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Water Quality Index of Natural Streams: A Case Study of Five Headwater Streams in Bald Eagle State Forest, Pennsylvania

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Abstract Water quality index (WQI) uses many weighted, measurable parameters to give one number that reflects the quality of the water. WQI is a standard approach to evaluate and compare results of different streams because of its concise form. The correct WQI expression for a specific stream can be challenging and requires a good stream water quality knowledge. In this study, five Penns Creek headwater streams located in the Bald Eagle State Forrest, PA were selected and assessed with five different Water Quality Indices and a new specific WQI expression was identified and implemented to simplify a water quality index value. The water quality data used for the five WQI and the specific WQI expressions was collected from the summer months of June and July from 2015 to 2017. Using these five different WQI expressions, revealed a range of values from 80 to 100 making these streams ranked between good and excellent quality. Since the WQI is meant for drinking water, the normalization factors of some parameters such as pH, temperature, and Biochemical Oxygen Demand (BOD_5), are excessively lowered and limits the application on natural headwater streams, where some parameters should not be weighted. Using this experimental site that is known to have a good water quality, with little to no human impact, the WQI has been rearranged taking in consideration the following steps: 1) the range of the pH has been expanded to more acidic and basic water 2) the range of temperature lowered for colder water 3) excess parameters, like BOD_5 and other ion concentration were removed.

Keywords: *Water Quality Index, Water Quality Standards, Water Quality Indicators, headwater streams*

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1. Introduction

Headwater streams are the origin of many larger streams, creeks, and rivers, playing a major role in the quality of water. Commonly, they account for large portions of expansive watersheds, often can be more than 75 percent of the total stream channel length [1]. Streams with larger volumes of water tend to receive more monitoring and assessments, due to their apparent impacts. Reference 20 noted that headwater streams are important sources of water and critical for nutrient processing, yet they are usually overlooked, especially if they are not critically impacted. This method of headwater monitoring will not allow full understanding of all chemical concentrations in higher order streams [2]. One of the best approaches to evaluate the quality of any stream is one that calls for multiple measurable parameters combined under a single index. Recently, many attempts have been made, but their level of effectiveness varies with the kind of stream under consideration and different parameter analytical weight.

Water Quality Index (WQI) uses a set of measurable water parameters to mathematically assess the quality of a stream [3,4]. This assessment evaluates the pollution, ecosystem heath, and drinking water availability. There are many different WQI expressions used to assess the quality with each using slightly different weighs and number of parameters [5,6,7]. The weight factor is applied to parameters intended to carry dominance in the assessment of quality of water mainly for drinking water. The number of parameters can change significantly from one study to another, depending on the nature of the stream and the objectives of the study. In certain studies, some of these parameters were even used individually in the evaluation of the water quality [7]. The ultimate result of an index is a numerical representation ranging from 0 to 100 where the higher the number, the better the quality of the water (Table 1).

Table 1. Scale values ranging from 1-100 representing the overall quality of the water reported by the WQI [7]

WQI Scale	Rating
91-100	Excellent water quality
71-90	Good water quality
51-70	Average water quality
26-50	Fair water quality
0-25	Poor water quality
0-25	Very bad water quality

For simplicity, there are many parameters that are not included in an index, only the most significant indicators of quality are used [8]. The presence, the absence, and/or the weight of the existent parameters dictate how accurate the WQI will be, but if the parameters are well selected and their weights are precisely calculated, the WQI can be highly accurate. To assess this hypothesis, five headwater streams in Bald Eagle State Forest in central Pennsylvania were selected (Figure 1). Previous studies have shown that these streams were spring feed and their water qualities were found to be good as they have little human impact [9]. Located in a forested area, these streams spring from shale, siltstones and sandstones formations and have generally low flow discharges. The data collection started in June 2015 and ended in July 2017.

Environmental issues that are generalized can incorrectly bring down the score [10]. One of the major parameters to bring down the calculation of the WQI is the pH. In the calculated indices, the normalization factor is usually 40 out of 100. This low value tends to drop the WQI several points. Spring fed streams for instance can have excellent water quality even if the pH is slightly acidic. A pH of 7 is not necessary found in natural spring water that is not used for drinking water, especially in non-carbonaceous formation as is the case with all the streams in this study. Similarly, the concentration of hydrogen in water become an issue when the pH drops below 4 [11]. Samples in sandstone and shale areas have shown to have a good water quality even with low pH ranging between 4 and 5.2 [12]. In general, headwaters are slightly acidic, especially in areas with less buffering capacities, yet all WQI indices dictate a pH of 7 for the water to be qualified as excellent. The pH of good water is acceptable to be below the typical measurement of 7, when it occurs naturally. The range of the highest normalization factor of 100, adopted in all WQI equations, does not have to be for water with neutral pH. The higher end of the normalization factors can be expanded to include a range of pH 5.5 to 7 and still considered high quality in a non-contaminated natural environment. The exception of this will acid mine drainage (AMD) water. When affected by AMD, water will have a pH of 2 to 4 which considered severe, and slightly higher when moderate [13,14]. If a stream is affected by an AMD or other unnatural processes the expanded range should not be applied.

In a study done in Shenandoah National Park on the importance of monitoring headwaters, it was found that headwaters, especially spring sites, are more subject to variation in water composition. Underlying geology was an important predictor of the parameters tested. The pH readings at the springs was significantly lower than the downstream sites [1].

Due to the steeper slopes and rapid runoff in headwater sites, it is believed that they are more subject to atmospheric deposition. Furthermore, if the geology does not have buffering capacities, the water will stay relatively acidic or can even further lower the pH. Also, since there is less water in headwater streams, small amounts of contaminates can have a larger impact on the quality [1]. In headwaters, base flow can be much greater contributor than along the valleys. Often, all the flow is from groundwater fed springs. Since it is difficult to know the boundary of the aquifer, to accurately determine what type of flow paths were taken by spring water, and the type of geological formation(s) it consists of, there is uncertainty of what the water chemistry should be based on [1].

Water temperature is very important for physical, biological, and chemical processes. Aquatic species have specific temperature range they can survive in. In fact, an increase of temperature in an optimally oxygenated water can increase the aquatic biological activities. The temperature of streams also significantly brings the normalization factor down. With the average ranging from 11° to 13°C, the normalization factor is 60 or 70. Since the stream is essentially groundwater, it is more acceptable for the water to be colder [4]. The sample sites are close to the sources of the stream. These streams emerge directly from groundwater that is generally cold and often stays that way over the length of headwater runs. The temperature of most springs ranges between 10°C to 15°C [12]. In addition, headwater streams are often located in forested and high-altitude areas, which allow the water to flow faster and stay cooler [15]. The variation of temperature is less than the broader and slower streams of higher orders.

The WQIs encountered in literature sources are generally created for rivers and major streams. They do not account for shaded areas and higher velocity water that causes the temperature to be outside of the highest normalization factor. Since the water is naturally colder than rivers, the normalization factor should have a range that expands to account for the spring fed streams.

The majority of WQI were created to assess the quality of polluted water and how it can be suitable for a drinking water. All parameters and normalization factors were made for these conditions. If applied to unpolluted stream water not necessarily used for drinking water, the calculated value may lead to a biased WQI. The goal of this study is to apply and assess the limits of application of published indices to synthesize a new WQI expression based on their trends and the streams under consideration, especially headwater streams with little to no human impact.

2. Methods

Main method of collection was grab samples from the five headwater streams between the summer months of June and July between June 2015 to July 2017. The site locations are Little Weikert (LW), Green Gap (GG), Lick Run (L), Coral Run (C), and Henstep (H) (Figure 1). These sites are in Bald Eagle State Forest in Pennsylvania. These are watersheds, the arrows indicate the water flow.

The collected samples were filtered with phosphate-free 47mm diameter filter paper, with a 0.45 µm pore size and ion concentrations were determined using an Ion Chromatography System ICS-2100. The following ions were tested according to reference to the 4110 A standard methods: Fluoride (F^-), Chloride (Cl^-), Nitrite (NO_2^-), Bromide (Br^-), Sulfate (SO_4^{2-}), Nitrate (NO_3^-), and Phosphate (PO_4^{3-}), Sodium (Na^+), Ammonium (NH_4^+), Potassium (K^+), Magnesium (Mg^{2+}), and Calcium (Ca^{2+}). A Multimeter (YSI 556) was used to measure the following physical parameters: Temperature (T^o), Electrical Conductivity (K_E), Total Dissolved Solids (TDS), Dissolved Oxygen (DO), pH, and Oxidation-

Reduction Potential (ORP). Alkalinity, Turbidity, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), and Total Suspended Solids (TSS) were measured in the laboratory. Each individual sample was tested, the averages were used for calculations.

To better understand the water quality without being biased on how suitable it should be for drinking water and using a smaller number of parameters. In this effort, multiple WQI expressions were examined, but only five were considered due to their direct relevance to this research. The five selected studies are explained below and summarized in Table 2. *WQI1*, was used to assess a polluted stream in Las Rozas-Madrid, Spain [7]. It was calculated based on 11 parameters and the normalization factors were based on standards for surface water used for drinking water. In this study, a linear relationship between the dissolved oxygen deficit and the WQI was established showing the importance of DO. *WQI2* depends on 22 parameters, which is the highest number of parameters encounter in the assessments of water quality using WQI [6]. *WQI3* was also part of this study, yet only 3 parameters were used. The *WQI* was used on tributaries of a river that was not as clean as any headwater streams in our study. There are parameters that are not very applicable to this site, like surfactants and oil and greases. These parameters are not observed in our streams, so they would not have any impact in this study. Turbidity was not in our study because the headwaters are very clear and the few measurements available were averaged to 11.34 ppm over the 5 headwater streams. *WQI4 and WQI5* focuses on using an index to assess the water quality of a polluted river [5]. *WQI4* uses a similar set of parameters as *WQI2*. The same equations were used, and the calculated parameters were comparable. The difference between *WQI4* and *WQI5* is the normalization factors. *WQI4* has more parameters; *WQI5* has only 5 parameters. *WQI5* did not include the weighting factor for the parameters, which caused it to underestimate the WQI. The WQI of the five headwater streams were either determined directly from Pesce and Wunderlin [6] empirical expression or an expression derived form of it (Table 3). Where *Pi* is the weight of the specific parameters, while C*i* is the normalization factor. The weight implies the importance of the specific parameter for the water quality. (Eq. 1).

$$\frac{\sum i P_i C_i}{\sum i P_i} \quad (1)$$

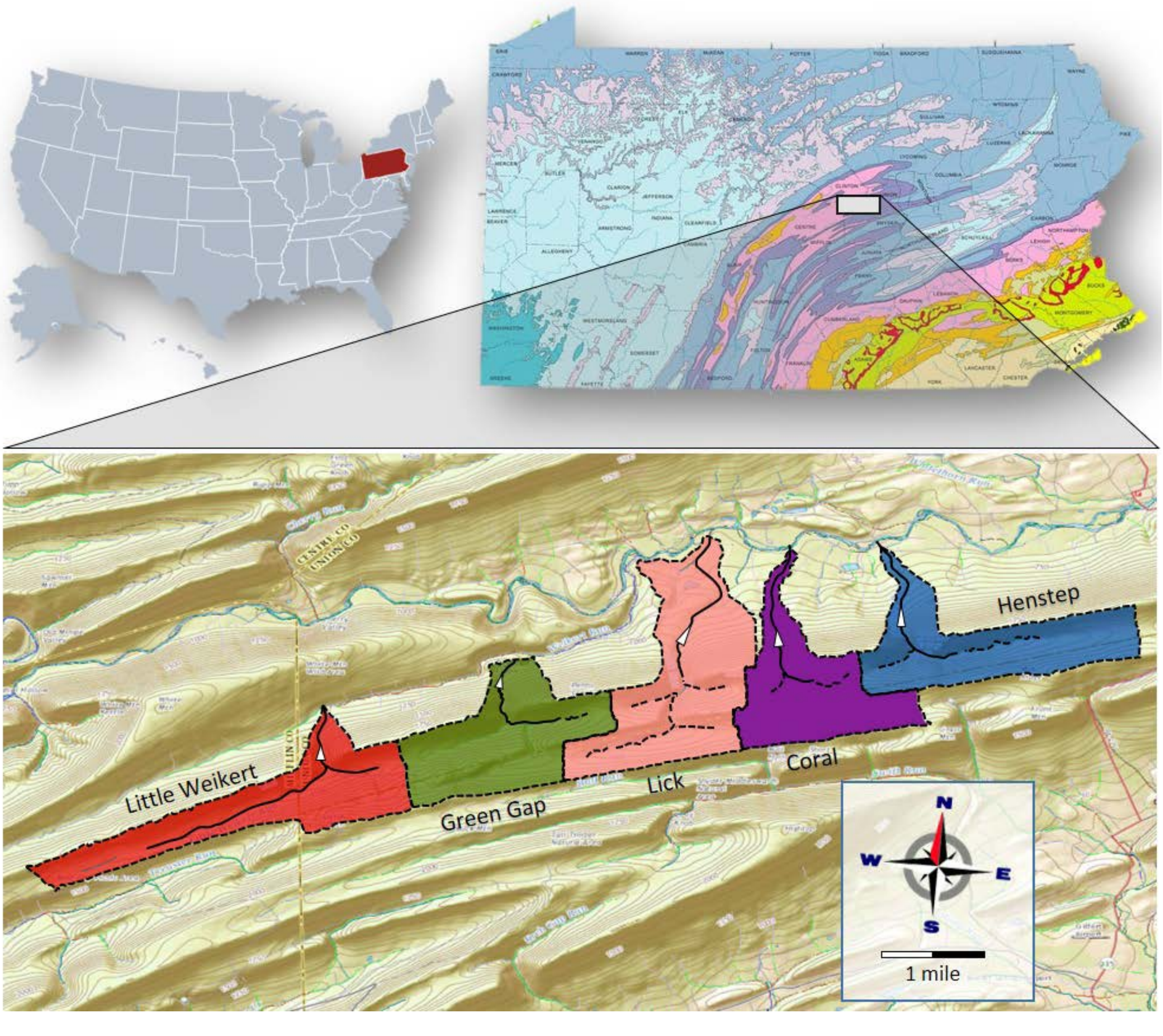

Figure 1. Location of the study area with the shaded areas representing the five watersheds. Little Weikert (LW) and Green Gap (GG) are tributaries of Weikert Run which is a tributary of Penns Creek. Lick (L), Coral (C) and Henstep (H) flow directly into Penns Creek

Table 2. WQI expressions with the list of parameters used

Index #	WQI Expression	Parameters
1	$\frac{\sum i\ P_i\ C_i}{\sum i\ P_i}$	pH, K_E, TSS, NO^{2-}, NO^{3-}, NH_4^+, P, COD, BOD_5, DO, and T(°C)
2	$\frac{\sum i\ P_i\ C_i}{\sum i\ P_i}$	NH_4^+, BOD_5, Ca^{2+}, Cl^-, COD, DO, Hardness, Mg^{2+}, NO^{2-}, NO^{3-}, Oil and greases, pH, P, TDS, TSS, Sulfates, Surfactants, T(°C), Total coliforms, and Turbidity
3	$\frac{C_{DO} + C_{cond} + C_{turb}}{3}$	Do, K_E or Dissolved solids, and Turbidity
4	$\frac{\sum i\ P_i\ C_i}{\sum i\ P_i}$	T(°C), pH, DO, K_E, TDS, TSS, Ca^{2+}, Mg^{2+}, Total Hardness, SO_4^{2-}, CL^-, Inorganic Phosphorus, Total phosphorus, NH4N, NO2N, NO3N, BOD_5, and COD
5	$\frac{\sum i\ P_i\ C_i}{5}$	T(°C), pH, DO, TSS, and K_E

The final calculation gives a number between 0-100; the higher the number, the higher the quality of water. To calculate the WQI, all the data available was used, however parameters that were not collected, were deducted from previous studies or by correlations with other similar streams. The weights and normalization factors remained the same as in the literature, so it would not affect the indices calculated.

3. Results and Discussion

The water in all five streams is in excellent quality since it is mostly groundwater fed and there is no evidence of any apparent pollution [8,9]. Table 3 summarizes the calculated WQI values based on the five expressions listed in Table 2. The WQI was calculated based on the number of parameters specified in each WQI expression shown in Table 2. All WQI values indicate that the water in these 5 streams were in good to excellent quality (Table 3).

Table 3. Calculated indices of each headwater stream based on the expressions listed in Table 2

		Streams				
WQI	**Parameters**	**H**	**C**	**L**	**GG**	**LW**
1	11	88.08	86.54	87.31	88.85	88.46
2	22	92.79	91.86	90.93	93.26	93.02
3	3	100	100	100	100	100
4	18	90.88	89.71	90.29	91.47	91.18
5	5	82.00	80.00	80.00	82.00	80.00

Generally, this method is reproducible and gives a single number as a result [16]. The parameters considered in the calculation of WQI should depend on the environment from which the water was sampled and what it is used for. In this project, the focus was on headwater streams and not for polluted ones. In the case of polluted streams, the approach should be taken with reference to specific WQI used for polluted streams.

All indices found in literature have the same range of normalization factors and weights and what makes the overall WQI different is the number of parameters included. Throughout this process it was found that index 1, 2, and 4 have different WQI values, but increase by the same factor (Figure 2). The trends of individual parameters versus the overall WQI correlate well and confirm the quality of the individual streams. The R-squared (R^2) was used to assess the goodness of fit of each WQI against individual parameters. Index 1, 2, and 4 graphed in this method for all the parameters with data, but only WQI4 vs. individual parameters were displayed in this study because of the direct correlation with the R^2 values in respect to the parameters. Since all correlations are the same, only WQI4 graphs are displayed to ovoid redundancy in data display. Except for Green Gap, all other streams showed linear trends when WQI was plotted versus other parameters. Green Gap was not considered in this study because it had higher conductivity probably due to its proximity to a gravely road [9]. The correlations were used to find the best parameters to be selected for WQI calculation for these streams. Similar methods have been done to attempt to simplify the WQI calculation [5,7,17]. For instance, reference 23 used the oxygen deficit versus WQI to give an estimation since it had a linear correlation with R^2 = 0.91.

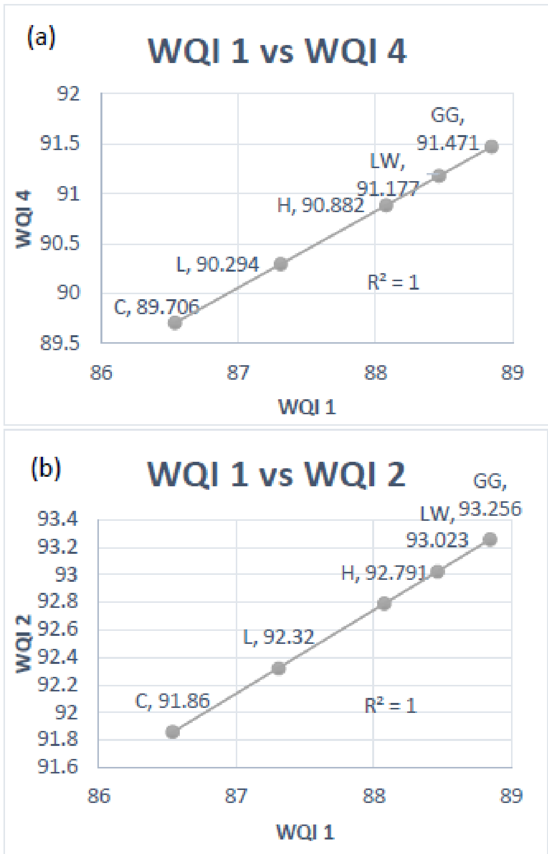

Figure 2. Relationship between WQI 1 vs WQI 4 and WQI 1 vs WQI 2 for the five sites studied

Furthermore, Reference [5] attempted to make water quality easily assessable, the parameters were graphed to find the strongest relationships, hence DO was used because WQI versus DO linearly fitted with R^2=0.88. When this was done with the collected data, there were similar results with four parameters. Figure 3 shows the linear trend with some individually measured parameters. Through the assessment of the goodness of fit of the data, DO, pH, COD and Ke had the strongest correlation to the WQI. This was used to assess the parameters with the greatest linear influence on the overall WQI to give reasoning to the reduction of parameters in a new WQI.

Based on the normalization, as K_E increases, WQI decreases and has a negative effect on the water quality (Figure 3d). Given the fact that WQI4 is in perfect correlation with K_E and K_E vs. TDS are dependable with R2 = 0.95,the TDS was not included. This shows that the K_E has a significant impact on the water quality. It can be used to report the amount of inorganic pollution and the ions in the water [18]. Since there are no excess dissolved solids also observed in low K_E values, they do not have a negative effect on the quality of the water. The geological formations of the aquifers providing water for all these streams does not have high calcium and magnesium and they were found to not affect the WQI. Phosphate and Nitrogen sources (NO^{2-}, NO^{3-}, and NH_4^+) were also found at low concentration. As a part of this newly designed WQI, all these elements were not included in the assessment of the water quality of these streams, they are naturally occurring and do not affect water quality. Since they are in the forest, there is little to no human interaction with these streams. In other indices, forms of nitrate are included because of impacts from agriculture and human wastes. In this area, the nitrogen concentrations originate from natural sources rather than waste. A low concentration can be generated by rainwater and organic decay, yet it was found to not significantly affect the WQI.

Furthermore, in this area, the concentrations of nitrogen in rainwater is much greater than the samples collected from the streams. There is some correlation between discharge and nitrogen concentration in water in shallower streams as more interaction with organic matter increases the nitrogen level [19]. Nitrogen in the form of ammonia is quickly removed from the aquatic systems, causing the observed concentration to be either small or negligible. Nitrate is not easily removed as it is used by living organisms when the oxygen is scarce. The headwaters have high oxygen concentration, so the nitrate is not used [20,21,22,23,24].

The normalization of these parameters is generally high, but do not need to be included since they do not negatively impact the quality of the water. A major factor in lowering the WQI is the BOD_5, with the normalization factor being very low. BOD_5 assesses the amount of organic pollution in the water. Bacterial activities can cause the depletion of DO. The removal of oxygen for plants and animals in this ecosystem can cause habitat loss [22]. Due to ripples and steep terrain, the DO in this case is high. Also, the correlation of DO and BOD_5 was very strong, showing no significant change in DO when BOD_5 increases. Little Weikert for instance, has the steepest slope when compared to other streams, allowing for more aeration. Due to this strong correlation between the BOD_5 and the steepness of stream slopes, DO seemed to play a major role hence, it was kept in the new expression.

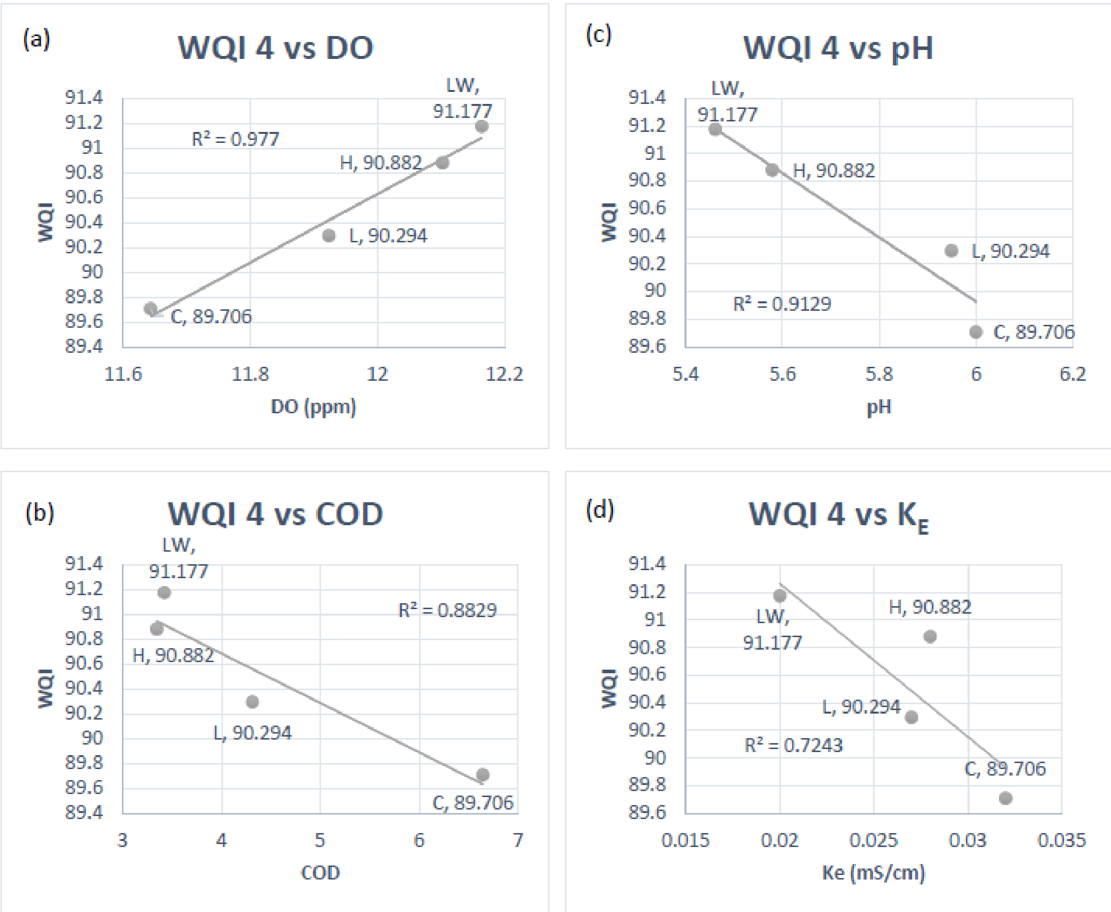

Figure 3. Relationship between WQI vs individual parameters

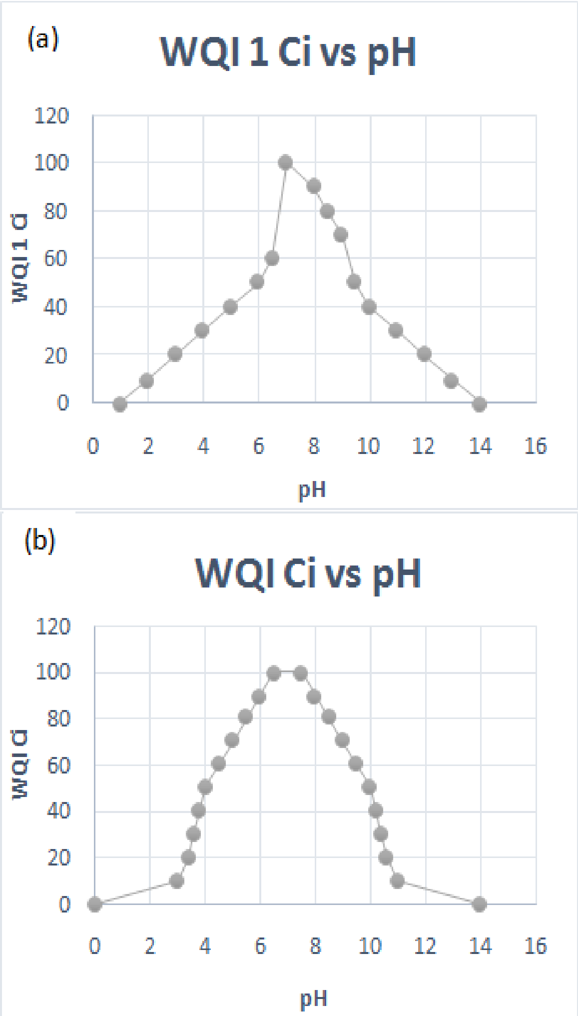

Figure 4. Normalization of pH from the literature values (a) and the improved values (b)

Most groundwater in the United States has a pH of 6.0 to 8.5 [11]. Since the headwater streams are generally fed by groundwater, it is not expected to be exactly neutral. The normalization of pH should be changed to allow for more variability to be accepted [20]. Spring water have been found to have high variation in pH. Low pH is expected to be found in geologic areas that do not have buffering capabilities such as sandstone and shale (Donovan et al. 2006). Higher pH is expected in carbonate rich areas, like limestone. Low pH can be influenced by low temperature of the water and the slightly acidic rain. Higher pH has also been found in other headwater sites typically not more than 9, but sometimes reaching up to 12 yet this happened in rare conditions (Hem 1985). The normalization factor of 100 being only given to 7.0 is not realistic for natural water (Figure 4a).

If the pH of water was 6.8, a perfectly fine pH, even for drinking water, the normalization would be brought all the way down to 60 with lowering the WQI. If the pH is affected naturally, it should equally go in the directions of acidic and alkaline in equal increments starting with 6.5 to 8.5 (think about it, is there any reference that we can use?). Until pH of 4 to 10 it changes by 0.5 increments. From 4 to 3.4 and 10 to 10.6 each normalization factor changes by 0.2 increments. This is because after 4 and 10 it is likely to be naturally, healthy water without having harmful impacts. After a pH of 3 or below and 11 or above, the normalization drops to 0 because it is no longer safe for aquatic species (Figure 4b).

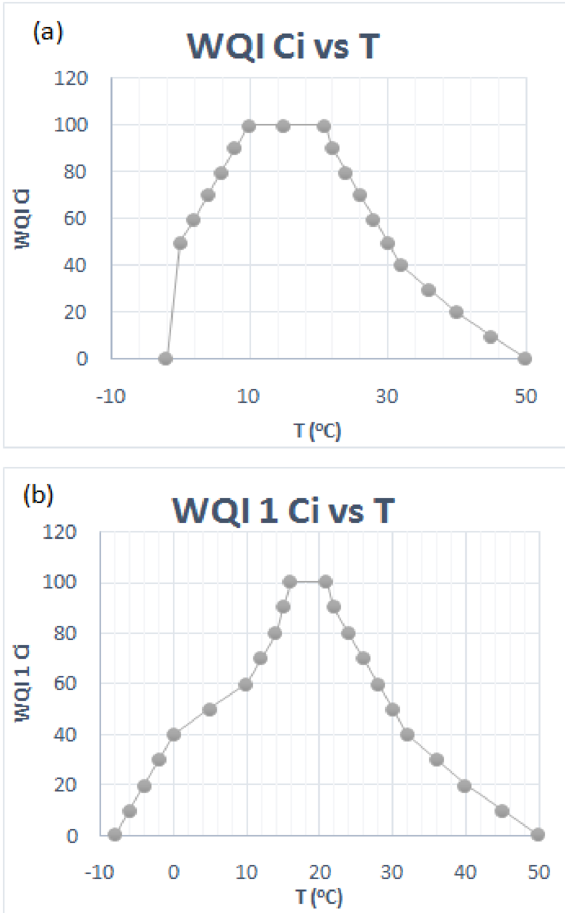

Figure 5. Normalization of temperature from the literature values (a) and the improved values (b)

Table 4. Parameters considered for the modified WQI calculation

		C_i										
Parameter	P_i	100	90	80	70	60	50	40	30	20	10	0
pH	1	6.5-7.5	6.0-8.0	5.5-8.5	5.0-9.0	4.5-9.5	4.0-10.0	3.8-10.2	3.6-10.4	3.4-10.6	3.0-11.0	0-14
Ke (mS/cm)	2	<0.75	<1.00	<1.25	<1.50	<2.00	<2.50	<3.00	<5.00	<8.00	<12.00	>12.00
TSS (mg/L)	4	<20	<40	<60	<80	<100	<120	<160	<240	<320	<400	>400
DO (mg/L)	4	≥7.5	>7.0	>6.5	>6.0	>5.0	>4.0	>3.5	>3.0	>2.0	>1.0	<1.0
COD (mg/L)	3	<5	<10	<20	<30	<40	<50	<60	<80	<100	<150	>150
T (ºC)	1	21/10	22/8	24/6	26/2	28/0	30/0	32/<0	36	40	45	50

Table 5. Application of the modified WQI compared to literature WQI

WQI	Parameters	Stream	H	C	L	GG	LW
1	11	WQI	88.08	86.54	87.31	88.85	88.46
		Status	Good	Good	Good	Good	Good
2	22	WQI	92.79	91.86	90.93	93.26	93.02
		Status	Excellent	Excellent	Good	Excellent	Excellent
3	3	WQI	100	100	100	100	100
		Status	Excellent	Excellent	Excellent	Excellent	Excellent
4	18	WQI	90.88	89.71	90.29	91.47	91.18
		Status	Excellent	Good	Good	Excellent	Excellent
5	5	WQI	82.00	80.00	80.00	82.00	80.00
		Status	Good	Good	Good	Good	Good
6	6	WQI	98.57	97.14	98.57	96.43	97.56
		Status	Excellent	Excellent	Excellent	Excellent	Excellent

In the literature, normalization values caused an underestimation of colder water quality because groundwater fed streams are usually colder [8]. Warmer water is known to have negative impacts on the health of aquatic ecosystems because it accelerates respiration [22]. The literature values of temperature had placed water ranging between 16 to 21°C at 100 (Figure 5a). However, groundwater is naturally colder, and if it is not drastically changing, is should be considered good. In this study, the changes made, expanded the 100 Ci to the range of temperature between 10 and 21°C. This is because most optimal living temperatures are in this range and includes the average groundwater temperature as well. At 0°C the Ci drops to 0 because it would cause problems with freezing. The warmer range of temperatures remained the same due to the biologic processes being catalyzed in this upper range [22] (Figure 5b).

These changes should only be made to the WQI if the conditions are naturally occurring, are not influenced by humans, and not used for drinking water [25], which is the case to these streams. This will be applicable to forested headwaters, with water flowing rapidly and no obvious pollution. Using less parameters allows for simplification of the WQI and would cost significantly less to assess [20]. The suggested WQI (Table 4) was applied to the collected data and the resulted values are higher than calculated by all five equations of WQIs in the literature (Table 5). Due to the changes made, the new WQI is enough to accurately assess the headwater streams. Generally, Green Gap has been known to be the lowest in quality, however, the literature values portray it as being the highest on the scale. With the new WQI, Green Gap was shown to be relatively low. In another study, a different site from Green Gap would be picked where the site remained constant relatively throughout the seasons. Based on this data, recommended changes are to find the quality of any type of water based on its intended use (e.g. measure quality, natural occurring changes) rather than if it is suitable for drinking. This would help in better understanding if the quality is changing or not without being biased and lowering the WQI for an unintended use. As the relationships are graphed, for a simplified WQI, one of the correlations can be used by the line of best fit equation to easily find the WQI.

4. Conclusion

From analysis of multiple literature WQI, it was determined that drinking water parameters are not suitable for accurate assessment of headwater streams. The five streams are known to have high quality and are not impacted by humans. Like other studies, trends of WQI and parameter concentrations were used to show which most directly correlated to the overall quality. In this case, BOD_5, pH, and temperature where the key parameters to lower the score of all the streams, due to naturally occurring processes. Changes have been made that more accurately reflect the quality of headwater streams. When the modified WQI was applied to the data set, the results showed higher overall quality, with all values falling in the excellent category. The new synthesized WQI correctly weights the factors that do affect the headwater streams, which is an important factor for environmental issues in streams, without having to measure if it is suitable for drinking water, while also lowering the number of parameters to more easily find the water quality index on parameters that have a direct correlation.

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