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Spatiotemporal Water Quality Variations in Smaller Water Supply Systems: Using Modified CCME WQI from Groundwater Source to Distribution Networks

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Abstract: Original Canadian Council of Minster of the Environment Water Quality Index (CCME WQI) is being used for assessing the water quality of surface water sources and distribution systems on a case by case basis. Its full potential as a management tool for complete water supply systems (WSSs) has yet to be recognized at the global level. A framework is developed using the modified CCME WQI to assess spatiotemporal water quality from groundwater source to treatment and distribution networks in smaller systems. The modified index resolves a limitation of the original index by also evaluating the microbiological water quality parameters which have to be completely absent for meeting desired drinking water quality standards. The framework divides the distribution network in different zones, which are further segregated into districts, to improve the decision-making process. Temporal assessment identifies the seasons with higher probabilities of failures, while the spatial assessment provides an insight on the performance (i.e., Excellent to Poor) of each district in a distribution network. In addition to failure probability, risk mapping gives appropriate attention to the number of consumers in different districts. Application of the framework on two smaller WSSs (population less than 50,000) in Qassim region revealed that the remotely located districts from the treatment facility underperform in comparison to the closely situated districts. Managers can effectively apply the proposed framework to identify the locations and periods of water quality failures in each component (i.e., source, treatment, and distribution) of a smaller WSS for effective utilization of their resources in Saudi Arabia and elsewhere with similar conditions.

Keywords: smaller water supply systems; water quality; CCME WQI; groundwater quality; risk-based water quality assessment; spatiotemporal water quality

1. Introduction

Water utilities in Kingdom of Saudi Arabia (KSA) are facing challenges related to both the quantity and quality of water due to low annual rainfall, depleting water resources, anthropogenic activities, and presence of naturally occurring substances in groundwater [1]. As a result, they are striving to meet municipal water demand with adequate water quality through intermittent water supplies. Presently, water quality is being monitored to check the water quality from source to distribution networks through routine (or random) sampling programs. However, water utilities have no mechanism to assess the composite water quality of their water supply systems. Index based water quality assessment of source water, treated supply, and the available product in distribution networks can facilitate the utility managers for effective (technical and policy levels) decision-making and public information.

Since 2001, both the regulatory agencies and researchers have been using the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) to aggregate the complex water quality data for regulatory purposes and compliance reporting. The original formulation of CCME WQI developed by the Technical Subcommittee of CCME is presented in the following equation [2]:

$$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{1}$$

where F_1 is scope and calculated as percentage of total number of failed samples, F_2 is frequency and calculated as percentage of regulatory violations, while the amount of these violations is calculated as amplitude (F_3).

CCME WQI was most frequently used for surface water quality assessment for various intended uses, such as agriculture, drinking, and protected aquatic life [3–5]. Recently, Duan et al. [6] used CCME WQI to assess the background concentrations of chemical oxygen demand, permanganate index, and ammonia nitrogen for water quality management of river systems in Heilongjang province of China. According to Sidoruk and Cymes [7] applied Equation (1) to assess the water quality of natural ponds for fish survival in Poland. Physiochemical water quality parameters included were total suspended solids, BOD5, NO_3, NO_2, ammonia nitrogen and Total Kjeldahl nitrogen, and total phosphorous.

Earlier, Islam et al. [8] modified Equation (1) by allocating weights to water quality parameters and used it for assessing the spatiotemporal variations of disinfection byproducts (DBPs) in distribution networks. Farzadkia et al. [9] used Equation (1) for spatiotemporal water quality assessment of the Yamchi Dam in Iran. In addition to the inadequate promulgations of environmental laws, they found higher concentrations of suspended solids as the main sources of pollution (for agricultural use) through discharge of wastewater from pisciculture and aquaculture centers along with urban areas in the dam's catchment. Previously, Hurley et al. [10] modified the Equation (1) by allocating relative weights to the factors (i.e., F_1, F_2, F_3) for surface source water quality assessment in Canada.

Review of past studies revealed that CCME WQI has been used for distinct assessment of source or distribution network of the water supply systems (WSSs). Around the world, smaller systems are facing diverse challenges (from source to tap) of supplying safe drinking water to their customers [11]. Groundwater in most regions of KSA is contaminated with naturally high concentrations of salts, iron, metals and radionuclides. Raw groundwater is being adequately treated with expansive treatment processes (i.e., iron oxidation, filtration, reverse osmosis, and chlorination) [12]. Intermittent nature of supply makes it difficult to maintain the desired water quality throughout the distribution network due to possible growth of biofilm or contaminant intrusion when the system is not pressurized. Further, the problem of low residual chlorine has also been noticed in the supply zones located distant form the point of supply [13].

Prior to a comprehensive risk-based water safety planning, it is important to assess the state of performance, in terms of spatiotemporal water quality variations, of source, treatment, and distribution systems. The factor F_3 in the original CCME WQI presented in Equation (1) cannot be estimated for presence or absence (e.g., 0 MPN/100 mL) microbiological water quality parameters (WQPs). In such cases, the microbiological contamination was stated in water quality assessment reports [14]. As per the literature, smaller systems face more operational problems in comparison to the larger systems [15]. Present research aims to modify Equation (1) to incorporate the impact of microbiological water quality failure in the assessment procedure. The modified CCME WQI is applied to assess the source water, treatment plant effluent supplied to the system, and different districts of three small WSSs in the city of Unayzah, Qassim, KSA. The study demonstrates an overall state of water quality in smaller WSSs and identify the underperforming components for detailed investigations. The proposed methodology can also be used to locate the underperforming district (subsection) in the distribution network over three assessment years.

2. Materials and Methods

2.1. Water Quality Assessment Framework

Water quality assessment framework developed in this study is presented in Figure 1. The first two steps were conducted in parallel. Water supply systems in the study area were selected based on three primary considerations: (i) Source water where some or all WQPs exceed drinking water quality standards (DWQS), (ii) presence and absence of treatment facilities, and (iii) distribution networks with relatively higher water quality failure events. After selecting WSSs in the study area, the modified CCME WQI is developed to identify and rank the components based on the state of their water quality. At this stage, spatiotemporal variations in CCME WQI are assessed and risk-based water quality assessment are conducted. Finally, underperforming components of the selected WSSs are identified for further investigations and potential improvement actions.

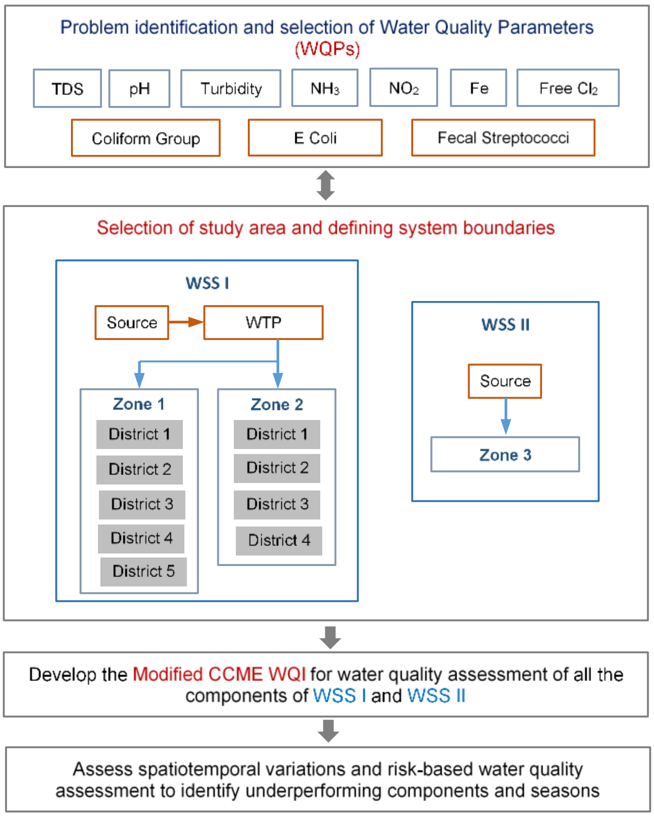

Figure 1. Proposed framework for water quality assessment of water supply systems in Qassim.

2.2. Study Area

City of Unayzah located at 26°5′38.7168″ N and 43°58′24.4344″ E is the second largest city of Qassim Province of KSA (see Figure 2). The distance of the study area is around 25 km from the capital (Buraydah). The population of city was reported to be 185,000 as of 2014 [16]. The main source of water supply is groundwater drawn from Saq Aquifer [17]. The municipality of the city has different operational scenarios of its WSSs. In some cases, for instance WSS I (see Figure 2), highly treated water is being supplied to the consumers residing in central part of the city. While in other cases (e.g., WSS II), low population density areas (generally located at cities' boundaries) are being supplied with chlorinated raw water. In later case, consumers have to rely on bottled water; however, the Water Directorate of Qassim Province, in collaboration with responsible water utilities, is exerting serious efforts to either install complete treatment or connect such areas with treated water supplies. Increasing installation capacities of existing treatment facilities is another challenge faced by the water utilities in the region. Both types of water supply systems were selected for water quality assessment.

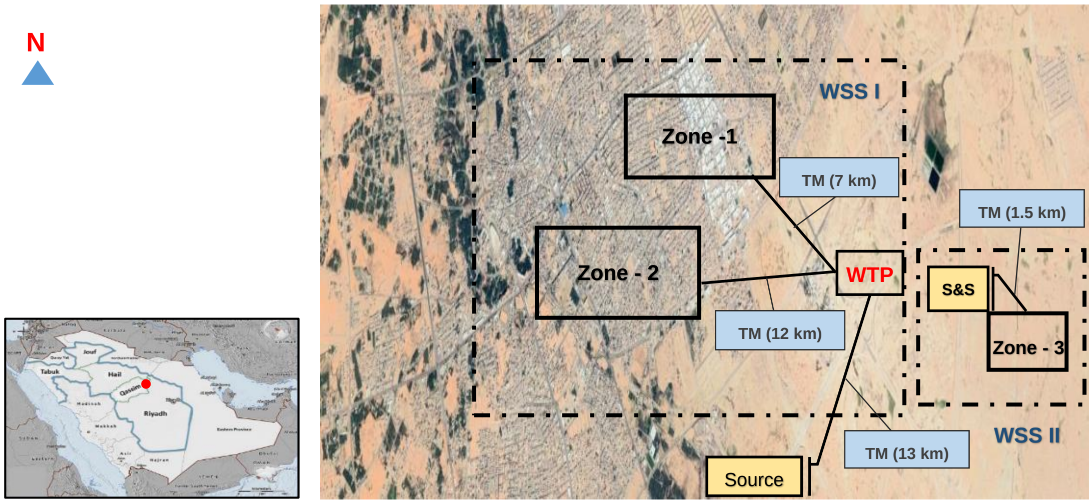

Figure 2. Location of study area. Red dot on the left figure showing the location of study area in Qassim Province, KSA.

2.3. Water Quality Parameters Selection and Target Values

Important WQPs (see first step in Figure 1) were selected based on availability of monitored data, human health risk, and possible impact on subsequent component of the WSS. High concentration of total dissolved solids (TDS) is the main issue in groundwater of study area. In most situations TDS are higher than the target value of 500 mg/L. There are no health-related standards, but some of the inorganic salts in TDS have health related significance, e.g., boron, fluoride, and nitrates [1]. Controlling TDS levels less than 500 mg/L through reverse osmosis generally guarantees concentrations of individual salts less than the maximum permissible limits as well which makes TDS as a robust parameter to control salinity in water supplies.

Iron (Fe) levels higher than 0.3 mg/L of target value exist in earth crust of the study area. In the absence of health based guidelines prescribed by World Health Organization (WHO), values less than 3 mg/L are assumed to be suitable for human consumption [18]. Further to avoid a possibility to *Crenothrix* growth in pipelines, 0.05 mg/L was established as a target value for distribution networks [19].

Presence of ammonia (NH_3) in raw water reflects probable exposure of groundwater to the contamination from anthropogenic activities, such as seepage from agricultural area, livestock farms, and landfill sites. Although, there are no health based guideline values, NH_3 can reduce the effectiveness of chlorination. Other possible issues are clogging of filtration system and formation of nitrite in distribution networks. Similarly, Nitrite (NO_2) can be found in raw groundwater exposed to agricultural activities or sewage intrusion through cross-connections in distribution networks. The health based guideline value for NO_2 in drinking water is 3 mg/L [18]. In present research, target value of 0.01 mg/L is used to avoid formation of chloramines and ensure effective chlorination in distribution systems [20].

Coliform group (Total Coliforms), E.Coli, and Fecal Streptococci (FS) are the WQPs to assess microbiological water quality in source water, treated water, and distribution system. Target to ensure safe drinking water quality is complete absence of all of these parameters.

Although desirable range of pH in drinking water is 6.5–8.5, pH should be less than 8 for effective disinfection through chlorine. Health-based guideline value of residual chlorine is 5 mg/L while to avoid taste and odor complaints, levels less than 0.3 mg/L are desirable in some cases [18]. In present research, the target value of minimum residual chlorine is established as 0.2 mg/L and maximum value of 4 mg/L [8]. Target level for turbidity is 1 NTU [18].

All the samples collected from the study area were transported to the main laboratory located inside the office of the Municipality of Buraydah, i.e., a nearby city and is the Capital of Qassim. Monitoring frequencies of water quality sampling and analysis are weekly for water treatment plant and monthly for source and distribution networks.

Tests for TDS and pH were performed using HACH 440d multi-parameter meter. Iron, ammonia, NO_2, and chlorine were tested with the help of HACH DR5000 UV-VIS Spectrophotometer, Canada. Turbidity in the collected samples was measured using HACH 2100Q Turbidity Meter. Total Coliforms an E.Coli were measured using 100 mL bottle with EC Blue 100 P powder purchased from Hyserve Company, Germany. The tests to estimate the numbers of FS in water samples were performed with filter (Enterococci) from Dorasan Company (Gyeonggi-do, South Korea) of 45 µm of pore size.

2.4. Modified CCME WQI

Selected WQPs include physical (turbidity and TDS), chemical (pH, NO_3, NO_2, Fe, and residual chlorine), and biological (total coliforms, E-Coli, and fecal Streptococci). As target for biological parameters is their complete absence, the original form of CCME WQI cannot be used. Therefore, Equation (1) is modified to include biological parameters in the overall water quality index.

The following form of Equation (1) can be used for physical and chemical WQPs as [2]:

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

where (*CCME WQI*)*pc* is the calculated index for physical and chemical WQPs.

***F_1* (Scope)** describes the level of non-compliance of all the WQPs in a given assessment period and can be estimated using the following equation:

$$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables} \right) \times 100 \tag{3}$$

where number of failed variables are the WQPs which exceeded their target values (objectives).

***F_2* (Frequency)** is estimated as the percentage of failed tests, i.e., individual tests for all the WQPs which did not meet the target or objectives value. F_2 can be calculated as:

$$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests} \right) \times 100 \tag{4}$$

***F_3* (Amplitude)** represents the amount by which the failed test values did not meet the target value. Calculating F_3 is a three step process.

Step 1: Calculate excursion which represents the number of times an individual WQP was found greater than (or less than) the objective. In present research all the WQPs are desired to be less than the objective, so excursion is estimated as:

$$excursion_i = \left(\frac{Failed\ test\ value_i}{Objective_i} \right) - 1 \tag{5a}$$

In case of WQPs which are desired to be higher than the objective, e.g., residual chlorine, numerator and denominator in Equation (5) will be reversed as:

$$excursion_i = \left(\frac{Objective_i}{Failed\ test\ value_i} \right) - 1 \tag{5b}$$

Step 2: Calculate normalized sum of excursion (nse) using the following equation:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{\# \, of \ tests} \quad (6)$$

Step 3: Finally calculate F_3 using the following equation:

$$F_3 = \left(\frac{nse}{0.01 \ nse + 0.01} \right) \quad (7)$$

Equation (7) is an asymptotic function that scales the nse between 0 and 100, so that F_3 can be analogous to F_1 and F_2. Subsequently, *(CCME WQI)$_{PC}$* can be calculated using Equation (2).

Step 4: To include the impact of microbiological WQPs, the following index is proposed:

$$(WQI)_{MB} = \left[1 - \left(\frac{Total \ number \ of \ failed \ microbiological \ tests}{Total \ number \ of \ microbiological \ tests} \right) \right] \times 100 \quad (8)$$

where *(WQI)$_{MB}$* is the microbiological water quality index.

Step 5: Finally, the modified CCME WQI can be calculated as:

$$Modefied \ CCME \ WQI = W_1 \times (CCME \ WQI)_{PC} + W_2 \times (WQI)_{MB} \quad (9)$$

where W_1 and W_2 are the relative importance weights for *(CCME WQI)$_{PC}$* and *(WQI)$_{MB}$*. As the importance of these indices varies for different components of a water supply system, a unique weighting scheme (based on expert opinion) is proposed in Table 1.

Finally, the modified CCME WQI can be categorized as per Table 2. Decision-makers can take effective improvement actions based on the estimated value of the index.

Table 1. Weighting scheme for different components of a WSS to calculate (CCME WQI)$_{\text{Modified}}$.

Component of Water Supply System (WSS)	Relative Weighs		Remarks/Rationale
	(CCME WQI)$_{PC}$ (W_1)	*(WQI)$_{MB}$* (W_2)	
Source Water	0.7	0.3	Due to the following reasons, relatively low weight is allocated to *(WQI)$_{MB}$*. • In most cases, deep aquifers are not affected by microbiological contamination. • Source water is always treated through disinfection prior to distribution.
Effluent of water treatment plant (WTP) after storage and chlorination prior to supply OR Effluent from raw water storage with only chlorination prior to supply	0.8	0.2	Due to the following reasons, relatively low weight is allocated to *(WQI)$_{MB}$*. • There is a very low possibility of microbiological contamination (MBC) after filtration and/or chlorination.
Water distribution system (WDS)	0.5	0.5	Due to the following reasons, equal weights are allocated to both the indices. • MBC in distribution network poses a very high risk to human health. • MBC in distribution system raises question on the effectiveness of chlorination practice.

Table 2. Categorization of the modified CCME WQI as defined by CCME (CCME [2]).

Modified CCME WQI	Performance Category	Description
95–100	Excellent	Water quality is protected with a virtual absence of impairment; conditions are very close to pristine levels; these index values can only be obtained if all measurements meet recommended guidelines virtually all of the time.
89–94	Very Good	Water quality is protected with a slight presence of impairment; conditions are close to pristine levels.
80–88	Good	Water quality is protected with only a minor degree of impairment; conditions rarely depart from desirable levels.
65–79	Fair	Water quality is usually protected but occasionally impaired; conditions sometimes depart from desirable levels.
45–64	Marginal	Water quality is frequently impaired; conditions often depart from desirable levels.
0–44	Poor	Water quality is almost always impaired; conditions usually depart from desirable levels.

2.5. Risk-based Water Quality Assessment

It is important to consider the population of each district along with the water quality variations for a conclusive water quality assessment in the study area. Risk is the product of probability of failure (P) and the consequence of that failure (C). Modified CCME WQI calculated using Equation (2) to Equation (9) considers the frequencies of water quality failures and actually presents the probability of water quality failure in a given study area (i.e., zone or district) or at a monitoring station. Consequence part of the risk relates to the population of a district which undergoes water quality assessment. As per the city review report published by UN HABITAT in year 2015, average household size in the City of Buraydah is 6.3 persons [21]. Study area is located in a very close vicinity of Buraydah with similar quality of standards and land uses; hence it is rational to use the same value.

Linguistic scales defined for both the P and C for risk calculations are given in Table 3. The risk matrix developed in Figure 3 is based on the information provided in Table 3.

Table 3. Linguistic scales defined for risk calculations.

Probability of Failure (P)		Consequence (C)	
Modified CCME WQI	**Linguistic Scale**	**Number of Connections [1]**	**Linguistic Scale**
95–100	Very Low	>1200	Very High
89–94	Moderately Low	800–1200	High
80–88	Low	500–800	Medium
65–79	Medium	200–500	Low
45–64	High	50–200	Moderately Low
0–44	Very High	<50	Very Low

[1] The idea was obtained from small water supply systems' tiered classifications in British Columbia (Ministry of Health, BC [22]).

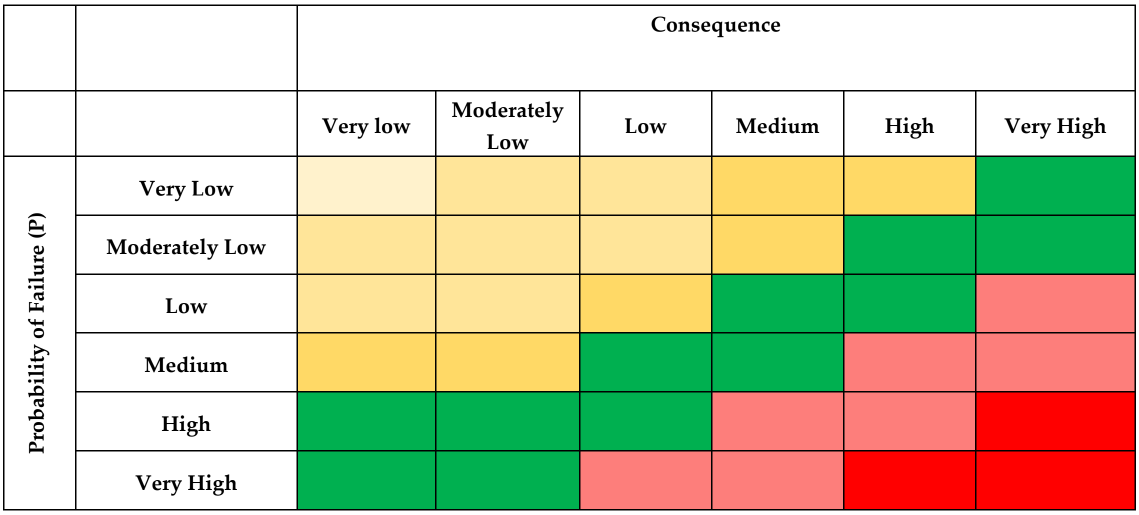

Figure 3. Risk Matrix used for water quality assessment in present study.

3. Results and Discussion

3.1. Water Quality Monitoring

Water quality data for all the components of both the WSSs described in Figure 1 were obtained from the Municipality of Unayzah and Water Directorate in Qassim Province, KSA. Mean (with 95% confidence interval), minimum (MIN), maximum (MAX), standard deviation (SD), and coefficient of variation (CV) for all the parameters (between FY 2016 and FY 2018) are presented in Table 4 for WSS-I and in Table 5 for WSS-II.

Table 4. Summary of water quality monitoring results for Water Supply System-I during the assessment period between 2016 and 2018.

Water Quality Parameter	Units	DWQS [1]	Concentration			Standard Deviation	CoV [5] (%)
			MIN [2]	MEAN [3]	MAX [4]		
SOURCE WATER							
Total dissolved solids (TDS)	mg/L	500	408	871.9 ± 122.3	1304	265	30.4
pH	-	6.5–8.5	6.99	7.46 ± 0.12	8.11	0.26	3.5
Ammonia (NH_3)	mg/L	0.01	0	0.002 ± 0.003	0.03	0.01	424
Nitrite (NO_2)	mg/L	0.01	0	0.002 ± 0.003	0.03	0.01	424
Iron (Fe)	mg/L	0.3	0	0.0008 ± 0.011	0.1	0.02	320
Turbidity	(NTU)	1	0	0.504 ± 0.259	2.5	0.56	111
Coliform Group	(MPN/100 mL)	Negative	Coliform group were found in 22.2% of the samples				
E.coli	(MPN/100 mL)	Negative	E coli were found in 22.2% of the samples				
Fecal Streptococci	(MPN/100 mL)	Negative	Fecal Streptococci were absent in all the samples				
WATER TREATMENT PLANT EFFLUENT							
Total dissolved solids (TDS)	mg/L	500	45.2	429.5 ± 11.78	1064	99.1	23.0
pH	-	6.5–8.5	6.46	7.215 ± 0.031	8.13	0.3	3.6
Ammonia (NH_3)	mg/L	0.01	0	0.000	0	0.0	0.000
Nitrite (NO_2)	mg/L	0.01	0	0.000	0	0.0	0.000
Iron (Fe)	mg/L	0.3	0	0.000	0	0.0	0.000
Turbidity	(NTU)	1	0	0.277 ± 0.037	2.94	0.26	92.4
Free chlorine	mg/L	0.2–0.5	0.1	0.313 ± 0.011	0.77	0.08	24.4
Coliform Group	(MPN/100 mL)	Negative	Coliform group were absent in all the samples				
E.coli	(MPN/100 mL)	Negative	E coli were absent in all the samples				
Fecal Streptococci	(MPN/100 mL)	Negative	Fecal Streptococci were absent in all the samples				
DISTRIBUTION SYSTEM							
Total dissolved solids (TDS)	mg/L	500	175	525.8 ± 42.8	4511	360.47	68.6
pH	-	6.5–8.5	6.7	7.34 ± 0.031	8.27	0.26	3.59
Ammonia (NH_3)	mg/L	0.01	0	0.000	0	0.00	0.000
Nitrite (NO_2)	mg/L	0.01	0	0.0003 ± 0	0.04	0.00	1176
Iron (Fe)	mg/L	0.3	0	0.02 ± 0.01	0.88	0.08	402
Turbidity	(NTU)	1	0.08	0.501 ± 0.1	9.11	0.84	168
Free chlorine	mg/L	0.2–0.5	0	0.252 ± 0.012	0.43	0.10	38.4

[1] Drinking Water Quality Standards, [2] Minimum; [3] 95% confidence interval; [4] Maximum, [5] Coefficient of Variation.

Table 4 demonstrates a large variation in TDS in source water for WSS I during the assessment period with a widespread SD of 265 mg/L. Higher values were observed more recently in 2017 and 2018 which shows natural deterioration of groundwater quality in terms of salts leaching. pH values are in line with the desired DWQS. Average values of ammonia and nitrates are less than the DWQS with few samples with concentrations larger than 0.01 mg/L. Iron and turbidity are also within the desired ranges most of the times. Biological contamination in 22.2% of the samples points towards possible groundwater interaction with anthropogenic activities, such as seepage from agricultural catchments and soakage pits in near vicinity of well field.

Table 5. Summary of water quality monitoring results for Water Supply System-II during the assessment period between 2016 and 2018.

Water Quality Parameter	Units	Concentration			Standard Deviation	CoV [4] (%)
		MIN [1]	MEAN [2]	MAX [3]		
SOURCE WATER						
Total dissolved solids (TDS)	mg/L	273	691.38 ± 55.68	868	139.18	20.131
pH	-	6.9	7.32 ± 0.09	7.77	0.22	3.072
Ammonia (NH_3)	mg/L	0	0.03 ± 0.05	0.65	0.13	418.390
Nitrite (NO_2)	mg/L	0	0.000	0	0.00	0.000
Iron (Fe)	mg/L	0	0.71 ± 0.12	1.04	0.30	42.992
Turbidity	(NTU)	0.49	5.14 ± 1.75	16	4.39	85.347
Coliform Group	(MPN/100 mL)	Coliform group was found in 29.1% of the samples				
E.coli	(MPN/100 mL)	E coli was found in 29.1% of the samples				
Fecal Streptococci	(MPN/100 mL)	Fecal Streptococci was found in 29.1% of the samples				
STORAGE						
Total dissolved solids (TDS)	mg/L	484	674.96 ± 48.24	871	120.58	17.865
pH	-	6.99	7.32 ± 0.08	7.96	0.21	2.859
Ammonia (NH_3)	mg/L	0	0.01 ± 0.01	0.09	0.02	261.634
Nitrite (NO_2)	mg/L	0	0.000	0	0.00	0.000
Iron (Fe)	mg/L	0	0.77 ± 0.08	1.06	0.21	27.078
Free chlorine	mg/L	0.01	0.07 ± 0.08	0.93	0.19	284.944
Turbidity	(NTU)	0.73	4.02 ± 1.51	14.2	3.77	93.973
Coliform Group	(MPN/100 mL)	Coliform group was found in 16.6% of the samples				
E.coli	(MPN/100 mL)	E coli was found in 16.6% of the samples				
Fecal Streptococci	(MPN/100 mL)	Fecal Streptococci was found in 16.6% of the samples				
DISTRIBUTION SYSTEM						
Total dissolved solids (TDS)	mg/L	500	689.29 ± 47.70	876	119.24	17.298
pH	-	7	7.35 ± 0.10	7.91	0.24	3.327
Ammonia (NH_3)	mg/L	0	0.01 ± 0.01	0.13	0.03	489.898
Nitrite (NO_2)	mg/L	0	0.000	0	0.00	0.000
Iron (Fe)	mg/L	0	0.62 ± 0.16	1.7	0.41	66.062
Free chlorine	mg/L	0.01	0.05 ± 0.05	0.48	0.11	210.625
Turbidity	(NTU)	0.7	1.83 ± 0.42	5.14	1.05	57.614
Coliform Group	(MPN/100 mL)	Coliform group was found in 20.8% of the samples				
E.coli	(MPN/100 mL)	E coli was found in 20.8% of the samples				
Fecal Streptococci	(MPN/100 mL)	Fecal Streptococci was found in 20.8% of the samples				

[1] Minimum; [2] 95% confidence interval; [3] Maximum, [4] Coefficient of Variation.

Mean TDS concentration in the WTP effluent lies within the desired drinking DWQS of 500 mg/L. On April 14, 2018 exceeding TDS value of 1064 mg/L points towards possible failure of RO process with an overall high performance, i.e., 95% confidence interval within the desired range. No failure incidence was observed for pH values. Excellent performance of water treatment facility can be seen in Table 4 in terms ammonia, nitrates, and iron removals. Similar to TDS, average values turbidity and residual chlorine met DWQS with 95% confidence interval. One time in three year assessment period turbidity reached to 2.94 and on August 11, 2016 residual chlorine exceeded 0.5 mg/L. No incidence of biological contamination was reported in WTP's effluent.

Average TDS values higher than desired DWQS in distribution system suggests further investigations to identify possible causes, e.g., leaching pipe material and soil intrusion due to intermittent supply. Nitrogen compounds were found insignificant in distribution networks of WSS I. Mean values of turbidity and iron were also found acceptable with 95% confidence interval. Maximum value of turbidity reached higher than 9 NTU, in District 3 of Zone 2, on 6 September 2016 while 0.88 mg/L of iron concertation was also found in the sample. Such a high value of turbidity could be due to soil intrusion from cracks. However, possibility of sampling and measurement errors cannot be disregarded. No incident of microbiological water quality failure was observed during the assessment period.

WSS II serving 45 number of service connections is a very small system where raw groundwater is being distributed after chlorination at storage facility (see Table 5). TDS levels were almost similar to source of WSS I. pH and nitrogen compounds do not seem to be problematic. Iron and turbidity levels are much higher than WSS I. Coliform group and E-Coli were observed in 29% of the samples due to possible instruction of leachate from the sanitary landfill located at 15 km from the well area.

In storage facility of WSS II, no significant difference was noticed, for almost all the WQPs, with some reduction in biological contamination in Table 5. Subsequently, similar behavior persists in distribution network. High bacterial contamination in distribution network manifests inadequate chlorination practice.

3.2. Temporal Water Quality Variations

Figure 4 shows the seasonal water quality variations in WSS I in terms of modified CCME WQI. At source, an overall water quality deterioration (from 'Good' to 'Marginal') is evident over the assessment period during winter season (see Figure 4a). These results show that some of the water quality parameters often exceeded the desired drinking DWQSs. While in the summer season, the source water quality fluctuates between 'Fair' and 'Good' which shows occasional deviation of one or more WQPs from the desired water quality levels. Modified CCME WQI for the WTP's effluent ranged between 'Excellent' and 'Good' during the summer season and between 'Very Good' and 'Good' during the winter season. These results suggest fewer water quality failure events and a need of a careful monitoring program with higher sampling frequency for precise identification of root causes.

In Zone 1 of WSS-I, the water quality in Districts 5 is 'Excellent' during both the seasons, expect winter of 2016 when it slightly reduced to 'Very Good'. Water quality in District 1&3 generally lies in 'Excellent' to 'Very Good' region in both the seasons, with the exception of 2018 winter in District 1. 'Good' in District 4, and 'Fair' in District 2 (see Figure 4b). District 4 had 'Very Good' water quality during winter season, except 2016 while in summers it deteriorated from 'Excellent' in 2016 to 'Good' in the following two years. In District 2 water quality has been consistently deteriorated from 'Excellent' to 'Fair'. Such water quality variations can be used to detect the problem areas and prioritize the improvement actions and the associated financial resources.

Overall, water quality in all the four districts of Zone 2 (WSS I) is inferior to Zone 1 during both the seasons. Consumers in District 1 received 'Excellent' water quality in winter season while a deteriorating behavior is evident in Figure 4c where CCME WQI reduced from 'Excellent' to 'Fair' during summers over the assessment period. Similar but less abrupt behavior can be observed for second best performing district, i.e., District 3, where CCME WQI reduced from 'Very Good' to 'Good' in summer season. In general, District 2 lied in 'Fair' water quality region throughout the assessment period with an exception of summer 2017 when it lowered down to 'Poor'. In District 4 CCME WQI gradually reduced from 'Good' to 'Fair' between 2016 and 2018.

Modified CCME WQI (2016–2018) for source water, storage facility, and distribution network for WSS II (Zone 3) is illustrated in Figure 5. Source water quality was generally lied in 'Marginal' zone. In the absence of an appropriate treatment facility (i.e., only chlorination), the water quality consistently found 'Marginal' irrespective of seasons in storage tank. Similar behavior can be observed for distribution network of WSS II.

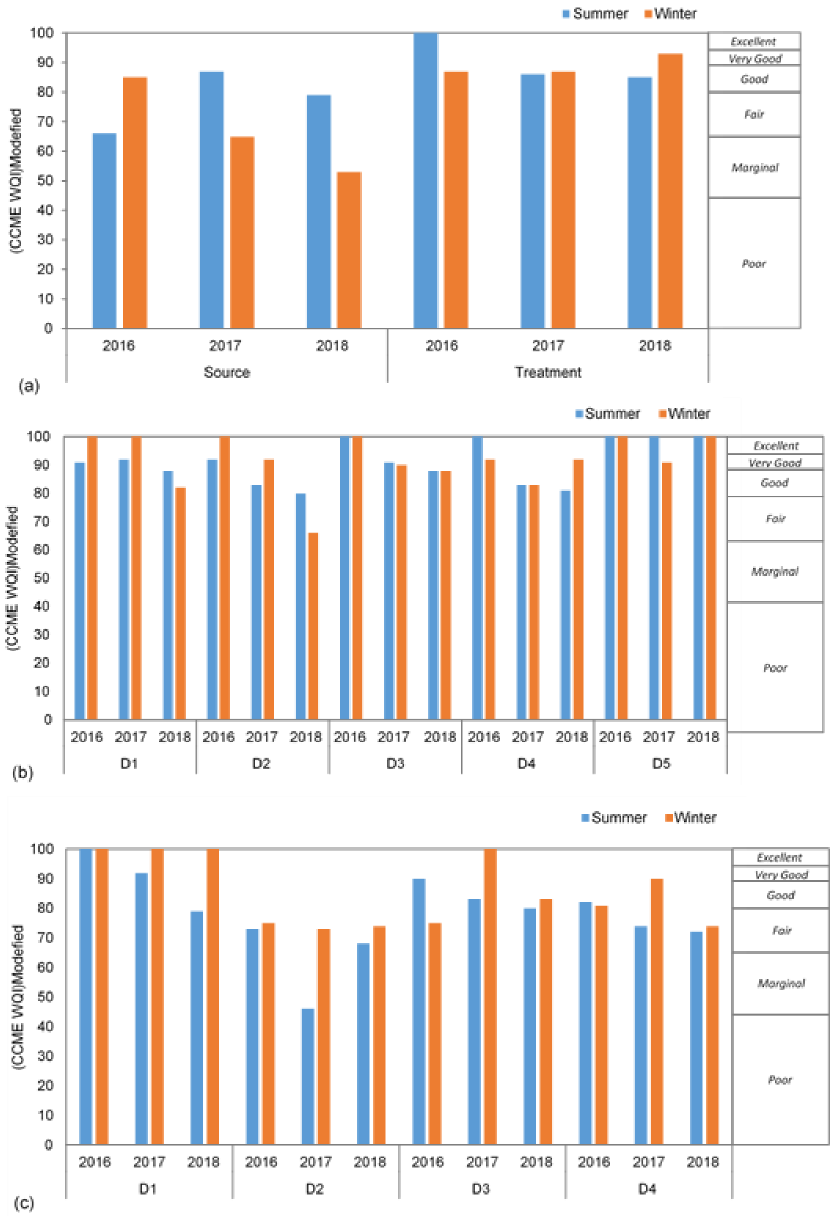

Figure 4. Modified CCME WQI in WSS-I, (**a**) Source water and water treatment plant, (**b**) zone 1, (**c**) zone 2.

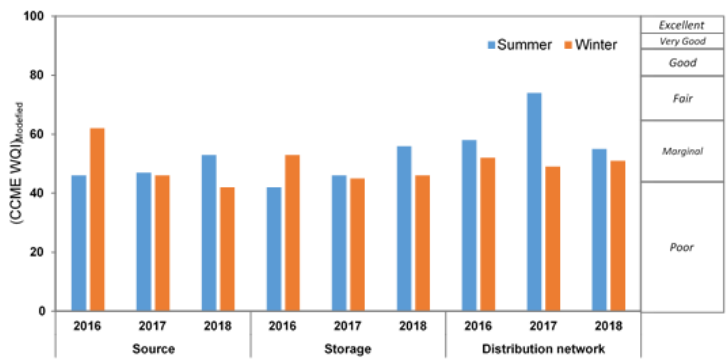

Figure 5. Modified CCME WQI in WSS-II (Zone 3).

3.3. Spatial Water Quality Variations

Spatial water quality variations in all the zones of both the WSSs are illustrated in Figure 6. Average estimated values, for the assessment period between 2016 and 2018, of the modified CCME WQI are spatially presented for both the seasons in all the districts (marked by black lines). In WSS I, water is being supplied to the consumers from the WTP through transmission mains. Overall water quality (i.e., average annual, irrespective of seasons) in Zone 1 located at 7 Km is 'Very Good' while it is 'Good' in Zone 2 located at 12 Km from the treatment facility. This shows that the service areas closer to the treatment facilities are receiving better quality water than the remoter areas due to the possibility of recontamination in long transmission mains, particularly for the case of intermittent water supplies.

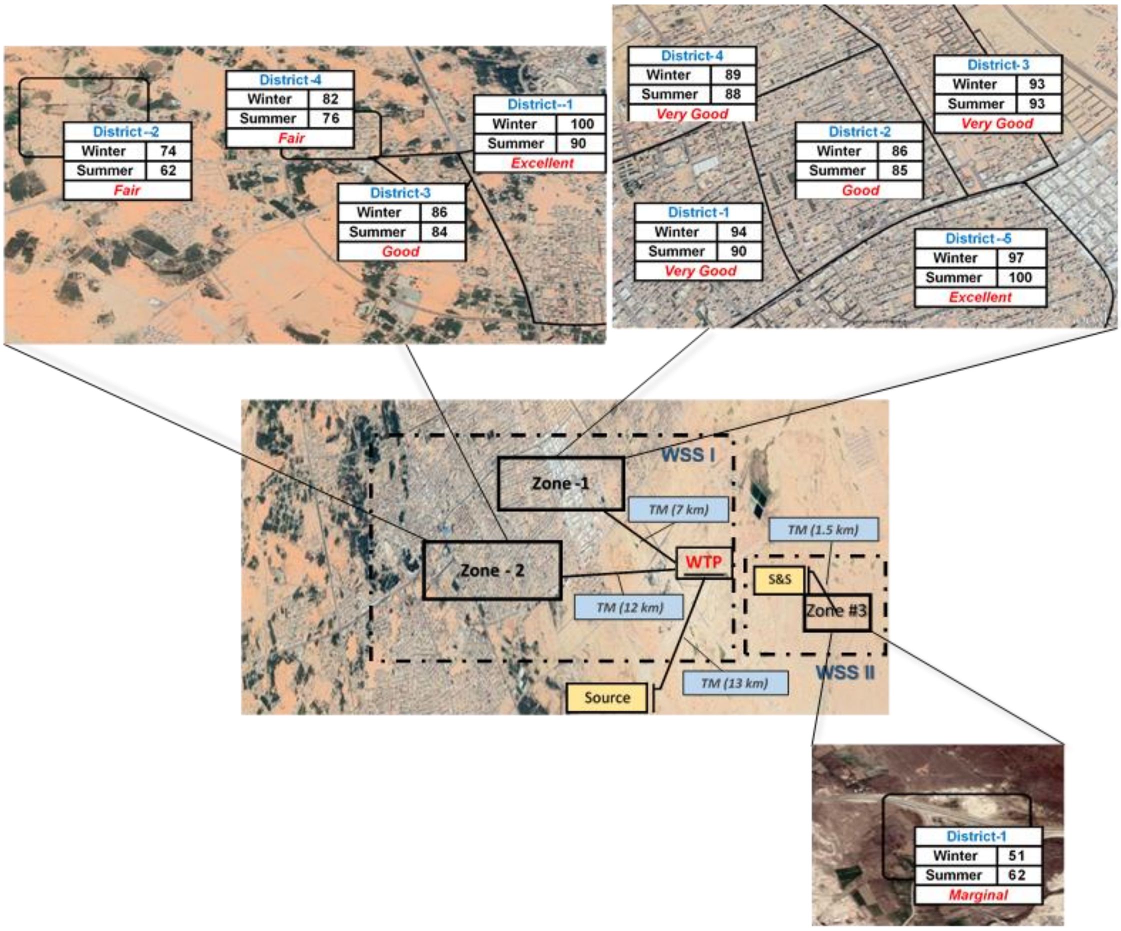

Figure 6. Vignette showing spatial water quality variations in WSS I and WSS II of the study area. [Abbreviations: Transmission Main (TM), Water supply system (WSS), Water Treatment Plant (WTP), Source and Storage (S and S)].

Figure 6 endorses this finding within the boundaries of both the Zone 1 and Zone 2 as well. Water quality is 'Excellent' in District 5 which is located at the beginning of Zone 1. Water quality in Districts 1, 3, and 4 are 'Very good' as they are located at the boundaries while water quality is 'Good' in the centrally located District 2. Likewise, water quality in District 1, which is located at the early part of Zone 2, is 'Excellent' followed by District 3 serving their consumers with 'Good' quality water. While District 3 and 4 received 'Fair' water quality from the treatment facility.

Zone 3 of WSS 2 receives chlorinated water, through 1.5 km long transmission main, from the water storage facility. The water quality is 'Marginal' in this zone.

3.4. Risk-Based Water Quality Assessment

Modified CCME WQI is used to assess the water quality from source to distribution networks in two smaller WSSs operating in Qassim Region of KSA. The results stated above are used to generate the risk maps (see Figure 7) to facilitate the municipality managers for effective water quality management of these systems. An important step in this regard is evaluating the impact of deteriorated water quality on the consumers (i.e., estimated through the number of service connections) residing in each district (see Table 6). For instance, in Zone 1, District 2 serving more than 8000 consumers face occasional water quality failures as the CCME WQI is 'Good'. Due to large number of consumers served, the system is under 'Medium' level of risk (see Table 6 and Figure 4). Managers need to focus on this district more than the rest in WSS I. The estimated risk is based on an average of 3 years monitoring results; however, seasonal and annual maps can also be generated for municipality operations and general public. Districts 2 and 4 in Zone 2 are under 'Medium' risk; the reason in this case is 'Fair' water quality instead of number of consumers and hence needs to be carefully monitored and improved.

Figure 7 shows that the WSS II serving less than 300 consumers, in the absence of a detailed WTP, is threatened by 'High' level of risk due to 'Marginal' CCME WQI.

Honing the WSS I revealed that the treatment facility faced operational problems during summer season in 2017 and 2018 which resulted in exceedance of TDS and thus the low values of Modified CCME WQI. In winters, high TDS values were also observed due to occasional clogging of RO membranes or minor unbalance in mixing to permeate of RO unit with sand filter's effluent. In addition, residual chlorine levels higher and lower than the desired range also contributed to reduction of CCME WQI values. High temperatures and growth of biofilm, when the system is not pressured can be considered as the primary reasons of low levels of residual chlorine in distribution networks. Turbidity levels higher than 1 NTU in distribution networks during repairs of main break were also noticed.

In WSS II, chlorine is being added into the storage tank; most of which is lost due to very large contact time as the system is very small. Consequently, very low residual was noticed in the distribution network. Secondly, the system is operating without a conventional groundwater treatment plant and supplies water with TDS levels higher than 500 mg/L all the time. Implementation of an all-inclusive treatment facility meeting desired drinking water quality is required to improve the CCME-WQI.

A modified CCME WQI is used in this research for assessing spatiotemporal water quality variations from source to distribution networks in smaller WSSs operating in Qassim Region. The study results revealed that all the three components, i.e., source, treatment, and distribution network, are facing water quality failures throughout the three year assessment period. Municipality managers can use the risk maps and the model results for effective decision-making after detailed root cause analysis.

Table 6. Population statistics in water supply systems of the study area.

District No.	Service Connections	Population	P [1]	C [2]	Risk	Potential Actions Required
			Water Supply System I (Zone 1)			
District 1	591	3723	Moderately Low	Medium	Low	- Very minor improvements required. - Very few parameters might be higher than the standards.
District 2	1289	8121	Low	Very High	Medium	- Minor improvements required. - Few parameters might be higher than the standards. - High population area, so careful monitoring is required.
District 3	181	1140	Moderately Low	Moderately Low	Very Low	- Very minor improvements required. - Very few parameters might be higher than the standards
District 4	1474	9286	Moderately Low	Very High	Low	- Very minor improvements required. - Very few parameters might be higher than the standards
District 5	1300	8190	Very Low	Very High	Low	- High population area, so careful monitoring is required. - No action required in terms of water quality. - Maintain water quality as all the parameters meet desired water quality standards.
			Water Supply System I (Zone 2)			
District 1	387	2438	Very Low	Low	Extremely Low	- No action required. - Maintain water quality as all the parameters meet desired water quality standards.
District 2	150	945	Medium	Moderately Low	Medium	- Minor improvements required. - Few parameters might be higher than the standards.
District 3	342	2155	Low	Low	Low	- Careful monitoring is required. - Parameters rarely exceed the desired standards.
District 4	315	1985	Medium	Low	Medium	- Careful monitoring is required. - Parameters occasionally exceed the desired standards.
			Water Supply System II			
-	45	284	High	Very Low	High	- Small population but water quality parameters frequently exceed the desired standards. - Major improvements might be required through detailed monitoring.

[1] Probability of failure (P), i.e., $(\text{CCME WQI})_{\text{Modified}}$ in this study; [2] Consequence, (C), i.e., number of consumers.

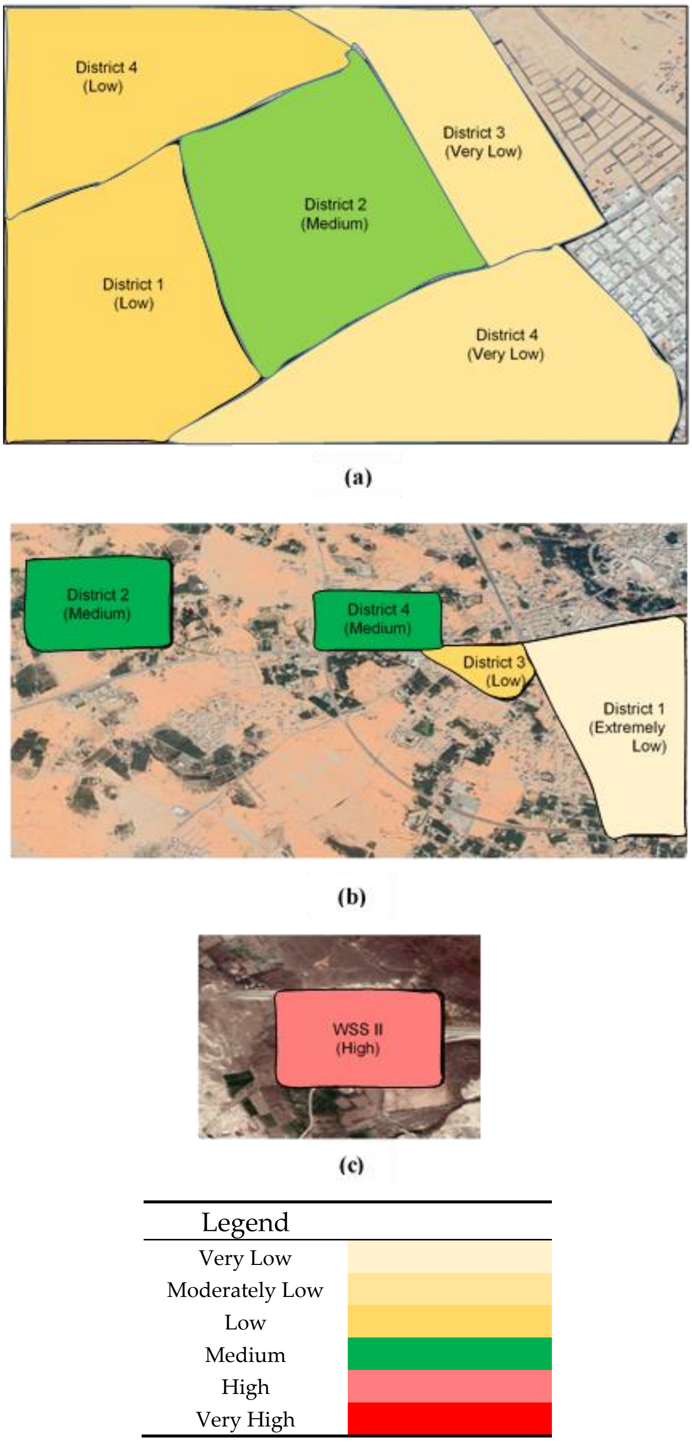

Figure 7. Risk mapping of water supply systems in study area. (**a**) Zone 1 of Water Supply System I, (**b**) Zone 2 of Water Supply System I, (**c**) Water Supply System II.

4. Conclusions and Recommendations

Original CCME WQI has been widely used in research and practice for assessing water quality of surface water sources and distribution systems. Its full potential as a management tool for water supply systems has yet to be recognized at global level. Original CCME WQI cannot evaluate those microbiological water quality parameters which have to be completely absent, in the distribution networks, to meet drinking water quality standards. In present research, a modified CCME WQI is developed to address this limitation.

The proposed framework assesses the spatiotemporal water quality variations from groundwater source to distribution network. Temporal water quality assessment helps the municipality managers to identify the problematic seasons with higher probabilities of water quality failures. While the spatial water quality assessment provides an insight on the districts in different zones of a distribution network with best and worst water quality. Managers can effectively highlight the locations and periods of water quality failures in each component (i.e., source, treatment, and distribution) of a smaller water supply system for effective utilization of their human and financial resources.

Number of service connections (consumers) in each district should also be given desired importance for estimating the risk of water quality failures. Districts with higher frequency of failures and/or serving larger number of consumers should be given higher priority for planning improvement actions. Highly sensitive areas, such as hospitals and schools, can also be highlighted using this approach. A risk map developed in present research effectively illustrates the importance of this aspect by including both the probability and the consequence of water quality failures in smaller systems.

Implementation of proposed framework on two small water supply systems in Qassim region of Saudi Arabia revealed that the remotely located districts from the treatment facility face larger incidents of water quality failures as compared to the closely situated districts.

'Very low' to 'high' risks observed in such small systems aims towards a detailed root cause analysis and risk-based water quality assessment to secure water safety in smaller water supply systems of Saudi Arabia and elsewhere with similar conditions.

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