Water Quality Index Methodology

The City and County of Denver's (CCoD) Department of Public Health and the Environment (DDPHE) has been collecting water quality samples from streams and lakes within Denver for almost 50 years. Samples are analyzed for a broad suite of pollutants, including nitrogen and phosphorous, *Escherichia coli* (E. coli), and metals. Results from sampling are used to determine:

- Whether water in Denver's streams meets the State of Colorado's water quality standards;
- Whether it is safe for people to wade, boat, or fish in Denver's streams;
- Whether Denver's efforts to reduce the amount of pollution entering our streams are effective;
- Trends in water quality, and;
- Progress towards achieving the Mayor's goal of ensuring all streams and lakes in Denver are safe for fishing and swimming.

Results of sampling efforts are summarized in annual reports which can be found on DDPHE's Water Quality Program website. Data from sampling efforts are available from Denver's Open Data Catalog, from the Colorado Data Sharing Network. The data can also be viewed and explored through DDPHE's interactive, map-based Water Quality Application.

DDPHE has developed a water quality index (WQI) with the objective of turning water quality data into information that is understandable and useable by the public. The index combines results from several water quality parameters to create a single unitless number which expresses overall water quality. The index will be used to communicate public health risks to people interested in recreating in Denver's streams, to evaluate long-term trends in water quality, and to help document whether Denver's efforts to reduce the amount of pollution entering our streams are effective. The WQI is a tool for simplifying reporting of water quality data. It is not intended to replace detailed assessment of water quality conditions using traditional water quality assessment methods.

This document describes the process used to create the WQI for Denver's streams.

Method

Denver's Water Quality Index is based on the water quality index described by the Canadian Council of Ministers of the Environment (2001) (CCME). The CCME WQI compares pollutant monitoring results to criteria or benchmarks. Individual monitoring results are compared to the criteria and a score is computed based on the number and magnitude of exceedances. The variables (i.e. pollutants) included in the CCME WQI are not specified which allows the user to select pollutants appropriate to describe conditions in the water bodies being scored. As a result, the number of pollutants that can be incorporated into the index is unlimited.

CCME's WQI is based on three measures of variance from selected water quality objectives or criteria. The measures are scope, frequency, and amplitude. Scope (F_1) is the number of analytes exceeding the water quality objectives over the total number of analytes. Frequency (F_2) is the percentage of individual tests that do not meet objectives. Amplitude (F_3) represents the amount by which failed tests do not meet their objectives. F_1 is calculated using the following formula:

$$F_1 = \left(\frac{Number\ of\ Analytes\ with\ a\ Result\ Failing\ to\ Meet\ Criteria}{Total\ Number\ of\ Analytes\ Included\ in\ WQI}\right) \times 100$$

F_2 can be derived using the following equation:

$$F_2 = \left(\frac{Number\ of\ Tests\ Failing\ to\ Meet\ Criteria}{Total\ Number\ of\ Tests}\right) \times 100$$

There are three steps to calculating F_3:

1. Calculate the amount of the excursion:
    a. When the test value must not exceed the criteria use the following formula:

$$Excursion_i = \left[\frac{Failed\ Test\ Value}{Criteria}\right] - 1$$

    b. When the test value must not fall below the criteria use the following formula:

$$Excursion_i = \left[\frac{Criteria}{Failed\ Test\ Value}\right] - 1$$

2. Calculate the normalized sum of excursions (nse):

$$nse = \frac{\sum_{i=1}^{n} Excursion_i}{Number\ of\ Tests}$$

3. Calculate F_3:

$$F_3 = \left[\frac{nse}{(0.01 \times nse) + 1}\right]$$

F_1, F_2, and F_3 are combined to determine the WQI using the following formula:

$$WQI = \left(\frac{\sqrt{{F_1}^2 + {F_2}^2 + {F_3}^2}}{1.732}\right)$$

The factor 1.732 is used to normalize the WQI to 100.

After the WQI has been calculated, the result is scored as described in Table 1.

The authors of the CCME recommend that the index include at least four pollutants sampled four times. If there are too few parameters, the F1 factor (scope) can overwhelm the other F2 (frequency) and F3 (amplitude) factors and result in low scores that are not representative of the overall picture of water quality. To overcome this issue, they recommend modifying the index to exclude the F1 factor (personal

communication, Vincent Mercier, Environment and Climate Change Canada, October 12, 2017). This modified technique is used to calculate indexes for recreation (measured with one parameter – E. coli), field readings (three parameters – pH, temperature, and dissolved oxygen), and nutrients (measured with two parameters – total nitrogen and total phosphorus). Use of the modified technique for some indexes results means that it is not possible to aggregate the index into an overall score for a stream because the indexes are not directly comparable.

Table 1. Water Quality Ratings

Color	Score	Rating	Description
	95-100	Excellent	Virtual absence of impairment; conditions are very close to pristine conditions.
	80-94	Good	Minor degree of impairment; conditions rarely depart from desirable conditions.
	65-79	Fair	Occasional impairment; conditions sometimes depart from desirable conditions.
	50-64	Marginal	Frequently impaired; conditions often depart from desirable conditions.
	<50	Poor	Almost always impaired; conditions usually depart from desirable conditions.

Testing of the CCME WQI has revealed one limitation. The number of parameters which exceed the criteria tends to be more heavily weighted than parameters which routinely exceed the criteria. As a result, a site with one sampling event that exceeds criteria for multiple parameters may score worse than a site which consistently exceeds the criteria for one parameter. Most sites in Denver consistently exceed criteria for the same parameters so it is likely that this limitation will have a minimal effect on Denver's WQI.

More information about the CCME WQI including examples of its application can be found in CCME (2001) which can be found in the Canadian Environmental Quality Guidelines.

Application to Denver's Streams

Denver's WQI is constructed to provide an overview of recreational and aquatic life uses. Each use is further broken down into categories which allow for easy identification of problem pollutants. Table 2 lists the indexes and the parameters used to score the stream. Because the number of parameters included in the direct contact use, and the field and nutrients categories is less than four, the F1 factor will be omitted from the calculation of the WQI.

WQI scores will be used to track improvements or degradation through time.

Pollutants/Parameters

Denver's WQI compares analytical results to State of Colorado water quality standards as described in the Colorado Water Quality Control Commission's Regulations 31 and 38. The index includes all parameters applicable to recreational (direct contact and fish ingestion) and aquatic life uses. To ensure consistency, the criteria will be based on the table value standard listed in the regulations; site specific

standards and temporary modifications will not be used. Criteria used for total nitrogen and total phosphorous are the interim standards described in Regulation 31.

Table 2. Hierarchy of Water Quality Indexes and Categories

Overall Stream Health Index				
Recreation			**Aquatic Life**	
Category / Use	Parameters Evaluated		Category / Use	Parameters Evaluated
Direct Contact	Bacteria (E. coli)		**Field**	pH
	Blue Green Algae / Microcystin (lakes only)			Temperature
Fish Ingestion[2]	Arsenic			Dissolved Oxygen
	Nickel		**Nutrients**	Total Nitrogen (TKN+NO2+NO3)[1]
	Selenium			Total Phosphorous
	Zinc		**Metals**[3]	Arsenic
				Cadmium[3]
				Chromium[3]
				Copper[2]
				Total Recoverable Iron
				Lead[3]
				Manganese[3]
				Total Mercury
				Nickel[3]
				Selenium
				Silver[3]
				Zinc[3]
			Habitat	Habitat

Notes:

1 For the purposes of calculating total nitrogen, 0 will be substituted for any non-detect value.

2 All metals are dissolved species unless indicated otherwise.

3 Standards for these metals are hardness based. Standards will be calculated for each sample using a paired hardness value.

Scores will be calculated on an annual basis using data from DEH's routinely monitored trend sites. Sites without results for all analytes in the index and sites with less than the minimum of four samples will not be included in the calculation. Scores will be calculated for each sampling location for display on a map.

Graphic Representation of Scores

Individual scores will be interpreted graphically for use in reports, social media, and on the Water Quality Program's water quality map. For the purposes of display, scores will be assigned a color with gray indicating no data collected. Gray also indicates a data gap. An example of a graphic representation of scoring is shown in Figure 1.

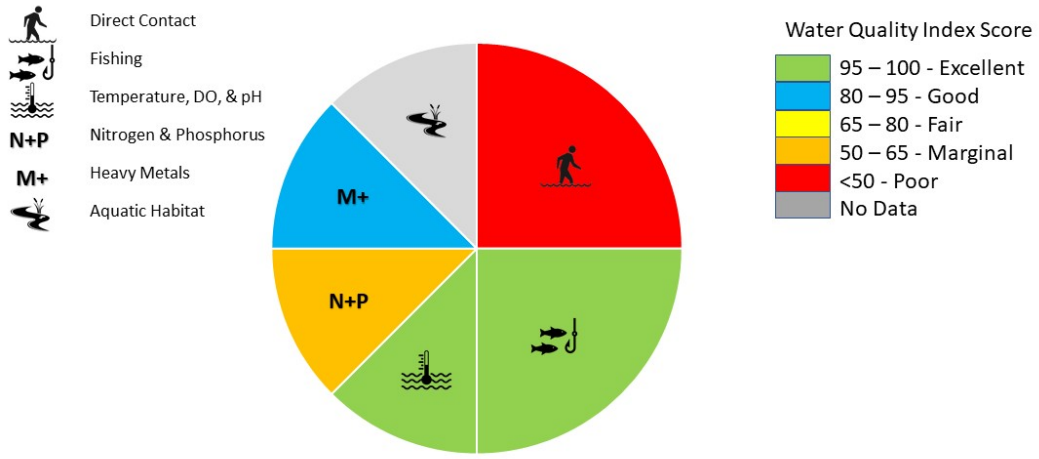

Figure 1. Example of Graphical Interpretation of WQI Scores

Examples

Denver's WQI is intended to be used as a tool for simplifying reporting of water quality data. It is not intended to replace detailed assessment of water quality conditions using traditional water quality assessment methods. The following are examples of how the tool might be used.

Map-Based Representations of Water Quality

When shown on a map, the WQI can provide a simple and easy to understand representation of water quality on a stream. An example is shown in Figure 2.

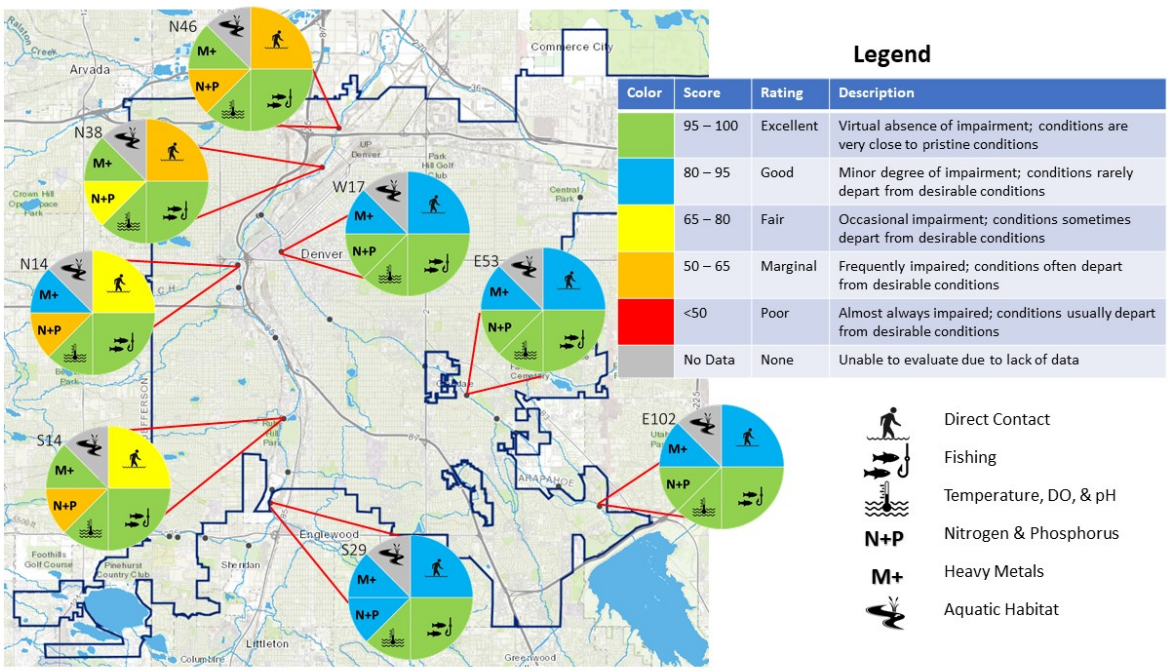

Figure 2. Example of a map showing water quality index scores for sampling locations on the South Platte River and Cherry Creek.

Identification of Problem Areas

When viewed longitudinally in a graph, the WQI can be used to identify problem areas in Denver's streams. This information can be used to trigger additional investigation to identify pollutant sources.

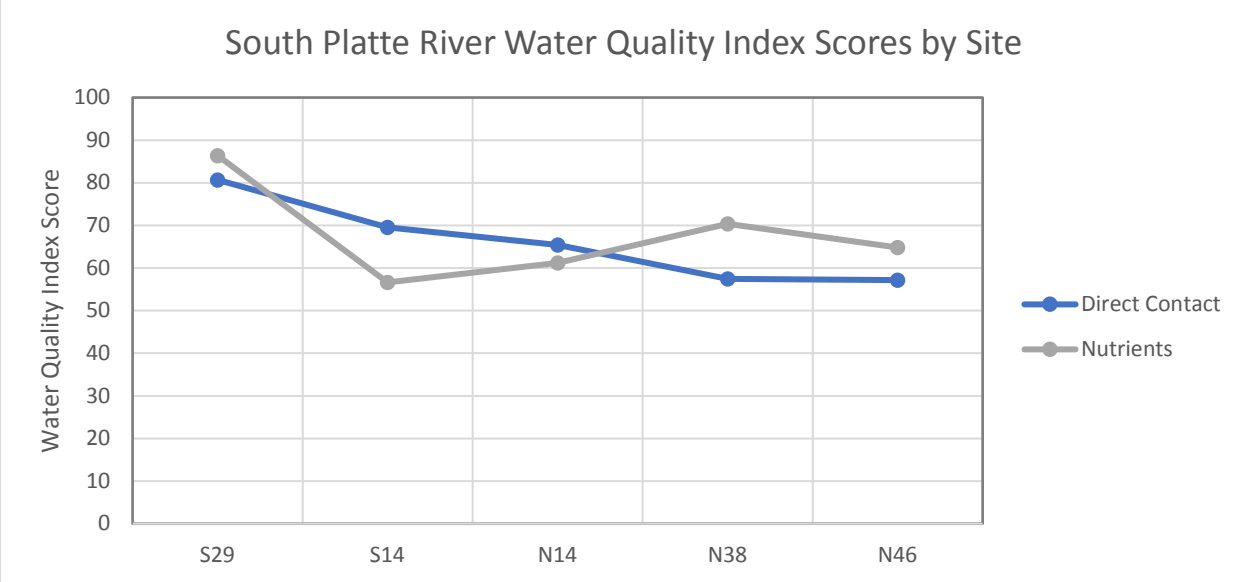

Figure 3. Example of a chart showing nutrient and direct contace water quality index scores in the South Platte River from upstream to downstream sites.

Tracking Water Quality Trends

Scores from the WQI can be used to track trends in water quality graphically and using statistical analyses. Both spatial and temporal trends can be examined. An example is shown in Figure 4.

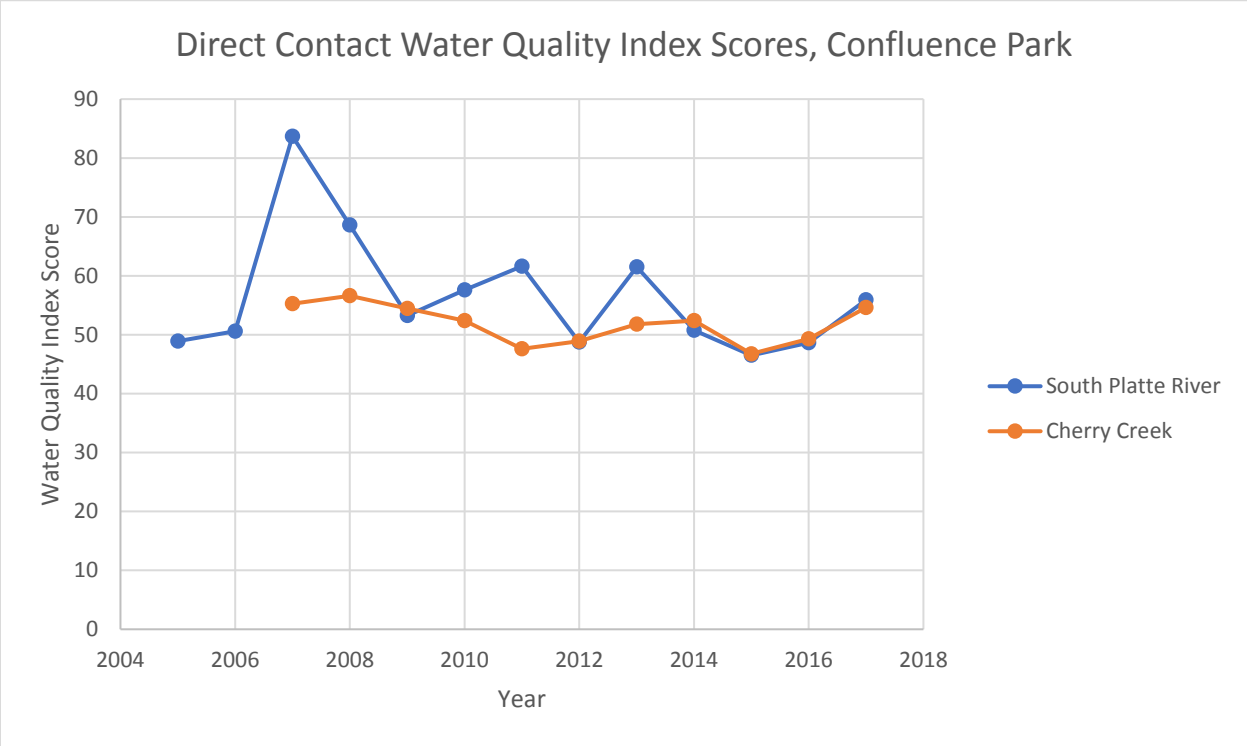

Figure 4. Example of a chart showing changes in annualized water quality scores for direct contact at Confluence Park.

References

Canadian Council of Ministers of the Environment (2001). *Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, Technical Report*. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg. Available at http://ceqg-rcqe.ccme.ca/download/en/137.

Canadian Council of Ministers of the Environment (2001). *Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, User's Manual*. In: Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg. Available at http://ceqg-rcqe.ccme.ca/download/en/138.

Colorado Water Quality Control Commission (2018). Regulation No. 31 - The Basic Standards and Methodologies for Surface Water. 5 CCR 1002-31, Department of Public Health and Environment, Effective January 31, 2018. Available at https://www.colorado.gov/pacific/sites/default/files/31_2018%2801%29.pdf.

Colorado Water Quality Control Commission (2018). Regulation No. 38 - Classifications and Numeric Standards for South Platte River Basin, Laramie River Basin, Republican River Basin, Smoky Hill River

Basin. 5 CCR 1002-38, Department o Public Health and Environment, Effective June 30, 2018. Available at https://colorado.gov/pacific/sites/default/files/38_2018%2806%29.pdf.