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Assessment of the Water Quality of WWTPs' Effluents through the Use of Wastewater Quality Index

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Abstract: Evaluating the efficiency of wastewater treatment plants (WWTPs) and their impact on receiving surface water bodies is a complex and highly significant task due to its regulatory implications for both environmental and public health. The monitoring of many water quality parameters related to the compliance of treated wastewater with environmental standards has led to the development of a unitless metric, the Wastewater Quality Index (WWQI), which serves as a practical tool for regulatory authorities. The aim of this research is to propose an appropriate WWQI methodology, incorporating a set of water quality indicators and a weighting approach, to evaluate wastewater effluents under operational monitoring. In this study, WWQI was successfully applied to access the operation of 21 WWTPs' effluents within a single monitoring campaign, outside the mandatory monitoring schemes. The WWQI was computed for physical-chemical parameters including chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), electrical conductivity (EC) and pH, priority substances (Cd, Ni and Pb) and a specific contaminant (Cr) using the weighted approach in the WWQI calculation, based on equal weighting, expert judgement and PCA weighing using factor loadings. The three approaches give similar results for the calculated WWQI. The expert judgment approach is more suitable for evaluating WWTP performance during a single monitoring campaign due to its simplicity compared to the PCA-based approach and its ability to prioritize specific water quality parameters over an equal weightage method.

Keywords: wastewater treatment plant; wastewater quality index; PCA; equal weights; expert judgement

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1. Introduction

About 80% of the water used is discharged to the natural water bodies without treatment. This makes water pollution ubiquitous and a globally (un)recognized problem [1]. Wastewater treatment plants (WWTPs) are designed to treat used water. As such, they have greatly improved the discharged water quality. However, treated effluents still contain a complex mixture of organic and inorganic pollutants, suspended solids, nutrients, bacteria, microbes, etc., whose environmental effects might be unknown. Furthermore, the effects could be unnoticed, or with great variability [2,3]. Acting as point sources of contamination, the WWTPs can completely deteriorate the water composition of the receiving surface water bodies [4]. The discharges into rivers act as supplemental water, where the element composition and microbial community of WWTP effluent and natural surface water often differ considerably [5]. Yet, treated wastewater from urban and industrial sources is considered an alternative water resource for crop irrigation, protecting aquifers from overexploitation and enabling sustainable water use [6]. Treated water use can negatively affect the environment through increased salinity, the introduction of pollution and pH change. Detailed analysis of different parameters is, consequently, needed to establish compliance with environmental quality standards [7].

Legislation in the field of water quality is vast. Depending on the water's intended use or the geographical region, numerous legislative documents apply. In Bulgaria, next to the national legislation, the European Directives also apply. Directive 91/271/EEC deals with the requirements (concentrations or percentage of reduction) for discharges from urban WWTPs [8]. Directive 2013/39/EU for priority substances sets limits for Cd, Ni and Pb in surface water bodies (SWBs) [9]. Finally, the maximum allowable concentrations for the most common physical-chemical parameters in the surface waters are set by Ordinance N-4 [10]. The use of so many legislative documents is necessary to ensure that treated waters do not negatively affect the SWBs.

To optimize the treatment processes, a unitless number [11]—the Wastewater Quality Index (WWQI), was introduced as an assessment tool of the overall wastewater quality. It takes into consideration all the monitored chemical, physical and microbiological quality parameters. Often, the interpretation of such huge quality sets is very difficult and requires the application of sophisticated statistical methods. In contrast, a single number (ranging from 1 to 100) is preferred in checking compliance with the established water quality standards [12]. The higher the WWQIs, the more efficient the treatment is, and the wastewater effluents are meeting the WWTPs' design objectives. In contrast, the influents generally have low WWQI values. This renders them harmful if released untreated directly into the water bodies. Therefore, the use of the WWQI benefits the decision makers to rapidly assess the wastewater quality and compare different treatment processes. Different sets of parameters are usually selected for devising the WWQI. Some authors select the minimum required four parameters [6,13], other investigators prefer fewer than 10—i.e., eight [7,11,14,15] or nine [16]—and few research groups use 10–20 (13 [17], 14 [18] or 15 [19]), while there are reports that use 21 [20,21] and even 23 water quality parameters [22]. The most parameters required by a method is 26 [23]. One of the pitfalls of the WWQI approach is that it establishes relationships between water quality indicators not allowing a straightforward interpretation of what causes the specific value of the WWQI, thus eclipsing or over-emphasizing a single bad parameter value.

The selection of parameters to be used in devising the WQI models is often based on the data (un)availability [24] and obtainability, expert opinion and the environmental significance or application type (e.g., drinking water, surface water, underground water, wastewater, etc.) [25]. The Canadian Council of Ministers of the Environment (CCME) WQI is currently one of the most widely used methods to evaluate surface water for the protection of aquatic life in accordance with specific guidelines due to its simplicity, possibility to vary the study parameters at different locations and adaptability to different legal requirements and different water uses [26–29]. The sampling protocol requires at least four parameters, sampled at least four times, which is suitable for water quality assessment of the mandatory sampling, but renders the method useless in random checks.

Since many WQIs exist [30,31], weighted [6,13–15,17,21,22] and unweighted [7,11,16,18–20] approaches are undertaken to assess the WWTPs' performance. The weights are assigned according to the parameters' relative importance for water quality. Usually, the highest weights are assigned to parameters that have major effects on water quality and are very important for water quality compliance. The minimum weight is usually assigned to parameters which are not considered harmful. A different approach utilizes the parameters with the lowest permissible limits as being the most harmful even on slight concentration fluctuations. Subsequently, the highest weights are assigned to low permissible limits' parameters, while the high permissible limits' parameters allow relatively fewer chances of pollution and, therefore, low weightings are assigned [32]. One approach is to assign equal weightage to all the studied parameters; another is based on an expert judgement [33]. Assigning equal weights to the selected parameters acknowledges their similar importance in the assessment and is close to the approach followed in the Water Framework Directive (WFD) [34]. Experts' opinions are used for the variables' choice and their weight assignments. In a third approach, the weights are defined as functions of the standards proposed in the water quality guidelines [35]. Regardless of the approach used, the weighting can deteriorate the final WWQI calculated value due to possible changes in the expert panel or when the guidelines are improved. Therefore, the weighting should be decided according to the use of water or to be determined locally. As different experts give sometimes different weights for the same parameters [21,36], Principal Component Analysis (PCA) was used to assign the weight based on the estimated eigenvalues and component loading for each parameter using the recommended standards for the corresponding parameters [37]. The PC-weight assignment has been used to monitor temporal wastewater quality [38], overcoming the shortness of the CCME WQI approach. PCA-based WQI minimizes the subjectivity and uncertainty from overrating or underrating [39], despite its inconsistencies [40].

The present work aims to evaluate the water quality of WWTPs' effluents by combining physical-chemical parameters, specific contaminants, a priority substance and common wastewater quality indices, in a single monitoring campaign, outside the mandatory monitoring schemes. For this reason, a weighted approach incorporating the deviations from environmental legislation norms, based on (i) equal weightage, (ii) expert judgement and (iii) PCA estimated factor loadings was introduced to the calculation of WWQI.

2. Materials and Methods

2.1. Sampling and Sample Preparation

Samples of 21 treated wastewater effluents at the outlets of the studied WWTPs were collected in August 2018 in typical hot weather conditions (>30 °C) without stormy events (Table 1).

The plants were selected based on their wide range of p.e. and the rivers they discharge in (Figure 1).

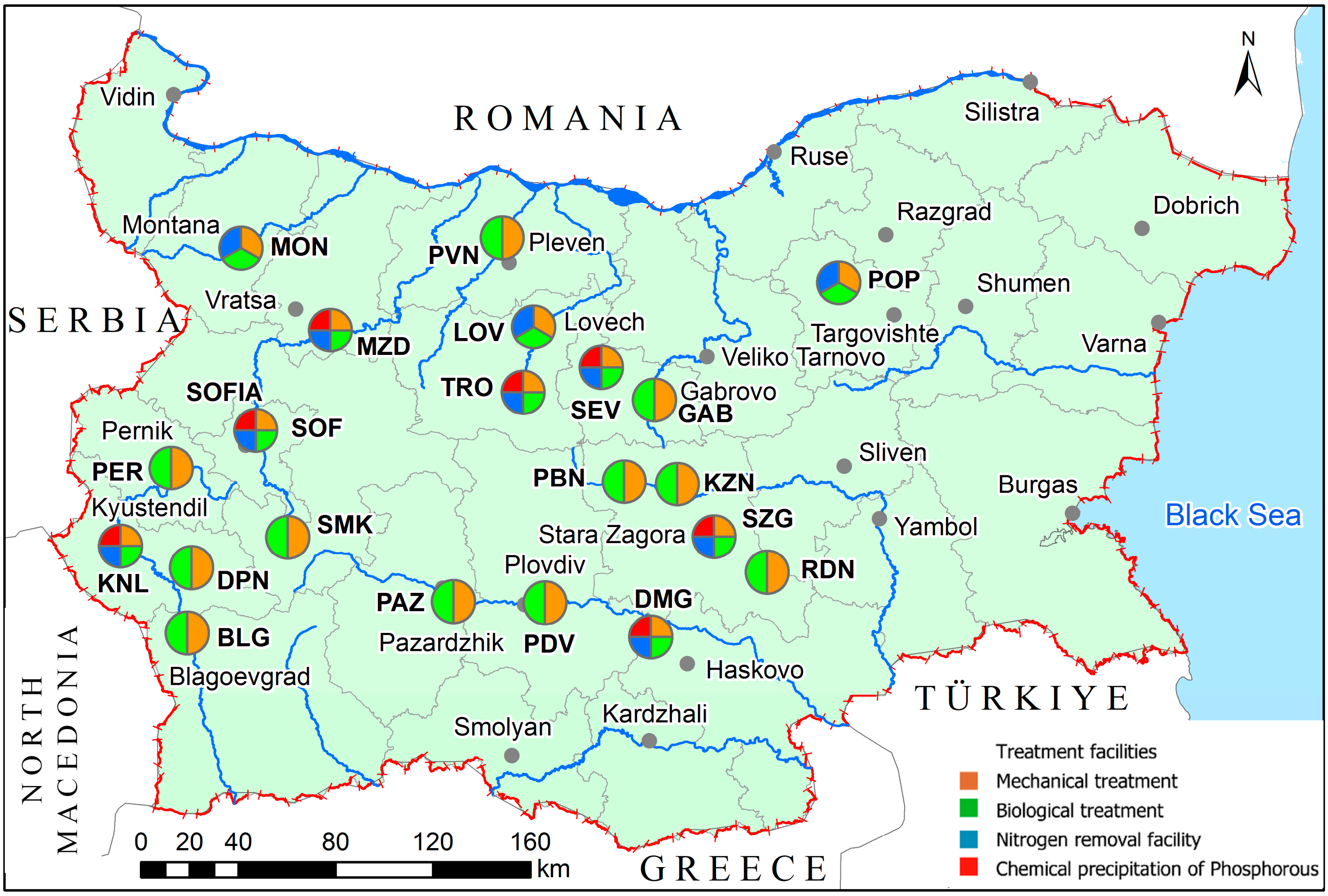

Figure 1. Sampling map.

Table 1. Acronyms, locations, population equivalent (p.e.), discharged volumes (Q), sampling dates and the receiving surface water bodies the WWPTs discharge in.

WWTP				Sampling Date	Receiving SWB
Acronym	Sampling Location	Population Equivalent	Q m^3/2018		
BLG	Blagoevgrad	87,520	3,468,098	13 August 2018	**Struma River**
DMG	Dimitrovgrad	70,350	2,233,651	17 August 2018	**Maritsa River**
DPN	Dupnitsa	55,240	5,915,566	13 August 2018	**Struma River** (through Djerman River)
GAB	Gabrovo	99,780	8,458,611	29 August 2018	**Yantra River**
KNL	Kyustendil	70,000	1,587,885	13 August 2018	**Struma River** (through Banshtnitsa River)
KZN	Kazanlak	80,000	9,988,652	16 August 2018	**Tundhza River**
LOV	Lovech	85,600	5,945,412	10 August 2018	**Osam River**
MON	Montana	98,617	8,468,560	17 August 2018	**Ogosta River**
MZD	Mezdra	15,984	381,028	17 August 2018	**Iskar River**
PAZ	Pazardzhik	156,000	31,17,426	27 August 2018	**Maritsa River**
PBN	Pavel Banya	3000	597,656	16 August 2018	**Tundhza River**
PDV	Plovdiv	596,000	17,101,385	17 August 2018	**Maritsa River**
PER	Pernik	82,000	3,277,632	14 August 2018	**Struma River**
POP	Popovo	37,000	1,583,874	30 August 2018	**Cherni Lom River**
PVN	Pleven	188,000	22,058,863	10 August 2018	**Vit River**
RDN	Radnevo	18,346	1,814,123	16 August 2018	**Maritsa River** (through Sazliyka River)
SEV	Sevlievo	54,000	3,269,429	29 August 2018	**Yantra River** (through Rositsa River)
SMK	Samokov	125,000	9,863,285	23 August 2018	**Iskar River**
SOF	Sofia	2,037,000	133,505,643	23 August 2018	**Iskar River**
SZG	Stara Zagora	256,300	7,671,645	16 August 2018	**Maritsa River** (through Bedechka River)
TRO	Troyan	80,000	2,158,541	10 August 2018	**Osam River**

Based on the sensitivity of the receiving SWBs, maximum allowable concentrations (MACs) for certain parameters are devised in the respective legislation (Table 2). Directive 91/271/EEC establishes the maximum allowable concentrations for chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) for the discharges. Directive 2013/39/EU sets the limits for the priority pollutants Cd, Ni and Pb. The national legislative document (Ordinance N-4) determines the maximum allowable concentrations for achieving at least a moderate status of the SWBs (lakes and rivers) for pH, electrical conductivity (EC) and Cr. According to the same document, the MAC for Cr is set at 32 µg/L for both the oxidation states—Cr (III) and Cr (VI).

Table 2. Maximum allowable concentrations for the WWTPs' effluents according to Directive 91/271/EEC (COD, TSS, TN and TP) [8], Directive 2013/39/EU (Cd, Ni and Pb) [9] and Ordinance N-4 (pH, EC and Cr) [10].

WWTP	Maximum Allowable Concentrations									
	COD mg/L O_2	TSS mg/L	TN mg/L	TP mg/L	pH	EC µS/cm	Cd µg/L	Cr µg/L	Ni µg/L	Pb µg/L
BLG	125	35	15	2	6.5–8.5	750	0.45	32	34	14
DMG	125	35	15	2	6.5–8.5	750	0.45	32	34	14
DPN	125	35	15	2	6.5–8.5	750	0.45	32	34	14
GAB	125	35	15	2	6.5–8.5	750	0.45	32	34	14
KNL	125	35	15	2	6.5–8.5	750	0.45	32	34	14
KZN	125	35	15	2	6.5–8.5	750	0.45	32	34	14

Table 2. *Cont.*

WWTP	Maximum Allowable Concentrations									
	COD mg/L O_2	TSS mg/L	TN mg/L	TP mg/L	pH	EC µS/cm	Cd µg/L	Cr µg/L	Ni µg/L	Pb µg/L
LOV	125	35	15	2	6.5–8.5	750	0.45	32	34	14
MON	125	35	15	2	6.5–8.5	750	0.45	32	34	14
MZD	125	35	15	2	6.5–8.5	750	0.45	32	34	14
PAZ	125	35	10	1	6.5–8.5	750	0.45	32	34	14
PBN	125	60	15	2	6.5–8.5	750	0.45	32	34	14
PDV	125	35	10	1	6.5–8.5	750	0.45	32	34	14
PER	125	35	15	2	6.5–8.5	750	0.45	32	34	14
POP	125	35	15	2	6.5–8.5	750	0.45	32	34	14
PVN	125	35	10	1	6.5–8.5	750	0.45	32	34	14
RDN	125	35	15	2	6.5–8.5	750	0.45	32	34	14
SEV	125	35	15	2	6.5–8.5	750	0.45	32	34	14
SMK	125	35	10	1	6.5–8.5	750	0.45	32	34	14
SOF	125	35	10	1	6.5–8.5	750	0.45	32	34	14
SZG	125	35	10	1	6.5–8.5	750	0.45	32	34	14
TRO	125	35	15	2	6.5–8.5	750	0.45	32	34	14

For the determination of the physical-chemical parameters, the water samples were collected in glass bottles and directly stored at 4 °C. The 50 mL samples for ICP-MS analysis were filtered with a 25 mm PES sterile syringe filter (0.45 µm), inserted into glass bottles, acidified with 1.5 mL conc. HNO_3 (67–69% Fisher Chemicals, Pittsburgh, PA, USA, TraceMetal Grade), stored at 4 °C and transported to the laboratory premises [41]. Upon receipt, the samples were analyzed in triplicate.

2.2. Physicochemical Analysis

The detailed measurement conditions and quality control (QC) measures are published elsewhere [41]. Briefly, the ICP-MS analysis of Cd, Cr, Ni and Pb was carried out using an ICP-MS PerkinElmer SCIEX—ELAN DRC-e instrument (MDS Inc., Concord, ON, Canada). The spectrometer was optimized to minimize CeO^+/Ce^+ and Ba^{2+}/Ba^+ values and provide the maximum intensity of the analytes. The use of a standard reference material NIST 1640a (Trace Elements in Natural Water) proved the accuracy of the measurement results as the analytical recovery (95–108%) was considered satisfactory.

Cuvette tests LCK 314, LCK 138 and LCK 348 for the determination of COD, TN and TP, respectively, were used following the producer's sample preparation steps (Hach Lange GmbH, Berlin, Germany). The detailed procedure is described in previous studies [41–45]. A portable spectrophotometer DR 3900 (Hach Lange GmbH, Berlin, Germany) was used for the determination of COD, TN and TP at 448, 370 and 890 nm, respectively. For the determination of pH and EC, a combined instrument SensIon+ MM734 (Hach Lange GmbH, Berlin, Germany) was used and the requirements of ISO 11923 [46] were followed for the determination of TSS using glass-fiber filters. All the measurements were performed at the accredited under ISO 17025 [47] water quality laboratory at the University of Architecture, Civil Engineering and Geodesy.

2.3. Principal Component Analysis

Multivariate analysis and visualization of wastewater effluents' datasets are achieved through the application of Principal Component Analysis (PCA) [48,49]. The PCA is used for dimensionality reduction of interrelated variables, keeping the variation in the original data as much as possible [50]. The latent factors (principal components) identify the variance sources and data structure, where the first few components, those with eigenvalues higher than 1, preserve the significant part of dataset variation [51]. The principal components (PCs) are calculated from the original input data matrix as a product of two orthogonal factor matrices: factor loadings and factor scores. Factor loadings present the weights of original variables in the formation of new variables (factors or PCs) and give information about the principal component origin. Factor scores present the projections of the original data on PCs and could be used for the identification of similarity groups between investigated samples.

Before the PCA analysis, the input data were auto-scaled and Venetian blinds as a cross-validation procedure was applied. All multivariate statistics models were performed in MATLAB R2021a using PLS Toolbox 9.0 (Eigenvector Research Inc., Manson, WA, USA).

2.4. Calculation of the Wastewater Quality Index

The flow chart of WWQI calculation is presented in Figure 2.

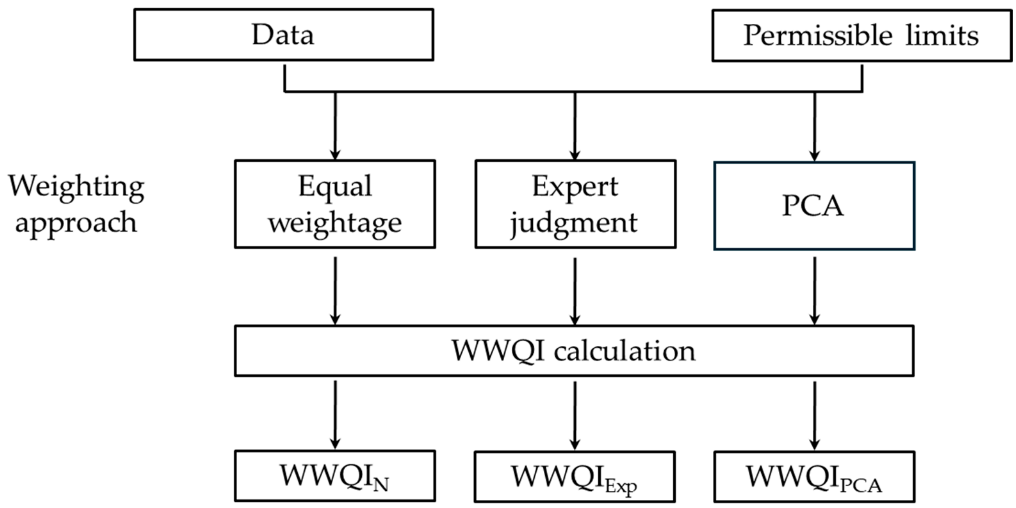

Figure 2. Flow chart of WWQI calculation.

The WWQI used in this study was adopted from [52] and is based on the sum of the water quality sub-indices of each parameter measured:

$$WWQI = \sum_{i=1}^{n} SI_i \quad (1)$$

where SI is the water quality sub-index of each parameter.

The SI is calculated according to the Equation (2):

$$SI = W_i \cdot q_i \quad (2)$$

where q_i is the quality rating and W_i is the relative weight.

The quality rating (q_i) is calculated using Equation (3):

$$q_i = \left(\frac{C_i}{S_i}\right) \cdot 100, \quad (3)$$

where C_i is the water quality parameter concentration in each sample and S_i is the water quality standard set by the respective legislation.

In this study, for pH, the desired limit interval is considered:

$$S_i = 100 - \frac{100(\text{excursion})}{(8.5 - 6.5)} \quad (4)$$

If the measured value (C_i) is within the desirable limit ($6.5 \leq C_i \leq 8.5$), there is no excursion and S_i is equal to 100. If $C_i > 8.5$, the excursion equals to C_i—8.5. If $C_i < 6.5$, the excursion equals to 6.5—C_i.

The relative weights (W_i) for each parameter are obtained from Equation (5):

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}, \quad (5)$$

where w_i is the weight of each parameter measured and n is the number of parameters measured.

The WWQI is computed using the relative weights (W_i) assigned to each of the water quality parameters based on (i) equal weightage ($WWQI_N$), (ii) expert judgement ($WWQI_{Exp}$) and (iii) PCA factor loadings for their overall importance for sustaining water quality ($WWQI_{PCA}$) [37]. When the equal weightage is used, a weight of 1 was assigned to all the 10 studied parameters.

Ascribing weighting to the studied water quality parameters influences the final WWQI value [35]. Usually, expert panels are used to assign weightings based on the environmental significance of the parameter, guideline values and use of the water body [32]. In the current study, when the expert judgement approach is used, the highest weight of 5 was assigned to parameters which have major effects on water quality—the priority substances Cd, Ni and Pb. A weight of 4 was assigned to the specific substance (Cr) and the eutrophication-causing parameters (COD, TN and TP). TSS and EC were assigned a weight of 3 and a minimum of 2 was assigned pH, which is considered as the least harmful.

In PCA weighting approach, the weights of water quality parameters (w_i) are assigned based on the eigenvalues and factor loadings of PCs with eigenvalues higher than 1:

$$w_i = \frac{\sum_{K=1}^{n} (E_K P_{iK})}{\sum_{k=1}^{n} E_K}, \quad (6)$$

where E_K is the eigenvalue of PCs, P_{iK} is the factor loadings of parameters and n is the number of PCs with eigenvalues higher than 1.

The relative weights (W_i) for all three weighting approaches are calculated according to the Equation (5).

Finally, the WWQI is evaluated through a simple comparison to the categories shown in Table 3 according to the originally proposed WQI scheme and a modified one, reflecting Bulgarian legislation.

Table 3. Water quality categorization scheme.

WQI	Water Status Original Scale [53]	WQI	Water Status Modified Scale [54]
80–100	Excellent	80–100	Very good
65–80	Good	65–80	Good
50–65	Fair	0–65	Moderate
25–50	Poor		
<25	Very poor		

The Bulgarian legislation follows the adopted WFD, with the main difference being the proposed scaling—the "Fair", "Poor" and "Very poor" water status is combined into a "Moderate" water status. The modified scale was used from this point on.

3. Results

Treated water was collected from 21 Bulgarian WWTPs receiving urban wastewater. The results obtained for six physicochemical indicators—pH, EC, COD, TSS, TN and TP, three priority substances (Cd, Ni and Pb) and one specific substance (Cr) were used for this study (Table 4). The highlighted values, shown in Table 2, mean that the concentrations of these parameters are greater than the maximum allowable concentrations.

Table 4. Physical-chemical parameters and potentially toxic elements concentration of the collected wastewater effluent samples.

WWTP	pH	EC µS/cm	COD mg/L O_2	TSS mg/L	TP mg/L	TN mg/L	Cr µg/L	Cd µg/L	Ni µg/L	Pb µg/L
BLG	7.91	386	16.50	2.0	0.25	5.24	2.16	0.00008	3.36	0.36
DMG	7.77	**1174**	17.80	3.4	0.25	13.40	2.76	0.00008	2.54	0.25
DPN	7.80	312	12.70	3.3	1.39	1.85	1.45	0.00008	2.65	0.34
GAB	8.27	232	10.80	2.4	**2.15**	5.40	13.94	0.09177	3.52	0.33
KNL	7.78	396	16.30	4.1	1.36	4.22	1.47	0.00008	1.89	0.72
KZN	7.57	454	10.00	7.1	0.90	5.88	1.95	0.00008	2.87	0.22
LOV	8.34	589	9.61	2.2	1.63	4.19	2.09	0.00008	2.73	0.30
MON	7.92	328	7.22	2.1	0.86	5.41	1.17	0.08511	2.50	0.47
MZD	8.40	711	8.78	4.3	1.63	7.22	1.47	0.00008	1.82	0.24
PAZ	8.23	346	9.83	1.7	**1.61**	**14.20**	1.77	0.00008	1.66	0.47
PBN	8.43	248	23.40	6.2	1.06	6.11	2.23	0.00008	1.91	0.37
PDV	8.28	261	12.00	9.4	**1.70**	8.30	2.90	0.03658	4.84	**14.45**
PER	8.42	323	12.90	1.2	**2.21**	6.20	1.61	0.00008	2.15	0.19
POP	8.13	485	9.62	4.0	**2.82**	12.20	2.78	0.00008	2.42	0.14
PVN	8.43	**841**	10.30	1.7	0.67	8.26	3.98	0.00008	1.77	0.57
RDN	8.39	**991**	8.69	4.5	1.23	11.20	1.66	0.00649	2.15	0.11
SEV	8.39	267	12.30	0.1	0.52	2.00	3.38	0.00008	9.72	0.17
SMK	8.01	87.3	5.69	3.5	0.71	4.50	0.51	0.00008	1.60	0.35
SOF	7.83	222	19.00	2.1	0.25	6.60	2.74	0.00008	3.45	0.24
SZG	7.91	570	11.10	1.8	0.25	6.49	1.66	0.00008	1.78	0.16
TRO	**8.51**	262	10.20	1.4	0.50	9.58	1.15	0.09177	2.06	0.20

As regards the different water quality parameters, excursions from the environmental water quality standards for the priority [9] and specific pollutants [10] were observed for Pb (14.45 mg/L at PDV), EC (1174 µS/cm at DMG, 441 µS/cm at PVN, 991 µS/cm at RDN) and pH (8.51 at TRO). For the water treatment quality parameters [8], excursions were observed for TP (2.15 mg/L at GAB, 1.61 mg/L at PAZ, 1.70 mg/L at PDV, 2.21 mg/L at PER, 2.82 mg/L POP) and TN (14.2 mg/L at PAZ). These results show that the treatment facilities generally meet the requirements posed by the legislation.

The PCA results show that the first five latent factors (PCs) with eigenvalues higher than 1 explain almost 80% of the total variance. The factor loadings of the selected PCs are presented in Table 5.

Table 5. Factor loadings for the first five latent factors.

	PC1	PC2	PC3	PC4	PC5
pH	−0.032	0.097	0.021	0.209	**0.893**
EC	−0.124	**0.813**	−0.083	−0.147	−0.013
COD	0.121	0.068	−0.032	**−0.812**	−0.083
TSS	**0.906**	0.116	−0.034	0.009	−0.213
TP	0.307	0.097	0.269	**0.589**	0.316
TN	0.138	**0.845**	−0.037	0.107	0.133
Cr	−0.054	0.010	**0.933**	−0.085	0.174
Cd	0.117	−0.223	**0.820**	0.289	−0.125
Ni	0.054	**−0.520**	0.179	−0.465	0.458
Pb	**0.884**	−0.128	0.073	−0.031	0.193
Eigenvalue	1.767	1.749	1.663	1.391	1.260
Explained variance %	17.67	17.49	16.63	13.91	12.60

Note: The maximum factor loadings in absolute value for each water quality parameter are given in bold.

The factor loadings reveal the relationships between water quality parameters with significant contributions to the formation of latent factors. For example, there are strong correlations between TSS and Pb in PC1, between EC and TN in PC2 and between Cd and Cr in PC3. The factor loadings of PC4 reflect the strong negative correlation between COD and TP. Furthermore, the weights of parameters (w_i) are calculated according to the Equation (6).

The calculated relative weights for water quality parameters according to the approaches described earlier are presented in Table 6.

Table 6. Relative weights assigned to the water quality parameters.

Water Quality Parameter	W_i		
	$WWQI_N$	$WWQI_{Exp}$	$WWQI_{PCA}$
pH	0.1	0.051	0.097
EC	0.1	0.077	0.102
TSS	0.1	0.077	0.092
COD	0.1	0.103	0.101
TN	0.1	0.103	0.097
TP	0.1	0.103	0.099
Cd	0.1	0.103	0.097
Cr	0.1	0.128	0.101
Ni	0.1	0.128	0.102
Pb	0.1	0.128	0.112
-	$\sum w_i = 1.0$	$\sum w_i = 1.0$	$\sum w_i = 1.0$

It could be noticed that relative weights obtained by equal weightage and PCA-based approaches are closer than expert judgment ones.

The calculated WWQIs for the investigated WWTPs are presented in Figure 3.

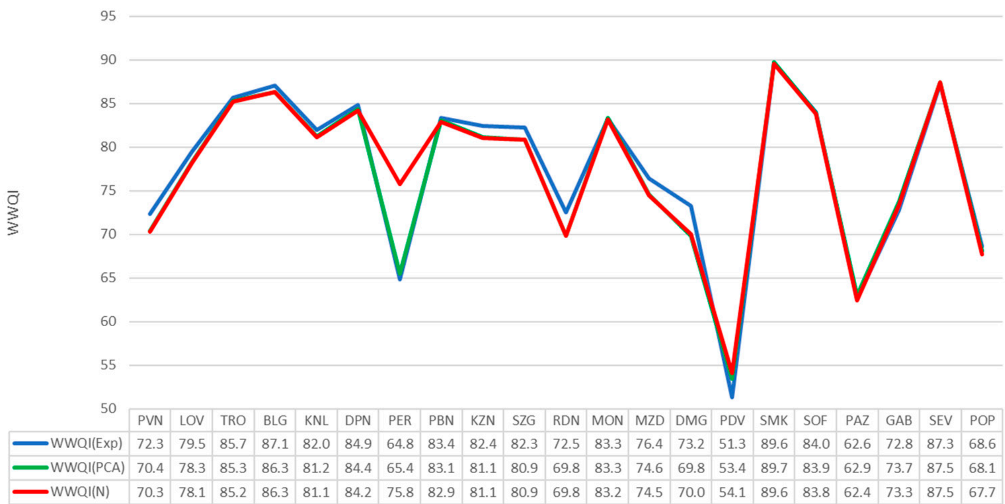

Figure 3. Calculated WWQI values for the outlets of the investigated WWTPs (n = 21).

The three approaches for the calculations give similar results, where the expert judgment gives higher WWQI (cleaner water), as opposed to the PCA-based and equal weightage, giving nearly equal results. The only exceptions are Pernik (PER) and Plovdiv (PDV), with the highest WWQIs calculated by an equal weightage approach.

The wastewater outlet status classifications of investigated WWTPs, based on applied WWQIs according to the modified WQI schemes, are presented in Table 7. There is full agreement between the three approaches used for the calculation of WWQI, excluding the classification of the WWTP located near Pernik (PER). Generally, the status of WWTP outlets is “good” to “very good” with the only exceptions being PDV and PAZ, for which a “moderate” status is given based on the WWQI.

Table 7. Water status classification of investigated WWTPs based on applied WWQIs and water quality parameters' exceedings.

WWTP	$WWQI_{Exp}$	$WWQI_{PCA}$	$WWQI_{N}$	Exceedings
BLG	very good	very good	very good	
DMG	good	good	good	EC
DPN	very good	very good	very good	
GAB	good	good	good	TP
KNL	very good	very good	very good	
KZN	very good	very good	very good	
LOV	good	good	good	
MON	very good	very good	very good	
MZD	good	good	good	
PAZ	moderate	moderate	moderate	TP, TN
PBN	very good	very good	very good	
PDV	moderate	moderate	moderate	TP, Pb
PER	moderate	good	good	TP
POP	good	good	good	TP
PVN	good	good	good	EC
RDN	good	good	good	EC
SEV	very good	very good	very good	
SMK	very good	very good	very good	
SOF	very good	very good	very good	
SZG	very good	very good	very good	
TRO	very good	very good	very good	pH

Note: —very good; —good; —moderate.

4. Discussion

The intercept (b_0 = 1.8947) indicates that, on average, $WWQI_{Exp}$ results are almost two units higher than $WWQI_{PCA}$ ones (Figure 4).

This outcome contradicts the observations in [55] that the PCA method gives different results than the expert judgement (sometimes referred to as the Delphi method) for weight assignment and is considered more accurate in the results' evaluation.

It is noteworthy to highlight that the calculated WWQIs using expert judgement and equal weights follow the same trend and are in good agreement (Figure 5), which partially contradicts the findings in [32], where the use of unequal parameter weighting is suggested. The only exception is PER where $WWQI_N$ is higher than $WWQI_{Exp}$ by 11 units. This difference leads to the different status classifications of treated wastewater at WWTP located close to Pernik. This result is in line with [32] and confirms the robustness of WWQI model when unequal weights are used (i.e., expert judgement, PCA weighting) compared to the equal weights assignment.

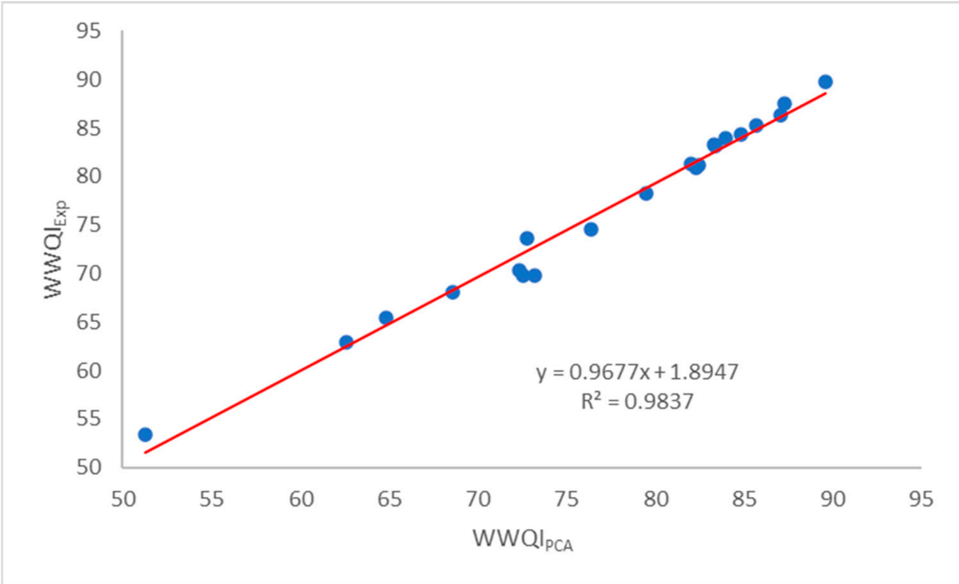

Figure 4. Comparison of WWQIs calculated using expert judgement and PCA-based approaches (n = 21).

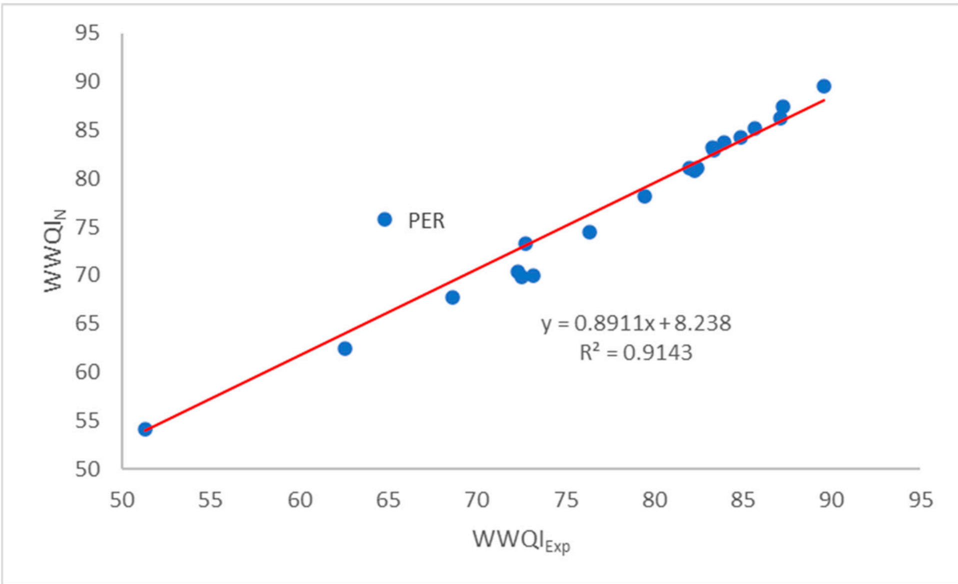

Figure 5. Comparison of WWQIs calculated using equal weights and expert judgement approaches (n = 21).

To assess the effectiveness of the three approaches used to calculate WWQI, it would be beneficial to compare the water status of wastewater outlets and excursions from environmental water quality standards.

Out of 21 WWTP effluents, 11 are classified as having very good status (TRO, BLG, KNL, DPN, PBN, KZN, SZG, SMK, SOF and SEV). This group includes WWTPs of varying sizes and treatment facilities. The excellent/very good status aligns with the absence of excursions from environmental water quality standards. The only exception is the effluent from TRO, where the pH of 8.51 slightly exceeds the very good status range of 6.5–8.5.

The second group of WWTP effluents (seven out of 21) is classified as having good water status. Among these, the effluents of two WWTPs (LOV and MZD) show no deviations from environmental standards, while the other five are associated with excursions from these standards. The effluents from PVN, RDN and DMG exhibit EC values exceeding the environmental standard, while those from GAB and POP have TP values above the corresponding standard. It can be concluded that the WWQIs of WWTPs with excursions are predominantly influenced by water quality parameters that meet environmental standards rather than those that do not. The elevated TP levels exceeding the limit for GAB and POP suggest the need for implementing phosphorus treatment facilities at both WWTPs.

Two WWTPs, PDV and PZD, have two water quality parameters that do not meet standards. Both effluents are classified as having a moderate water status, aligning with a previous study [42] that identified issues at these facilities.

The only WWTP effluent classified into different classes by the three approaches used is PER. The expert judgment approach assigns a moderate status, while both the equal weighting and PCA-based methods underestimate the TP excursion, resulting in a classification of a good water status for the treated wastewater. $WWQI_N$ is 10 units higher than $WWQI_{Exp}$ and $WWQI_{PCA}$, likely due to lower heavy metal concentrations in the PER effluent and the underestimation of relatively elevated wastewater quality parameters such as COD and TN. The difference between $WWQI_{Exp}$ and $WWQI_{PCA}$ is minimal, just 0.6 units (64.8 for $WWQI_{Exp}$ and 65.4 for $WWQI_{PCA}$), with both values hovering near the WWQI threshold of 65, which separates a moderate from a good water status.

5. Conclusions

The use of WWQI to access the operation of WWTPs is successfully applied to 21 treated water effluents. Generally, the status of WWTP outlets is "good" to "very good", with the only exceptions being PDV and PAZ, for which a "moderate" status is determined, based on the WWQI.

The WWQI was computed for physical-chemical parameters, specific contaminants, a priority substance and common wastewater quality indices using the weighted approach, based on equal weighting, expert judgement and PCA estimated factor loadings. Contrary to the other published results, in the current study, the three approaches give similar results for the calculated WWQI. Based on the results obtained, it can be concluded that the expert judgment approach is more suitable for evaluating WWTP performance during a single monitoring campaign due to its simplicity compared to the PCA-based approach and its ability to prioritize specific water quality parameters over an equal weightage method. Additionally, the expert judgment approach offers greater flexibility, making it well-suited for targeted operational monitoring aimed at assessing specific types of pollution.

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