	90.71	90.79	4.66	86.43	86.39	4.60	86.67	86.50	6.11	93.65	93.71	3.72	89.06	89.18	4.54	87.93	88.01	6.41
CCME	96.45	96.23	1.70	95.03	94.91	1.36	93.47	93.54	0.50	96.45	96.41	1.69	96.16	95.95	1.65	96.32	96.20	1.91
WJ	82.68	82.51	8.97	72.07	71.78	10.86	70.80	70.61	11.19	86.39	86.93	8.96	78.55	78.65	10.29	77.10	77.59	11.52
NSF	83.23	82.85	7.61	74.83	74.20	8.20	76.23	76.23	9.67	88.35	88.33	5.89	80.26	80.48	7.76	78.17	78.58	11.13
Hanh	47.87	47.70	6.70	32.73	34.28	14.91	47.33	47.93	5.23	51.45	51.78	4.57	47.87	47.76	6.49	49.17	49.17	2.37
SRDD	82.71	82.73	7.47	74.30	73.72	8.84	75.57	75.48	10.61	87.97	88.47	6.70	79.61	79.84	8.41	77.57	77.86	11.17

*AMV = Average measured values; APV = average predicted values; ASE = Average standard error

4.2 MODEL PERFORMANCE AND UNCERTAINTY ANALYSIS

WQIs calculated for 31 monitoring stations were interpolated over the domain of Cork Harbour. From a range of interpolation techniques, the EBK was selected to perform the interpolation of WQI scores.

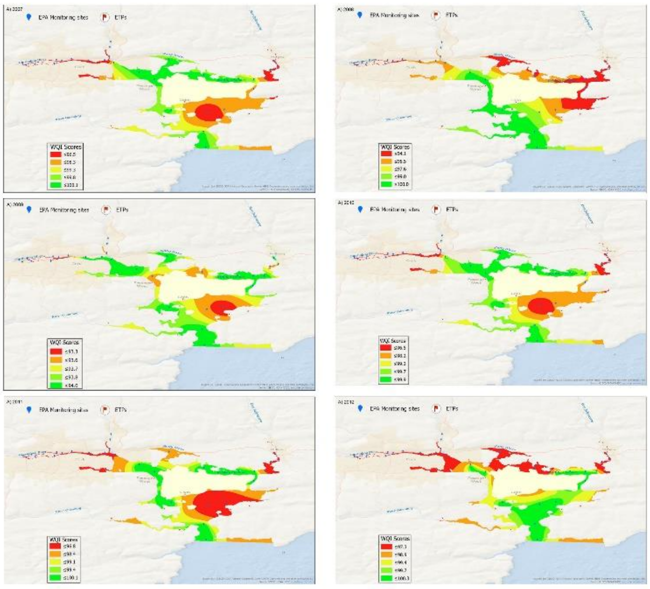

Figure 2. Maps of CCME WQIs spatially interpolated using EBK technique.

The cross-validation process was utilized to estimate the propagation of uncertainties in EBK predicted values. This analysis was conducted to establish for which of WQI models the EBK performs best. In general, the smallest RMSE and MAE values indicate the best performance of the EBK with the lowest propagation of uncertainties [3]. The CRPS scores were used to estimate the interpolation uncertainty [22].

Table 6 summarizes statistics of EBK predictions for various WQI models. The lowest cross-validation parameter values were obtained by the CCME model for each year in the range 2007 – 2012. In contrast, the West-Java and Hanh models were generating the highest RMSE values, and as such the EBK for these model data exhibits worst performance.

The EBK model uncertainty was estimated using the average continuous ranked probability score (CRPS) of predicted values. The lowest uncertainty was associated with the CCME WQI model while the highest with the NSF, SRDD and West Java models. Based on the uncertainty analysis, the EBK model was found to exhibit the best performance in conjunction with the CCME model outputs. Consequently, CCME is further used here to produce maps of water quality indices and ranks in Cork Harbour.

Table 6: Statistical analysis of the EBK model performance.

Temporal variation	EBK model validation parameters	Applied WQI model						
		Horton	WJ	SRDD	NSF	Hanh	CCME	Bascaron
2007	ACRPS	2.065	4.48	3.728	3.649	3.209	**0.851**	2.123
	RMSE	3.991	8.84	7.072	6.827	10.22	**1.611**	4.04
	MSE	0.030	-0.021	-0.013	-0.028	0.243	**-0.056**	-0.012
	RMSSE	1.021	0.988	0.93	0.921	2.705	**0.903**	0.861
	ASE	3.908	9.154	7.673	8.089	7.466	**1.865**	4.837
2008	ACRPS	2.547	6.008	4.762	4.225	7.828	**0.677**	2.367
	RMSE	4.984	10.807	8.821	8.255	16.788	**1.421**	4.664
	MSE	0.001	-0.012	-0.029	-0.038	0.066	**-0.011**	-0.022
	RMSSE	1.117	0.994	0.99	0.954	1.181	**0.852**	0.866
	ASE	4.640	10.93	9.039	8.594	16.901	**1.604**	4.845
2009	ACRPS	2.822	5.68	5.264	4.847	3.157	**0.309**	3.053
	RMSE	4.942	10.382	9.419	8.851	10.187	**0.567**	5.438
	MSE	-0.064	-0.008	-0.002	0.002	0.228	**0.19**	-0.024
	RMSSE	0.952	0.89	0.89	0.893	2.381	**1.211**	0.918
	ASE	6.064	11.428	10.786	9.872	5.611	**0.502**	6.215
2010	ACRPS	2.467	4.598	3.61	2.878	2.653	**0.831**	1.902
	RMSE	4.439	9.06	7.012	5.884	10	**1.658**	3.716
	MSE	-0.005	0.047	0.053	-0.02	0.232	**0.015**	0.007
	RMSSE	0.974	1.078	1.09	0.937	2.665	**0.961**	0.984
	ASE	4.691	9.105	6.805	5.985	5.043	**1.714**	3.794
2011	ACRPS	2.702	5.429	4.569	4.173	3.127	**0.766**	2.422
	RMSE	4.750	10.187	8.367	7.862	10.325	**1.441**	4.471
	MSE	-0.005	0.031	0.044	0.053	0.271	**-0.046**	0.052
	RMSSE	0.961	1.106	1.098	1.153	2.912	**0.839**	1.122
	ASE	5.163	10.377	8.506	7.873	7.261	**1.738**	4.614
2012	ACRPS	7.350	6.567	6.172	6.225	1.186	**0.925**	3.664
	RMSE	19.534	12.5	12.087	12.157	2.357	**1.755**	7.381
	MSE	0.161	0.01	-0.004	0.002	0.007	**-0.03**	0.01
	RMSSE	2.121	1.013	0.962	0.971	1.102	**0.856**	1.046
	ASE	15.232	11.95	11.725	11.663	2.436	**2.072**	6.816

Figure 2 presents distribution of WQI calculated using the CCME model and interpolated using EBK. In general, higher WQI scores (better water quality) are found at the Harbour mouth and along the western coastline while river inflows are characterized by low WQIs (worst water quality). This is a temporarily consistent spatial pattern. The water quality in Lower Cork Harbour varies substantially on the horizontal and temporal scale with generally high variability along eastern coastline.

4.3 RANKING OF THE WATER QUALITY

The CCME WQI model was employed to establish water quality status in Cork Harbour. Three ranks A1, A2 and A3 as described in the EC surface water quality guideline (1998) are adopted in this study. The WQI ranges corresponding to each class are shown in Table 7.

Table 7: WQI scores and corresponding water quality classes.

Best interpolated WQI	Categorization schemes	Water Classes*	Description
CCME model	95 - 100	A1	Excellent
	80 - 95 65 - 79	A2	Good
	45 - 64 0 - 44	A3	poor

*Based on EC guidelines for the surface water

A ranked water quality map allows to determine spatial distribution of water quality, assess water quality status and enhance understanding of water quality spatial variability. Figure 3 shows that within the study period, the water quality varies from good to excellent and this confirms assessments conducted by the EPA, Ireland. There is no consistency in spatial or temporal variations, and this implies that Cork Harbour is a highly hydrologically dynamic system with many sources of instantaneous pollution.

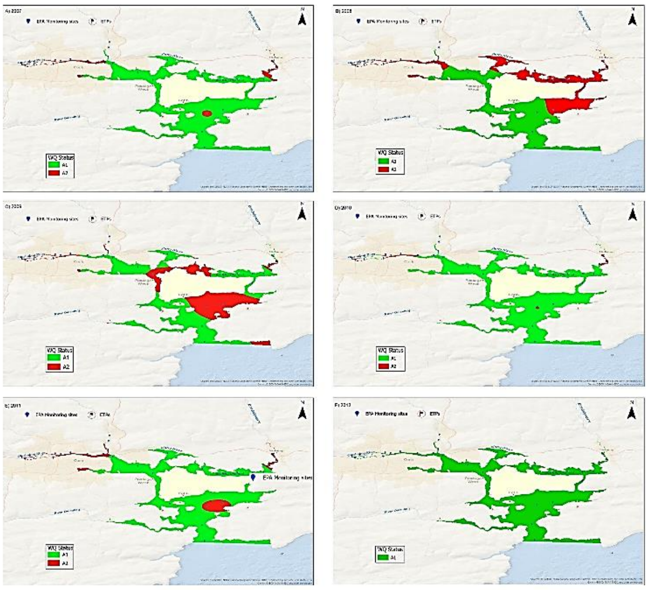

Figure 3. Maps of WQ ranks based on CCME WQIs.

5. CONCLUSION

The aim of this study was to apply various WQI models to assess surface water quality in Cork Harbour. To Authors knowledge the application of WQI to assess water quality is the first of this kind of studies in Ireland. Each model has been substantially modified in terms of parameter selection and aggregation method for the most accurate assessment of water quality.

The results show that water quality is good to excellent depending on the WQI model used. This implies that the right selection of WQI is paramount to a correct determination of water quality status. Also, a choice of the interpolation technique plays a fundamental role in understanding of spatial variations in water quality. The EBK interpolation model produces the least uncertainty levels when combined with the CCME model. The EBK interpolated WQIs were ultimately used to produce ranked water quality maps. Such maps are excellent tools to understand dynamics of water quality, optimize network of field observations, and to communicate status of the water quality and associated issues to non-expert stakeholders. Based on the analysis of WQI models, it was concluded that the Cork Harbour water quality was of ‘good’ to ‘excellent’ status during the period of analysis 2007-2012.

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