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Composite water quality indices for supply networks

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***Abstract*— This paper presents a comprehensive framework for the assessment and operational monitoring of water quality in water supply networks, as well as representative application based on data from the SCADA system of the water supply system of Lamia, Greece. Compliance requirements, based on European and international regulations and guidelines, are summarized for the most critical water quality indices. Distinction between single-parameter water metrics and composite water quality indices is summarized. Indicative composite quality indices suitable for real time applications to several stations of Lamia's water supply network are suggested. Real time monitoring of composite quality indices is proposed to be used as a tool for summary quality assessment and as a basis for early event detection and decision support.**

***Keywords*— Water supply networks, water quality indices, composite quality indices, real-time monitoring, real time quality assessment**

I. INTRODUCTION

Ensuring the quality of water for human consumption is a critical pillar of public health and reliability of water services. In water distribution networks, quality is not a static characteristic of the water entering the supply network, but a multi-parametric function with spatiotemporal variations, that is affected by several factors, such as disinfection policy, residence time of the water within the tanks, mixing of water from different sources, functional changes in the subsystems of the water supply network, as well as by physicochemical changes and biological mechanisms that may favor the emergence of harmful microorganisms. In this context, systematic quality assessment requires tools that transform data into coherent and usable information for verifying compliance with national and international regulations and guidelines, risk assessment and operational decision-making. The present work focuses on real-time quality assessment tools that are based on real-time measurements and provide early detection of quality deterioration.

Metrics and indices perform this role by providing standardized ways of quantifying the quality state. A metric can directly express a measured or observed parameter. Composite indices combine multiple parameters into an overall but also concise assessment, which is useful for the timely detection of deviations. The value of quality indices is particularly important when they can be mapped to clear physical interpretations and when they are used with clearly defined quality thresholds and quality performance criteria. The regulatory framework for the quality of water intended for human consumption is based on a multi-layered network of rules and technical guidelines, imposed by international public health organizations as well as by supranational and national regulatory decisions. At the European level, the main body of regulatory restrictions is set by Directive (EU) 2020/2184, which shifted the emphasis from the exclusive monitoring of parameter compliance to a more integrated risk management scheme, incorporating elements of prevention and operational control throughout the "water supply chain" [1].

At the international level, the World Health Organization provides a technical-scientific reference framework through the Guidelines for Drinking-Water Quality, which, although not binding, constitute an established basis for setting parameters, documenting risks and supporting national health policies [2]-[4]. Moreover, useful frameworks are provided by several national regulatory models, such as those of the USA National Primary Drinking Water Regulations [5] and the Australian Drinking Water Guidelines [6].

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This paper aims to summarize the compliance requirements, based on European and international regulations and guidelines, for the most critical quality indices. Moreover, it aims to provide an objective understanding of the quantitative assessment of water quality with the use of composite quality indices, which can support both compliance and operational surveillance. Emphasis will be placed on the transition to real-time practices, where early recognition of deviations and evidence-based decision-making are key factors in protecting public health and the effective operation of water systems.

II. COMPOSITE WATER QUALITY INDICES

Traditional drinking-water assessment checks many parameters one-by-one against regulatory limits. This step has the potential to mask the overall quality status in instances where rapid interpretation or operational decision support is requested, and may underestimate cumulative impacts that end users are able to sense. Composite water quality indices (WQIs) respond to this need through the combination of heterogeneous metrics, including normalization, weighting and mathematical mapping of individual metrics, into a single comparable score that facilitates clear communication and spatiotemporal comparability (see [7]-[15] and the references therein). But most WQIs were developed for surface/groundwater classification, which makes their application in drinking-water distribution networks nontrivial. Network quality depends strongly on hydraulics (see [16]-[18] and the references therein), residence time, disinfectant residuals, and local degradation, often requiring adaptation or redesign of WQIs. Hence, WQIs in distribution systems should be treated as tools for system-level assessment and operational awareness (not only compliance), with explicit purpose definition, justified parameter selection, and clear acknowledgment of the limitations of compressing complex dynamics into a 0–1 or 0–100 metric. Based on the main purpose that they serve, composite indices may be classified as follows:

i. Compliance / regulatory assessment indices: These map measured parameters to regulatory limits or guideline values to provide a concise view of compliance. They are useful for reporting, but often weak for operational diagnosis because they are largely point-limit oriented and can underweight spatiotemporal variability.
ii. Acceptability / aesthetic quality indices: These emphasize consumer-perceived attributes (e.g., taste, odor, turbidity, color), supporting complaint management and “social acceptance” quantification. They are operationally relevant, yet they do not necessarily track health risk, and may highlight visually evident events that are not hygienically critical.
iii. Operational monitoring indices for distribution networks: These are tailored to network operation and include indicators of chemical/biological stability and distribution safety (e.g., residual disinfectant, turbidity as an incident proxy, corrosion/deposition-related measures). For real-time use, they may also integrate hydraulic drivers that shape quality evolution. This category is the most mature, but it must balance interpretability with locality and causal attribution.
iv. Health-priority indices: These indices embed risk logic (e.g., probability–consequence, health-significance weighting) to better align with decision-making. Their limitation is practical since they rely on documented assumptions and risk data that may be unavailable, uncertain, or not measurable at the required temporal resolution.

The mathematical formulation of each composite index is important, because it determines what each index ignores or emphasizes. Based on this formulation, composite indices may be classified as follows:

i. Aggregate weighted indices with linear or non-linear normalization and weighting: They are simple and easily communicated, but they are vulnerable to phenomena, where an undesirable value of a parameter can be hidden by many other parameters with good or moderate values.
ii. Multiplicative/geometric indices: They are indices that reduce the compensation effects and highlight low performance, but they have increased sensitivity to noise and normalization errors.
iii. Minimum/maximum operators: They are excellent for investigating network security as they highlight the worst-case scenario, but they lose the information of the remaining parameters and so they can be over-conservative in data with high volatility.
iv. Fuzzy or multi-criteria indices: These are indices that allow the introduction of verbal rules and incorporate experience, increasing interpretability in the operational context, but require consistent calibration and attention to any generalizations.

v. Statistical indices: They are particularly powerful for discovering structural characteristics of the network and functional or exogenous anomalies, but they are not directly interpretable to non-specialists and are very sensitive to changes in the functional characteristics of the network.

III. SUITABILITY ANALYSIS FOR INDICES IN DISTRIBUTION NETWORKS

In water distribution networks, a composite index is judged less by delivering a “good” score and more by whether it respects three core peculiarities: spatial heterogeneity, temporal dynamics, and a causal link to network operation. In practice:

- Dead ends, low-circulation zones, varying pipe materials, and differing disinfectant residual conditions create localized “islets” of distinct behavior. A single network-wide score may support situational awareness, but it can miss local degradations; therefore, zone/subnetwork indices and/or hierarchical aggregation are often needed.
- Quality is tightly coupled to flow dynamics, demand variability, and water residence time. Indices designed for quasi-static water bodies may under-represent transient events (e.g., turbidity spikes, hydraulic redistributions, residual disinfectant decay). Network-suitable indices should use careful temporal smoothing that does not mask events or adopt real-time formulations with change-detection.
- Classical weighted-sum structures can “average out” a critical parameter excursion. This is risky in networks where a small set of locations can face high exposure. A common remedy is a hybrid scheme, i.e. an overall summary index complemented by local alarm indices for critical parameters.
- Beyond numerical stability, an index must be interpretable: when it changes, operators should quickly identify which parameter drove the change and where. More complex indices may detect events better, but typically require companion explanation layers (attribution, drill-down views) to be usable.
- Practical value hinges on what can be measured/estimated reliably and at what sampling rate. If driven by sparse sampling or delayed lab results, the index becomes periodic assessment rather than real-time support. Coupling with estimates (e.g., from software sensors) can increase operational usefulness.

IV. FORMULATION OF COMPOSITE INDICES

A critical decision for the effectiveness of the composite index concerns the selection of the parameters involved in the index. In the following, we emphasize on composite indices that are based on parameters that are usually measured in real time or that may be estimated, also in real-time, with the use of soft sensors. Indicatives sets of such parameters are the following: a) Physicochemical variables such as pH, turbidity, electrical conductivity, and temperature, b) Concentrations of inorganic ions or nutrients such as nitrate, chloride or ammonium, c) Disinfection and related parameters such as residual free chlorine, as well as, in advanced applications, disinfection by-products, d) Operational parameters of the network such as the age of the water in the network (residence time), measurements of flow, pressure, tank levels or other variables calculated from hydraulic or water quality models. To make the individual parameters (with different units and scales) comparable, they are transformed into dimensionless quality indices, indicatively on a scale of 0–100. This transformation is essentially an evaluation function that incorporates the desired range and the critical values for the corresponding parameter. Moreover, an “indifference zone” is allowed, where small deviations do not substantially change the index. For each parameter p_i $(i=1,\dots,n_q)$ that will participate in an index, a transformation of the form $Q_i(t_j;s)=f_i(x_{p_i,s}(t_j))$ is used, where $x_{p_i,s}(t_j)$ is the measurement (or estimation) of the parameter p_i at the time instant t_j and at the location (measurement point) indicated by s. The function $f_i(\cdot)$ transforms the measurement $x_{p_i,s}(t_j)$ into the normalized index $Q_i(t_j;s)$. The function $f_i(\cdot)$ is typically designed so that the values of $Q_i(t_j;s)$ are bounded in the region $[0,100]$. When $x_{p_i,s}(t_j)$ is at the desired range, then $f_i(\cdot)$ gives value of $Q_i(t_j;s)$ equal to 100. When $x_{p_i,s}(t_j)$ is at the worst range then $f_i(\cdot)$ gives value of $Q_i(t_j;s)$ equal to 0. In the intermediate ranges, $f_i(\cdot)$ varies monotonically with respect to the measured quantity. The desired, as well as the worst range, are determined by clear reference points, such as points of the type "target value", "limit", "extreme unacceptable value". Ideally, $f_i(\cdot)$ should be robust to measurement noise (especially in real time) and at the same time should not show drastic changes near the boundaries of its domain of definition. To determine the function f_i, one or more of the following are typically taken into account: i) the target value or the center of the optimal operation area, let $x^*_{p_i,s}$, ii) the acceptable range (upper and lower acceptable value), iii) the compliance limits (upper or lower), let S_i, and iv) a worst-case value, let $x^w_{p_i,s}$, which corresponds to $Q_i = 0$. For the design of linear functions $f_i(\cdot)$, three cases are distinguished: a) The measurable quantity under study is considered qualitatively better when its value is small (e.g. turbidity, nitrates, chlorides, disinfection by-products), b) The measurable quantity under study is considered qualitatively better when its value is large (e.g. minimum operating pressure, percentage of time in compliance with a restriction), and c) The measurable quantity under study has an optimal range with the ends of the range indicating poor behavior (e.g. pH, hardness, conductivity, concentration of residual disinfectant). In the first two cases, the following functions are proposed:

$$f_i(x_{p_i,s}(t_j)) = \begin{cases} 100, & x_{p_i,s}(t_j) \le S_i \\ 100\dfrac{x^w_{p_i,s} - x_{p_i,s}(t_j)}{x^w_{p_i,s} - S_i}, & S_i < x_{p_i,s}(t_j) < x^w_{p_i,s} \\ 0, & x_{p_i,s}(t_j) \ge x^w_{p_i,s} \end{cases}, \quad f_i(x_{p_i,s}(t_j)) = \begin{cases} 0, & x_{p_i,s}(t_j) \le x^w_{p_i,s} \\ 100\dfrac{x_{p_i,s}(t_j) - x^w_{p_i,s}}{S_i - x^w_{p_i,s}}, & x^w_{p_i,s} < x_{p_i,s}(t_j) < S_i \\ 100, & x_{p_i,s}(t_j) \ge S_i \end{cases} \quad (1)$$

Finally, in the third case, the use of the following function is proposed:

$$f_i\left(x_{p_i,s}(t_j)\right) = \begin{cases} 0, & x_{p_i,s}(t_j) \le L^w_i \\ 100\dfrac{x_{p_i,s}(t_j) - L^w_i}{L^b_i - L^w_i}, & L^w_i < x_{p_i,s}(t_j) < L^b_i \\ 100, & L^b_i \le x_{p_i,s}(t_j) \le U^b_i \\ 100\dfrac{U^w_i - x_{p_i,s}(t_j)}{U^w_i - U^b_i} & U^b_i < x_{p_i,s}(t_j) < U^w_i \\ 0 & x_{p_i,s}(t_j) \ge U^w_i \end{cases} \quad (2)$$

where L^w_i, L^b_i, U^w_i and U^b_i are appropriate parameters. The parameters L^b_i and U^b_i constitute the lower and upper limits, respectively, of the ideal range of values. Measurement values being less than or equal to L^w_i and greater than or equal to U^w_i correspond to the worst-case scenario.

The most widespread form for a composite index is the weighted aggregate index of the form $WQI = \left(\sum_{i=1}^{n_q} W_i Q_i\right) \Big/ \left(\sum_{i=1}^{n_q} W_i\right)$, where W_i is the weighting factor of the transformed index Q_i and n_q is the number of transformed indices participating in the composite index. This form is simple and interpretable, but in distribution networks it presents two main risks, since a critical degradation can be covered by many good values, while if a transformed index has strong noise, then it can cause spurious fluctuations. To mitigate the above risks, hybrid options are often used, such as indices focusing on worst-case scenarios for critical parameters or dual indices, where one focuses on the overall picture, while the other on alarm phenomena. The definition of the final composite quality index requires the selection of appropriate weighting factors that express the relative importance of each parameter. The selection of weighting factors is essentially a statement of priorities, i.e. it expresses which deviations are considered most critical for water quality, either from a health or preventive decision-making perspective. The most common approaches use one or more of the following methods: a) Regulatory weighting: Parameters that are close to their limit values receive a higher weighting factor, so as to highlight the need for their correction, b) Expert / operational weighting: Weighting factors reflect the importance of the safety of the distributed water (e.g. residual disinfectant and pH may have increased priority as indices of adverse events), c) Data-driven weighting: The weighting factors are derived from historical data (frequency of exceedances, correlations, contribution to incidents), with care taken not to "train" the index on a single operating condition. For water distribution networks, the weighting should emphasize parameters of health importance and parameters for early warning of adverse events, while at the same time avoid distortion due to parameters that vary strongly but have little operational value.

V. CASE-STUDY FOR REAL-TIME COMPOSITE INDICES

In what follows we propose real-time composite indices for the water supply network of Lamia, Greece. The WDN under study comprises many local control stations, that monitor and control corresponding subsectors of the network. Moreover, the water network is supervised by a SCADA system. The proposed composite indices will be based on real-time measurements of quality related variables, which are collected from the sensors established to the local control stations, through the local PLCs and the SCADA system. The quality variables that are measured in several local control stations are residual chlorine concentration (p_1), pH (p_2), conductivity (p_3), water turbidity (p_4), and nitrate concentration (p_5). The desired values for these quality variables are determined by corresponding directives and guidelines (see [1]-[6]).

For the residual chlorine concentration, values below 0.2 mg/l indicate insufficient disinfection and values above 0.5 mg/l affect the taste and odor of the water [2]. Values above 1 mg/l and below 5mg/l, for short period of time, do not involve immediate health risk, but are not desired. The ideal pH range is between 7 and 8.5 [2]. The acceptable range is between 6.5 and 9.5 [1]. The maximum permissible limit for conductivity is 2.500 μS/cm (at 20°C) [1]. The typical range of conductivity is between 300 up to 800 μS/cm. The ideal range for turbidity is lower than 0.3 NTU [1] (or 0.5 according to [4]), while its maximum permissible limit is 1 NTU [1]. The nitrates concentration is indirectly estimated sensors measuring the concentration of nitrogen. The safe operational threshold for nitrogen concentration is 5.65 mg/l (corresponding to 25mg/l of nitrates), while the maximum permissible nitrogen concentration is 11.3 mg/l (corresponding to 50mg/l of nitrates) [1].

Based on the above, the indices $Q_{i,s}, i=1,\ldots,8$ are considered, where $Q_{i,s}, i=1,3,5$ monitor the low thresholds values of residual chlorine concentration, pH, and conductivity, respectively, based on the 2nd equation of (1). The corresponding thresholds are: $x^{w}_{p_1,s}=0.2$, $S_1=0.21$, $x^{w}_{p_3,s}=6.5$, $S_3=7$ and $x^{w}_{p_5,s}=200$, $S_5=300$. The indices $Q_{i,s}, i=2,4,6,7,8$ monitor the high thresholds values of residual chlorine concentration, pH, conductivity, water turbidity, and nitrate concentration, respectively, based on the 1st equation of (2). The corresponding thresholds are: $x^{w}_{p_2,s}=1$, $S_2=0.5$, $x^{w}_{p_4,s}=9$, $S_4=8.5$, $x^{w}_{p_6,s}=2500$, $S_6=800$, $x^{w}_{p_7,s}=1$, $S_7=0.3$ and $x^{w}_{p_8,s}=11.3$, $S_8=5.65$.

For the water network under study, the use of two classes of composite indices are proposed. The first aims to early detection of critical abnormal quality behaviour of the total network and is expressed as follows: $MQ_i=\prod_{s\in S_i}\left(Q_{i,s}\right)^{0.1}$ $i=1,\ldots,8$, where S_i denotes the set of all locations of measurement for the corresponding quality index. MQ_i goes to zero if any of the normalized indices $Q_{i,s}$ goes to zero. This way, any critical event that may take place at any point of the network, where measurements are available, is immediately detected. The second class of composite indices aim to identify critical events at each local control station of the water network. This class is described by the formula $WQ_{i,s}=\left(\sum_{i=1}^{9}W_i(Q_{i,s})Q_{i,s}\right)\Big/\left(\sum_{i=1}^{9}W_i(Q_{i,s})\right)$, where $W_i(Q_{i,s})=k_i/(Q_{i,s}+\varepsilon)$, k_i and ε are positive parameters to be selected. Each weight $W_i(Q_{i,s})$ increases as $Q_{i,s}$ decrease, while it gets its maximum value when $Q_{i,s}$ gets equal to zero. The parameter ε has a small positive value, so that $W_i(Q_{i,s})$ is well defined for $Q_{i,s}=0$. The parameter k_i is selected to have greater values for those indices that are critical for human health (e.g., residual chlorine, pH, nitrates). Here, we propose $\varepsilon=0.01$, $k_i=50$ for $i=1,2,3,4,8$, $k_7=20$ and $k_5=k_6=1$.

VI. CONCLUSIONS

In this paper, a comprehensive framework for the assessment and operational monitoring of water quality in supply networks has been proposed. The framework has been based on data derived by the SCADA systems, used for supervision and control of water supply networks, and has been applied to indicative cases in the water supply network of Lamia, Greece. Distinctions between single-parameter metrics and composite quality indices have been studied. Indicative composite quality indices, being applicable in real time data of water stations of Lamia have been suggested. Real time monitoring of the proposed composite quality indices can be used as a tool for quality assessment and as a basis for early event detection and decision support. The enrichment of composite quality indices with operational parameters of the network such as the age of the water in the network (residence time), measurements of flow, pressure, tank levels or other variables calculated from hydraulic or water quality models, is currently under investigation.

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