Aquatic macroinvertebrate multimetric scores along a dissolved selenium gradient in in the Lower Big Thompson River, Colorado

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Abstract

Elevated dissolved selenium can negatively affect aquatic organisms and communities and can result in portions of waterbodies being designated as "impaired" on the United States Environmental Protection Agency 303(d) list. Dissolved selenium levels in the lower portion of the Big Thompson River, CO are relatively high due in part to the presence of Pierre Shale bedrock although activities related to land use may be increasing selenium levels further. However, the degree to which macroinvertebrate communities are affected in systems such as the Big Thompson River where elevated selenium levels are naturally occurring is unclear. There is a significantly negative linear relationship between an index of macroinvertebrate community structure (Colorado Multi-metric Index) and dissolved selenium levels based on samples at three sites in six different years between 2007 and 2017 in the lower Big Thompson River. This relationship predicts a multi-metric index score of 29.2 under the current dissolved selenium standard of 4.6 ug/L, 38.6 under the suggested lower standard of 3.1 ug/L, and 44 under the average dissolved selenium value in our samples at sites with elevated selenium (2.16 ug/L). Dissolved selenium levels would have to be decreased to near zero to expect macroinvertebrate communities to be similar to the site with little Pierre Shale bedrock although improvements may result with any reduction in dissolved selenium. However, other land uses such as development and agriculture would still likely limit the macroinvertebrate multi-metric scores in the absence of selenium as the intercept of the relationship is 57.9 on a scale of 0-100.

Keywords: macroinvertebrate communities, dissolved selenium, Big Thompson River, multi-metric index

Introduction

Elevated selenium levels in waterbodies can negatively affect aquatic organisms (Hamilton 2004, deBruyn and Chapman 2007). Negative consequences of elevated dissolved selenium levels on aquatic organisms include growth (Ogle and Knight 1988) and reproduction (Gillespie and Baumann 1986, Coyle et al. 1993, Rudolph et al. 2008). In addition, long term chronic or short-term acute exposure to selenium can result in mortality of individual aquatic organisms (Ingersoll et al. 1990) and can result in population level impairments (Van Kirk and Hill 2007).

Concern over the effects of selenium levels on aquatic life resulted in the development of water quality standards for selenium by the United States Environmental Protection Agency (USEPA). Initially in 1980, the USEPA recommended that total recoverable inorganic selenite not exceed 35 ug/L as a 24-hour average to protect aquatic life (USEPA 1980). However, the 1980 standard did not account for the potential for selenium to bioaccumulate and the USEPA revised the recommended chronic exposure standard to 5 ug/L total dissolved selenium in 1987 (U.S. EPA 2016). Science and understanding of the effects of selenium on aquatic life progressed and a review of the available information by the USEPA and a peer consultation workgroup in 1998 resulted in a recommendation that a fish tissue-based standard was more reflective of bioaccumulative effects (USEPA 1998). While the fish tissue-based standard was preferred, the water column standard remained at 5.0 ug/L total dissolved selenium (4-day average) (USEPA 2016). Recently, the USEPA updated this standard again and recommended basing selenium standards on egg/ovary selenium concentrations in fish and in the absence of these data, water column values not to exceed 3.1 ug/L (30-day average) only once every three years in lotic systems (USEPA 2016).

The most recent recommended water column standard of 3.1 ug/L total dissolved selenium is likely to be broadly appropriate to protect aquatic life as it was developed using data from a wide array of waterbodies (USEPA 2016). The effects of selenium on aquatic life depend on the type of organism, species, and the amounts of other constituents in the water column such as sulfate and mercury. Therefore, the level of selenium present in the water column necessary to protect aquatic life will be, to some degree, site specific (USEPA 2016).

Water quality in the Big Thompson River is of central ecological, economic, and social importance. The headwaters of the Big Thompson River begin in Rocky Mountain National Park which had approximately 4.5 million visits in 2017 (USEPA 2018). Numerous communities and agricultural interests rely on water from the Big Thompson River. The Big Thompson River, as a central component of the Colorado-Big Thompson Project, provides drinking water to approximately 925,000 people and irrigation for 640,000 acres of farmland (Billica 2017).

Selenium levels in the lower portion of the Big Thompson River are relatively high (Hydros 2015) and are sporadically above water quality standards adopted by the Colorado Department of Public Health and Environment Water Quality Control Commission (Regulations 31 and 38) and the Clean Water Act Section 303(d) water quality impairments as adopted by the Colorado Water Quality Control Commission and contained in Colorado's 2016 303(d) List (Regulation

93) (WQCCa, WQCCb, WQCCc). The corresponding acute dissolved selenium standard instituted by the Colorado Department of Public Health and Environment, Water Quality Control Commission is currently 4.6 ug/L (WQCC 2018b).

Elevated selenium levels in the Big Thompson River exclusively occur in the lower portion of the river which is characterized by a low gradient and a prevalence of Pierre Shale bedrock (Hart 1974). Pierre Shale contains relatively high concentrations of selenium (Tourtelot 1962) and therefore the lower portion of the Big Thompson River has likely had somewhat elevated concentrations for a long period of time. However, the elevated selenium levels in this portion of the river are likely to be at least partly the result of land use practices and agriculture that have occurred since European settlement (Blann et al. 2009).

Although some have suggested that aquatic organisms may have developed tolerance to elevated selenium levels in areas where environmental selenium levels are naturally high (Kennedy et al 2000), there have been no studies that provide evidence to support this hypothesis (Hamilton 2004). Vital population rates (i.e. growth, reproduction, and mortality) are affected by many metals including selenium. The degrees to which these rates and different species are affected can vary (Swift 2002, deBruyn and Chapman 2007). However, some populations persist despite the presence of relatively high levels of selenium (Lemly 1985, May et al. 2001). The degree to which current and historically elevated selenium levels in the lower portion of the Big Thompson River have impacted aquatic communities is not clear.

Biological communities, in terms of species diversity and abundance, reflect the suitability of ambient conditions for a particular ecosystem (Karr 1981). Therefore, measurements of these metrics should be correlated with levels of selenium that are high enough to negatively impact aquatic communities. The USEPA and many states (including Colorado) utilize indices of community integrity to make determinations regarding the degree of impairment of waterbodies.

The Colorado Benthic Macroinvertebrate Multi-metric Index (MMI) is a macroinvertebrate community bioassessment tool developed for streams and rivers in Colorado (Jessup and Stribling 2017). The MMI utilizes various macroinvertebrate species and genera and site-specific conditions (slope, summer mean water temperature, elevation, date of sample collection, and ecoregion) to quantify the condition of the macroinvertebrate community at that site. The MMI scores range from 0 to 100 with 0 representing a severely impaired community and 100 representing a community that is expected to exist in minimally impacted or "reference" conditions (Stoddard et al. 2006). The Colorado Department of Public Health and Environment Water Quality Control Commission (WQCC) utilizes these scores to determine the condition of reaches of streams and rivers throughout Colorado as outlined in WQCC Policy 10-1 (WQCC 2017).

The objectives of this project are to 1) determine if a relationship between dissolved selenium and MMI scores exists in the lower Big Thompson River and if so, to quantify it, and 2) if a relationship is found, estimate the dissolved selenium level which would result in community integrity similar to aquatic macroinvertebrate communities which do not experience elevated selenium levels in the Big Thompson River, CO.

Methods

The sites on the Big Thompson which had both selenium and macroinvertebrate data available were all in the lower portion of the Big Thompson River (Figure 1). Macroinvertebrate data have been collected in the Big Thompson River 1980-2014 and several investigations utilizing these data have been completed (e.g. Rice and Bestgen 2014). However, none have specifically focused on the effects of selenium. The uppermost site (A) is located near the City of Loveland, CO drinking water intake and is generally very low in dissolved selenium levels because the bedrock is generally lacking Pierre Shale. Other sites were located in areas of moderate urbanization and contained bedrock of Pierre Shale. Other differences between sites exist as well. For example, site B is located above the City of Loveland wastewater discharge and site C is located below the discharge. While there are clearly other factors that contribute to the aquatic macroinvertebrate community at each site, our goal was not to develop an exhaustive explanatory model but simply to examine the potential role of selenium in determining the composition of the aquatic macroinvertebrate community.

Macroinvertebrate data were collected and enumerated by Rice and Bestgen (2007, 2009, 2010, 2013, 2015, and 2017). Briefly, macroinvertebrate samples were collected from three sites in the lower portion of the Big Thompson River in the fall using a kick net. Samples were taken from a 1 m^2 section of riffle/run habitat at each site. In the laboratory, the entire kick net sample was placed in a gridded pan and distributed. Grids were then randomly selected and all organisms from the selected grid were identified to the lowest possible taxonomic classification. This process continued until 400 organisms were selected and identified.

Multi-metric Index scores were calculated using the methodology outlined by Jessup and Stribling (2017) and incorporated into the Ecological Data Application System (EDAS). The Colorado Department of Public Health and Environment (CDPHE) uses EDAS to calculate MMI scores. CDPHE staff provided a copy of the EDAS system and appropriate predictor values (slope, summer mean water temperature, elevation, date of sample collection, and ecoregion) were determined. The MMI was developed and calibrated using samples of 300 individual macroinvertebrates. A random subsampling procedure incorporated into EDAS reduces samples with more than 360 individuals to 300 individuals. Samples containing between 300 and 360 individuals are not subsampled but were included as is. Big Thompson River samples that included more than 360 individuals were subsampled. MMI scores were generated for each of the sites and years of available data in the Big Thompson River area of interest.

The CPDHE standards state that MMI scores of 42 or higher suggest that aquatic life uses of the river segment have been attained, while MMI scores of 29 or lower suggest impairment (WQCC 2017). Scores between 29 and 42 require examination of additional metrics to determine attainment status (WQCC 2017).

One of the assumptions of the analysis is that the aquatic macroinvertebrate community measures are temporally and spatially independent from one another. Complete independence is unlikely. However, the sites and years be were treated as functionally independent. The life span of most aquatic macroinvertebrates ranges between <1 month to >2 years (Huryn and Wallace 2000, Jackson and Fureder 2006) with mussels representing a number of the longer-lived species (e.g. Comfort 1957, Ziuganov et al. 2000). Similarly, the source populations for uncolonized portions of rivers are generally spatially proximal with the first kilometer being most important (Tonkin et al. 2014). Our sites were a minimum of 2.2 km apart. Given the relatively short life span of most aquatic macroinvertebrates and the distance between sites, samples were considered to be roughly independent.

A generalized linear model (GLM) was used to develop a relationship between selenium concentrations and MMI scores. Mean selenium and macroinvertebrate data were available for each site from each of seven years (2006, 2008, 2009, 2011, 2012, 2014, and 2016) (Rice and Bestgen 2007, 2009, 2010, 2013, 2015, and 2017). The number of selenium samples available to calculate mean values in each year and site ranged from 2 to 12 (Table 1). An alpha level of 0.05 was used to determine significance.

Dissolved selenium levels were collected and analyzed by the United States Geological Survey (USGS) using methods outlined by Garbarino et al. (2006). Reporting limits for dissolved selenium ranged from 0.03-0.08 ug/L depending on the year. However, estimates for dissolved selenium concentrations were available for all samples including those below the reporting limit. These values were included in the analysis.

Results

The GLM results suggest that there is a significant relationship between MMI scores and dissolved selenium levels in the lower Big Thompson River as the coefficient associated with MMI score was significantly different from zero (coefficient = -6.249, $p < 0.001$, $t = -5.428$) as was the intercept value (coefficient = 57.944, $p < 0.001$, 26.451) The linear equation estimating the relationship between MMI score and dissolved selenium is:

$$MMI = 57.944 - 6.249\ Se$$

Where MMI is the multi-metric index score and Se is the concentration of dissolved selenium in ug/L. The estimated R^2 value for this relationship is 0.61. The intercept value represents the expected MMI score in the lower Big Thompson River in the absence of selenium.

Selenium levels were relatively high in portions of the Big Thompson River where Pierre Shale was a large component of the bedrock. The mean value of dissolved selenium at sites B and C over the study period was 2.16 ug/L (s.d. = 0.91) while the mean value at site A was 0.07 ug/L (s.d. = 0.01).

The linear relationship suggests that essentially eliminating dissolved selenium from the Big Thompson River would be necessary to obtain macroinvertebrate communities similar to sites upstream where Pierre Shale is absent.   However, expected MMI scores associated with dissolved selenium levels of 4.6 ug/L (the current water quality standard), 3.1 ug/L (the recommended water quality standard), and 2.16 ug/L (the mean value in the lower sites) are 38.6, 29.2, and 44 respectively.

Discussion

The significantly negative relationship between dissolved selenium and MMI scores in the lower Big Thompson River suggests that aquatic macroinvertebrate communities may be negatively affected by elevated dissolved selenium in this section of the river. One of the primary concerns with elevated dissolved selenium levels is the potential for bioaccumulation through the food chain which can negatively affect aquatic animals (Lemly 1996, Van Deveer et al. 1997, Hamilton 2004) although some macroinvertebrate populations can also be affected (Swift 2002, deBruyn and Chapman 2007). Macroinvertebrates communities can also be negatively affected by elevated dissolved selenium levels (Kuchapski and Rasmussen 2015) although dissolved selenium levels may also have no significant effect (Crane et al. 1992, Swift 2002). Different species of macroinvertebrates respond differently to a given level of dissolved selenium (deBruyn and Chapman 2007) and therefore the response of community metrics will depend on the relative importance of species sensitive to selenium in metric calculations.

Results suggest that selenium standards generated using diverse data sources (Jessup and Stribling 2017) are strikingly similar to those that appear to be appropriate for the lower Big Thompson River. Using the standard values and the corresponding MMI values from the linear relationship, it appears that in the Big Thompson River dissolved selenium levels of 4.6 ug/L would result in an expected MMI score of 29.2. This value is very close to the suggested impairment value of < 29. In other words, if the current standard value of 4.6 ug/L is met, the MMI score would be expected to be just higher than a value that would require a designation of "impaired" and additional metrics would need to be examined to determine whether the designation of "attaining" was warranted (WQCC 2017). Similarly, the currently recommended standard of 3.1 ug/L would result in a MMI score of 38.6. This value is just slightly lower than the value of 42, which is the standard for aquatic life use attainment for a river segment (WQCC 2017). Based on the regression relationship in the lower Big Thompson River, the MMI scores would suggest near attainment under the recommended standard and potentially attaining under the current standard but the impaired designation would not be supported under either standard without additional supporting evidence.

The intercept of the linear relationship is an MMI score of is 57.9 which is substantially lower than the theoretical maximum of 100. This departure from a score that would represent reference conditions reflects stressors to macroinvertebrate communities other than selenium. Stressors such as urbanization (Voelz et al. 2005), mining (Griffith et al. 2001), grazing (Griffith et al 2001), and climate change (Moe et al. 2012) affect aquatic macroinvertebrate communities in the Rocky Mountain West and would act to decrease MMI scores from those expected under reference conditions.

Voelz et al. (2005) examined macroinvertebrate data in the lower Big Thompson River at sites very similar to those included in this investigation and suggested that a variety of community metrics were lower in sites further downstream due to increasing urbanization in these locations rather than increased selenium. However, while Voelz et al (2005) did measure some water quality parameters, dissolved selenium was not among them. The longitudinal distribution of dissolved selenium values mirrors urbanization patterns in the Big Thompson River. Since selenium values and measures of urbanization are confounded, it is difficult to separate the influence of each on macroinvertebrate communities in the Big Thompson River and it is entirely possible that urbanization is causative or contributes to changes in macroinvertebrates communities that appear in our analysis. Indeed, without an experimental design that includes manipulation and control of dissolved selenium, causation can only be implied. However, the negative effects of selenium on macroinvertebrates have been documented (Swift 2002, deBruyn and Chapman 2007), results align with assessment standards from the WQCC (2017), and another study in the same area (Front Range of the Rocky Mountains) was unable to find any strong relationships between measures of aquatic macroinvertebrate communities and urban development (Sprague et al. 2006). Therefore, it seems that although selenium levels and degree of urbanization are confounded, the effects of selenium cannot be discounted. In addition, dissolved selenium levels are generally higher in areas with land use activities such as industry and agriculture that disturb the bedrock (Ackerman and Schiff 2003). Therefore, it is possible that increased urbanization may increase the amount of dissolved selenium which in turn results in changes to the macroinvertebrate community.

Elevated dissolved selenium levels in the lower Big Thompson River are associated with decreased MMI scores suggesting that lower levels of dissolved selenium may result in macroinvertebrate communities which are more similar to those found under reference conditions. Effects of urbanization may exacerbate negative conditions caused by elevated dissolved selenium levels. Improvements in MMI scores would likely occur with reduced dissolved selenium levels. Under current conditions and suggested standards for dissolved selenium limits, macroinvertebrate communities in the lower Big Thompson River would appear to be relatively close to levels suggesting “attainment” of aquatic life use.

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Table 1. Mean selenium values, number of selenium samples, and associated multi-metric index scores for each site and year in the lower Big Thompson River.

Year	Site	Mean Selenium	Selenium Samples	Multimetric Index
2006	A	0.06	11	52.0
2006	B	2.42	2	43.4
2006	C	1.40	2	44.4
2008	A	0.06	12	62.9
2008	B	2.14	4	43.4
2008	C	1.41	3	44.9
2009	A	0.07	10	61.8
2009	B	3.40	3	37.3
2009	C	2.83	3	35.8
2011	A	0.07	9	56.9
2011	B	2.59	3	45.6
2011	C	1.78	3	44.9
2012	A	0.07	9	70.7
2012	B	1.17	2	45.2
2012	C	1.27	2	46.8
2014	A	0.09	10	57.6
2014	B	1.54	4	39.2
2014	C	1.67	4	39.2
2016	A	0.07	10	66.4
2016	B	4.34	9	44.1
2016	C	2.28	9	42.3

Figure 1. Macroinvertebrate and dissolved selenium sampling locations in the lower Big Thompson River, CO.

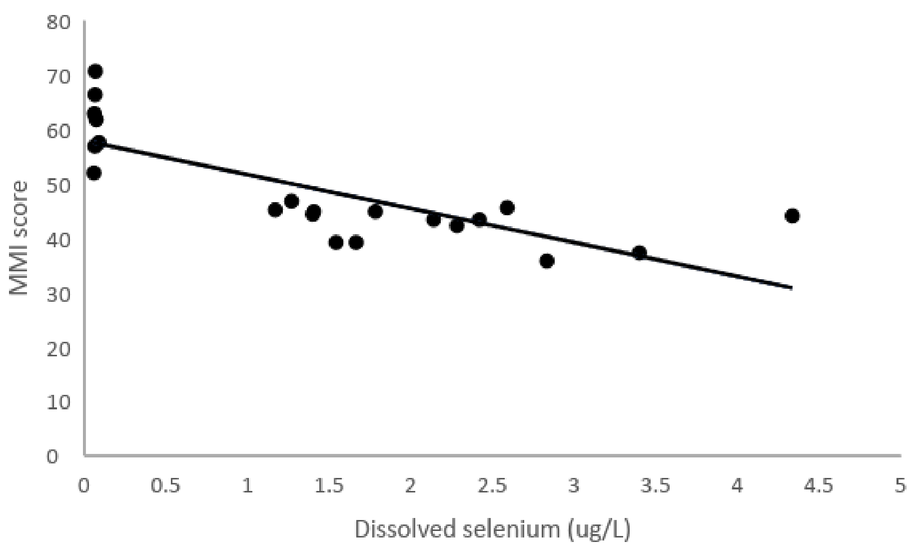

Figure 2. Mean dissolved selenium values at each site and year and corresponding MMI score. Solid line represents the equation MMI =57.944 - 6.249 * dissolved selenium (ug/L).