An Analysis of Daily Patterns of Dissolved Oxygen Change in Flowing Waters of Montana

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Prepared by:
Michael Suplee, PhD
Montana Department of Environmental Quality
Water Quality Standards & Modeling Section
1520 E. Sixth Avenue
P.O. Box 200901
Helena, MT 59620-0901

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Executive Summary

The daily curve of dissolved oxygen (DO) change in flowing waters is recognized as a key indicator of the balance between aquatic community respiration, plant photosynthetic production, and atmospheric diffusion of oxygen. A simple way to characterize the magnitude of the daily DO curve is to subtract the daily minimum DO concentration from the daily maximum. This daily DO change is referred to as DO Δ. When DO Δ is excessive, demonstrable impacts to aquatic life can occur as shown by work in Ohio, Minnesota, and Montana.

The objective of this report was to identify DO Δ thresholds protective of aquatic life in Montana streams and medium-sized rivers. The report has two parts: **Part I** is applicable to low-gradient western Montana streams and medium rivers, while **Part II** pertains to eastern Montana waterbodies. Each part of the report indicates the specific geographic areas to which the work applies. **Part I** comprises **Part I-A**, an initial investigation using extant data that was available in fall 2022, and **Part I-B** which incorporates field data collected in 2023 for the purpose of augmenting and refining the initial analysis.

Part I relies on bottom-dwelling macroinvertebrates to identify a protective DO Δ threshold. Macroinvertebrate metrics (i.e., quantitative population descriptions) provide a way to determine if Montana's narrative nutrient standards at ARM 17.30.637 are achieved: *(1) State surface waters must be free from substances attributable to municipal, industrial, agricultural practices or other discharges that will: (e) create conditions which produce undesirable aquatic life.* Macroinvertebrate metrics give DEQ a direct means of assessing aquatic pollution effects vis-à-vis this water quality standard. For example, the "EPT" Orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) are major components of the aquatic life community and a food source for salmonids in western Montana. A decline in sensitive EPT and a corresponding increase in tolerant taxa (e.g., scuds, Amphipoda) is undesirable, and when linked to a stressor like elevated DO Δ the relationship between the two can be used to identify a DO Δ threshold protective of aquatic life.

Data in **Part I** consistently showed that with increasing DO Δ there is a decline in sensitive macroinvertebrate taxa, including those in the EPT Orders and Families within EPT. There is a corresponding increase in the percent of tolerant taxa—for example the Hydropsychidae. Well established biotic indices (Beck's Biotic Index version 3; Hilsenhoff Biotic Index) responded strongly and in the expected direction to increasing DO Δ and showed that there is a loss of sensitive species and a general decline in water quality as DO Δ goes up. Based on the findings in the **Part I-A** initial investigation and the follow-up analyses in **Part I-B**, DEQ recommends a DO Δ threshold of **3.0 mg/L** which should be protective of aquatic life in low-gradient western Montana streams and medium rivers.

In eastern Montana streams and medium rivers (**Part II**), DEQ assembled findings from a series of studies carried out in the region from 2010 to 2022. A significant relationship between weekly average DO Δ and weekly average DO minimums was shown. This relationship, along with weekly DO minimum standards in **Circular DEQ-7**, was used to identify a DO Δ threshold of **6.0 mg/L** which should be protective of aquatic life in eastern Montana streams and medium rivers. The DO Δ threshold of **6.0 mg/L** will ensure minimum stream DO levels are maintained, and is the same threshold recommended by (and based on a similar relationship used by) the Ohio Environmental Protection Agency. Drought was shown to substantially increase DO Δ independently of other environmental factors, therefore it is recommended that the eastern MT DO Δ threshold only be applied during non-drought periods.

TABLE OF CONTENTS

List of Part I Tables (Part IA has A Suffix, Part IB has B Suffix)

LIST OF PART I FIGURES (PART IA HAS A SUFFIX, PART IB HAS B SUFFIX)

LIST OF PART II TABLES

LIST OF PART II FIGURES

ACRONYMS

ARM	Administrative Rules of Montana
BPJ	Best Professional Judgement
BHWC	Big Hole Watershed Committee
DEQ	Montana Department of Environmental Quality
DO	Dissolved Oxygen
DO Δ	Dissolved oxygen delta (daily maximum minus daily minimum concentration)
EMAP	Environmental Monitoring and Assessment Program (of the EPA)
EPA	United States Environmental Protection Agency
EPT	Macroinvertebrates from the Orders Ephemeroptera, Plecoptera, and Trichoptera
EQuIS	Environmental Quality Information System
HBI	Hilsenhoff Biotic Index
MBMG	Montana Bureau of Mines and Geology
MCA	Montana Code, Annotated
SOP	Standard Operating Procedure
TMDL	Total Maximum Daily Load
USGS	United States Geological Survey
WWTP	Wastewater Treatment Plant

GENERAL INTRODUCTION: DISSOLVED OXYGEN DELTA

The daily curve of dissolved oxygen (DO) change in flowing water (**Figure 1**) has long been recognized as a key indicator of the balance between aquatic community respiration, photosynthetic production, and atmospheric diffusion of oxygen (Odum, 1956). A simple way to characterize the magnitude of the daily DO curve is to subtract the daily minimum DO concentration from the daily maximum. This daily DO change, or DO Δ, can be used as an indicator of overall community productivity and respiration and is more pronounced in lower-gradient streams and rivers where atmospheric reaeration is much reduced. DO Δ integrates all forms of community photosynthesis whether they be from phytoplankton, periphyton (attached algae), macrophytes, or combinations thereof. The same is true for respiration; respiration of DO by plants, algae, bacterial decomposition (in the water and sediment), macroinvertebrates, fish, etc., are all integrated into the daily DO curve.

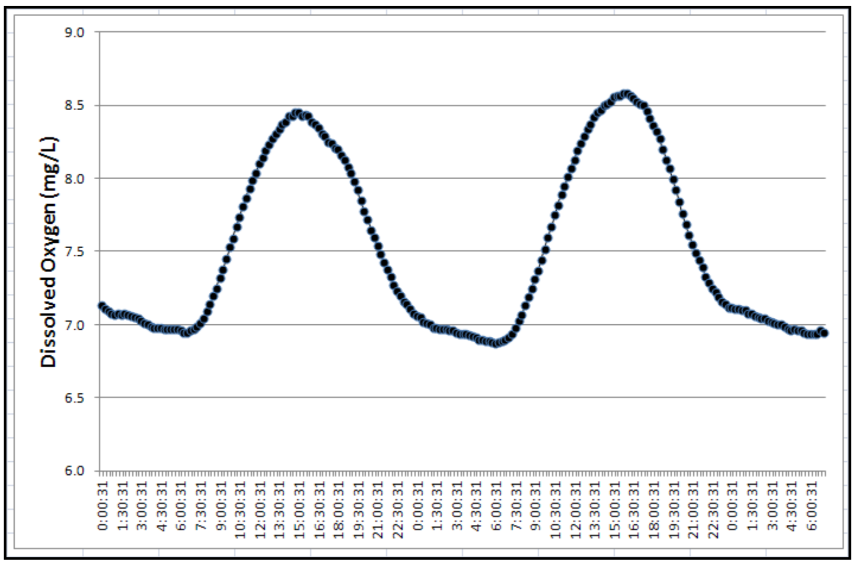

Figure 1. Example of a Daily Curve of DO in a Stream over the Course of Two Days (Time of Day on the Horizontal Axis). In flowing waters, DO is usually at its lowest just before dawn and at its highest in the mid-afternoon.

Work in Minnesota (Heiskary and Bouchard, 2015) shows that when aquatic plant (sestonic or benthic) and microbial growth and biomass are stimulated by excess nutrient (nitrogen and phosphorus) enrichment, stream DO Δ can increase to the point where demonstrable impacts to aquatic life occur (**Figure 2**). These impacts have been shown to affect multiple fish and macroinvertebrate metrics used by Minnesota to evaluate stream health (Heiskary et al., 2013). Work in Ohio links high DO Δ with the co-occurrence of low DO concentrations below their state water quality standard minimum of 4 mg/L (Miltner, 2010). And as found in numerous Ohio-based watershed assessment documents, a primary determinant of the presence of deformities, lesions, and tumors in sampled fish was the frequency of high DO Δs– the higher organisms are stressed by continuous adaptation to changing DO conditions (GLEC, 2021).

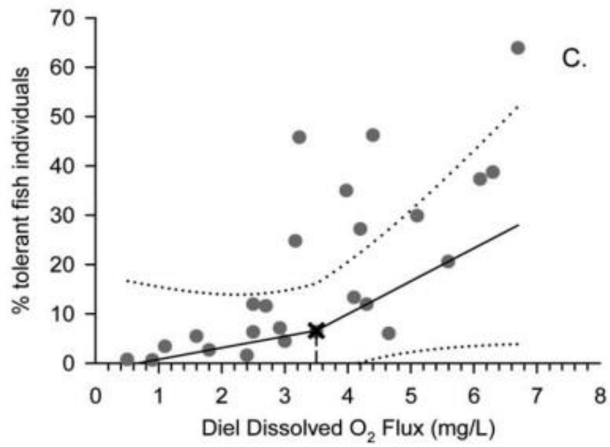

Figure 2. Changes in a Fish Assemblage with DO Δ. As stream DO Δ (or flux, as shown here) increases, more sensitive fish species (e.g., greater redhorse, various shiners) are lost and highly tolerant species (e.g., carp) come to dominate the population. From Figure 3C in Heiskary and Bouchard (2015).

In Montana, Suplee et al. (2019) show that adding low concentrations of inorganic nitrogen and phosphorus to a low-gradient prairie stream led to large increases in benthic algal biomass in summer which, in turn, resulted in large and significant increases in stream DO Δ; when fall arrived, the plants senesced *en masse* and DO concentrations dropped to around 1 mg/L near the stream bottom (**Figure 3**). This work shows that DO problems in streams can occur after peak algal growth has passed and can be delayed until the algae die back later in the year.

Considering the findings from Heiskary et al. (2013), Heiskary and Bouchard (2015), and Suplee et al. (2019) together, a coherent pattern emerges in which elevated nutrient concentrations result in excessive floral biomass that leads to high diel changes in oxygen concentration which can then cause seasonal/episodic crashes in DO; these changes in DO patterns can impact aquatic life. Thus, DO Δ is demonstrated to be a useful indicator of stream eutrophication and, importantly, an indicator of DO problems that may happen in the near future, either episodically or at the onset of a seasonal change. This latter point is important, because Montana's adopted DO standards (DEQ, 2019) might not always be exceeded during a routine, short data collection period (note in **Figure 3** that DO never fell below 5 mg/L—the stream's DO standard—until the very end); in contrast, high DO Δ is indicative of likely future DO problems.

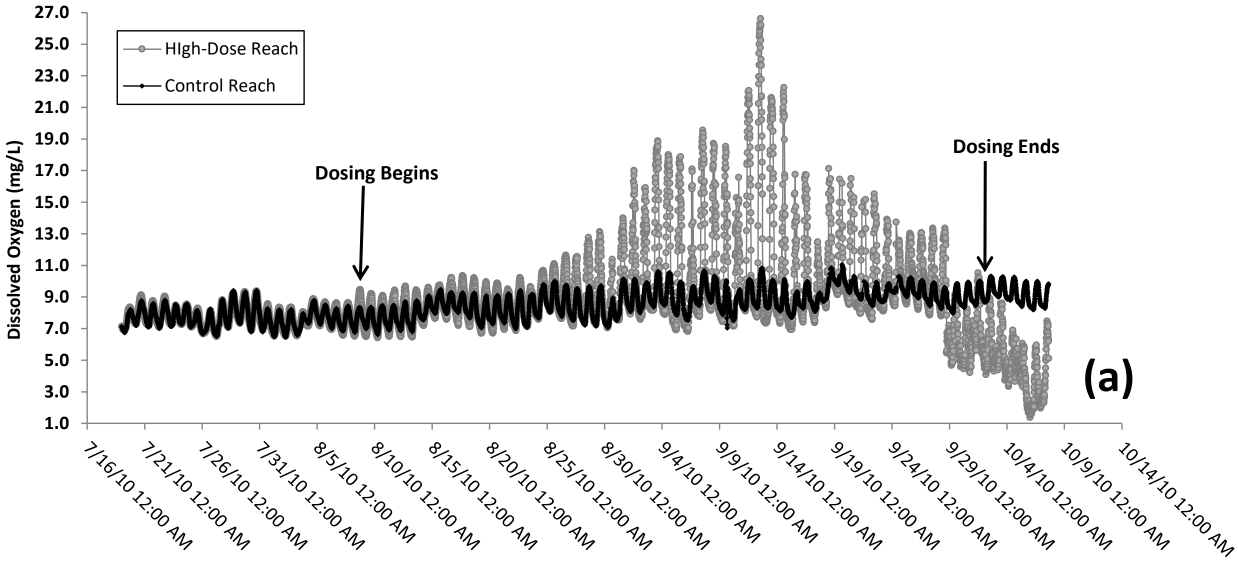

Figure 3. High DO Δ can Indicate Future Low DO Problems. Relative to an upstream control reach where no nutrients were added, an experimental reach (high dose reach) receiving nitrogen and phosphorus additions showed significant increases in DO Δ in summer and then, in fall, DO concentrations crashed (to near 1 mg/L on the bottom) due to senescence of the accumulated benthic algae. The site's DO standard is 5 mg/L. From Figure 6a in Suplee et al. (2019).

DO Δ IN THE WATER QUALITY REGULATORY SETTING

DEQ already uses DO Δ to assess eutrophication status of eastern Montana streams (Suplee and Sada, 2016), most or all of which are low gradient and meandering. DEQ has, since 2010, used a DO Δ threshold of 5.3 mg/L to assess prairie stream eutrophication (Suplee and Sada, 2016). Other states also use DO Δ thresholds for the purpose of assessing stream/river eutrophication impacts caused by excess nitrogen and phosphorus concentrations. Minnesota has adopted regulations for streams and rivers for three regions (north, central, and south) each with different DO Δ criteria (values range from 3.0 to 5.0 mg/L; Minnesota administrative rule 7050.0222(2)). Ohio EPA's proposed stream nutrient assessment procedure uses a DO Δ threshold of 6.5 mg/L. And today, with the availability of small, reasonably priced deployable instruments, acquiring continuous DO datasets—essential for calculating DO Δ—is now much easier.

ORGANIZATION OF THE REST OF THIS DOCUMENT

- **Part I**: Analyses for western Montana pertaining to low-gradient streams and medium rivers.
    - **Part I-A**: An initial investigation to identify a range of candidate DO Δ thresholds protective of aquatic life based on extant data.
    - **Part I-B**: Integration of DEQ's 2023 field data with data from **Part IA** for purposes of improving the analyses, refining conclusions, and recommending a DO Δ threshold protective of aquatic life in western Montana low gradient streams and medium rivers.
- **Part II**: Analyses pertaining to Eastern Montana streams and medium rivers for purposes of recommending a DO Δ threshold protective of aquatic life in those waterbodies.

PART I WESTERN MONTANA

Part I of this document presents work relevant to low gradient streams (stream slope ≤ 1%) in the western part of the state. The overarching purpose of **Part I** is to identify a dissolved oxygen delta (DO Δ) threshold protective of aquatic life in low gradient streams of western Montana. **Part I-A** documents an initial investigation based on extant macroinvertebrate and continuous dissolved oxygen data which were available in 2022. **Part I-B** presents analyses which include data collected during field season 2023 for purposes of augmenting and improving the work undertaken in **Part I-A**. Ecoregions (Woods et al., 2002) comprising the western region discussed in **Part I** of this report are shown in **Table 1**.

Table 1. Ecoregions Comprising the Region Under Investigation in Part I of this Report.

Ecoregions (Whole number prefix: Level III. Number-letter prefix: Level IV)
15. Northern Rockies
16. Idaho Batholith
17. Middle Rockies
41. Canadian Rockies
42l. Sweetgrass Uplands
42n. Milk River Pothole Upland
42q. Rocky Mountain Front Foothill Potholes
42r. Foothill Grassland
43s. Non-calcareous Foothill Grassland
43t. Shield-Smith Valleys
43u. Limy Foothill Grassland
43v. Pryor-Bighorn Foothills
43o. Unglaciated Montana High Plains

Part I-A: An Initial Investigation Using Extant Data to Identify a Dissolved Oxygen Delta Threshold Protective of Aquatic Life in Low-gradient Western Montana Streams and Medium Rivers

1.0 Problem Definition and Project Background

Changes in Montana law[1] necessitated the development of a structured translation process to interpret the state's narrative water quality standards applicable to total nitrogen and phosphorus concentrations (ARM 17.30. 637(1)(e)). DEQ proposed that this translation process include, among other parameters, the daily change in dissolved oxygen, or DO Δ. Although DEQ had been using DO Δ in eastern Montana for over ten years, the need for the translation process to function statewide required the identification of a DO Δ threshold specific to lower-gradient waterbodies in western Montana.

Work to identify a DO Δ threshold protective of aquatic life for low-gradient western MT streams began in earnest in fall 2022. At that time, the only way to proceed with the analysis was to leverage extant DO and macroinvertebrate data that had been collected for other purposes. **Part I-A** of this document describes this initial investigation to derive a preliminary DO Δ threshold for western Montana wadeable streams and medium rivers using the extant data. The next part of this document, **Part I-B**, presents analysis of DO Δ and macroinvertebrate data collected in summer and fall 2023; the 2023 work was undertaken to support and further advance the initial investigation described here in **Part I-A**.

2.0 Methods

The investigation in **Part I-A** relied exclusively on extant (found) datasets. Continuous DO datasets, macroinvertebrate samples, and other extant information were all identified and acquired from readily available sources (details on sources below). Use of extant data necessitated the use of careful quality control (QC) procedures to ensure data quality, as well as the implementation of various assumptions necessary to carry the analysis forward. Details on QC methods and assumptions, and analyses undertaken to support them, are provided throughout the document and in appendices.

2.1 Framework for the Investigation

Sample Frame: Low gradient wadeable streams and medium rivers (not large rivers, per Flynn and Suplee, 2010) in the western Montana level III ecoregions Northern Rockies, Middle Rockies, Canadian Rockies and Idaho Batholith, and transitional level IV ecoregions (Suplee and Sada, 2016) along the Rocky Mountain Front that are subcomponents of the Northwestern Glaciated and Great Plains level III ecoregions (**Table 2-1A**).

[1] 75-5-321, MCA

Table 2-1A. Geographic Regions Comprising the Sample Frame for the Investigation

Ecoregion Scale	Ecoregion Name	Ecoregion Number
Level III	Northern Rockies	15
Level III	Idaho Batholith	16
Level III	Middle Rockies	17
Level III	Canadian Rockies	41
Level IV	Sweetgrass Uplands	42l
Level IV	Milk River Pothole Upland	42n
Level IV	Rocky Mountain Front Foothill Potholes	42q
Level IV	Foothill Grassland	42r
Level IV	Unglaciated Montana High Plains	43o
Level IV	Non-calcareous Foothill Grassland	43s
Level IV	Shields-Smith Valleys	43t
Level IV	Limy Foothill Grassland	43u
Level IV	Pryor-Bighorn Foothills	43v

Sampling Unit: An available continuous DO dataset, macroinvertebrate sample, or other relevant data point from a site that was collected within the sample frame during the summer and fall index period as described in DEQ (2012).

2.2 Dissolved Oxygen Datasets from Western Montana Wadeable Stream and Medium Rivers

In late 2022 and early 2023, DEQ obtained all readily locatable continuous DO datasets which had been collected from western Montana wadeable streams and medium rivers. Sources included DEQ, the Montana Bureau of Mines and Geology (MBMG), the United States Geological Survey (USGS), environmental consulting firms, local Water Quality Districts, a doctoral dissertation, and the peer-reviewed scientific literature. DEQ located thirty stream and medium river sites from which continuous DO data had been collected between 2000 and 2022. Data collection time-steps in the continuous datasets were usually 10 or 15 minutes, a few were 30 minutes. If not already completed, each dataset was screened and data were flagged consistent with Wagner et al. (2016). DO delta (daily maximum minus the daily minimum; Δ), daily DO minimum, daily DO maximum, average and median daily water temperature were extracted for each day in each dataset using a DEQ Excel tool. The Excel tool excludes certain flagged data (e.g., those flagged as "R" for reject) and provides, along with the summary results for each daily time step, the percent completeness of each daily time period. DEQ only carried forward daily values where completeness was ≥95% (i.e., <5% of the data were flagged and excluded for any given day). Some sites had multiple years of DO data, some had as little as a single day's DO data, others had more than a month of daily values over a summer/fall period. One site (Clark Fork above Little Blackfoot-Kohrs Bend) had data which extended into November (beyond the summer and fall index period), and for this site these late-season data were retained for analysis because the daily DO patterns continued to maintain the same general patterns and magnitudes they had earlier in the fall.

For purposes of this work, only sites from locations where water surface slope is ≤1% were analyzed further (consistent with the narrative nutrient standards translator in draft **Circular DEQ-15** (DEQ, 2023, and earlier versions). Water surface slopes based on laser field measurements were used when available, while at other sites slope was calculated using a geographic information system. For the latter, DEQ used USGS's StreamStats online tool[2]. Where they could be cross-checked, slopes obtained from the online USGS tool were, on average, within 9% of field-measured slopes (and thus in reasonable agreement). Five sites which had continuous DO datasets were eliminated due to excess stream gradient; a map of the 26 remaining sites used in this analysis is shown in **Figure 2-1A**.

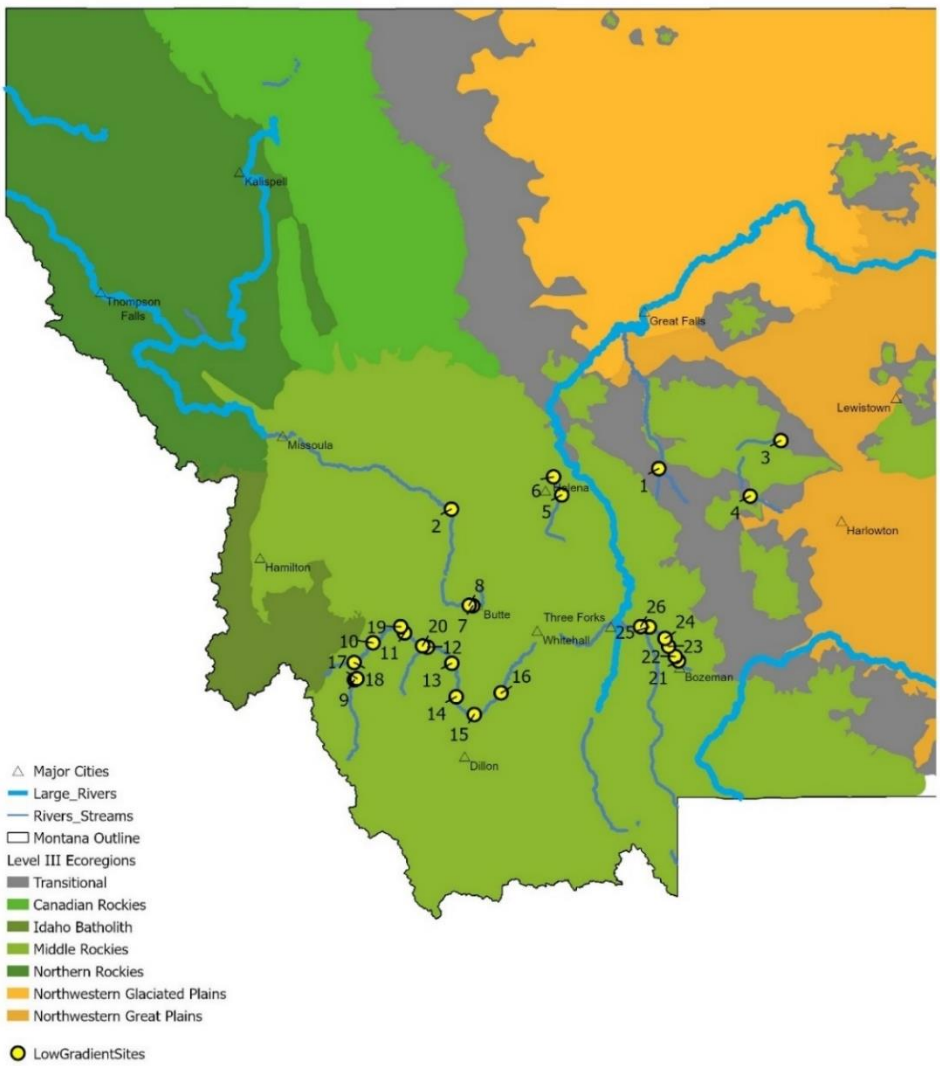

Figure 2-1A. Map of Sites Used in this Analysis. Site numbers correspond to sites listed in Table 2-3A in Section 2.7 below.

[2] https://streamstats.usgs.gov/ss/

2.3 Benthic Macroinvertebrate data

2.3.1 Benthic Macroinvertebrates and Water Quality Standards

Macroinvertebrate metrics are descriptions of specific attributes of the macroinvertebrate community derived from each macroinvertebrate sample. Macroinvertebrate metrics provide a way to determine if Montana's narrative nutrient water quality standards (at ARM 17.30.637) are achieved: *(1) State surface waters must be free from substances attributable to municipal, industrial, agricultural practices or other discharges that will: (e) create conditions which produce undesirable aquatic life.*

Macroinvertebrate metrics give DEQ a direct means of assessing aquatic pollution effects vis-à-vis this water quality standard. For example, the "EPT" Orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) are major components of the aquatic life community and a food source for salmonids in western Montana. A decline in EPT, if linked to water pollution (like elevated total nitrogen and total phosphorus) or indictors thereof (like elevated DO Δ), is undesirable. Shifts in macroinvertebrate communities from sensitive clean water taxa (many of which are EPT taxa) to tolerant taxa such as aquatic sow bugs (Isopoda), scuds (Amphipoda), and adult aquatic beetles (Coleoptera) can be assessed with macroinvertebrate metrics and, again, these changes reflect undesirable changes to aquatic life.

2.3.2 Benthic Macroinvertebrate Data in the Extant Dataset

Benthic macroinvertebrate samples collected from study sites (**Figure 2-1A**) were identified in DEQ's EQuIS database. Macroinvertebrate data were available from 22 of the 26 low-gradient sites where continuous DO data were also collected. Population metrics were computed for each macroinvertebrate sample using BioMonTools in R (Leppo et al., 2021; R Core Team, 2022).

Macroinvertebrate samples found in the EQuIS database were collected using one of several protocols (HESS, traveling kick, Jab, EMAP targeted riffle, and EMAP reachwide) and all protocols were retained for purposes of this analysis;[3] a protocol comparison is provided in **Appendix A**. DEQ has assumed for this initial investigation that sampling protocol plays a minor role in the analytical results and that any effects due to sampling protocol will be random in nature.

2.4 Assessing the Usability of Benthic Macroinvertebrate data Not Co-collected with the DO Data

It was common for sites to have multiple macroinvertebrate samples collected over a number of years. However macroinvertebrate data were often, but not always, co-collected with the extant continuous DO datasets. In order to try to retain and evaluate as many sites with continuous DO data as possible (since continuous DO datasets were relatively scarce), DEQ explored whether macroinvertebrate data not co-collected during the same year as the DO data at a site could reasonably be associated with the

[3] Four protocols (travelling kick, jab, EMAP targeted riffle, and EMAP reachwide) were used to collect macroinvertebrates from a site over two consecutive summers; no clear pattern in terms of an effect on the macroinvertebrate metrics due to protocol could be discerned (**Appendix A**), consistent with findings by others (Jessup et al., 2005). Less is known about comparability to the HESS protocol, however Jessup et al. (2005) show the single HESS-collected sample in their analysis grouped tightly with the site it was collected from along with other samples from that site collected using other protocols (see **Appendix A**).

DO data from that site for purposes of carrying out inferential statistics. DEQ posed the following question:

Is a site's multi-year average macroinvertebrate metric score sufficiently similar to the score obtained during a year when macroinvertebrates and DO were co-collected that the multi-year site average score could reasonably serve as a proxy?

To answer, two approaches were undertaken using eight sites where macroinvertebrate data were collected over a number of years and where macroinvertebrate samples were also co-collected at the same time as a continuous DO dataset.

In the first approach, nine key macroinvertebrate metrics[4] known for their consistent responses to perturbations (Davis and Simon, 1994; Bukantis, 1998; Barbour et al., 1999; Suplee and Sada, 2016; S. Sullivan, aquatic ecologist, personal communication 11/30/2022) were computed as (a) an all-data average metric score for a site and as (b) the score only for the year the DO data were collected. The percent % difference between (a) and (b) was calculated as follows:

$$[\text{ABS}\ (\text{METRIC}\ X_{\text{ALL-DATA AVERAGE}} - \text{METRIC}\ X_{\text{DO YEAR}})] \div [(\text{METRIC}\ X_{\text{ALL-DATA AVERAGE}} + \text{METRIC}\ X_{\text{DO YEAR}}) \div 2]$$

where ABS is the absolute value; the final result is expressed as a percent. This was carried out for each of the nine key metrics and for all eight sites, resulting in 72 individual comparisons.

There was an absolute mean percent difference of 18% between the all-data average and the DO-year metric scores; a box and whisker plot of the 72 comparisons is in **Figure 2-2A**. The interquartile range of the differences was 7 to 25% and there were more cases where the percent difference was lower than the mean than higher than the mean.

[4] Total taxa richness, EPT richness, % EPT, number intolerant taxa, number tolerant taxa, % tolerant taxa, % dominant taxa, % clinger taxa, and the MT Hilsenhoff Biotic Index (HBI).

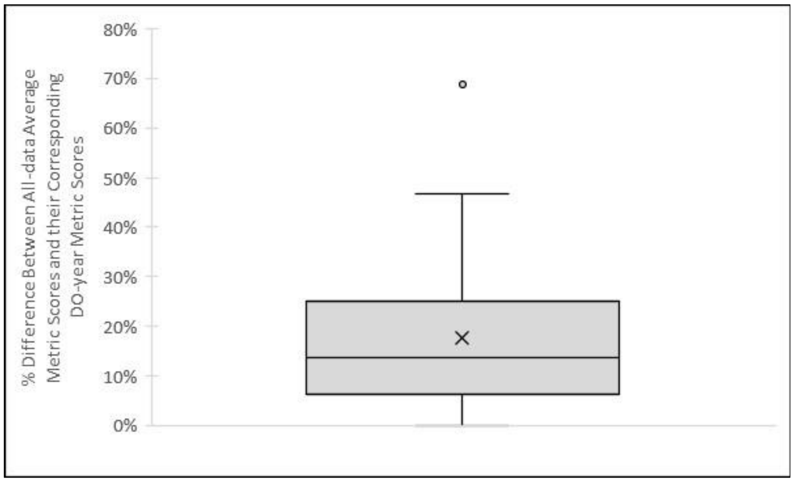

Figure 2-2A. Box and Whisker Plot of the Percent Difference Between the All-data Average Metric Scores and their Corresponding DO-year Metric Scores for Nine Macroinvertebrate Metrics. Horizontal line in the box is the median, the X is the mean.

In the second approach, DEQ again calculated scores for key macroinvertebrate metrics as (a) an all-data average metric score for a site and (b) the score only for the year the DO data were collected. The two scores were then compared to see if a decision made about the health of stream macroinvertebrate populations based on one or the other score would differ substantially. The objective was to see if decision-making would differ strongly between an all-data average vs. a DO-year metric score. DEQ used previously established stream health benchmarks from Bukantis (1998; **Figure 2-3A**) applicable to the intermountain valley and foothills physiographic province[5] to define three decision-making bands; macroinvertebrate scores rated as 3 (i.e., the best macroinvertebrate scores) made up one decision-making band, scores rated from 1-2 comprised the middle band (mid-range), and those rated zero (worst) the third. Bukantis (1998) only reported on five of the nine key metrics under consideration here so the analysis was restricted to them, resulting in (5 metrics X 8 sites) forty individual comparisons.

[5] A geographic region corresponding to the Montana Valley and Foothill Prairies ecoregion of earlier Montana ecoregion maps (Omernik and Gallant, 1987; see also Map 1 and 2 in Bahls et al., 1992); nearly all study sites in the present investigation are located in this geographic region.

SCORE:	3	2	1	0
PLAINS				
Taxa Richness	>24	24-18	18-12	<12
EPT Richness	>8	8-6	5-3	<3
Biotic Index	<5	5-6	6-7	>7
% Dominant Taxon	<30	30-45	45-60	>60
% Collectors (g+ff)	<60	60-80	80-95	>95
% EPT	>50	50-30	30-10	<10
Shannon Diversity	>3.0	3.0-2.4	2.4-1.8	<1.8
% Scrapers + Shredders	>30	30-15	15-3	<3
# Predator Taxa	>5	4-5	3-4	<3
% Multivoltine	<40	40-60	60-80	>80
INTERMOUNTAIN VALLEY AND FOOTHILLS				
Taxa Richness	>28	28-21	21-14	<14
EPT Richness	>14	14-13	12-11	<11
Biotic Index	<4	4-5	5-6	>6
% Dominant	<30	30-40	40-50	>50
% Collectors (g+ff)	<60	60-75	75-90	>90
% Scrapers + Shredders	>30	30-20	20-10	<10
% Hydropsychinae of Trichoptera	<75	75-85	85-95	>95
% EPT	>60	60-45	45-30	<30
MOUNTAIN				
Taxa Richness	>28	28-24	24-19	<19
EPT Richness	>19	19-17	17-15	<15
Biotic Index	<3	3-4	4-5	>5
% Dominant	<25	25-35	35-45	>45
% Collectors (g+ff)	<60	60-70	70-80	>80
% Scrapers + Shredders	>55	55-40	40-25	<25
% EPT	>70	70-55	55-40	<40

Figure 2-3A. Ranges of Macroinvertebrate Metrics from Bukantis (1998) used to Define Decision-making Bands in the Comparative Analysis. Scores (from three, best; to zero, worst) associated with the metric ranges are at the top of the figure. Only the metric ranges from the Intermountain Valley and Foothills (mid-figure) were used to define the decision bands.

For the second approach, the all-data average score and the single-year (DO year) score fell within the same decision-making band in 72.5% of cases. In 27.5% of cases the two scores fell in adjacent bands. In no case did the results fall at opposite ends of the decision bands (best, worst). Thus, most of the time (73%), DEQ's decision about the health of stream macroinvertebrate populations would be the same if it were based on the all-data site average or the single year (DO year) metric score. This result is consistent with Stribling et al. (2008) who show that in Montana duplicate field samples of macroinvertebrates (i.e., those collected the same day at the same site) will agree, in terms of indicating stream impairment or non-impairment, 81.6% of the time, on average.

Appendix B contains all of the case-by-case computations supporting the two approaches just described.

Based on the findings from these two approaches DEQ concluded it was reasonable, where temporally co-collected data were not available, to associate an all-data site average macroinvertebrate score with a continuous DO and temperature dataset at a site where DO and macroinvertebrate data were not collected in the same year. But because co-collected data are preferred, when macroinvertebrate and DO data were collected from a site during the same year only the co-collected macroinvertebrate data will be used even if other years of macroinvertebrate data were available from the site. In this way DEQ is leveraging the most information it can from the extant dataset. DEQ assumed that error introduced by this approach was random in nature and would not skew inferential statistics in any particular direction. For clarity, X-Y scatterplots presented later in Results (**Section 3.0**) will include Y error bars reflecting the average percent difference (18%) between the all-data average and DO-year metric scores identified here, but only for sites where the all-data average macroinvertebrate metric score was used.

Methods used for associating continuous DO and macroinvertebrate data are detailed further in **Section 2.8**.

2.5 Benthic Macroinvertebrate and Continuous DO Data from Low-Gradient Reference Sites

DEQ has eleven western and transitional low-gradient reference sites which meet the ≤1% slope criterion (**Appendix C**). However, only one low-gradient reference stream site (per Suplee et al., 2005)—the Middle Fork Judith River—had extant continuous DO data. Later in the report (**Section 3.0**), this single site will be highlighted in the scatterplots for ease of identification.

2.6 Best Professional Judgement (BPJ) Eutrophication Rating Based Primarily on Floral and Nutrient Concentration Characteristics

Independently from the acquisition and examination of macroinvertebrate data, an assessment—using best professional judgement (BPJ) and based mainly on water chemistry and floral characteristics—was undertaken to assign a eutrophication rating to each site which had continuous DO data; ratings and definitions are in **Table 2-2A.** This approach provided an independent method for assessing eutrophication and its effects on DO Δ and could therefore be used to corroborate or contest the findings based on macroinvertebrates.

As noted, ratings were based mainly on floral characteristics and nutrient concentrations (total nitrogen and total phosphorus) of the waterbodies. For example, a rating of four would be associated with a site showing extensive bottom-attached algal growth (characterized as benthic chlorophyll *a* and ash free dry mass), elevated nutrient concentrations, low DO problems, etc. Ratings reflect, as best possible, the condition of the waterbody at the time the DO data were collected. The rating assessments were completed before the macroinvertebrate metric data were acquired and no ratings were adjusted after the macroinvertebrate data were examined. Generally speaking, sites with ratings of 3 to 4 would be listed as impaired on DEQ's 303(d) list (DEQ, 2021a), but this is only a general statement and exceptions exist.

Table 2-2A. Numeric Ratings Associated with a Gradient of Eutrophication for Low-gradient Western Montana Streams and Medium Rivers

RATINGS	Description
1	No known eutrophication impacts
2	Low eutrophication impacts
3	Medium eutrophication impacts
4	High eutrophication impacts

Information to derive the ratings included assessment records from DEQ's 303(d) list, a doctoral thesis dissertation, peer-reviewed scientific publications, technical reports and data from DEQ, MBMG, and local Watershed Districts, ambient nutrient concentrations in DEQ's EQuIS database, and DEQ staff knowledge. In addition, all of DEQ's eutrophication ratings for sites in the Big Hole River watershed were reviewed by the Big Hole Watershed Committee[6] (personal communication, P. Marques, 2/9/2023). The committee concurred with all of DEQ's scores. Notes on each site's evaluation process and specific citations are in **Appendix D**.

2.7 Final Site List

The final 26 sites used in the analyses, the data available from each site, and the BPJ eutrophication scores are in **Table 2-3A.** Note that macroinvertebrate data were only available for use at 22 of the 26 sites but one of these sites (Big Hole River @ Wisdom Bridge) was not usable due to QC issues with its continuous DO dataset, leaving 21 sites available for DO Δ-macroinvertebrate analysis.

Table 2-3A. Final Sites used in the DO Δ Analyses. See also, Figure 2-1A (map with site numbers).

Number	Site Name	Latitude	Longitude	Water Surface Slope (%)	Continuous DO Data (years)	Macroinvertebrate Data (years)[a]	Eutrophication Rating
1	Camas Creek at mouth	46.70431	-111.19278	0.80	2022	1995 & 2005	2.0
2	Clark Fork River above Little Blackfoot River-Kohrs Bend	46.49687	-112.73715	0.50	2013	Multiple	4.0
3	Judith River Middle Fork near mouth*	46.84650	-110.28600	0.44	2021	2021 & others	1.0
4	Musselshell River North Fork	46.56390	110.51240	0.34	2015	2015 & 2016	2.5
5	Prickly Pear Creek at Kleffner Ranch	46.56931	-111.91540	0.80	2009	None	1.0
6	Prickly Pear Creek at Montana Law Enforcement Acadamy	46.66123	-111.97619	0.04	2009	Multiple	4.0
7	Silver Bow Creek (SBC-2)†	45.99940	-112.57680	0.60	2007, 2008	None	4.0
8	Silver Bow Creek at Rocker-post remediation-old plant (SBC-3)†‡	46.00167	-112.60490	0.60	2007, 2008	2010 to 2016	4.0
9	Big Hole River at Wisdom Bridge	45.61528	-113.45778	0.26	Failed QC	2002	2.5
10	Big Hole River at Mudd Creek Bridge	45.80722	-113.31861	0.22	2000	2002	4.0
11	Big Hole River near Dickie Bridge	45.85972	-113.08361	0.60	2000	Multiple	3.0
12	Big Hole River at Jerry Creek Bridge	45.78472	-112.91389	0.30	2000	2002	2.0
13	Big Hole River at Maiden Rock	45.70139	-112.73444	0.29	2000	2002	2.0
14	Big Hole River at Kalsta Bridge	45.52667	-112.70083	0.50	2000	2002	2.5
15	Big Hole River at Notchbottom	45.43528	-112.56639	0.22	2000	2002	2.5
16	Big Hole River near Twin Bridges	45.54667	-112.36639	0.01	2000	Multiple	2.5
17	Steel Creek	45.62180	-113.43840	0.60	2000	None	2.5
18	North Fork Big Hole River	45.70528	-113.45944	0.14	2000	2003	2.0
19	Deep Creek	45.89080	-113.11330	0.70	2000	None	2.0
20	Wise River	45.79190	-112.95160	1.00	2000	Multiple	1.5
21	East Gallatin Site A	45.71410	-111.04760	0.50	2015	2015 & 2020	2.5
22	East Gallatin Site D	45.73630	-111.07105	0.55	2015	2015 & others	4.0
23	East Gallatin Site G	45.78880	-111.11950	0.54	2015	2015 & others	3.0
24	East Gallatin Site H	45.83059	-111.14617	0.30	2015	2015 & others	4.0
25	East Gallatin Site I	45.88921	-111.26408	0.07	2015	2015 & others	3.5
26	East Gallatin Site J	45.89230	-111.32860	0.15	2015	2015 & 2014	3.5

*DEQ Stream Reference Site (Suplee et al., 2005)
†Site names in parantheses follow the naming convention of Gammons et al. (2011).
‡Remediation was completed at this location in 2003. The wastewater treatment plant was upgraded and operational in 2017.
[a] "Multiple" means ≥ 3 years of samples were available but none of them corresponded to the DO year.

2.8 Spearman Rank Correlation, Scatterplots, and Changepoint Analysis

Average site macroinvertebrate metric scores were joined to their corresponding average daily DO Δ values for 21 sites as follows. When macroinvertebrate data were collected from a site the same year as the DO data, only the average macroinvertebrate metric score from the DO year was joined to the DO data, even if there were other years of macroinvertebrate data available from the site. For sites where

[6] https://bhwc.org/

DO data were not co-collected with the macroinvertebrates, the all-data average site macroinvertebrate score was joined with the corresponding DO Δ data for the site (per **Section 2.4**). This resulted in a flat data table having one average DO Δ value and one average macroinvertebrate metric score for each site, so that each site in the analyses had equal weight. At one site a specific time range was isolated due to known changes in stream conditions resulting from stream remediation work and, later on, a wastewater treatment plant upgrade (see **Table 2-3A,** site number 8, and associated footnote).

Besides the nine key macroinvertebrate metrics discussed already, DEQ had available an additional 208 macroinvertebrate metrics generated via the BioMonTools in R (Leppo et al., 2021; R Core Team, 2022). DEQ analyzed the DO Δ vs. macroinvertebrate metric correlations for all 217 (9+208) metrics using the analytical methods described in the next two paragraphs. The complete list of 217 macroinvertebrate metrics analyzed is in **Appendix E**.

Spearman's rank correlation test (non-parametric; Conover, 1999) was used to identify significant monotonic (linear or non-linear) relationships between DO Δ and the macroinvertebrate metrics as well as DO Δ and the eutrophication ratings. For all 217 available macroinvertebrate metrics, Spearman's rank was run two-sided (more conservatively) with a significance level of <0.01[7]. For any of the 217 metrics which significantly correlated to DO Δ, their scatterplots were further examined to see if the relationship behaved in an ecologically coherent manner (aquatic insect experts were consulted on this)[8]. Locally weighted scatterplot smoothing lines (LOWESS; data not shown) generated in Minitab (v 21) and logarithmic model line fits (Excel) were used for these examinations. All retained, significant relationships were carried forward as candidates for change-point analysis.

A change-point is the point along an environmental or stressor gradient at which there is a high degree of change in a response variable. Change-point analysis divides the data into two groups above and below a threshold, where each of the two groups is internally similar and the difference among the two groups is high. To determine a change-point between site average DO Δ and a site average macroinvertebrate metric, DEQ used mvpart in R (R Core Team, 2022) to run regression tree analysis, setting the tree depth to one (i.e., the root node, which equals the change-point; Qian et al. 2003, King and Richardson 2003). The method always finds a change-point, even in a dataset with a straight-line relationship between X and Y; but because linear relationships represent a gradual continuum of change in Y over X they do not lend themselves well to threshold identification. Therefore, for threshold identification, DEQ only carried out change-point analysis on relationships with a stronger non-linear than linear response[9]. DEQ also eliminated highly redundant metrics (e.g., HBI vs. HBI version 2; HBI version 2 was eliminated) as they do not provide important additional information.

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[7] A Bonferroni adjustment (Cabin and Mitchell, 2000) for 217 tests at significance 0.05 equates to a family-wide adjusted p-value of 0.0002 (note: Bonferroni is considered very conservative). DEQ opted not to institute such a low p value due to the potential for greatly increased type II error (i.e., concluding there are no significant relationships when there truly are). Instead, DEQ opted for a family-wide significance level of <0.01 (i.e., >99% confidence) since each relationship was going to be scrutinized by other criteria (see text).

[8] Running large numbers of correlations can result in some significant correlations occurring purely be chance, especially since DEQ departed from the Bonferroni adjustment. A review of each significant case was undertaken in light of ecological knowledge about the organisms in question in order to screen out possible spurious relationships.

[9] One scatterplot had essentially identical R^2 values for the linear and logarithmic model lines.

DO concentrations are affected by water temperature and DEQ wanted to examine the importance of this co-variable before proceeding. Average site water temperature was calculated by averaging all continuous temperature data co-collected at a site with the DO data using the same data handling methods described earlier for DO Δs. Average site water temperature ranged from 12.2 to 17.8°C, with an interquartile range of 13.7 to 14.8 °C. Temperature effect on DO Δ across these temperature ranges is relatively modest—even at the temperature endpoints of 12.2 and 17.8 °C the effect on DO saturation is only about 1 mg DO/L. Further, average DO Δ did not correlate significantly with average daily water temperature (Spearman's rho, $p > 0.1$). Therefore, water temperature effects were not further considered in this investigation.

3.0 RESULTS

3.1 SPEARMAN RANK CORRELATIONS AND THRESHOLD ANALYSIS

Among the 217 macroinvertebrate metrics examined, 23 significantly correlated with DO Δ. After consultation with a macroinvertebrate ecologist (S. Sullivan, personal communication 2/27/2023) regarding expected or potential behavior of lesser-known metrics to perturbation, examination of the scatterplots to identify those with non-linear relationships, and elimination of highly redundant metrics, DEQ carried seven significant relationships on to change-point analysis.

Table 3-1A shows the seven significant, non-linear relationships and provides the non-parametric inferential statistics and threshold analysis for each. They are ordered by strength of the Spearman's rho coefficient. For these seven relationships, variation in DO Δ explained between 57% and 76% of the variation in the macroinvertebrate metric scores (Spearman's rho, **Table 3-1A**). Change-point analysis on the seven relationships showed DO Δ threshold concentrations ranging from 1.50 to 3.94 mg DO/L, with a mean and median threshold concentration of 3.08 and 3.14 mg DO/L, respectively. Spearman rank correlation statistics for all 217 metrics are found in **Appendix F.**

As expected, the BPJ eutrophication rating (see **Section 2.6**) was significantly and strongly correlated with DO Δ ($p < 0.000$; Spearman's rho =0.827); this was the strongest correlation in the investigation.

Table 3-1A. Macroinvertebrate Metrics and Their Response to DO Δ. Associated inferential statistic values are shown; relationships are ordered by correlation strength (highest to lowest).

Causal Variable	Response Variable - Code	Response Variable - Description	Predicted Response to Increasing purtubation	Spearman Rank Correlation		Change-point Analysis	
				Rho	p-value	DO Δ change-point (mg/L)	Relative Error†
DO Δ	x_Becks3	Beck's Biotic Index v3	decrease	-0.758	<0.000	1.50	0.497
DO Δ	pi_Hydro2EPT	Percent (0-100) individuals - Family Hydropsychidae of Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)	increase	0.737	<0.000	3.63	0.443
DO Δ	pi_tv_intol4	percent (0-100) individuals - tolerance value - intolerant < 4	decrease	-0.634	0.002	2.75	0.536
DO Δ	nt_ffg_pih	number taxa - Functional Feeding Group (FFG) - piercer-herbivore (PH)	probably increase	0.631	0.002	3.94	0.276
DO Δ	pt_Coleo	percent (0-100) taxa - Order Coleoptera	probably increase	0.574	0.007	3.14	0.537
DO Δ	nt_Ephemerellid	number taxa - Family Ephemerellidae	decrease	-0.572	0.007	3.84	0.689
DO Δ	x_HBI	Hilsenhoff Biotic Index (references the TolVal field) using Montana DEQ values	increase	0.571	0.007	2.75	0.619

†Relative error is 1 – R^2 root mean square error. This is the error for predictions of the data that were used to estimate the model.

3.2 X-Y Scatterplots Between DO Δ and Response Variables

Scatterplots of the seven macroinvertebrate metrics which were best explained by non-linear responses to DO Δ are in **Figures 3-1A** through **3-8A**. A logarithmic model was the best fit to these relationships and is shown in each scatterplot. Y error bars are provided for sites where macroinvertebrate data were not co-collected with the continuous DO data (see details in **Section 2.4**). The Middle Fork Judith River reference site (triangle in the scatterplots) exhibited the lowest average DO Δ in the dataset (1.1 mg/L) and its position in the scatterplots was always in the anticipated region of the plots in relation to the DO Δ stressor gradient. Examples of DO Δ-macroinvertebrate metric scatterplots which significantly correlated with but which were *not* carried forward to change-point analysis are in **Appendix G**.

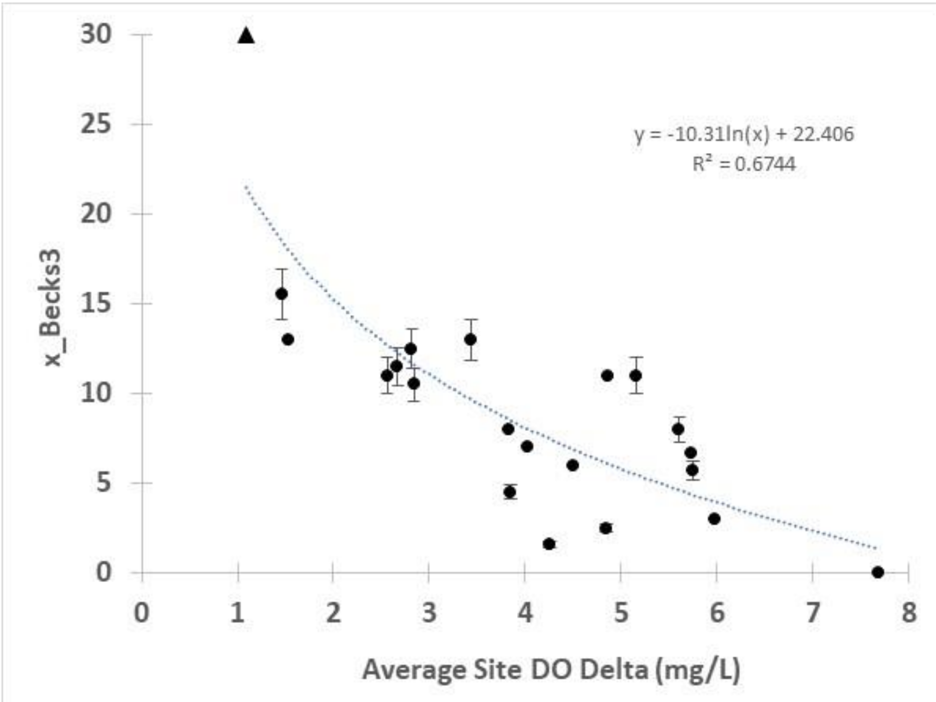

Figure 3-1A. Scatterplot of DO Δ vs. Beck's Biotic Index (version 3). The triangle is the reference site. See text for explanation of error bars.

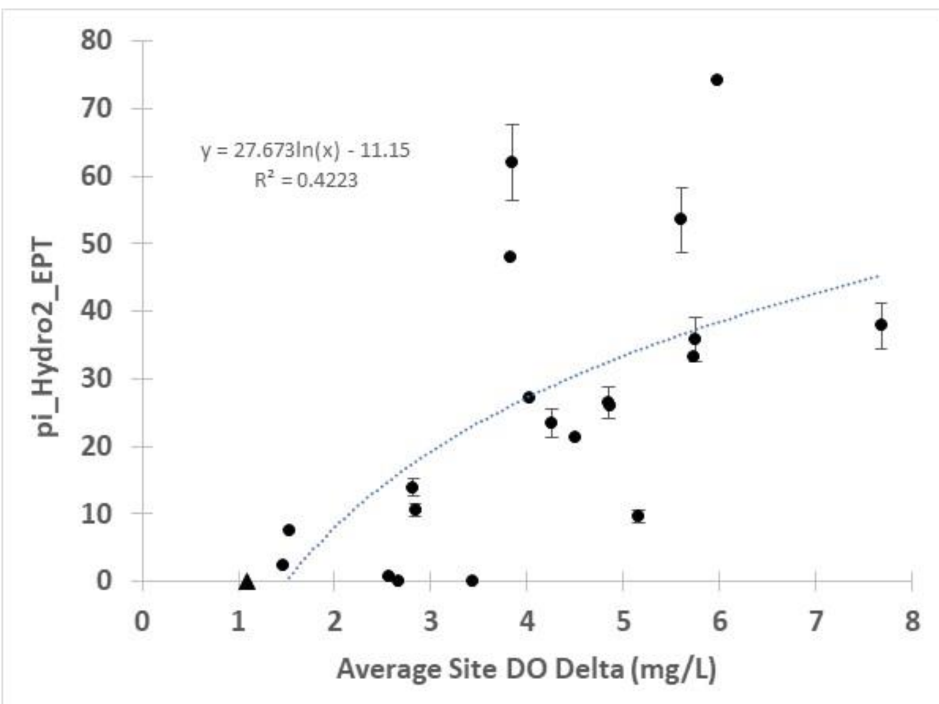

Figure 3-2A. Scatterplot of DO Δ vs. Percent Individuals in the Family Hydropsychidae of the Orders Ephemeroptera, Plecoptera, and Trichoptera. The triangle is the reference site. See text for explanation of error bars.

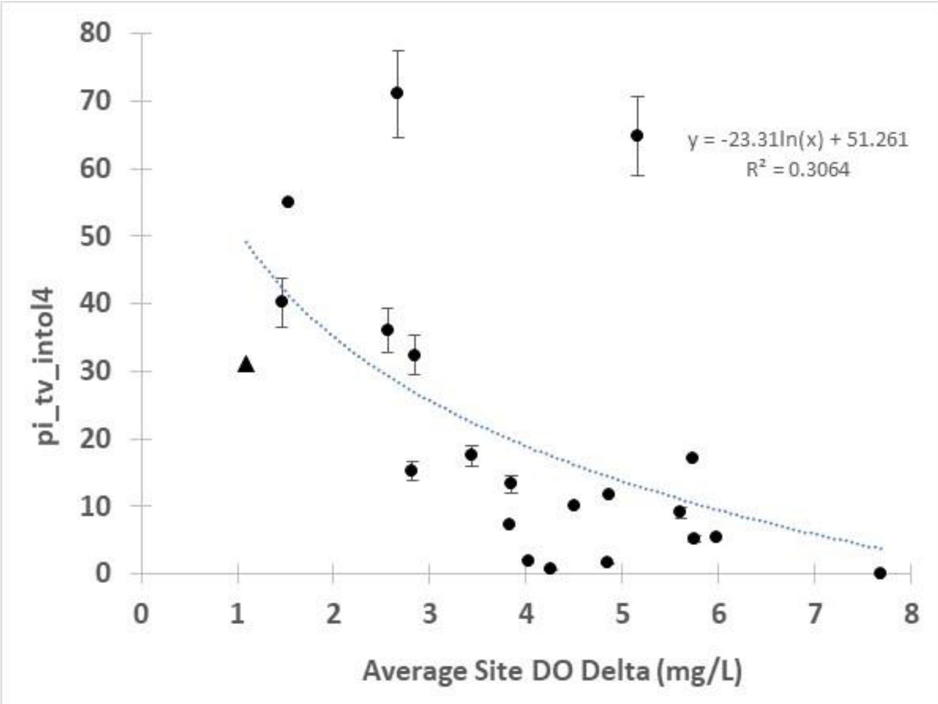

Figure 3-3A. Scatterplot of DO Δ vs. Percent Intolerant Individual (Tolerance Value <4). The triangle is the reference site. See text for explanation of error bars.

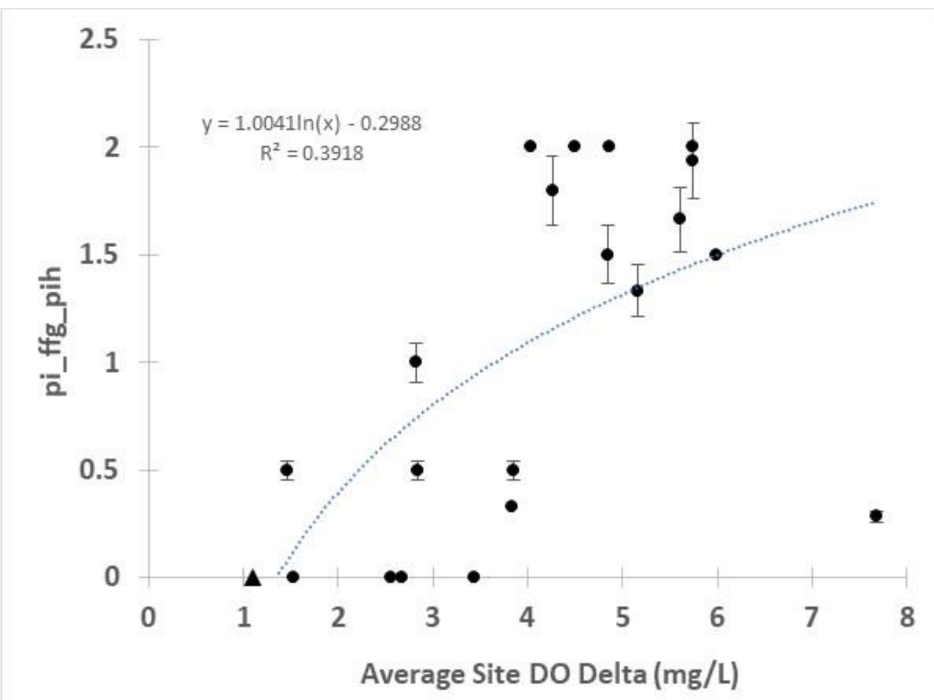

Figure 3-4A. Scatterplot of DO Δ vs. Number of Taxa in the Functional Feeding Group Piercer-Herbivore. The triangle is the reference site. See text for explanation of error bars.

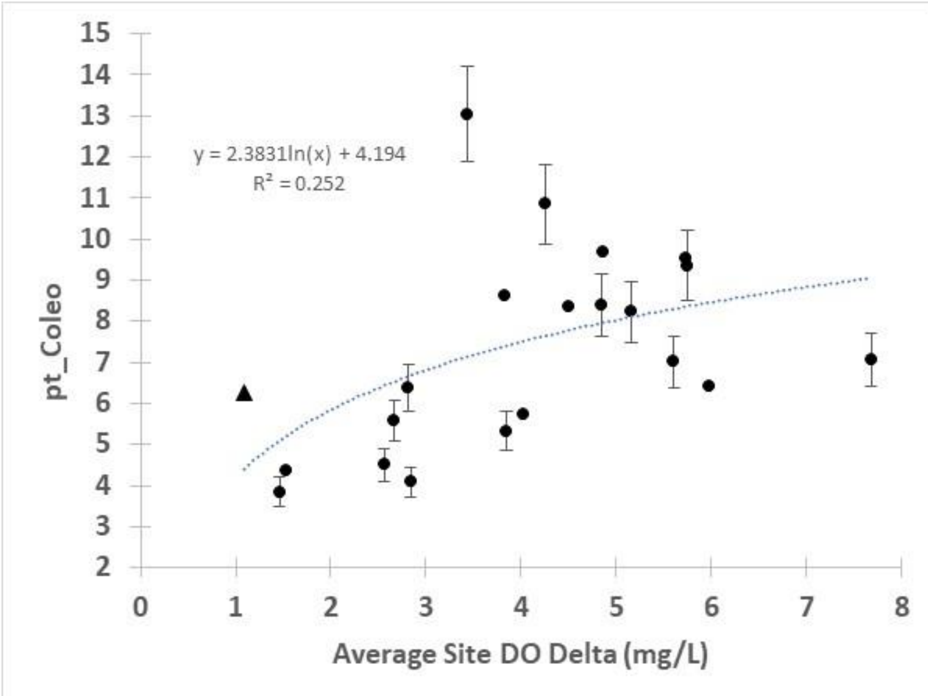

Figure 3-5A. Scatterplot of DO Δ vs. Percent Taxa in the Order Coleoptera (beetles). The triangle is the reference site. See text for explanation of error bars.

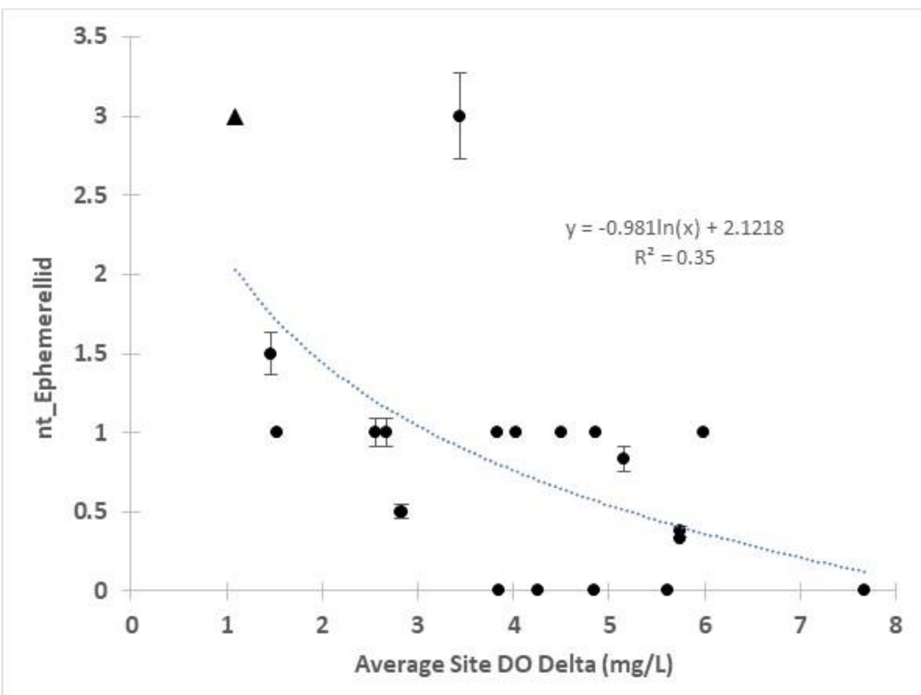

Figure 3-6A. Scatterplot of DO Δ vs. Number of Taxa in the Family Ephemerellidae (spiny crawler mayflies). The triangle is the reference site. See text for explanation of error bars.

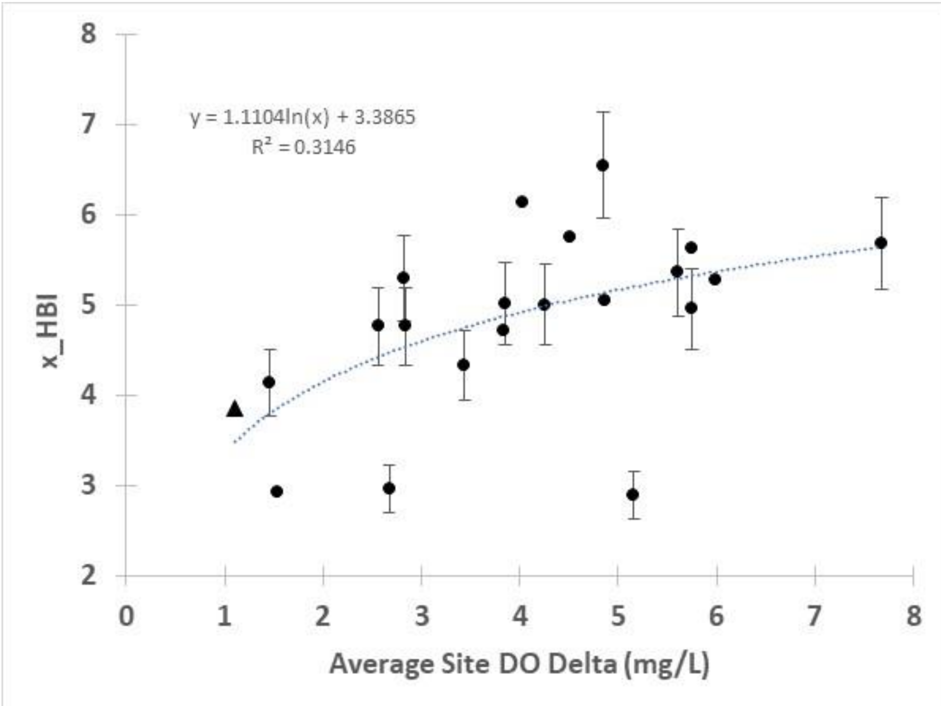

Figure 3-7A. Scatterplot of DO Δ vs. the Hilsenhoff Biotic Index (HBI). The triangle is the reference site. See text for explanation of error bars.

Finally, **Figure 3-8A** shows DO Δ vs. the BPJ eutrophication ratings. It is the only relationship presented in this report that is based on waterbody flora and nutrient concentrations and not exclusively on macroinvertebrate metrics. Its results corroborate the overall patterns manifested between DO Δ and macroinvertebrates.

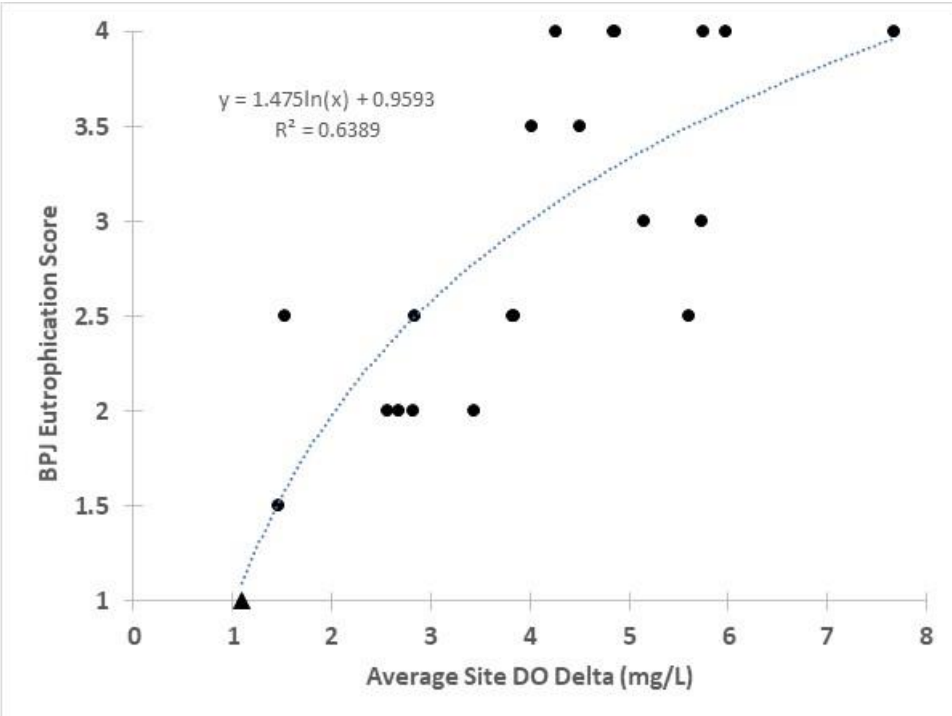

Figure 3-8A. Scatterplot of DO Δ and a Site Eutrophication Rating (1 Least, 4 Most) for the Sites, Based on Best Professional Judgement. The triangle is the reference site.

4.0 Discussion

The data in this initial investigation indicate that with increasing DO Δ there is a general decline in sensitive macroinvertebrate taxa, including those in the EPT Orders and Families within EPT, and a corresponding increase in the percent of tolerant taxa—for example the Hydropsychidae (see Barbour et al., 1999 for details on this group). Biotic indices (Beck's, HBI) responded strongly to increasing DO Δ and show there is a loss of sensitive species and a general decline in water quality as DO Δ goes up.

Work in western Montana low-gradient streams shows that Beck's Biotic Index (v3) is one of the metrics most strongly correlated with nitrogen and phosphorus concentration gradients (Schulte and Craine, 2023). The present work shows Beck's Biotic Index (v3) is strongly, negatively, correlated with DO Δ, whether looked at non-parametrically (Spearman's rho = -0.758; **Table 3-1A**) or parametrically (negative log relationship, R^2 = 0.674; **Figure 3-1A**). DO Δ increases with increasing nutrient concentrations (Suplee et al., 2019) and increasing DO Δ, in turn, strongly effects macroinvertebrate indices like Beck's, as shown here.

The other biotic index is the Hilsenhoff Biotic Index (HBI). HBI has long been used by DEQ to assess western Montana streams and medium rivers (Bahls et al., 1992; Bukantis, 1998; Suplee and Sada, 2016). Like Beck's, it was closely related to DO Δ in this study and, due to its expected behavior under perturbation (its values increase with stress), it is essentially a mirror-image of Beck's (**Figures 3-1A**, **3-7A**). Hilsenhoff (1987) states that transitioning from 4.5 to 5.5 on the HBI scale equates to a change from good water quality (some organic pollution) to fair water quality (fairly significant organic pollution); this nationally applied shift in water quality conditions brackets the identified DO Δ threshold of 2.75 mg/L in the present study (**Table 3-1A; Figure 3-7A**). Bukantis (1998) and McGuire (2004) indicate <4 is the optimal HBI score for intermountain valley and foothill streams, but based on the present analysis this may be to too stringent an expectation given that the reference site had an HBI of 3.85 at a very low DO Δ of 1.1 mg/L. The difference between the earlier work and the current investigation is likely related to more conservative (lower) percentiles of reference used to set the expectation (via the RBP III method (EPA, 1989)) as applied by those earlier authors.

The family Ephemerellidae (spiny crawler mayflies, **Figure 3-6A**) are sensitive to disturbance and their decline with increasing DO Δ is consistent with a decline due to increased DO Δ observed for other sensitive species, such as the intolerant taxa with tolerance values <4 shown in **Figure 3-3A**.

The present study also showed significant, non-linear relationships for macroinvertebrate groups or taxa with less well-documented expectations in terms of response to perturbation (**Figures 3-4A**, **3-5A**). In spite of less being known about these groups, they provided fairly clear patterns in the present study especially when the position of the reference site is considered. The piercer-herbivores (**Figure 3-4A**) are almost certainly responding to the increase in floral biomass which co-occurs with (and causes) increasing DO Δ.

The mean of the DO Δ thresholds for the seven non-linear relationships used in this analysis was 3.1 mg/L. Heiskary and Bouchard (2015) identify similar DO Δ thresholds to protect aquatic life in flowing waters in geographic regions (level III ecoregions Northern Lakes and Forests, North Central Hardwood Forests, and Driftless Area; EPA 2006) which are the closest physiographic analogs to the current investigation. For their ecoregions, Heiskary and Bouchard (2015) recommend DO Δ values from 3.0 to 3.5 mg/L[10].

Overall, the data in this initial investigation—whether considered via parametric or non-parametric statistics—indicate that with increasing DO Δ there is a decline in sensitive macroinvertebrate taxa, including those in the EPT Orders and Families within EPT. There is a corresponding increase in the percent of tolerant taxa—for example the Hydropsychidae. Biotic indices (Beck's, HBI) responded strongly and in the expected direction to increasing DO Δ and show that there is a loss of sensitive species and a general decline in water quality as DO Δ goes up. For low gradient western Montana streams and medium rivers, these changes mean that DO Δ is linked to conditions which produce undesirable aquatic life. Based on this initial investigation using extant data, a DO Δ threshold in the range of 3 to 3.5 mg/L appears to be appropriate for minimizing undesirable changes in aquatic life in low gradient streams of the region.

5.0 Acknowledgements

DEQ would like to acknowledge the assistance of Nick Banish, District Manager with the Gallatin Local Water Quality District, for providing macroinvertebrate and water quality data for the East Gallatin River. DEQ thanks Pedro Marques (Executive Director, Big Hole Watershed Committee) for facilitating his organization's review of DEQ's eutrophication ratings for sites in the Big Hole watershed, and Darrin Kron (DEQ) for his independent review of the same Big Hole sites. Special thanks to Sean Sullivan of Rhithron Associates, Inc. for multiple helpful insights and conversations regarding macroinvertebrate ecology. Thanks to Christy Meredith (DEQ) for assistance with R programming. DEQ very much

[10] These have been adopted into water quality regulations at Minnesota administrative rule 7050.0222(2).

appreciates the time spent by Sean Sullivan (*Rhithron*), Dr. Will Bouchard (Minnesota Pollution Control Agency), Christy Meredith (MT DEQ), and Tina Laidlaw (U.S. EPA) in carrying out peer reviews on an earlier version of this report; their suggestions were very helpful.

PART I-B: AUGMENTING AND ENHANCING THE WORK IN PART 1-A USING 2023 FIELD DATA FOR PURPOSES OF IDENTIFYING A PROTECTIVE DISSOLVED OXYGEN DELTA THRESHOLD

1.0 PROJECT OBJECTIVE, PROBLEM DEFINITION, PROJECT BACKGROUND

The overarching purpose of **Part I** is to identify a dissolved oxygen delta (DO Δ) threshold protective of aquatic life in low gradient streams of western Montana. Here in **Part I-B,** analyses will be presented that incorporate/integrate data collected in field season 2023 with the data from **Part I-A** for purposes of improving the analyses and refining the conclusions. Shortcomings of the **Part I-A** initial investigation were (1) a limited number of continuous DO datasets from low-gradient western MT sites and (2) only a single reference site (per Suplee et al., 2005) having both continuous DO data and macroinvertebrate samples. DEQ set out to correct these issues in 2023 by setting as its goal summer and fall sampling of approximately 20 western MT low-gradient sites, about half of which would be low-gradient reference sites (see list in **Appendix C**). For comparative purposes, two sites were sampled which overlapped with sites analyzed in **Part I-A;** the remaining 2023 sites were new to the project. A sampling and analysis plan (SAP) was finalized in summer 2023 (Suplee, 2023) and is available from DEQ as a separate document.

Part I-A identified a range of candidate thresholds for dissolved oxygen delta (DO Δ) protective of aquatic life. **Part I-B** will present data and analyses supporting a final recommendation for a dissolved oxygen delta (DO Δ) threshold protective of aquatic life for low gradient streams and medium rivers of western Montana.

2.0 METHODS

Table 2-1B and **Figure 2-1B** shows the sites sampled in 2023. Detailed field sampling methodology is provided in Suplee (2023) but in brief:

- Continuous DO meters were deployed at each site starting in early August 2023 and were left *in situ* for a minimum of two weeks, a maximum of 36 days.
- Macroinvertebrate samples were collected per DEQ (2012) upon return to each site to retrieve the DO meters.
- A visual assessment of stream flora was completed per DEQ (2021b).
- Water quality samples for nutrients (total nitrogen, total phosphorus) were collected and field conductivity, temperature, and pH were also measured.

Table 2-1B. Low-gradient Sites Sampled in 2023

Number	Site Name	Site Type	Reference or Non-Reference site	Station ID	Lat (DD)	Long (DD)	Level III Ecoregion	HUC	% Water Surface Slope	Stream Gradient Determination Method
1	Pipe Creek	Stream	Non-reference	K01PIPEC03	48.48895	-115.52419	Northern Rockies	17010101	0.77	USGS StreamStats
2	Deep Creek	Stream	Non-reference	M09DEEPC10	46.33449	-111.17180	Middle Rockies	10030101	0.82	USGS StreamStats
3	Sun River	Medium River	Non-reference	M13SUNR64	47.61764	-112.69146	Northwestern Glaciated Plains (Transitional)	10030104	0.60	USGS StreamStats
4	Beaverhead River	Medium River	Non-reference	M02BVHDR90	45.06626	-112.80031	Middle Rockies	10020002	0.29	USGS StreamStats
5	Red Rock Creek	Stream	Non-reference	M01RDRKC01	44.61604	-111.65712	Middle Rockies	10020001	0.96	USGS StreamStats
6	Little Blackfoot	Medium River	Non-reference	C01LTBLR65	46.43888	-112.46151	Middle Rockies	17010201	0.45	USGS StreamStats
7	West Fork Madison River	Medium River	Non-reference	M05MDWFR05	44.88117	-111.58234	Middle Rockies	10020007	0.71	USGS StreamStats
8	East Fork Bitterroot River	Medium River	Non-reference	C05BITER60	45.89515	-113.82223	Idaho Batholith	17010205	0.79	USGS StreamStats
9	Rock Creek	Stream	Non-reference	C02ROCKC60	46.41035	-113.70605	Middle Rockies	17010202	0.54	USGS StreamStats
10	Monture Creek	Stream	Non-reference	C03MONTC10	47.12479	-113.14748	Middle Rockies	17010203	0.96	USGS StreamStats
11	Prickly Pear Creek	Stream	Non-reference	M09PRPEC01	46.51747	-111.94721	Middle Rockies	10030101	0.66	USGS StreamStats
12	Prickly Pear Creek at Montana Law Enforcement Acadamy*	Stream	Non-reference	M09PREP02	46.66137	-111.97619	Middle Rockies	10030101	0.04	USGS StreamStats
13	Clark Fork River above Little Blackfoot River-Kohrs Bend*	Medium River	Non-reference	C01CKFKR03	46.49829	-112.74309	Middle Rockies	17010201	0.50	USGS StreamStats
14	Belly River	Medium River	Reference	S02BELYR01	48.96806	-113.68263	Canadian Rockies	9040002	0.30	USGS StreamStats
15	Blackfoot River	Medium River	Reference	C03BLACR01	46.89977	-113.75606	Middle Rockies	17010203	0.09	USGS StreamStats
16	Gallatin River	Medium River	Reference	M05GLTNR01	45.05443	-111.15651	Middle Rockies	10020008	0.50	USGS StreamStats
17	Blacktail Deer Creek East Fork in Robb Creek Wildlife Area	Stream	Reference	M02BDEFC01	44.86583	-112.21864	Middle Rockies	10020002	1.00	EMAP
19	Elk Springs Creek	Stream	Reference	M01ELKC01	44.64441	-111.6649	Middle Rockies	10020001	0.08	Laser
19	Middle Fork Judith River*	Medium River	Reference	M22JUDMF01	46.84653	-110.2860	Northwestern Great Plains (Transitional)	10040103	0.44	Laser
20	Sweet Grass Creek	Stream	Reference	Y03SWTGC07	46.15294	-110.18171	Northwestern Great Plains (Transitional)	10070002	0.24	Laser

*A stream or medium river site that provided data and was analyzed in **Part I-A**.

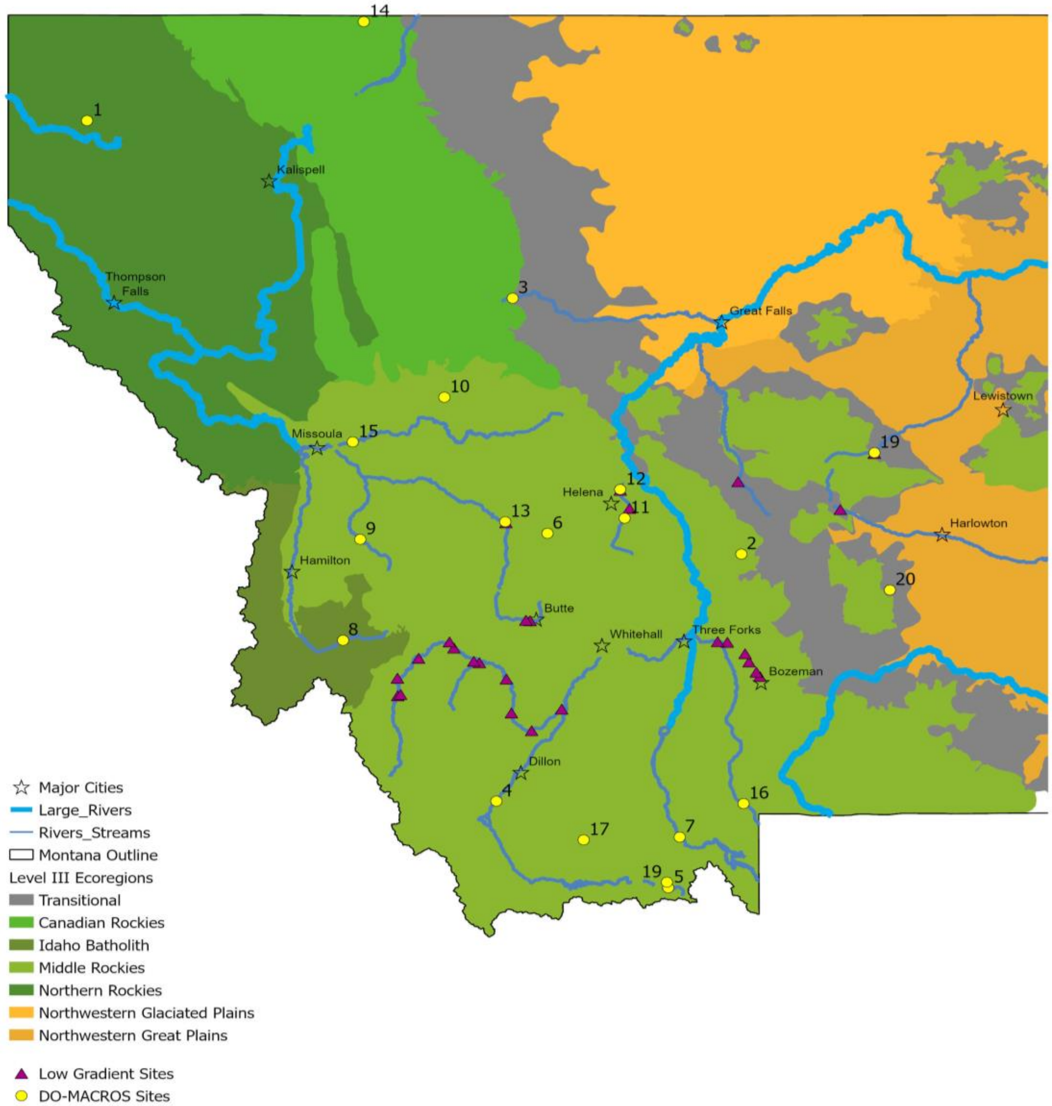

Figure 2-1B. Map of Sites Sampled in 2023. 2023 sites are the yellow circles and the numbers correspond to site numbers in Table 2-1B. Sites which were part of the initial investigation (Part I-A of this report) are shown as purple triangles.

MiniDOT® DO meters (10-minute logging interval) were subject to a pre-deployment calibration check (Suplee, 2023) and then, post-deployment, the continuous DO datasets were QCed and processed per methods in Section 2-2 of **Part 1-A**. The DO meter deployed at the reference site Blacktail Deer Creek East Fork (**Table 2-1B**) failed almost immediately upon deployment and no DO or temperature record could be extracted from it. Macroinvertebrate samples were processed by *Rhithon* Associates consistent with DEQ (2012) and population metrics were computed for each macroinvertebrate sample using BioMonTools in R (Leppo et al., 2021; R Core Team, 2022).

Using the complete daily DO record collected by each instrument (covering early August to mid-September, depending on the site), average site DO Δ and water temperature was computed and then joined with the corresponding macroinvertebrate metric scores to carry out correlation analysis. The

2023 data were then combined with analogous **Part I-A** data to create a "complete dataset." One 2023 site (Elk Springs Creek, a reference site, Table 2-1) was excluded as it is a spring creek. Montana spring creeks are inventoried (Decker-Hesse, 1989), are ecologically distinct from runoff-influenced streams, and are proposed to have different regulatory requirements; they will be addressed in a separate DEQ document. As a result, the complete dataset comprised 39 sites with one DO Δ value and one score for each macroinvertebrate metric per site.

Relationships with Spearman rank correlation p-values ≤0.01 were considered significant, consistent with **Part I-A**. Analysis here in **Part I-B** was focused on significant DO Δ-macroinvertebrate relationships from **Part 1-A** (see Table 3-1, Section 3.0 of **Part I-A**) for which a meaningful[11] Y-axis threshold could be identified. Y-axis thresholds provide a means of identifying a protective DO Δ threshold from the X-axis based on statistically fitted model lines. Using the complete dataset, significant DO Δ-macroinvertebrate scatterplots meeting the Y-axis criterion were plotted with best-fit parametric model lines (e.g., logarithmic) and non-parametric model lines (LOWESS; smoothing factor = 0.5).

Section 2.4 of **Part I-A** explains the rationale for the error bars shown for some sites in the **Part I-A** scatterplots (the error bars are associated with sites where continuous DO and macroinvertebrate data were not temporally co-collected). Analogous error bars will be associated with the same sites here in **Part I-B**. (No error bars are needed for 2023 data—in all cases continuous DO and macroinvertebrates were temporally co-collected.) The 2023 field work provided six more sites with which the error bar uncertainty analysis in Section 2.4 of **Part I-A** could be augmented. The same methods in Section 2.4 of **Part I-A** were carried out on data from the six new sites and the results were compiled with the earlier tabulations. The updated, augmented analysis shows that, on average, there is an absolute mean percent difference of 13% between an all-data average macroinvertebrate score at a site and the DO-year macroinvertebrate metric score. This is a reduction in uncertainty (previously it was found to be 18%), and highlights what DEQ has observed and the scientific literature (Stribling et al., 2008) supports—that macroinvertebrate metric scores at stream sites tend to be stable over time, barring any known changes (e.g., stream restoration or remediation). But to ensure readers who may be concerned with the inclusion of the "error bar" sites (i.e., sites where continuous DO and macroinvertebrate data were not temporally co-collected), key DO Δ-macroinvertebrate relationships will be re-examined and presented after excluding the "error bar" sites. The reduced dataset, as it will be referred to hereafter, comprised 26 sites.

3.0 Results

Per Spearman rank test, average water temperature was not significantly correlated to average DO Δ for the complete dataset nor for the 2023 dataset. Water temperature effects were not further considered in this analysis.

Meaningful Y-axis relationships were identified for two of the seven macroinvertebrate metrics/indices from **Part I-A**. A threshold for Beck's Biotic Index version 3 (Beck's) of 18.68 was derived from a TN-Beck's logistic relationship for low-gradient western Montana streams and medium rivers (Schulte and Craine, 2023). This threshold is considered by DEQ to be protective of aquatic life and is being proposed

[11] Meaningful in this context means a threshold for the macroinvertebrate metric in question that could be identified in the scientific literature or in DEQ technical reports and that is protective of aquatic life beneficial uses.

for adoption in draft **Circular DEQ-15**. A threshold for the Hilsenhoff Biotic Index (HBI) of 5.0 was identified and represents the general transition from good to fair water quality per Hilsenhoff (1987). In the past DEQ has considered an HBI of 4.0-4.5 for low-gradient western streams as appropriate to protect aquatic life (Bukantis, 1998; McGuire, 2004), but four of six (67%) of the low-gradient reference sites in this dataset exceed 4.0 and one reference site exceeds 5.0. Thus, 4.0 is evidently too conservative based on the current data.

Based on the complete dataset, Beck's and HBI were significantly and strongly correlated to DO Δ (Spearman's rho = -0.792, $p < 0.000$, and Spearman's rho = 0.505, P= 0.001, respectively). The biotic indices' scatterplots, including fitted regression lines, are in **Figure 3-1B** and **3-2B**.

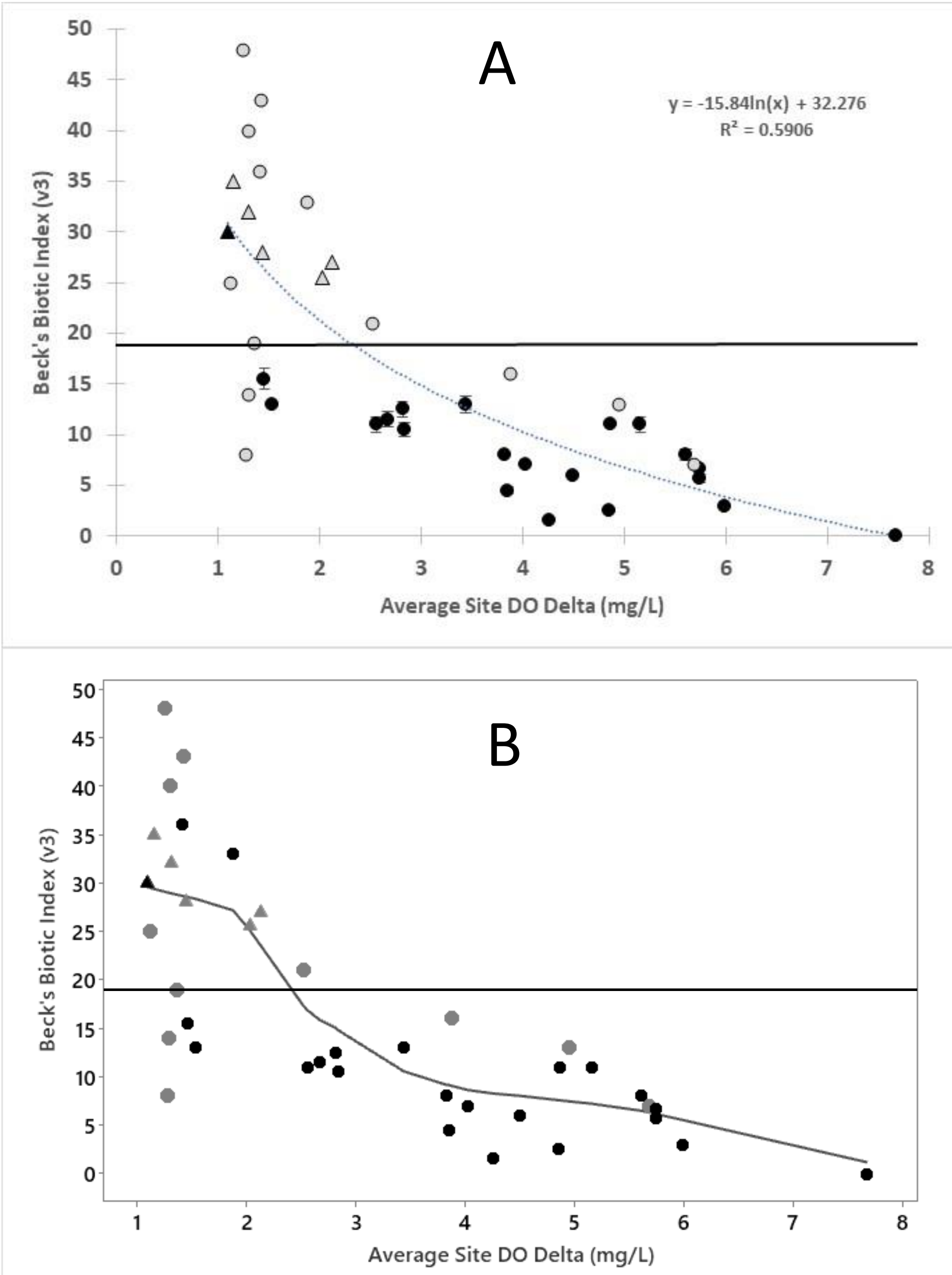

Figure 3-1B. Scatterplots of Beck's Biotic Index (v3) vs. Average Site DO Δ. Black symbols are sites from Part I-A, gray symbols are 2023 field season sites. Triangles are low-gradient reference sites. Horizontal lines are the threshold identified for this biotic index in Schulte and Craine (2023). See text for explanation of error bars. Panel A. Parametric, logarithmic regression line and associated line equation. Panel B. Non-parametric LOWESS line.

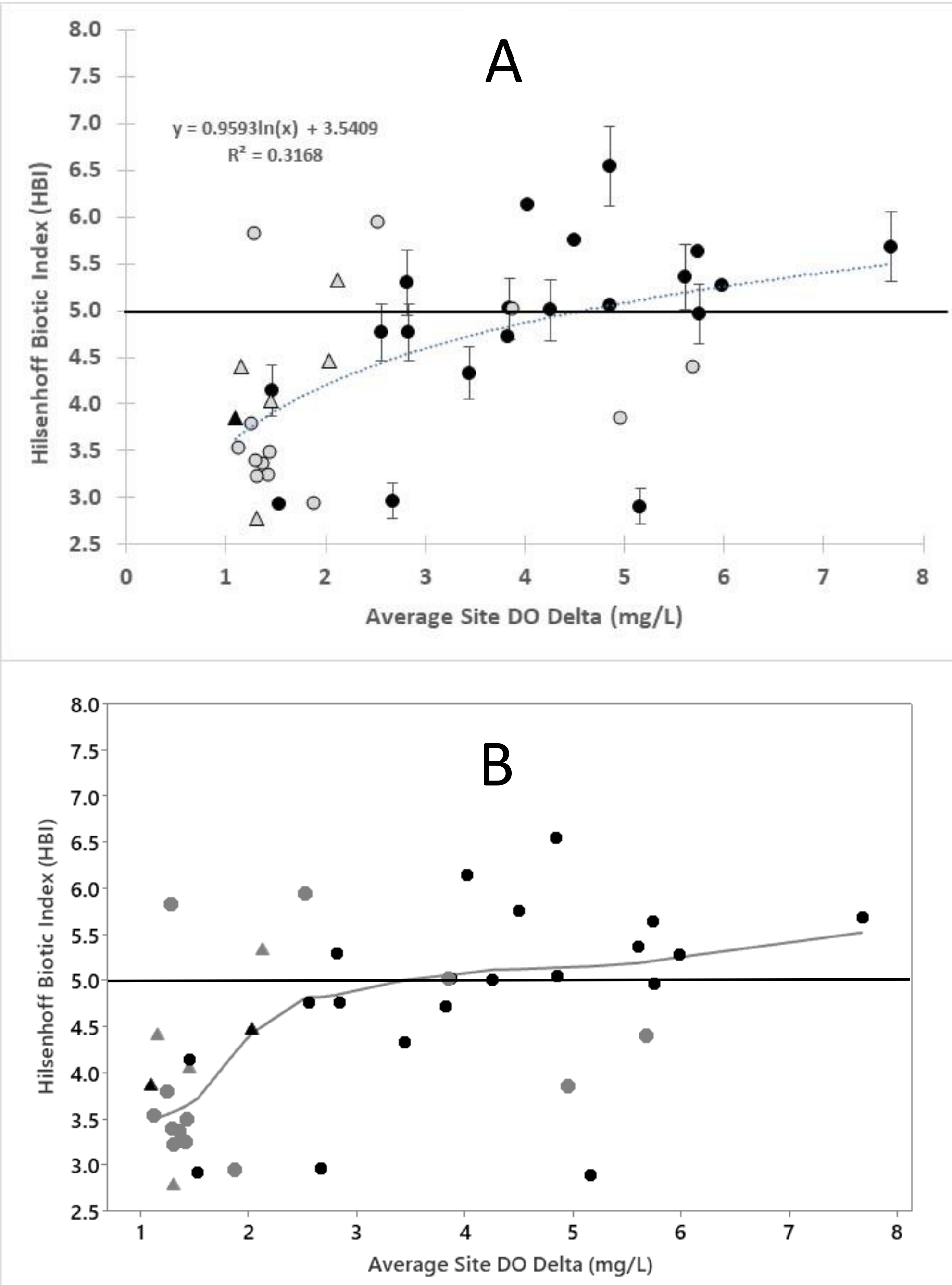

Figure 3-2B. Scatterplots of HBI vs. Average Site DO Δ. Black symbols are sites from Part I-A, gray symbols are 2023 field season sites. Triangles are low-gradient reference sites. Horizontal lines show the threshold identified per Hilsenhoff (1987). See text for explanation of error bars. Panel A. Parametric, logarithmic regression line and associated line equation. Panel B. Non-parametric LOWESS line.

Based on the best-fit logarithmic equation in panel A of **Figure 3-1B**, a Beck's threshold of 18.68 corresponds to a DO Δ value of 2.36 mg DO/L. Similarly, the same scatterplot but based on the LOWESS line (panel B of **Figure 3-1B**) equates to a DO Δ of approximately 2.4 mg DO/L. For HBI, the parametric line equation (panel A **Figure 3-2B**) equals a DO Δ of 4.58 mg DO/L while the LOWESS line in panel B of **Figure 3-2B** equals approximately 3.4 mg DO/L.

The two relationships in **Figures 3-1B** and **3-2B** were then re-examined without the "error bar" sites (i.e., sites where continuous DO and macroinvertebrate data were not temporally co-collected) and these are presented in **Figures 3-3B** and **3-4B**. Based on the reduced dataset (n=26 sites), Beck's and HBI were still significantly and strongly correlated to DO Δ (Spearman's rho = -0.689, p <0.000, and Spearman's rho = 0.506, p = 0.008, respectively). Using the same Y-axis thresholds earlier applied to each relationship, the corresponding DO Δ values are 2.6 mg DO/L (Beck's) and 4.2 mg DO/L (HBI).

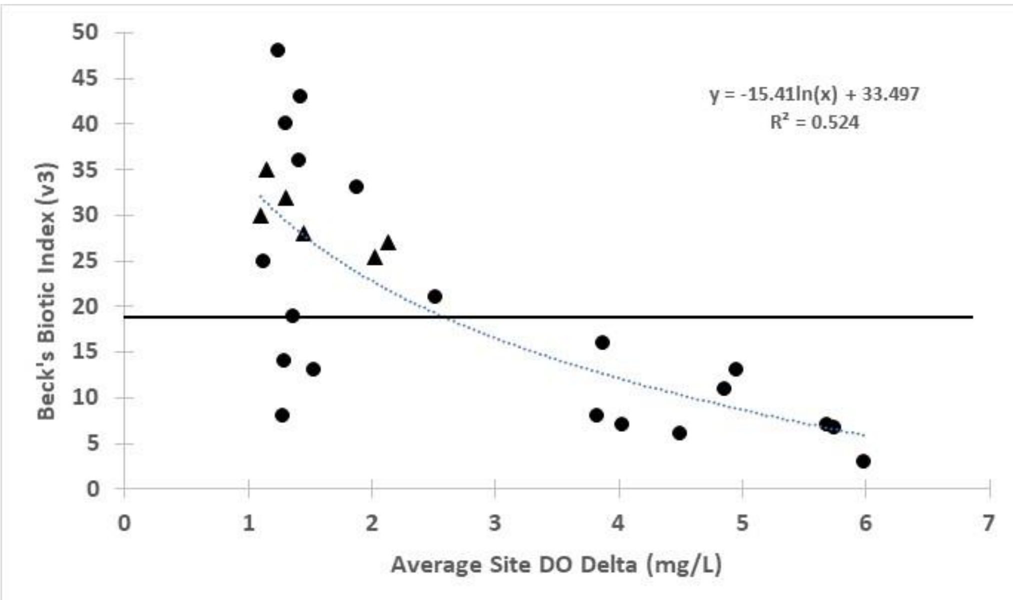

Figure 3-3B. Scatterplot of Beck's Biotic Index (v3) vs. Average Site DO Δ for a Reduced Dataset Comprising 26 Sites (see text for details). Triangles are low-gradient reference sites. The horizontal line is the threshold identified for this biotic index in Schulte and Craine (2023).

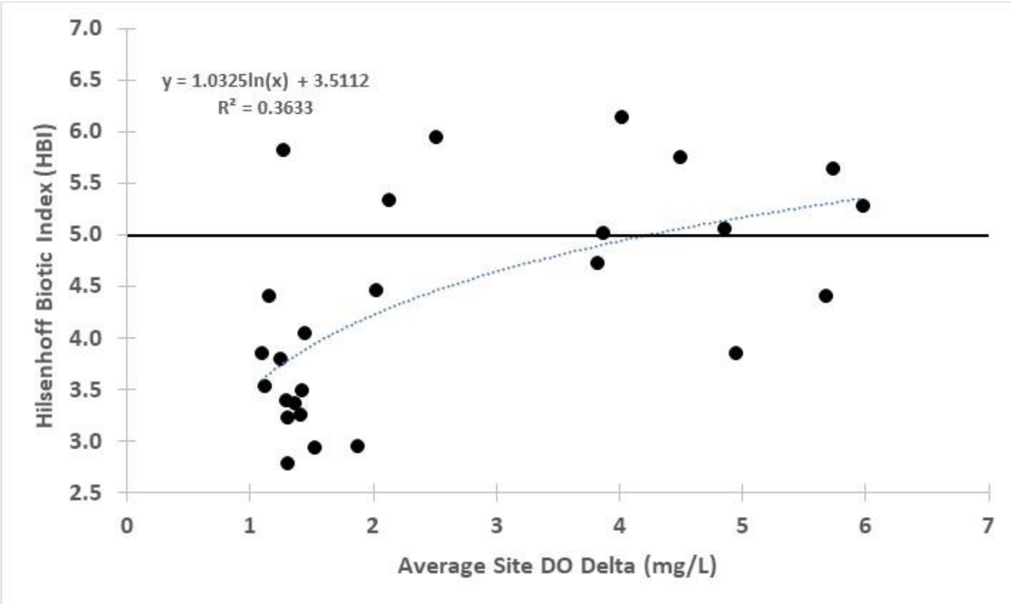

Figure 3-4B. Scatterplot of HBI vs. Average Site DO Δ for a Reduced Dataset Comprising 26 Sites (see text for details). Triangles are low-gradient reference sites. The horizontal line is the threshold identified for this biotic index per Hilsenhoff (1987).

4.0 DISCUSSION

Combining the 2023 dataset with the initial investigation dataset from **Part 1-A** resulted in robust relationships between biotic indices (Beck's, HBI) and DO Δ. These biotic indices were designed by the biologist who made them to respond to organic pollution (Beck, 1955; Hilsenhoff, 1987; Barbour et al., 1999) and their responsiveness here is consistent with this purpose. Hilsenhoff (1987) ties his metric directly to stream water quality, reporting that as HBI values move beyond about 5 there is a shift from some stream organic pollution to fairly significant organic pollution.

After a detailed analysis of the relationship between total nitrogen and total phosphorus concentrations and macroinvertebrate metrics for a 17-year Montana dataset, Schulte and Craine (2023) identified version 3 of Beck's Biotic Index (Beck's) as the representative metric for the low valleys and transitional zone of western Montana. These authors also identified Beck's as the best representative metric for the steeper, mountainous regions of western Montana (although with a different protection threshold than the low valleys and transitional zone). Beck's was found to be strongly correlated with DO Δ in the initial investigation of the present study (**Part 1-A**), and the addition of 19 sites from 2023—five of them reference sites—only further strengthened these findings (**Figures 3-1B**, **3-3B**). Similarly, the well-recognized HBI (Davis and Simon, 1994) correlated well with DO Δ in the initial investigation (**Part IA**), the complete dataset, and the reduced dataset (**Figures 3-2B**, **3-4B**).

By tying the threshold for Beck's (18.68) from Schulte and Craine (2023) and the HBI threshold of 5.0 from Hilsenhoff (1987) back to DO Δ patterns in low gradient western Montana streams and medium rivers, it was possible to identify a protective DO Δ threshold range from 2.36 to 4.58 mg DO/L. The Y-axis threshold method used here in **Part IB** is independent from the change-point analysis method in **Part 1-A**, yet the change-points produced an average DO Δ threshold (3.1 mg DO/L) that falls very centrally in the 2.36 to 4.58 mg DO/L range. In Minnesota, Heiskary and Bouchard (2015) analyzed 14 biological metrics (fish and macroinvertebrates) and, using change point and other methods, identify similar DO Δ thresholds for aquatic life protection. In flowing waters of geographic regions (level III ecoregions Northern Lakes and Forests, North Central Hardwood Forests, and Driftless Area; EPA 2006) which are the closest physiographic analogs to the current investigation, Heiskary and Bouchard (2015) recommend DO Δ values from 3.0 to 3.5 mg/L. Minnesota has adopted these DO Δ thresholds into their administrative rules (MAR 7050.0222(2)) for purposes of protecting aquatic life.

Considering together the work of Hilsenhoff (1987), Heiskary and Bouchard (2015) and Suplee et al. (2019) (discussed in the **General Introduction**), and Schulte and Craine (2023), a coherent ecological pattern emerges. Elevated nutrient concentrations result in excessive floral biomass that leads to high diel changes in oxygen concentration which can then cause nightly or seasonal/episodic crashes in DO; these changes in DO patterns impact aquatic life. A simple conceptual model of this is shown in **Figure 4-1B**. As demonstrated in the present study and by Schulte and Craine (2023), in low-gradient western Montana streams DO Δ correlates more strongly with macroinvertebrates (R^2 = 0.591, Beck's) than with nutrient concentrations (R^2 = 0.26, Beck's); this is because DO Δ is the proximate stressor (as are low DO and food resource changes), whereas excess nitrogen and phosphorus are the ultimate stressors.

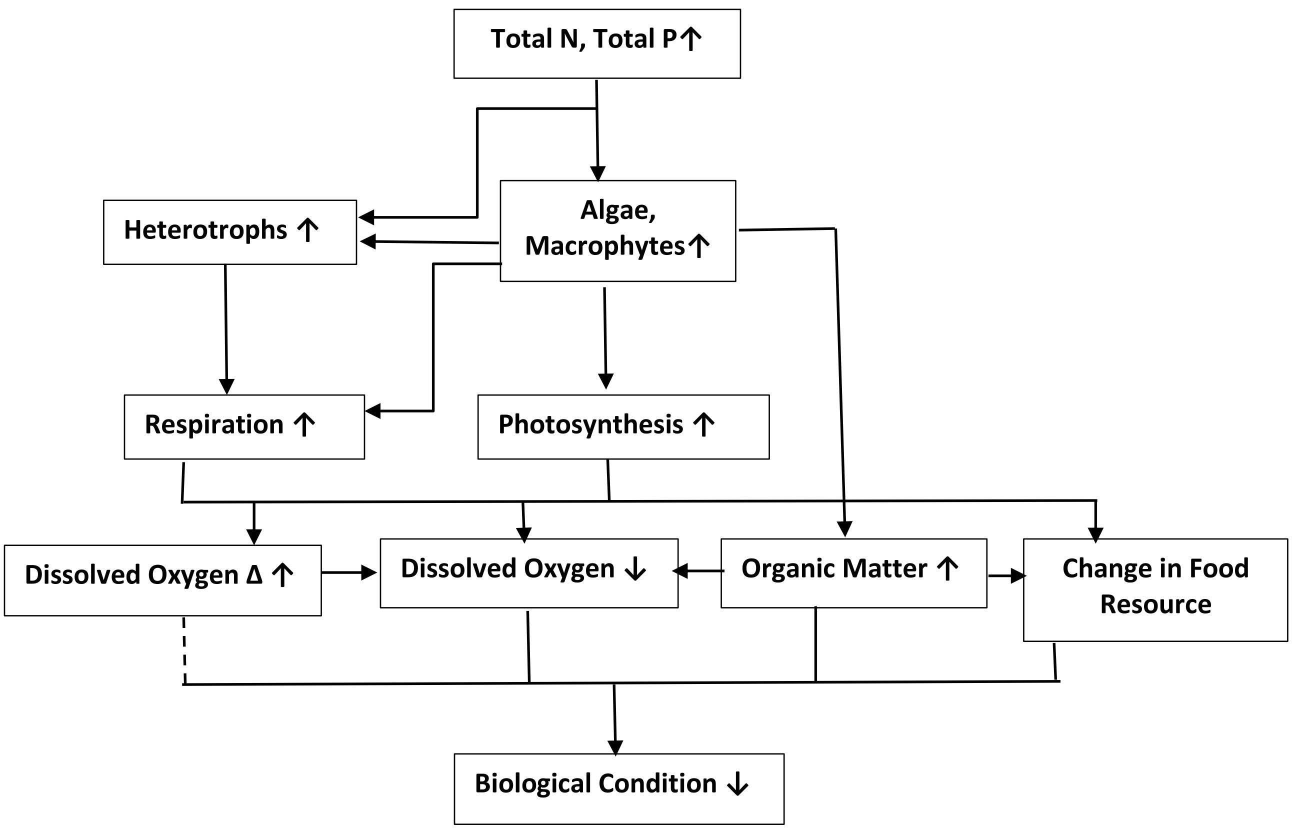

Figure 4-1B. Simplified Conceptual Model of the Impacts of Nutrient Enrichment on Stream and Medium River Biological Condition. Modified from Heiskary and Bouchard (2015).

5.0 CONCLUSION AND RECOMMENDATIONS

It can be concluded from the totality of work presented in **Part I** of this report that excessive DO Δ is linked to undesirable changes in aquatic life in low-gradient western Montana streams and medium rivers. As the objective of the work was to identify a DO Δ threshold protective of aquatic life in low gradient streams and medium rivers of western Montana, **Table 5-1B** provides a summary of candidate DO Δ thresholds for that purpose.

Table 5-1B. Compilation of Identified DO Δ thresholds Protective of Stream Aquatic Life

Source	DO Δ Threshold Derivation Method	DO Δ Range or Value (mg DO/L)
Miltner (2010)	Linkage between high DO Δ and co-occurrence of low DO concentrations falling below Ohio's minimum standard of 4 mg DO/L	<6.0
Heiskary and Bouchard (2015)	Correlation between DO Δ and undesirable changes in Minnesota fish and macroinvertebrate taxa	3.0 to 3.5
Part I-A, Initial Investigation, Present Study	Change-point analysis on seven macroinvertebrate metrics correlated with DO Δ	1.5 to 3.9
Part I-A, Initial Investigation, Present Study	Average of the seven change-point analyses	3.1
Part I-B, Full Dataset, Present Study	DO Δ thresholds identified via statistically modeled line relationships and using Beck's and HBI thresholds from other sources	2.36 to 4.58
Part I-B, Full Dataset, Present Study	Average of DO Δ thresholds identified via statistically modeled line relationships and using Beck's and HBI thresholds from other sources	3.2
Part I-B, Reduced Dataset, Present Study	DO Δ thresholds identified via statistically modeled line relationships and using Beck's and HBI thresholds from other sources	2.6 to 4.2
Part I-B, Reduced Dataset, Present Study	Average of DO Δ thresholds identified via statistically modeled line relationships and using Beck's and HBI thresholds from other sources	3.4

Collectively, the data in **Table 5-1B** suggest a DO Δ value bracketing 3.0 is appropriate. Giving particular consideration to the present work and that of Heiskary and Bouchard (2015), a DO Δ thresholds of **3.0 mg/L** is recommended and should be protective of aquatic life in low-gradient western Montana streams and medium rivers.

6.0 ACKNOWLEDGEMENTS

Thanks to the Rein Anchor Ranch who granted DEQ access permission to carry out stream sampling on ranch property. A big thanks to Rosie Sada, Brady Grigsby, Nate Gong (all from DEQ), and Guy Mitchell (University of Montana) for help in completing sampling during the challenging 2023 field season.

PART II EASTERN MONTANA

Part II of this document presents work pertaining to streams and medium rivers in the eastern part of the state. The overarching purpose of **Part II** is to update a dissolved oxygen delta (DO Δ) threshold protective of aquatic life in the low gradient streams and medium rivers of eastern Montana. DEQ has for many years been using a DO Δ threshold of 5.3 mg/L as part of its plains streams 303(d) list assessments. However, the threshold was developed from a relatively small dataset and much additional work was carried out in the 2010s and 2020s to further refine the DO Δ threshold and to understand the environmental factors influencing it. **Part II** of this report documents the entire body of work leading to DEQ's updated threshold recommendation for eastern Montana streams and medium rivers.

1.0 PROBLEM DEFINITION, BACKGROUND INFORMATION, PROJECT OBJECTIVES

Ecoregions (Woods et al., 2002) comprising the eastern Montana region addressed here in **Part II** of this report are shown in **Table 1-1**.

Table 1-1. Ecoregions Comprising the Region Under Investigation in Part II of this Report

Ecoregions (Whole number prefix: Level III. Number-letter prefix: Level IV)
18. Wyoming Basin
42. Northwestern Glaciated Plains (excluding level IV ecoregions listed below)
42l. Sweetgrass Uplands
42n. Milk River Pothole Upland
42q. Rocky Mountain Front Foothill Potholes
42r. Foothill Grassland
43. Northwestern Great Plains (excluding level IV ecoregions listed below)
43s. Non-calcareous Foothill Grassland
43t. Shield-Smith Valleys
43u. Limy Foothill Grassland
43v. Pryor-Bighorn Foothills
43o. Unglaciated Montana High Plains

As noted in **Part I** of this report, changes in Montana law[12] necessitated the development of a structured translation process to interpret the state's narrative water quality standards applicable to nitrogen and phosphorus concentrations (ARM 17.30. 637(1)(e)). DEQ proposed in draft **Circular DEQ-15** that this translation process include, among other parameters, the response variable DO Δ.

[12] 75-5-321, MCA

From 2009 to 2011 DEQ carried out a whole-stream nutrient addition study in a reference condition prairie stream (Suplee et al., 2016; Suplee et al., 2019). At the time, the eastern region of the state was less well studied than the western region and DEQ wanted to better understand the behavior of the region's waterbodies when subjected to elevated nutrient concentrations. The study showed that low concentrations of inorganic nitrogen and phosphorus added to the stream led to large increases in benthic algal biomass in summer which, in turn, resulted in large and significant increases in stream DO Δ; when fall arrived, the algae senesced *en masse* and DO concentrations dropped to ~1 mg/L along the reach receiving the highest nutrient dose.

Later, following up on the nutrient-addition study, DEQ identified a DO Δ threshold of 5.3 mg/L based on change-point analysis (Qian et al. 2003, King and Richardson 2003) using the continuous DO datasets collected as part of the dosing study plus other continuous DO datasets from nearby plains streams. DEQ assigned a eutrophication rating to each reach or site using methods described in Section 2.6 of **Part I** of this report, and carried out change-point analysis on the relationship which is shown in **Figure 1-1**. As can be seen, once eutrophication intensity rises to medium to high (ratings 3 to 4), there is a sharp rise in DO Δ.

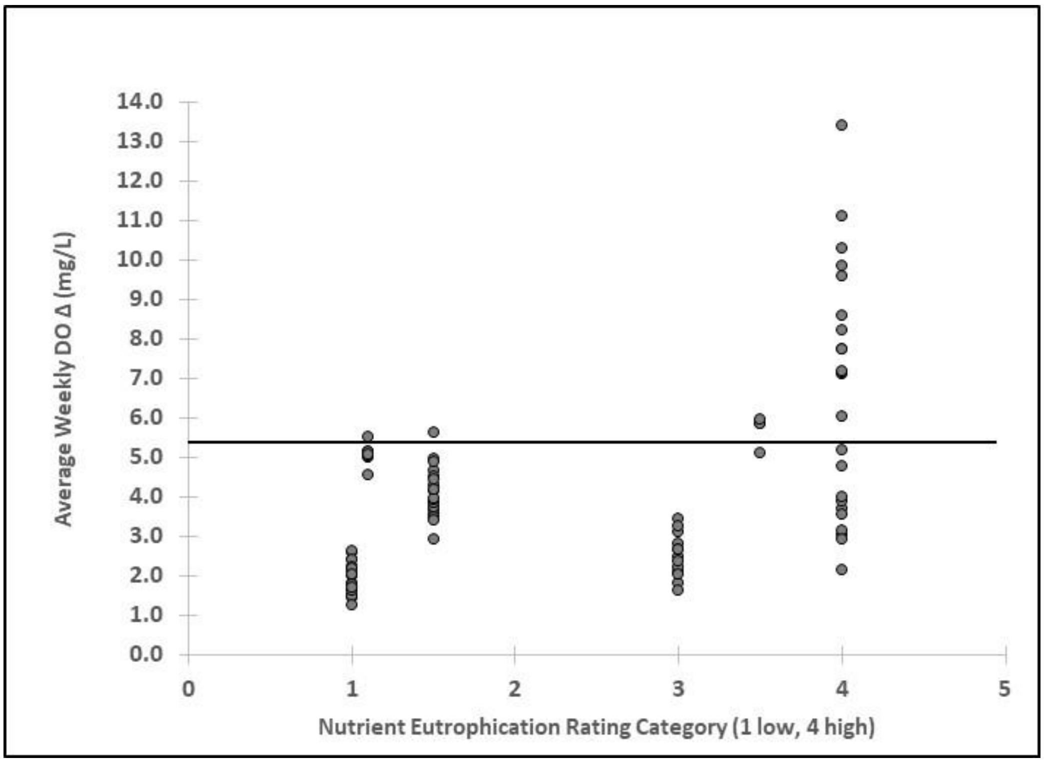

Figure 1-1. Dataset used by DEQ to Undertake Change-point Analysis. A rating of 1 (low eutrophication) was assigned, for example, to the control reach, 3.5 was assigned to the low-dose reach, and 4 to the high-dose reach; see Suplee et al. (2019) for details on each reach. The black horizontal line is the change-point of 5.3 mg/L identified from the relationship.

The 5.3 mg/L DO Δ threshold identified was based to a high degree on the stream (Box Elder Creek) where the controlled nutrient-addition study in Suplee et al. (2019) took place. But DEQ wanted to know more about DO Δ patterns across a wider range of plains streams. Therefore, from 2013 to 2017, DEQ sampled 73 unique plains stream sites, many of which were sampled over multiple years of the five-year study. The complete analytical work carried out on the dataset is documented in GLEC (2021) and germane aspects of the report are detailed here. Finally, in 2021 and 2022, DEQ targeted a number of plains reference sites and collected continuous DO datasets which had not previously been acquired. Collectively, all these studies and data inform the final DO Δ recommendations at the conclusion of **Part II** of this report.

2.0 DO Δ AND ENVIRONMENTAL VARIABLES IN PLAINS STREAMS

GLEC (2021) used Classification and Regression Trees (CART) to explore the relationships of watershed stressors and mitigators to a response. The monitoring dataset—collected between 2013 and 2017—was comprised of continuous DO, water chemistry, and aquatic plant metrics for 73 stations located in eastern Montana extending from the north at tributaries to the Missouri River to the south at the Wyoming state border (**Figure 2-1**).

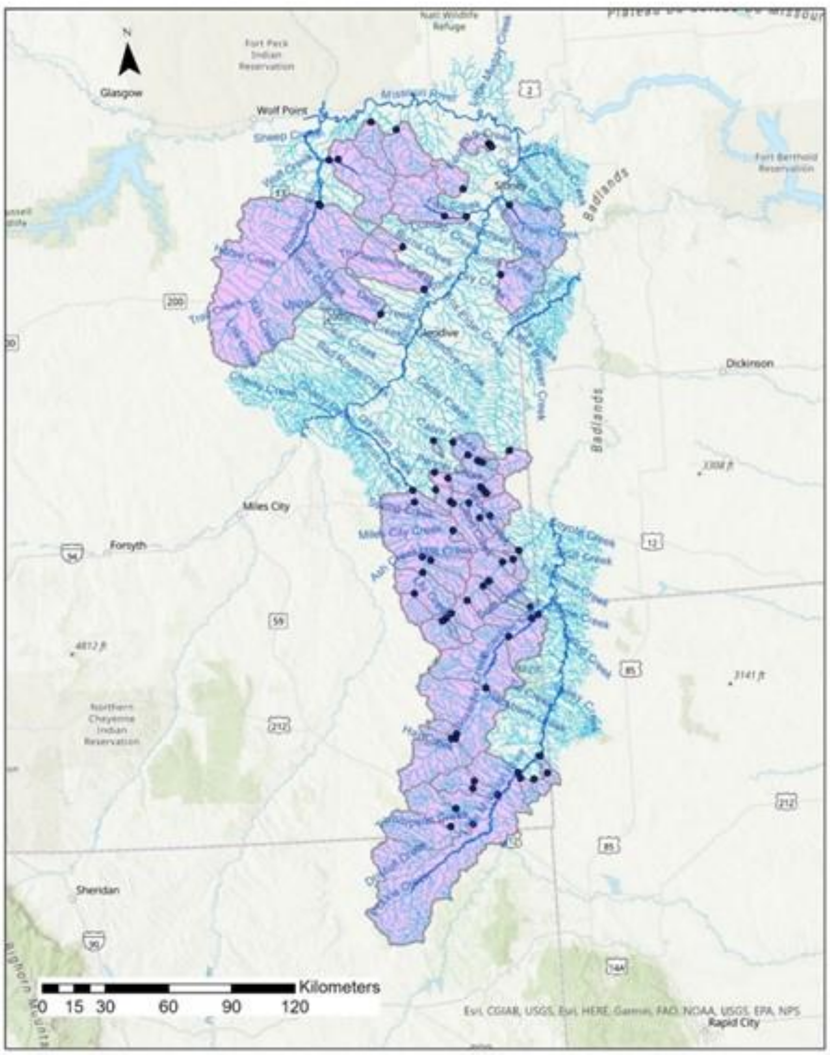

Figure 2-1. Stream Sampling Stations (Black Dots) and their Corresponding Watersheds (in Pink) in the 2013-2017 Study. Major stream segments in each basin are labeled.

The datasets comprise three model categories – predictor variables, pure response variables that are affected by stressors or mitigators, and those that may serve a dual role and behave either as predictor or response variables. Several regression tree models were built and interpreted, for example responses of mean DO Δ, maximum DO Δ, and count/week of days exceeding the DO Δ threshold of 5.3 mg/L (5.3 being based on DEQ's earlier work as described in **Section 1.0**). In each tree, the splits that occur first are for predictor variables that explain the largest amount of variation in the data. Helsel (2019) suggests regression trees as a modern approach to examining relationships in water quality and notes that regression trees are non-parametric and not significantly impacted by outliers. He expounds on the advantages of using regression tree methods, namely:

1. they make use of a machine learning tool to classify data into groups by relating the target variable to cutoffs of explanatory variables;
2. the method is flexible because there are no assumptions of linearity or normality;
3. data at the 'high end' do not affect relationships at the 'low end'; thus, they are not as restricted as are traditional regression methods;
4. evaluation of success is done by cross-validation – the percent of correct predictions of categories for the response variables – rather than by p-values; and
5. predictions are made for individual observations rather than the mean of observations (as done in regression).

Overall, the CART analyses in GLEC (2021) showed that low levels of watershed disturbance and the absence of prolonged drought conditions were the most consistent predictors for optimal stream DO conditions, expressed as either DO Δ or as a DO minimum. Other predictors like conductivity, nutrient concentrations, drainage area, and water temperature were also important. Summary measures of DO (average per week) were found to be the most stable.

2.1 Effect of Drought on DO Δ

The CART model for weekly mean DO Δ is presented in **Figure 2-2**. **Figure 2-2** shows, at the first split, that weekly mean DO Δ is inherently lower (3.28 mg/L) in watersheds with low (<16.3%) land use disturbance[13] compared to watersheds where managed lands dominate; in the latter, DO Δ averages 6.59 mg/L. Managed land use classes include Pasture/Hay, Cultivated Crops, and Introduced Upland Vegetation – Annual and Biennial Forbland. Streams in watersheds with low land disturbance (the left-hand branch) show a range of DO Δ from 2.74 to 6.19 mg/L depending on site specific conductivity (but note that the split occurs at a relatively high specific conductance of 3,923 µS/cm). Under the managed lands (right-hand) branch, the next split in the tree is the number of consecutive weeks at low intensity drought (D_{ZERO} are abnormally dry conditions as indicated by the U.S. Drought Monitor Index[14]; see

[13] Low-disturbance land use classes consisted of individual classes such as the Great Plains Badlands, Great Plains Ponderosa Pine Woodland and Savanna, and Great Plains Wooded Draw and Ravine. All were derived from the Natural Heritage Program for Montana (NHP) and the National Land Cover Dataset (NLCD) of the US Geological Survey. Both datasets were time stamped 2015-2016.

[14] GLEC (2021) examined a number of different drought indices, and several proved to be important predictors of DO. The U.S. Drought Monitor Index compiles results from several drought indices into a single drought metric and was an important factor affecting mean weekly DO Δ; we recommend its use.

https://droughtmonitor.unl.edu and **Figure 2-3**). GLEC (2021) observes that a given region does not experience a higher intensity drought (e.g., D_{THREE} -D_{FOUR}) until some duration of lower intensity drought (D_{ZERO} -D_{ONE}) exists. When weather conditions are wetter (D_{ZERO} ≤6 weeks), plains streams located in watersheds dominated by managed lands will have an average DO Δ of 5.31 mg/L (**Figure 2-2**). But if low intensity drought conditions persist for greater than six weeks, stream DO Δ will increase due to drought alone—to an average of 8.47 mg/L if no further environmental factors in the tree are considered.

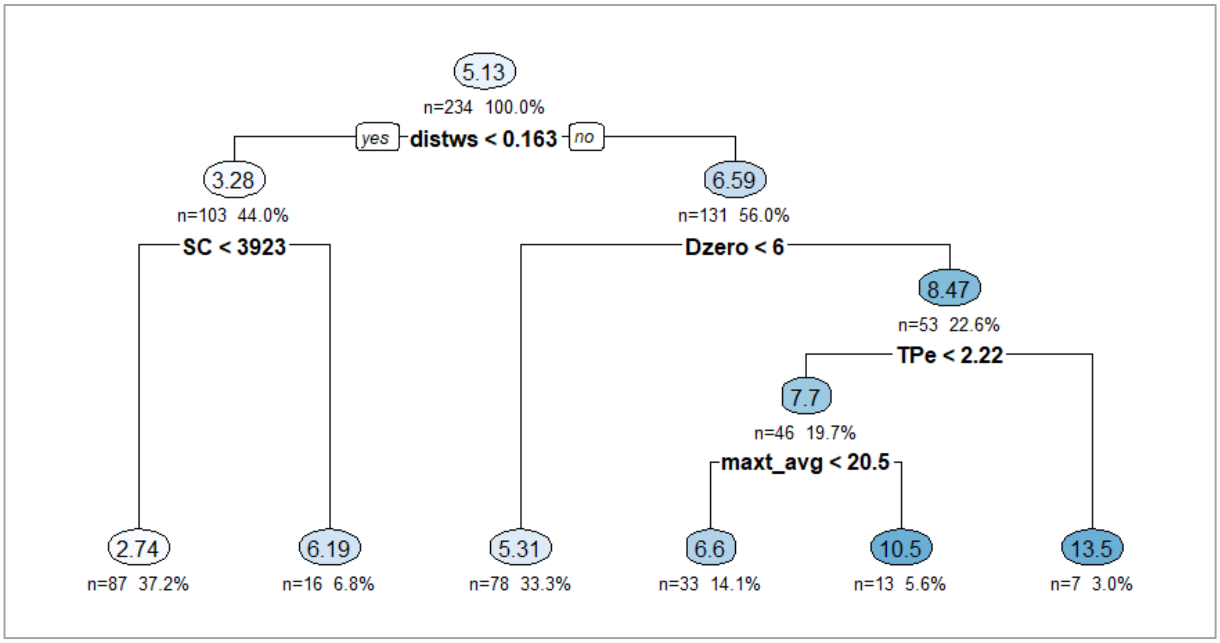

Figure 2-2. Regression Tree for Average Weekly DO Δ (mg/L). The predicted value and the number and percentage of total observations are shown for each node. The decision statement to split is located under each node (in bold) – traverse left if the statement is true (yes), otherwise traverse right (no). Branching to the left of "Dzero ≤ 6" represents wetter conditions (i.e., fewer weeks of Dzero drought, whereas its corollary (Dzero > 6) to the right reflects drier conditions. From Figure 4.1 in GLEC (2021).

			Ranges					
Category	Description	Possible Impacts	Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	Going into drought: ▪ short-term dryness slowing planting, growth of crops or pastures Coming out of drought: ▪ some lingering water deficits ▪ pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	▪ Some damage to crops, pastures ▪ Streams, reservoirs, or wells low, some water shortages developing or imminent ▪ Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	▪ Crop or pasture losses likely ▪ Water shortages common ▪ Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	▪ Major crop/pasture losses ▪ Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	▪ Exceptional and widespread crop/pasture losses ▪ Shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

Figure 2-3. The U.S. Drought Monitor Index.

Reference streams (per Suplee et al., 2005) are affected by drought as well. **Figure 2-4** illustrates the effect of drought on a DEQ plains reference stream from the same study. Over the 2013-2017 period, both drought (>6 weeks at D_{ZERO}) and non-drought (≤6 weeks at D_{ZERO}) periods occurred. The site's land ownership and management was unchanged over this time, therefore changes observed in DO Δ are due to drought—which induces reduced water volume, warmer water temperatures, and more flora per unit water volume.

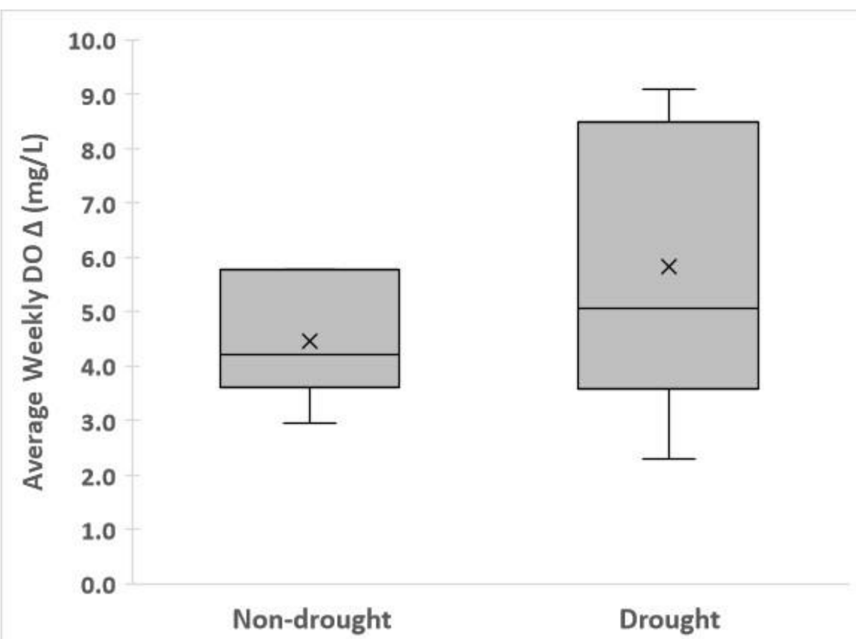

Figure 2-4. Changes in Weekly Average DO Δ During Non-drought and Drought Periods at a Plains Reference Stream. Data were collected over the 2013-2017 period. Drought here is defined as >6 weeks at D_{ZERO} of the U.S. Drought Monitor Index.

2.2 Analysis of Exceedance Frequency in Relation to the 5.3 mg/L DO Δ Threshold

The DO Δ exceedance-rate model from GLEC (2021) is shown in **Figure 2-5.** This model evaluated exceedance frequency of the 5.3 mg/L DO Δ threshold DEQ has used for plains streams assessments. This model counts the number of days per week the threshold is exceeded—and so suggests the number of days the aquatic system is stressed by high DO Δ. Note again that watershed disturbance (splitting at 33% land area in this case) plays a primary role, with fewer exceedances of the 5.3 mg/L threshold in watersheds with a lower % of managed lands (1.61 exceedances/week, on average). Following to the far right-hand branch, note that nearly every day of the week experiences an exceedance (6.84 days on average) when managed land cover in the watershed exceeds 33% of total area and drought is severe. (Note: in this model an alternate drought index was identified. Values of the Palmer Meteorological Drought Index, or PMDI, less than -4.8 are considered extreme drought.) Exceedances are less frequent when drought is less severe in managed watersheds, ranging from 1.87 to 4.22/week (see middle part of **Figure 2-5**). Over on the left-hand branch, where managed land area is <33%, the minimal presence of aquatic vascular plants, i.e., macrophytes (0,1 – the two lowest areal coverage categories) results in the lowest number of exceedances of the 5.3 mg/L threshold in the entire tree (1.3/week), whereas higher macrophyte higher densities nearly doubles this frequency (2.39/week). This finding is consistent with the observation that macrophyte photosynthesis contributes to DO supersaturation and (therefore) more exceedances of the threshold.

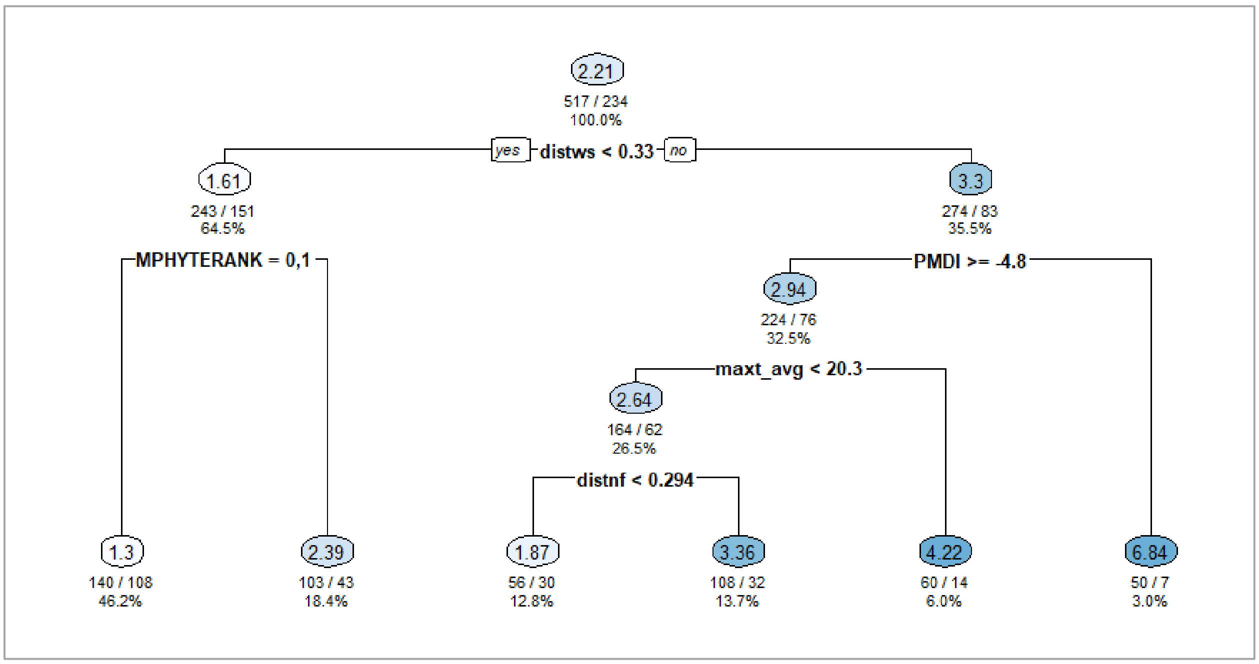

Figure 2-5. Regression Tree for the Number of Exceedances (Days) per Week of DEQ's Earlier DO Δ Threshold of 5.3 mg/L. Shown for each node is the predicted value, then a pair separated by "/" listing the total number of events (1 event = 1 day of exceedance) and the number of observations, and the percentage of total observations. The decision statement to split is located under each node (in bold) – traverse left if the statement is true (yes), otherwise traverse right (no). ***From*** **Figure 4.16 in GLEC (2021).**

The conclusion that can be drawn from **Figure 2-5** is that even plains streams in undisturbed watersheds during non-drought will exceed DEQ's 5.3 mg/L DO Δ threshold once or twice a week (recall that computation of DO Δ results in a single DO Δ value per day). In managed watersheds exceedance is higher, around 3 exceedances per week.

2.3 Relationship between DO Δ and DO Minimum in Eastern Montana Streams

Montana has minimum DO standards for surface waterbodies which are found in DEQ-7 (DEQ, 2019) and these apply to the plains regions as well. Based on the same 2013-2017 dataset discussed above, the relationship between average weekly DO Δ and average weekly DO minimum during non-drought is shown in **Figure 2-6**[15]. This significant relationship (Spearman's rho = -0.521, $p < 0.000$) is presented with its 90% confidence band. Streams in the 2013-2017 study are mostly classified C-3 but one is classified B-2. C-3 streams have a 7-day mean minimum DO of 4.0 mg/L, while for B-2 streams it is 5.0 mg/L (DEQ, 2019); these minimum DO requirements protect aquatic life from low DO and are shown as a gray horizontal band in the figure. The modeled relationship shows that if a minimum of 5 mg/L is to be maintained, weekly average DO Δ should be held to about 6 mg/L. In Ohio, Milter (2010) identified the same basic relationship and it is reproduced below in **Figure 2-7**. Based on his work, Milter (2010) recommends DO Δ of 6.0 mg/L or less.

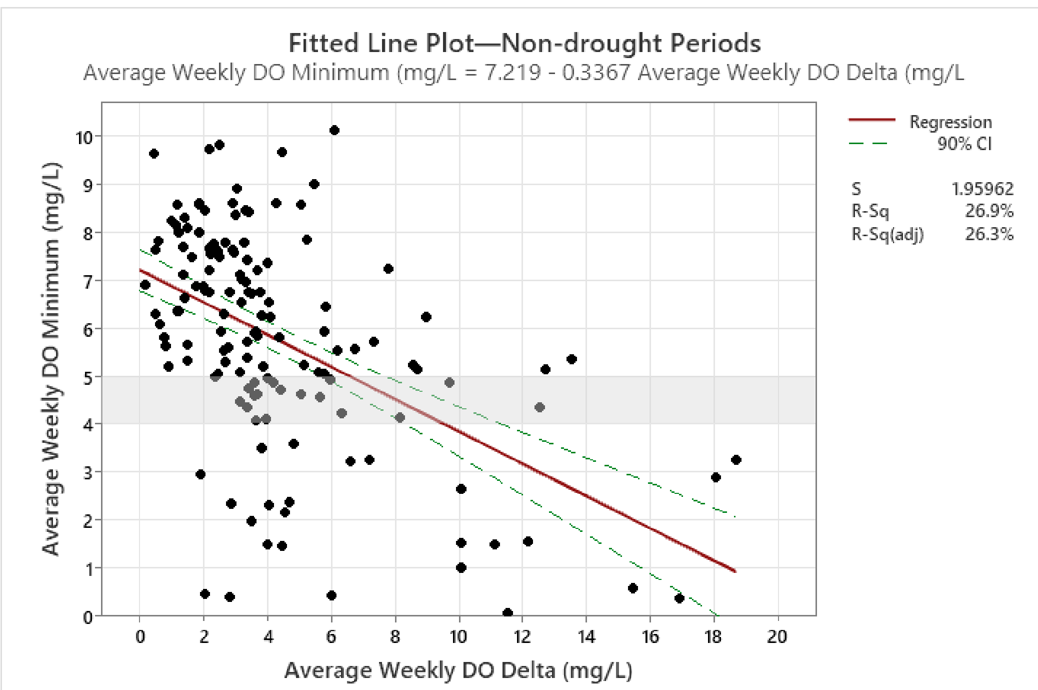

Figure 2-6. Relationship between DO Δ and DO Minimum in Montana Plains Streams. Data are from the 2013-2017 period.

[15] Five datapoints clustered very close to the origin (0,0) were excluded as they were most likely instrument error.

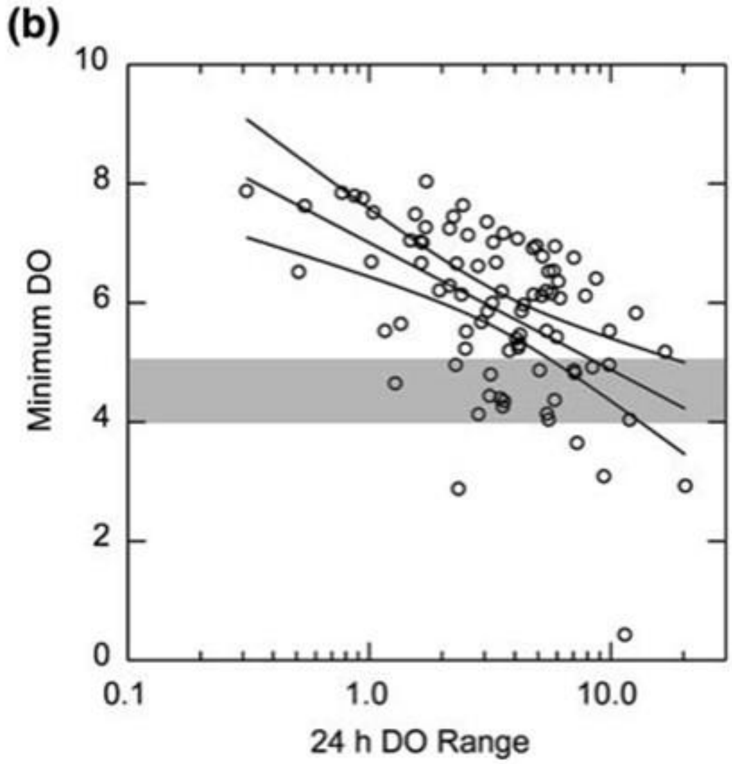

Figure 2-7. Relationship between DO Δ and DO Minimum in Ohio Streams. From Figure 3b in Milter (2010).

2.4 Additional Exceedance Frequency Analysis using 2013-2017 and 2021/2022 Reference Stream Data

2.4.1 Reference Sites During Drought

The effect of drought on streams in minimally disturbed eastern Montana streams was further analyzed using continuous DO datasets collected by DEQ from 14 regional reference streams in 2021 and 2022. All 14 reference sites were experiencing drought (>6 weeks at D_{ZERO}) when the DO instruments were deployed. Although all 14 sites had been reviewed and met reference site criteria per Suplee et al. (2005), an additional criterion of <16.3% managed lands was applied here to better synchronize this analysis with that of GLEC (2021); see also **Figure 2-2**. The extra screening criterion retained ten "best of" plains reference sites. These included ''Rock Creek below Horse Creek, Near Int. Boundary'' which is a USGS Hydrologic Benchmark Network (HBN) site located on the U.S.-Canadian border in the Northwestern Glaciated Plains ecoregion. Much of Rock Creek's watershed upstream of the site is contained within the Grasslands National Park of Canada and only about 7% is used for crop agriculture (U.S. and Canada combined). Also included was the reference site ''Bitter Creek'' (same ecoregion) which has as its immediate upstream drainage a land area that has been described by the Montana Natural Heritage Program as the largest intact grassland in northern Montana, and one of the most extensive naturally functioning glaciated plains grasslands in North America (Cooper et al., 2001).

Among the ten "best of" plains reference sites, during drought, four could meet a DO Δ threshold of 6.0 mg/L all the time. However, the other six (including Bitter Creek) could not meet the threshold within any reasonable exceedance frequency (exceedance frequencies ranged from 24 to 100%). Based on these findings, it can reasonably be concluded that a DO Δ threshold is best applied to all plains streams during drought, not just to those in managed lands >16.3% per findings in GLEC (2021). Otherwise, there is a risk of applying an overly stringent standard, resulting in determinations of standards non-achievement for otherwise healthy waterbodies that were simply experiencing drought-induced effects.

2.4.2 Reference and Comparison Sites During Non-Drought

For the 2013-2017 study, GLEC (2020; 2021) applied a screening process to identify sites with minimal local and watershed-scale disturbance. The process was analogous to the process DEQ uses to identify reference sites. DEQ further screened these sites using best professional judgement to ensure they were consistent with reference-site screening criteria. This resulted in 24 sites referred to here as comparison sites; these were combined with four DEQ plains reference sites sampled over the same period. Weekly average DO Δs for the 28 comparison plus reference sites during non-drought were compiled and the DO Δ exceedance frequency of this dataset was examined. The analysis showed that the sites could achieve a DO Δ threshold of 6.0 mg/L 87% of the time. Based on this, DEQ recommends a 15% allowable exceedance rate to accompany the 6.0 mg/L DO Δ threshold.

3.0 Conclusions, Recommendations

DEQ's five-year study of DO patterns in eastern Montana plains streams showed that DO Δ is significantly related to DO minimum (**Figure 2-6**) and this relationship provided a means to identify a DO Δ threshold protective of the region's aquatic life. The data indicate that a DO Δ threshold of 6 mg/L (expressed as a weekly average) would be protective of the B-2, B-3, and C-3 streams of the region as it will ensure that weekly DO minima standards (per **Circular DEQ-7**) are attained. Miltner (2010) comes to the same conclusion for Ohio low gradient streams. He states that, "A daily DO range >6.0 mg/l carries a significant risk of minimum concentrations falling below the established water quality standard of 4.0 mg/l (Fig. 4). Conversely, ranges <6.0 mg/l tend to maintain minima >5.0 mg/l (the water quality standard for average daily minimum DO) and, therefore, should be protective of aquatic life based on both water quality standards, and the change points for macroinvertebrate indicators identified in this study…."

As found in numerous Ohio-based watershed assessment documents, a primary determinant of the presence of deformities, lesions, and tumors in sampled fish was the frequency of high DO Δs – higher organisms are stressed by continuous adaptation to changing DO conditions (GLEC, 2021). Thus, it is important to ensure the DO Δ threshold is not exceeded too often but, also, it is important to ensure that otherwise healthy streams are not judged to be impaired when they are not. Based on analyses presented here, DEQ recommends a 15% allowable exceedance frequency accompany the weekly average DO Δ threshold of 6.0 mg/L.

The DO Δ threshold of 6.0 mg/L is just slightly higher than DEQ's earlier assessment threshold of 5.3 mg/L for the plains but is twice that recommended for low-gradient streams of western Montana (see Section 5.0 in **Part I-B**). But it should be borne in mind that plains streams are very different from their low-gradient western counterparts. For one, macrophytes are a ubiquitous component of plains streams, at least in those that don't experience excessive scouring flows (Suplee, 2004). DO Δ increases due to macrophytes (e.g., **Figure 2-5**, left hand branch) and this fact influences the threshold identified for these steams.

DEQ's 5-year study of DO patterns in Montana plains streams also shows that drought alone can increase DO Δ, even in reference streams (**Section 2.4.1**). DEQ recommends that the 6.0 mg/L DO Δ threshold only be applied during non-drought periods, using the U.S. Drought Monitor Index value of ≤6 weeks at D_{ZERO} as the breakpoint between drought and non-drought periods.

4.0 ACKNOWLEDGEMENTS

Many, many thanks to Rosie Sada (MT DEQ) for making sure the five-year plains streams study was completed; that study formed the basis of most of the conclusions in **Part II** of this report. Thanks to the Carter, Little Beaver, Dawson, and Richland County Conservation Districts who assisted us in completing the five-year plains study. Thanks also to Dale White (Great Lakes Environmental Center, Inc.) for valuable conversations regarding approaches to data analysis for the five-year dataset.

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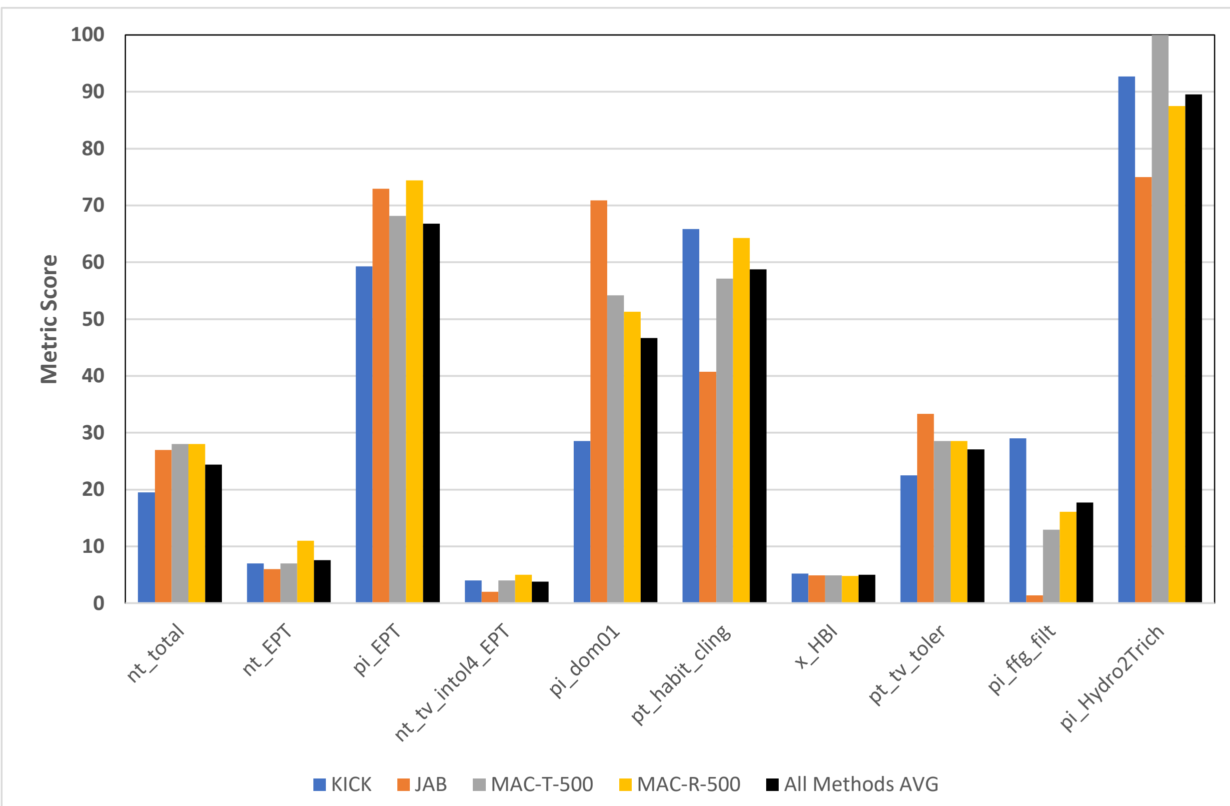
APPENDIX A: METHODS COMPARISON

Datasets used in the **Part IA** initial investigation included a site (Prickly Pear Creek at Montana Law Enforcement Academy) which was repeatedly sampled using multiple protocols over two consecutive summers; no method was isolated to a single year. The results of that work are shown in the figure below. **The all-methods average for each metric is shown as the black bar**. No clear protocol effect is apparent; for example, a protocol producing the highest metric score in one metric does not mean that that method will manifest the highest metric score for a different metric. In one case, all four protocols produced nearly identical results (x_HBI, the Hilsenhoff Biotic Index).

The HESS method could not be compared because, in this dataset, it was never collected at a site along with one or more of the other methods. Jessup et al. (2005) show the single HESS-collected sample in their analysis grouped tightly, in a principal components analysis of taxa relative abundance, with the site it was collected from along with other samples from that site collected via other protocols (see blue diamond, site "DOG" in Figure 6 below, which is reproduced from their document). Others find HESS samples provide mixed results in relation to other protocols—no detectable differences as well as consistent differences from them—depending on the metric, site, year, etc. (Kerans et al., 1992).



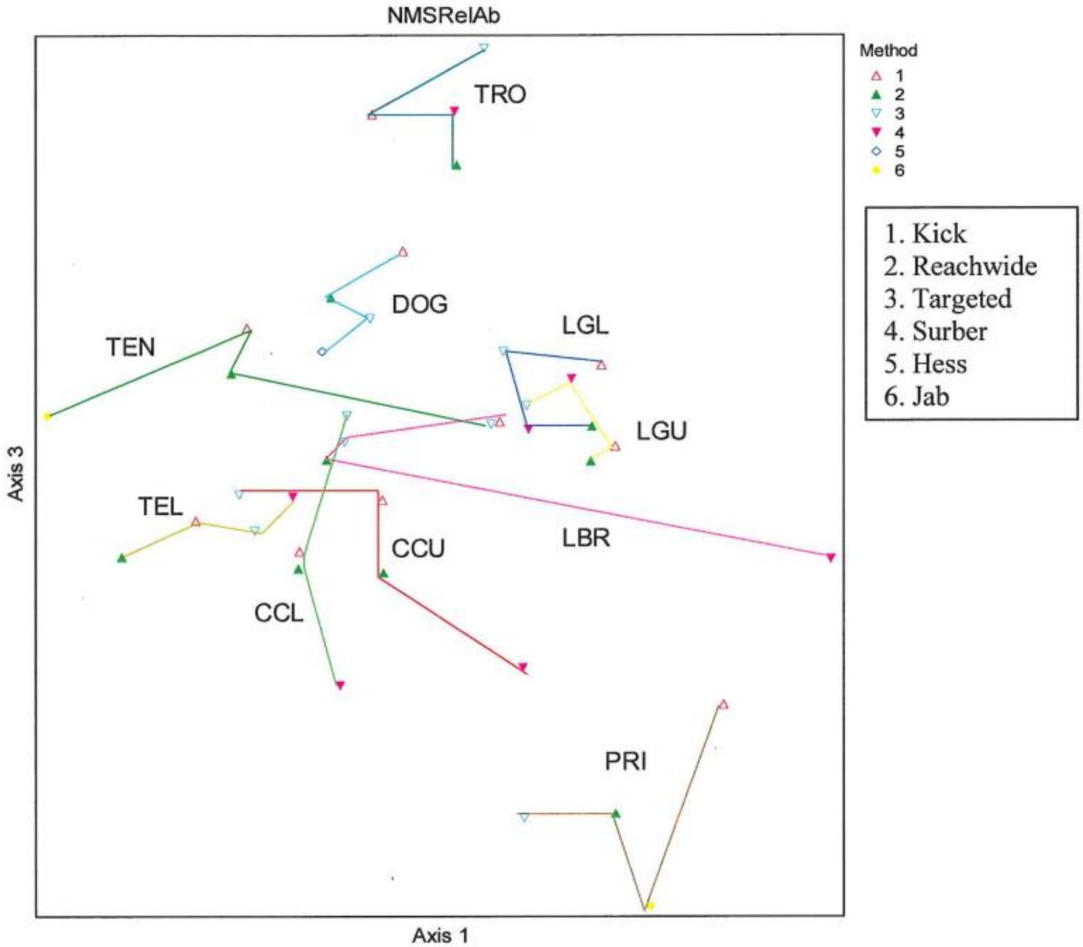


Figure 6. Ordination diagram of samples in taxa space. Three-letter abbreviations are site codes that correspond to the closest grouping of linked samples. Symbols distinguish the protocol used to collect the sample.

Reproduced from Jessup et al. (2005), page 30. The HESS sample is the blue diamond in the “DOG” site cluster.

Appendix B: Comparison of Macroinvertebrate Metrics Scores Computed as an All-Data Average vs. the Score from the Year Continuous DO Data were Collected

Metrics highlighted in green are those which were compared to Bukantis (1998).

Site	Data Type, Decision Correspondance,* and % Difference	Year with both Macro-invertebrate and DO Data	Macroinvertebrate Metric Name and Code								
			Taxa Richness	*EPT Richness*	*% EPT*	*Intolerant Taxa Richness*	*% Dominant Taxa*	*% Clingers*	*MT HBI*	*% Tolerant*	*Tolerant Taxa Richness*
			nt_total	nt_EPT	pi_EPT	nt_tv_intol4_EPT	pi_dom01	pt_habit_cling	x_HBI	pt_tv_toler	nt_tv_ntol
MF Judith River	Metric Score from Year Having Continuous DO Data	2021	48.0	17.0	24.1	16.0	15.5	52.1	3.9	10.4	33.0
MF Judith River	All Data Average Metric Score	n/a	37.3	13.5	17.9	12.8	19.8	49.7	4.3	15.5	24.8
MF Judith River	Decision Correspondance†	n/a	Same	Same	Same		Same		Same		
MF Judith River	Percent Difference	2021	25.0%	23.0%	29.5%	22.0%	24.6%	4.8%	10.0%	39.0%	28.2%
East Gallatin Site I	Metric Score from Year Having Continuous DO Data	2015	36.0	10.0	37.0	5.0	26.3	50.0	5.8	25.0	17.0
East Gallatin Site I	All Data Average Metric Score	n/a	33.3	9.3	53.9	5.0	27.5	52.1	5.1	24.0	17.7
East Gallatin Site I	Decision Correspondance†	n/a	Same	Same	Same		Same		Same		
East Gallatin Site I	Percent Difference	2015	7.7%	6.9%	37.3%	0.0%	4.6%	4.1%	12.3%	4.3%	3.8%
East Gallatin Site J	Metric Score from Year Having Continuous DO Data	2015	35.0	11.0	36.8	6.0	34.6	54.3	6.1	28.6	18.0
East Gallatin Site J	All Data Average Metric Score	n/a	32	11.5	51.1	7.5	28.0	56.5	5.2	17.7	19.5
East Gallatin Site J	Decision Correspondance†	n/a	Same	Same	Same		Close		Close		
East Gallatin Site J	Percent Difference	2015	9.0%	4.4%	32.4%	22.2%	21.1%	3.9%	16.2%	46.8%	8.0%
East Gallatin Site A	Metric Score from Year Having Continuous DO Data	2015	27.0	11.7	67.0	8.3	28.2	55.5	4.7	13.2	18.0
East Gallatin Site A	All Data Average Metric Score	n/a	29.3	11.5	58.9	8.3	28.8	55.5	5.1	16.9	18.8
East Gallatin Site A	Decision Correspondance†	n/a	Close	Same	Close		Same		Same		
East Gallatin Site A	Percent Difference	2015	8.0%	1.4%	12.9%	1.0%	2.2%	0.0%	7.7%	24.2%	4.1%
East Gallatin Site D	Metric Score from Year Having Continuous DO Data	2015	24.5	7.5	52.0	5.0	29.4	49.9	5.3	22.1	13.0
East Gallatin Site D	All Data Average Metric Score	n/a	30.2	10.2	50.6	7.0	25.8	53.9	5.2	20.2	17.6
East Gallatin Site D	Decision Correspondance†	n/a	Close	Same	Same		Same		Same		
East Gallatin Site D	Percent Difference	2015	20.8%	30.5%	2.7%	33.3%	13.1%	7.7%	1.0%	8.8%	30.1%
East Gallatin Site G	Metric Score from Year Having Continuous DO Data	2015	31.7	9.7	36.8	5.7	32.0	55.9	5.6	22.1	17.0
East Gallatin Site G	All Data Average Metric Score	n/a	33.3	12.0	52.0	7.7	35.2	55.6	5.1	18.9	19.5
East Gallatin Site G	Decision Correspondance†	n/a	Same	Close	Same		Same		Same		
East Gallatin Site G	Percent Difference	2015	5.1%	21.5%	34.2%	30.0%	9.5%	0.5%	10.0%	15.5%	13.7%
East Gallatin Site H	Metric Score from Year Having Continuous DO Data	2015	31.0	11.0	53.9	7.0	27.1	51.6	5.1	22.6	18.0
East Gallatin Site H	All Data Average Metric Score	n/a	27.0	9.0	38.4	5.8	41.5	53.6	6.2	24.1	15.3
East Gallatin Site H	Decision Correspondance†	n/a	Close	Same	Same		Close		Close		
East Gallatin Site H	Percent Difference	2015	13.8%	20.0%	33.6%	19.6%	41.9%	3.7%	20.0%	6.4%	16.5%
Musselshell River North Fork	Metric Score from Year Having Continuous DO Data	2015	23.0	7.0	58.4	6.0	31.1	47.8	2.9	21.7	14.0
Musselshell River North Fork	All Data Average Metric Score	n/a	32.0	14.3	42.5	12.3	38.3	54.1	3.6	17.9	22.0
Musselshell River North Fork	Decision Correspondance†	n/a	Close	Close	Same		Same		Same		
Musselshell River North Fork	Percent Difference	2015	32.7%	68.8%	31.4%	69.1%	20.8%	12.2%	21.2%	19.1%	44.4%

*When ≥ 2 macroinvertebrate samples where collected in a year corresponding to a DO year, the average of the macroinvertebrate samples for that year is shown.

†Since Bukantis provided no decimals, standard rounding protocol were used to compare to Bukantis ranges (e.g., a score of 14.1 to 14.4 is ≤14, a score of 14.5 to 14.9 would be >14).

APPENDIX C: LOW GRADIENT (≤ 1.0 %) REFERENCE SITES (SUPLEE ET AL., 2005) IN WESTERN MONTANA AND TRANSITIONAL LEVEL IV ECOREGIONS

Reference Site Name	Station ID	Latitude	Longitude	Water Surface Slope (%)	Macroinvertebrate and Continuous DO Data Available in 2022?
Blackfoot River	C03BLACR01	46.89944	-113.75610	0.09	no
Flathead River South Fork abv Hungry Horse Reservoir	C08FRSFK01	47.97890	-113.56080	0.05	no
Blacktail Deer Creek East Fork in Robb Creek Wildlife Area	M02BDEFC01	44.86583	-112.21861	1.00	no
Gallatin River	M05GLTNR01	45.05444	-111.15640	0.50	no
Rock Creek near Clinton at mouth	RC-CFR	46.72250	-113.68220	0.30	no
Clear Creek (Nutrient Pilot Project)	REFCC	48.30611	-109.49060	0.25	no
Belly River at 3-mile campsite (Glacier NP)	S02BELYR01	48.96806	-113.68263	0.30	no
Judith River Middle Fork near mouth	M22JUDMF01	46.84650	-110.28600	0.44	yes
Sweet Grass Creek on private ranch	Y03SWTGC07	46.152900	-110.181500	0.24	no
Elk Springs Creek	M01ELKC01	44.64444	-111.66360	0.08	no
Flathead River South Fork abv Hungry Horse and abv Bunker Creek	C08FRSFK03	47.79726	-113.41529	0.9	no

APPENDIX D: ASSESSMENT NOTES FOR EUTROPHICATION RATINGS

Site Name	Review Notes	Final BPJ Site Rating
Camas Creek at mouth	Slope is 0.8% (OK). Rating based on 2019-2022 nutrient sampling near mouth, photos. Nutrients slightly elevated, P in particular.	2.0
Clark Fork River above Little Blackfoot River-Kohrs Bend	Slope 0.5% (OK). Based on Suplee et al. (2012), Flynn (2014), 1998-2017 Clark Fork River trend report (HydroSolutions, 2019), etc.	4.0
Four Mile Creek (Reference Site)	Slope is 2.3%, **ELIMINATED**. DEQ stream reference site.	n/a
Judith River Middle Fork near mouth	Slope is 0.44% (OK). DEQ stream reference site.	1.0
Musselshell River North Fork	Slope 0.34% (OK). Per 303(d) list, no chlorophyll *a* or AFDW exceedences, nitrogen levels (soluble and total) low, but four elevated TP samples (up to 51 ug/L) and sources present. Overall suggests specific nutrient enrichment (P) with limited effects so far.	2.5
Prickly Pear Creek at Kleffner Ranch	Slope is 0.8% (OK). 2020 data shows total nutrients at expected concs., nitrate a bit high (0.16 mg/L). (No earlier nut. data found.) No flow withdrawals here, and no known land use changes here since the DO data were collected. Sources: EQuIS, 303d, and Schade (2019).	1.0
Prickly Pear Creek at Montana Law Enforcement Acadamy	Slope is 0.04% (OK). Rating based on repeated nutrient sampling (concentrations elevated, including at times HIGH ammonia), EPA (2006) TMDL prepared for DEQ.	4.0
Shields River	Slope is 1.3%, **ELIMINATED.** USGS dissolved oxygen data.	n/a
Crooked Creek (Reference Site)	Slope is 5.4%, **ELIMINATED**. DEQ stream reference site.	n/a
Silver Bow Creek (SBC-2)	Slope averages 0.6% (OK). Rating based on Gammons et al. (2011) which was after metals cleanup but prior to upgrades at Butte WWTP.	4.0
Silver Bow Creek at Rocker-post remediation-old plant (SBC-3)	Slope averages 0.6% (OK). Rating based on Gammons et al. (2011) which was after DEQ remediation metals cleanup but prior to upgrades at Butte WWTP in 2017.	4.0
Big Hole River at Wisdom Bridge	Slope 0.26% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document (M03-TMDL-01A), BHWC (2012), and review by the Big Hole Watershed Committee.	2.5
Big Hole River at Mudd Creek Bridge	Slope is 0.22% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012) and review by the Big Hole Watershed Committee.	4.0
Big Hole River near Dickie Bridge	Slope 0.6% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012) and review by the Big Hole Watershed Committee.	3.0
Big Hole River at Jerry Creek Bridge	Slope is 0.3% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012) and review by the Big Hole Watershed Committee.	2.0
Big Hole River at Maidenrock	Slope is 0.29% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012) and review by the Big Hole Watershed Committee.	2.0
Big Hole River at Kalsta Bridge	Slope 0.5% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012), and review by the Big Hole Watershed Committee.	2.5
Big Hole River at Notchbottom	Slope 0.22% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012), and review by the Big Hole Watershed Committee.	2.5
Big Hole River near Twin Bridges	Slope 0.01% (OK). Rating based on Gammons 2001, 2003 303(d) list, 2009 DEQ TMDL document, BHWC (2012), and review by the Big Hole Watershed Committee.	2.5
Steel Creek	Slope is 0.6% (OK). Rating based on 2004 nutrient data, 1999 303(d) list assessment record, and 2009 TMDL document (M03-TMDL-02A), and review by the Big Hole Watershed Committee.	2.5
North Fork Big Hole River	Slope 0.14% (OK). Rating based on 303(d) list, 2003 nutrient data, Upper Big Hole TMDL (M03-TMDL-01A), and review by the Big Hole Watershed Committee.	2.0
Deep Creek	Slope is 0.7% (OK). Rating based 2002 303(d) list assessment record, 2009 TMDL document (M03-TMDL-02A), and review by the Big Hole Watershed Committee.	2.0
Wise River	Slope is right at 1% (OK). Rating based on older nutrient data, 1999 303(d) list assessment record, and 2009 TMDL document (M03-TMDL-02A), and review by the Big Hole Watershed Committee.	1.5
East Gallatin Site A	Slope 0.5% (OK). Rating based on 303(d) list datasets, 2014-2015 data from the Gallatin Local Water Quality District.	2.5
East Gallatin Site D	Slope 0.55%(OK). Rating based on 303(d) list datasets, 2014-2015 data from the Gallatin Local Water Quality District.	4.0
East Gallatin Site G	Slope 0.54% (OK). Rating based on 303(d) datasets, 2014-2015 data from the Gallatin Local Water Quality District.	3.0
East Gallatin Site H	Slope 0.3% (OK). Ratings based on 303(d) list datasets, 2014-2015 data from the Gallatin Local Water Quality District.	4.0
East Gallatin Site I	Slope 0.07% (OK). Ratings based on 303(d) list, 2014-2015 data from the Gallatin Local Water Quality District.	3.5
East Gallatin Site J	Slope 0.15% (OK). Ratings based on 303(d) list, 2014-2015 data from the Gallatin Local Water Quality District.	3.5
Trail Creek nr NF Musselshell confluence	Slope 1.8%, **ELIMINATED**.	n/a

APPENDIX E: COMPETE LIST OF MACROINVERTEBRATE METRICS EXAMINED IN THIS INVESTIGATION

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-1
li_total	natural log number individuals - total
ni_Chiro	number individuals - Family Chironomidae
ni_EPT	number individuals - Orders Ephemeroptera, Plecoptera and Trichoptera (EPT)
ni_total	number individuals - total
ni_Trich	number individuals - Order Trichoptera
nt_Amph	number taxa - Order Amphipoda
nt_Bival	number taxa - Class Bivalvia
nt_Chiro	number taxa - Family Chironomidae
nt_COET	number taxa - Orders Coleoptera, Odonata, Ephemertopera, and Trichoptera (COET)
nt_Coleo	number taxa - Order Coleoptera
nt_CruMol	number taxa - Phylum Mollusca and SubPhylum Crustacea
nt_Deca	number taxa - Order Decapoda
nt_Dipt	number taxa - Order Diptera
nt_ECT	number taxa - Orders Ephemeroptera, Coleoptera, and Trichoptera (EPT)
nt_Ephem	number taxa - Order Ephemeroptera
nt_Ephemerellid	number taxa - Family Ephemerellidae
nt_EPT	number taxa - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)
nt_ET	number taxa - Orders Ephemeroptera and Trichoptera (ET)
nt_ffg_col	number taxa - Functional Feeding Group (FFG) - collector-gatherer (CG or GC)
nt_ffg_filt	number taxa - Functional Feeding Group (FFG) - collector-filterer (CF or FC)
nt_ffg_mah	number taxa - Functional Feeding Group (FFG) - macrophyte herbivore (MH)
nt_ffg_omn	number taxa - Functional Feeding Group (FFG) - omnivore (OM)

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-2
nt_ffg_par	number taxa - Functional Feeding Group (FFG) - parasite (PA)
nt_ffg_pih	number taxa - Functional Feeding Group (FFG) - piercer-herbivore (PH)
nt_ffg_pred	number taxa - Functional Feeding Group (FFG) - predator (PR)
nt_ffg_pred_scrap_shred	number taxa - Functional Feeding Group (FFG) - predator (PR), scraper (SC), or shredder (SH)
nt_ffg_scrap	number taxa - Functional Feeding Group (FFG) - scraper (SC)
nt_ffg_shred	number taxa - Functional Feeding Group (FFG) - shredder (SH)
nt_Gast	number taxa - Class Gastropoda
nt_habit_burrow	number taxa - Habit - burrowers (BU)
nt_habit_climb	number taxa - Habit - climbers (CB)
nt_habit_climbcling	number taxa - Habit - climbers (CB) and clingers (CN)
nt_habit_cling	number taxa - Habit - clingers (CN)
nt_habit_sprawl	number taxa - Habit - sprawlers (SP)
nt_habit_swim	number taxa - Habit - swimmers (SW)
nt_Hemipt	number taxa - Order Hempitera
nt_Hepta	number taxa - Family Heptageniidae
nt_Insect	number taxa - Class Insecta
nt_Isop	number taxa - Class Isopoda
nt_Mega	number taxa - Order Megaloptera
nt_Mol	number taxa - Phylum Mollusca
nt_Nemour	number taxa - Family Nemouridae
nt_NonIns	number taxa - not Class Insecta
nt_Odon	number taxa - Order Odonanta
nt_OET	number taxa - Orders Odonanta, Ephemeroptera, and Trichoptera (OET)
nt_Oligo	number taxa - Class Oligochaeta
nt_oneind	number of taxa - one individual
nt_Perlid	number taxa - Family Perlidae
nt_Pleco	number taxa - Order Plecoptera
nt_POET	number taxa - Orders Plecoptera, Odonanta, Ephemeroptera, and Trichoptera (POET)
nt_Ptero	number taxa - Genus Pteronarcys
nt_Rhya	number taxa - Genus Rhyacophila
nt_Tipulid	number taxa - Family Tipulidae
nt_total	number taxa - total

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-3
nt_Trich	number taxa - Order Trichoptera
nt_Tromb	number taxa - Family Trombidformes
nt_Tubif	number taxa - Family Tubificidae
nt_tv_intol4_EPT	number taxa - tolerance value - intolerant < 4 and Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)
nt_tv_ntol	number taxa - tolerance value - ntol < 6
nt_tv_stol	number taxa - tolerance value - stol ≥ 8
nt_tv_toler	number taxa - tolerance value -tolerant ≥ 7
nt_volt_multi	number taxa - multivoltine (MULTI)
nt_volt_semi	number taxa - semivoltine (SEMI)
nt_volt_uni	number taxa - univoltine (UNI)
pi_Amph	percent (0-100) individuals - Order Amphipoda
pi_AmphIsop	percent (0-100) individuals - Order Amphipoda, Isopoda
pi_Baet	percent (0-100) individuals - Family Baetidae
pi_Bival	percent (0-100) individuals - Class Bivalvia
pi_Caen	percent (0-100) individuals - Family Caenidae
pi_ChCr2Chi	percent (0-100) individuals - Genera Chironomus or Cricotopus of Family Chironomidae
pi_Chiro	percent (0-100) individuals - Family Chironomidae
pi_ChiroAnne	percent (0-100) individuals - Order Chironomidae and Phylum Annelida
pi_COC2Chi	percent (0-100) individuals - Genera Chironomus, Cricotopus, Cricotopus/Orthocladius, or Orthocladius of Family Chironomidae
pi_COET	percent (0-100) individuals - Orders Coleoptera, Odonata, Ephemeroptera, and Trichoptera
pi_Coleo	percent (0-100) individuals - Order Coleoptera
pi_Colesens	percent (0-100) individuals - Order Coleoptera and not Family Hydrophilidae

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-4
pi_Corb	percent (0-100) individuals - Genus Corbicula
pi_CorixPhys	percent (0-100) individuals - Family Corixidae or Physidae
pi_CraCaeGam	percent (0-100) individuals - Genus Crangonyx, Caecidotea, or Gammarus
pi_Cru	percent (0-100) individuals - SubPhylum Crustacea
pi_CruMol	percent (0-100) individuals - SubPhylum Crustacea and Phylum Mollusca
pi_Deca	percent (0-100) individuals - Order Decapoda
pi_Dipt	percent (0-100) individuals - Order Diptera
pi_DiptNonIns	percent (0-100) individuals - Order Diptera OR Class not Insecta
pi_dom01	percent (0-100) individuals - most dominant taxon; max(N_TAXA)
pi_dom02	percent (0-100) individuals - two most dominant taxa
pi_dom03	percent (0-100) individuals - three most dominant taxa
pi_dom04	percent (0-100) individuals - four most dominant taxa
pi_dom05	percent (0-100) individuals - five most dominant taxa
pi_dom06	percent (0-100) individuals - six most dominant taxa
pi_dom07	percent (0-100) individuals - seven most dominant taxa
pi_dom08	percent (0-100) individuals - eight most dominant taxa
pi_dom09	percent (0-100) individuals - nine most dominant taxa
pi_dom10	percent (0-100) individuals - ten most dominant taxa
pi_ECT	percent (0-100) individuals - Orders Ephemeroptera, Coleoptera, and Trichoptera (EPT)
pi_Ephem	percent (0-100) individuals - Order Ephemeroptera
pi_EphemNoCae	percent (0-100) individuals - Order Ephemeroptera and not Family Caenidae
pi_EphemNoCaeBae	percent (0-100) individuals - Order Ephemeroptera and not Family Caenidae or Baetidae
pi_EPT	percent (0-100) individuals - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)
pi_EPTNoBaeHydro	percent (0-100) individuals - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) and not Family Baetidae or Hydropsychidae
pi_EPTNoCheu	percent (0-100) individuals - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) and not Family Cheumatopsyche
pi_EPTNoHydro	percent (0-100) individuals - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) and not Family Hydropsychidae
pi_ET	percent (0-100) individuals - Orders Ephemeroptera and Trichoptera (ET)
pi_ffg_col	percent (0-100) individuals - Functional Feeding Group (FFG) - collector-gatherer (CG or GC)
pi_ffg_col_filt	percent (0-100) individuals - Functional Feeding Group (FFG) - collector-gatherer (CG or GC) or collector-filterer (CF or FC)
pi_ffg_filt	percent (0-100) individuals - Functional Feeding Group (FFG) - collector-filterer (CF or FC)
pi_ffg_mah	percent (0-100) individuals - Functional Feeding Group (FFG) - macrophyte herbivore (MH)
pi_ffg_omn	percent (0-100) individuals - Functional Feeding Group (FFG) - omnivore (OM)

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-5
_ffg_par	percent (0-100) individuals - Functional Feeding Group (FFG) - parasite (PA)
_ffg_pih	percent (0-100) individuals - Functional Feeding Group (FFG) - piercer-herbivore (PH)
_ffg_pred	percent (0-100) individuals - Functional Feeding Group (FFG) - predator (PR)
_ffg_scrap	percent (0-100) individuals - Functional Feeding Group (FFG) - scraper (SC)
_ffg_shred	percent (0-100) individuals - Functional Feeding Group (FFG) - shredder (SH)
_ffg_xyl	percent (0-100) individuals - Functional Feeding Group (FFG) - xylophage (XY)
pi_Gast	percent (0-100) individuals - Class Gastropoda
_habit_burrow	percent (0-100) individuals - Habit - burrowers (BU)
_habit_climb	percent (0-100) individuals - Habit - climbers (CB)
pi_habit_climbcling	percent (0-100) individuals - Habit - climbers (CB) and clingers (CN)
_habit_cling	percent (0-100) individuals - Habit - clingers (CN)
pi_habit_cling_PlecoNoCling	percent (0-100) individuals - Habit - clingers (CN) and Order Plecoptera (not clingers)
_habit_sprawl	percent (0-100) individuals - Habit - sprawlers (SP)
_habit_swim	percent (0-100) individuals - Habit - swimmers (SW)
pi_Hemipt	percent (0-100) individuals - Order Hemiptera
_Hydro	percent (0-100) individuals - Family Hydropsychidae
_Hydro2EPT	percent (0-100) individuals - Family Hydropsychidae of Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)
_Hydro2Trich	percent (0-100) individuals - Family Hydropsychidae of Order Trichoptera
_Insect	percent (0-100) individuals - Class Insecta
_IsopGastHiru	percent (0-100) individuals - Order Isopoda, Class Gastropoda, SubClass Hirudinea
_Mol	percent (0-100) individuals - Phylum Mollusca
_Nemata	percent (0-100) individuals - Phylum Nemata

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-6
_NonIns	percent (0-100) individuals - Class not Insecta
_Odon	percent (0-100) individuals - Order Odonata
_OET	percent (0-100) individuals - Orders Odonata, Ephemeroptera, and Trichoptera
_Oligo	percent (0-100) individuals - Class Oligochaeta
pi_Orth2Chi	percent (0-100) individuals - SubFamily Orthocladiinae of Family Chironomidae
_Ortho	percent (0-100) taxa - SubFamily Orthocladiinae
_Pleco	percent (0-100) individuals - Order Plecoptera
_POET	percent (0-100) individuals - Orders Plecoptera, Odonata, Ephemeroptera, and Trichoptera
_SimBtri	percent (0-100) individuals - Family Simuliidae and Genus Baetis tricaudatus complex
pi_Sphaer	percent (0-100) individuals - (Bivalvia) Family Sphaeriidae
pi_SphaerCorb	percent (0-100) individuals - (Bivalvia) Family Sphaeriidae and Genus Corbicula
_Tanyp	percent (0-100) individuals - SubFamily Tanypodinae
pi_Tanyp2Chi	percent (0-100) individuals - SubFamily Tanypodina of Family Chironomidae
_Tanyt	percent (0-100) individuals - Tribe Tanytarsini
_Trich	percent (0-100) individuals - Order Trichoptera
_TrichNoHydro	percent (0-100) individuals - Order Trichoptera and not Family Hydropsychidae
pi_Tromb	percent (0-100) individuals - Order Trombidiformes
pi_Tubif	percent (0-100) individuals - Family Tibuficidae
_tv_intol	percent (0-100) individuals - tolerance value - intolerant ≤ 3
_tv_intol4	percent (0-100) individuals - tolerance value - intolerant < 4
_tv_ntol	percent (0-100) individuals - tolerance value - ntol < 6
_tv_stol	percent (0-100) individuals - tolerance value - stol ≥ 8
_tv_toler	percent (0-100) individuals - tolerance value - tolerant ≥ 7
_tv_toler6	percent (0-100) individuals - tolerance value - tolerant > 6
_tv2_intol	percent (0-100) individuals - intolerant (tolerance value 2)
_volt_multi	percent (0-100) individuals - multivoltine (MULTI)
_volt_semi	percent (0-100) individuals - semivoltine (SEMI)
_volt_uni	percent (0-100) individuals - univoltine (UNI)
pt_Amph	percent (0-100) taxa - Order Amphipoda
pt_Bival	percent (0-100) taxa - Class Bivalvia
_Chiro	percent (0-100) taxa - Family Chironomidae
_COET	percent (0-100) taxa - Orders Coleoptera, Odonata, Ephemeroptera, Trichoptera

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-7
pt_Coleo	percent (0-100) taxa - Order Coleoptera
pt_Deca	percent (0-100) taxa - Order Decapoda
pt_Dipt	percent (0-100) taxa - Order Diptera
pt_ECT	percent (0-100) taxa - Orders Ephemeroptera, Coleoptera, and Trichoptera (EPT)
pt_Ephem	percent (0-100) taxa - Order Ephemeroptera
pt_EPT	percent (0-100) taxa - Orders Ephemeroptera, Plecoptera, and Trichoptera (EPT)
pt_ET	percent (0-100) taxa - Orders Ephemeroptera and Trichoptera (ET)
pt_ffg_col	percent (0-100) taxa - Functional Feeding Group (FFG) - collector-gatherer (CG or GC)
pt_ffg_filt	percent (0-100) taxa - Functional Feeding Group (FFG) - collector-filterer (CF or FC)
pt_ffg_mah	percent (0-100) taxa - Functional Feeding Group (FFG) - macrophyte herbivore (MH)
pt_ffg_omn	percent (0-100) taxa - Functional Feeding Group (FFG) - omnivore (OM)
pt_ffg_par	percent (0-100) taxa - Functional Feeding Group (FFG) - parasite (PA)
pt_ffg_pih	percent (0-100) taxa - Functional Feeding Group (FFG) - piercer-herbivore (PH)
pt_ffg_pred	percent (0-100) taxa - Functional Feeding Group (FFG) - predator (PR)
pt_ffg_scrap	percent (0-100) taxa - Functional Feeding Group (FFG) - scraper (SC)
pt_ffg_shred	percent (0-100) taxa - Functional Feeding Group (FFG) - shredder (SH)
pt_ffg_xyl	percent (0-100) taxa - Functional Feeding Group (FFG) - xylophage (XY)
pt_Gast	percent (0-100) taxa - Class Gastropoda
pt_habit_burrow	percent (0-100) taxa - Habit - burrowers (BU)
pt_habit_climb	percent (0-100) taxa - Habit - climbers (CB)
pt_habit_climbcling	percent (0-100) taxa - Habit - climbers (CB) and clingers (CN)
pt_habit_cling	percent (0-100) taxa - Habit - clingers (CN)

Macroinvertebrate Metric Code	Macroinvertebrate Metric Description-8
pt_habit_sprawl	percent (0-100) taxa - Habit - sprawlers (SP)
pt_habit_swim	percent (0-100) taxa - Habit - swimmers (SW)
pt_Hemipt	percent (0-100) taxa - Order Hemiptera
pt_Insect	percent (0-100) taxa - Class Insecta
pt_NonIns	percent (0-100) taxa - not Class Insecta
pt_Odon	percent (0-100) taxa - Order Odonata
pt_OET	percent (0-100) taxa - Orders Odonata, Ephemeroptera, and Trichoptera (OET)
pt_Oligo	percent (0-100) taxa - Class Oligochaeta
pt_oneind	percent of taxa - one individual
pt_Pleco	percent (0-100) taxa - Order Plecoptera
pt_POET	percent (0-100) taxa - Orders Plecoptera, Odonata, Ephemeroptera, and Trichoptera (POET)
pt_Trich	percent (0-100) taxa - Order Trichoptera
pt_Tromb	percent (0-100) taxa - Order Tombidiformes
pt_tv_intol	percent (0-100) taxa - tolerance value - intolerant ≤ 3
pt_tv_intol4	percent (0-100) taxa - tolerance value - intolerant < 4
pt_tv_ntol	percent (0-100) taxa - tolerance value - ntol < 6
pt_tv_stol	percent (0-100) taxa - tolerance value - stol ≥ 8
pt_tv_toler	percent (0-100) taxa - tolerance value - tolerant ≥ 7
pt_volt_multi	percent (0-100) taxa - multivoltine (MULTI)
pt_volt_semi	percent (0-100) taxa - semivoltine (SEMI)
pt_volt_uni	percent (0-100) taxa - univoltine (UNI)
x_Becks	Becks Biotic Index
x_Becks3	Becks Biotic Index v3
x_D	Simpson's Index; 1-sum((N_TAXA/ni_total)^2, na.rm = TRUE)
x_D_G	Gleason's Index; (nt_total) / log(ni_total)
x_D_Mg	Margalef's Index; (nt_total - 1)/log(ni_total)
x_Evenness	Peilou's Index (Evenness); x_Shan_e/log(nt_total)
x_HBI	Hilsenhoff Biotic Index (references the TolVal field) THIS IS THE MONTANA DEQ values
x_HBI2	Hilsenhoff Biotic Index 2 (references the TolVal2 field) THIS IS THE RAI values
x_NCBI	North Carolina Biotic Index (references the TolVal2 field)
x_Shan_10	Shannon Wiener Diversity Index (log base 10); -x_Shan_Num/log(10)
x_Shan_2	Shannon Wiener Diversity Index (log base 2); -x_Shan_Num/log(2)
x_Shan_e	Shannon Wiener Diversity Index (natural log); -x_Shan_Num/log (exp(1))

APPENDIX F: SPEARMAN RANK CORRELATION STATISTICS FOR 217 MACROINVERTEBRATE METRICS EXAMINED IN PART IA.

Significant relationships (P ≤ 0.01) are highlighted in green. All tests are two-sided.

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
ni_total	AVG Daily DO delta (mg/L)	21	0.078	(-0.367, 0.494)	0.737

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
li_total	AVG Daily DO delta (mg/L)	21	0.086	(-0.360, 0.500)	0.712

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
ni_Chiro	AVG Daily DO delta (mg/L)	21	0.068	(-0.376, 0.485)	0.771

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
ni_EPT	AVG Daily DO delta (mg/L)	21	0.027	(-0.409, 0.454)	0.907

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
ni_Trich	AVG Daily DO delta (mg/L)	21	0.025	(-0.411, 0.452)	0.915

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_total	AVG Daily DO delta (mg/L)	21	-0.006	(-0.436, 0.427)	0.980

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Amph	AVG Daily DO delta (mg/L)	21	0.165	(-0.290, 0.559)	0.474

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Bival	AVG Daily DO delta (mg/L)	21	0.229	(-0.230, 0.605)	0.317

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Coleo	AVG Daily DO delta (mg/L)	21	0.259	(-0.202, 0.626)	0.257

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_COET	AVG Daily DO delta (mg/L)	21	0.036	(-0.402, 0.461)	0.875

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_CruMol	AVG Daily DO delta (mg/L)	21	0.275	(-0.186, 0.637)	0.228

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Deca	AVG Daily DO delta (mg/L)	21	0.037	(-0.401, 0.461)	0.874

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Dipt	AVG Daily DO delta (mg/L)	21	-0.137	(-0.539, 0.315)	0.553

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ECT	AVG Daily DO delta (mg/L)	21	0.047	(-0.393, 0.469)	0.840

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Ephem	AVG Daily DO delta (mg/L)	21	-0.167	(-0.561, 0.288)	0.468

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Ephemerellid	AVG Daily DO delta (mg/L)	21	-0.572	(-0.817, -0.151)	0.007

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_EPT	AVG Daily DO delta (mg/L)	21	-0.237	(-0.610, 0.223)	0.302

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ET	AVG Daily DO delta (mg/L)	21	-0.038	(-0.463, 0.400)	0.869

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Gast	AVG Daily DO delta (mg/L)	21	0.184	(-0.273, 0.573)	0.425

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Hemipt	AVG Daily DO delta (mg/L)	21	0.611	(0.204, 0.838)	0.003

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Hepta	AVG Daily DO delta (mg/L)	21	-0.178	(-0.569, 0.278)	0.440

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Insect	AVG Daily DO delta (mg/L)	21	-0.095	(-0.507, 0.352)	0.682

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Isop	AVG Daily DO delta (mg/L)	21	0.037	(-0.401, 0.461)	0.874

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Mega	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Mol	AVG Daily DO delta (mg/L)	21	0.275	(-0.186, 0.637)	0.228

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Nemour	AVG Daily DO delta (mg/L)	21	-0.074	(-0.490, 0.370)	0.750

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_NonIns	AVG Daily DO delta (mg/L)	21	0.168	(-0.287, 0.561)	0.467

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Odon	AVG Daily DO delta (mg/L)	21	0.184	(-0.272, 0.573)	0.423

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_OET	AVG Daily DO delta (mg/L)	21	-0.007	(-0.437, 0.426)	0.978

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Oligo	AVG Daily DO delta (mg/L)	21	-0.098	(-0.509, 0.349)	0.672

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Perlid	AVG Daily DO delta (mg/L)	21	-0.361	(-0.694, 0.098)	0.108

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Pleco	AVG Daily DO delta (mg/L)	21	-0.516	(-0.787, -0.079)	0.017

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_POET	AVG Daily DO delta (mg/L)	21	-0.227	(-0.604, 0.232)	0.321

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Ptero	AVG Daily DO delta (mg/L)	21	-0.334	(-0.676, 0.126)	0.138

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Rhya	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Tipulid	AVG Daily DO delta (mg/L)	21	-0.035	(-0.460, 0.403)	0.880

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Trich	AVG Daily DO delta (mg/L)	21	0.327	(-0.134, 0.672)	0.148

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Tromb	AVG Daily DO delta (mg/L)	21	0.091	(-0.356, 0.503)	0.696

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Tubif	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Amph	AVG Daily DO delta (mg/L)	21	0.167	(-0.288, 0.560)	0.470

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_AmphIsop	AVG Daily DO delta (mg/L)	21	0.150	(-0.304, 0.548)	0.517

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Baet	AVG Daily DO delta (mg/L)	21	-0.467	(-0.758, -0.020)	0.033

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Bival	AVG Daily DO delta (mg/L)	21	0.227	(-0.232, 0.604)	0.322

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Caen	AVG Daily DO delta (mg/L)	21	0.111	(-0.338, 0.519)	0.633

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Coleo	AVG Daily DO delta (mg/L)	21	0.114	(-0.335, 0.521)	0.622

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_COET	AVG Daily DO delta (mg/L)	21	-0.187	(-0.575, 0.270)	0.417

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Corb	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_CorixPhys	AVG Daily DO delta (mg/L)	21	0.480	(0.035, 0.766)	0.028

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_CraCaeGam	AVG Daily DO delta (mg/L)	21	0.254	(-0.207, 0.622)	0.267

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Cru	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_CruMol	AVG Daily DO delta (mg/L)	21	0.279	(-0.182, 0.640)	0.221

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Deca	AVG Daily DO delta (mg/L)	21	0.037	(-0.401, 0.461)	0.874

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Dipt	AVG Daily DO delta (mg/L)	21	0.055	(-0.387, 0.475)	0.814

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_DiptNonIns	AVG Daily DO delta (mg/L)	21	0.190	(-0.267, 0.577)	0.410

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ECT	AVG Daily DO delta (mg/L)	21	-0.177	(-0.568, 0.279)	0.444

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Ephem	AVG Daily DO delta (mg/L)	21	-0.140	(-0.541, 0.312)	0.544

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EphemNoCae	AVG Daily DO delta (mg/L)	21	-0.152	(-0.550, 0.302)	0.511

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EphemNoCaeBae	AVG Daily DO delta (mg/L)	21	-0.090	(-0.503, 0.357)	0.699

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EPT	AVG Daily DO delta (mg/L)	21	-0.191	(-0.578, 0.266)	0.407

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EPTNoBaeHydro	AVG Daily DO delta (mg/L)	21	-0.471	(-0.761, -0.025)	0.031

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EPTNoCheu	AVG Daily DO delta (mg/L)	21	-0.191	(-0.578, 0.266)	0.407

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_EPTNoHydro	AVG Daily DO delta (mg/L)	21	-0.525	(-0.792, -0.090)	0.015

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ET	AVG Daily DO delta (mg/L)	21	-0.170	(-0.563, 0.285)	0.461

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Gast	AVG Daily DO delta (mg/L)	21	0.204	(-0.255, 0.587)	0.376

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Hemipt	AVG Daily DO delta (mg/L)	21	0.482	(0.038, 0.768)	0.027

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Hydro	AVG Daily DO delta (mg/L)	21	0.593	(0.179, 0.828)	0.005

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Hydro2EPT	AVG Daily DO delta (mg/L)	21	0.737	(0.400, 0.899)	0.000

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Hydro2Trich	AVG Daily DO delta (mg/L)	21	0.579	(0.160, 0.821)	0.006

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Insect	AVG Daily DO delta (mg/L)	21	-0.270	(-0.634, 0.191)	0.236

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_IsopGastHiru	AVG Daily DO delta (mg/L)	21	0.195	(-0.263, 0.581)	0.398

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Mol	AVG Daily DO delta (mg/L)	21	0.279	(-0.182, 0.640)	0.221

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Nemata	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_NonIns	AVG Daily DO delta (mg/L)	21	0.270	(-0.191, 0.634)	0.236

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Odon	AVG Daily DO delta (mg/L)	21	0.184	(-0.272, 0.573)	0.423

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_OET	AVG Daily DO delta (mg/L)	21	-0.166	(-0.560, 0.289)	0.471

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Oligo	AVG Daily DO delta (mg/L)	21	0.238	(-0.222, 0.612)	0.298

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Pleco	AVG Daily DO delta (mg/L)	21	-0.503	(-0.779, -0.063)	0.020

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_POET	AVG Daily DO delta (mg/L)	21	-0.194	(-0.580, 0.264)	0.401

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Sphaer	AVG Daily DO delta (mg/L)	21	0.227	(-0.232, 0.604)	0.322

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value

pi_SphaerCorb	AVG Daily DO delta (mg/L)	21	0.227	(-0.232, 0.604)	0.322

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Trich	AVG Daily DO delta (mg/L)	21	-0.148	(-0.547, 0.305)	0.522

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_TrichNoHydro	AVG Daily DO delta (mg/L)	21	-0.273	(-0.635, 0.188)	0.232

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Tromb	AVG Daily DO delta (mg/L)	21	-0.044	(-0.467, 0.395)	0.850

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Tubif	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Amph	AVG Daily DO delta (mg/L)	21	0.178	(-0.278, 0.569)	0.440

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Bival	AVG Daily DO delta (mg/L)	21	0.227	(-0.232, 0.604)	0.322

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Coleo	AVG Daily DO delta (mg/L)	21	0.574	(0.154, 0.818)	0.007

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_COET	AVG Daily DO delta (mg/L)	21	0.201	(-0.257, 0.585)	0.382

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Deca	AVG Daily DO delta (mg/L)	21	0.037	(-0.401, 0.461)	0.874

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Dipt	AVG Daily DO delta (mg/L)	21	-0.262	(-0.628, 0.199)	0.251

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ECT	AVG Daily DO delta (mg/L)	21	0.188	(-0.269, 0.576)	0.414

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Ephem	AVG Daily DO delta (mg/L)	21	-0.256	(-0.624, 0.205)	0.263

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_EPT	AVG Daily DO delta (mg/L)	21	-0.239	(-0.612, 0.221)	0.297

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value

pt_ET	AVG Daily DO delta (mg/L)	21	0.061	(-0.381, 0.480)	0.793

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Gast	AVG Daily DO delta (mg/L)	21	0.221	(-0.238, 0.600)	0.335

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Hemipt	AVG Daily DO delta (mg/L)	21	0.657	(0.271, 0.861)	0.001

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Insect	AVG Daily DO delta (mg/L)	21	-0.340	(-0.680, 0.120)	0.131

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_NonIns	AVG Daily DO delta (mg/L)	21	0.340	(-0.120, 0.680)	0.131

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Odon	AVG Daily DO delta (mg/L)	21	0.184	(-0.272, 0.573)	0.423

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_OET	AVG Daily DO delta (mg/L)	21	0.043	(-0.396, 0.466)	0.854

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Oligo	AVG Daily DO delta (mg/L)	21	0.023	(-0.413, 0.451)	0.920

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Pleco	AVG Daily DO delta (mg/L)	21	-0.511	(-0.784, -0.072)	0.018

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_POET	AVG Daily DO delta (mg/L)	21	-0.240	(-0.613, 0.220)	0.294

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Trich	AVG Daily DO delta (mg/L)	21	0.075	(-0.369, 0.491)	0.748

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Tromb	AVG Daily DO delta (mg/L)	21	0.115	(-0.334, 0.522)	0.618

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_Chiro	AVG Daily DO delta (mg/L)	21	-0.075	(-0.491, 0.369)	0.748

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Chiro	AVG Daily DO delta (mg/L)	21	-0.138	(-0.539, 0.315)	0.552

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_Chiro	AVG Daily DO delta (mg/L)	21	-0.136	(-0.538, 0.316)	0.556

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Ortho	AVG Daily DO delta (mg/L)	21	-0.347	(-0.684, 0.113)	0.124

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Tanyt	AVG Daily DO delta (mg/L)	21	0.352	(-0.108, 0.688)	0.118

Pairwise Spearman Correlations (Note: no pattern discernable, Y values almost all the same)

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Tanyp	AVG Daily DO delta (mg/L)	21	0.656	(0.269, 0.860)	~~0.001~~

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_COC2Chi	AVG Daily DO delta (mg/L)	21	-0.400	(-0.718, 0.056)	0.072

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ChCr2Chi	AVG Daily DO delta (mg/L)	21	0.134	(-0.318, 0.536)	0.563

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Orth2Chi	AVG Daily DO delta (mg/L)	21	-0.471	(-0.761, -0.025)	0.031

Pairwise Spearman Correlations (Note: no pattern discernable, Y values almost all the same)

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Tanyp2Chi	AVG Daily DO delta (mg/L)	21	0.592	(0.179, 0.828)	~~0.005~~

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ChiroAnne	AVG Daily DO delta (mg/L)	21	0.074	(-0.370, 0.491)	0.750

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_SimBtri	AVG Daily DO delta (mg/L)	21	0.169	(-0.286, 0.562)	0.464

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_Colesens	AVG Daily DO delta (mg/L)	21	0.116	(-0.334, 0.522)	0.618

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv_intol	AVG Daily DO delta (mg/L)	21	-0.634	(-0.849, -0.237)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv_intol4	AVG Daily DO delta (mg/L)	21	-0.634	(-0.849, -0.237)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_tv_intol4_EPT	AVG Daily DO delta (mg/L)	21	-0.429	(-0.736, 0.024)	0.052

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_tv_ntol	AVG Daily DO delta (mg/L)	21	-0.280	(-0.640, 0.181)	0.219

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv_toler6	AVG Daily DO delta (mg/L)	21	0.117	(-0.333, 0.523)	0.614

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_tv_intol	AVG Daily DO delta (mg/L)	21	-0.630	(-0.847, -0.231)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_tv_intol4	AVG Daily DO delta (mg/L)	21	-0.630	(-0.847, -0.231)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_tv_toler	AVG Daily DO delta (mg/L)	21	0.312	(-0.150, 0.661)	0.169

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_tv_stol	AVG Daily DO delta (mg/L)	21	0.327	(-0.133, 0.672)	0.147

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv_ntol	AVG Daily DO delta (mg/L)	21	-0.245	(-0.617, 0.215)	0.284

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv_stol	AVG Daily DO delta (mg/L)	21	0.255	(-0.206, 0.623)	0.265

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_tv_ntol	AVG Daily DO delta (mg/L)	21	-0.481	(-0.766, -0.036)	0.027

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_tv_stol	AVG Daily DO delta (mg/L)	21	0.406	(-0.049, 0.722)	0.067

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_tv2_intol	AVG Daily DO delta (mg/L)	21	-0.617	(-0.841, -0.213)	0.003

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_col	AVG Daily DO delta (mg/L)	21	-0.357	(-0.691, 0.103)	0.113

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_filt	AVG Daily DO delta (mg/L)	21	0.201	(-0.257, 0.585)	0.382

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_pred	AVG Daily DO delta (mg/L)	21	-0.142	(-0.542, 0.311)	0.541

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_scrap	AVG Daily DO delta (mg/L)	21	0.188	(-0.269, 0.576)	0.414

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_shred	AVG Daily DO delta (mg/L)	21	0.025	(-0.411, 0.452)	0.915

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_mah	AVG Daily DO delta (mg/L)	21	0.110	(-0.339, 0.518)	0.635

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_omn	AVG Daily DO delta (mg/L)	21	-0.589	(-0.827, -0.174)	0.005

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_par	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_pih	AVG Daily DO delta (mg/L)	21	0.631	(0.233, 0.848)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_ffg_pred_scrap_shred	AVG Daily DO delta (mg/L)	21	0.069	(-0.374, 0.487)	0.766

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_col	AVG Daily DO delta (mg/L)	21	-0.071	(-0.489, 0.372)	0.758

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_filt	AVG Daily DO delta (mg/L)	21	0.774	(0.465, 0.915)	0.000

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_pred	AVG Daily DO delta (mg/L)	21	-0.201	(-0.585, 0.257)	0.382

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_scrap	AVG Daily DO delta (mg/L)	21	-0.017	(-0.445, 0.418)	0.942

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_shred	AVG Daily DO delta (mg/L)	21	0.242	(-0.219, 0.614)	0.291

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_mah	AVG Daily DO delta (mg/L)	21	0.419	(-0.035, 0.730)	0.059

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_omn	AVG Daily DO delta (mg/L)	21	-0.562	(-0.812, -0.138)	0.008

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_par	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_pih	AVG Daily DO delta (mg/L)	21	0.565	(0.141, 0.813)	0.008

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_xyl	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_ffg_col_filt	AVG Daily DO delta (mg/L)	21	0.397	(-0.059, 0.717)	0.074

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_col	AVG Daily DO delta (mg/L)	21	-0.510	(-0.784, -0.072)	0.018

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_filt	AVG Daily DO delta (mg/L)	21	0.429	(-0.025, 0.736)	0.053

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_pred	AVG Daily DO delta (mg/L)	21	-0.243	(-0.615, 0.217)	0.289

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_scrap	AVG Daily DO delta (mg/L)	21	0.342	(-0.119, 0.681)	0.130

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_shred	AVG Daily DO delta (mg/L)	21	0.123	(-0.327, 0.528)	0.594

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_mah	AVG Daily DO delta (mg/L)	21	0.263	(-0.198, 0.628)	0.250

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_omn	AVG Daily DO delta (mg/L)	21	-0.494	(-0.774, -0.051)	0.023

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_par	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_pih	AVG Daily DO delta (mg/L)	21	0.709	(0.352, 0.886)	0.000

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_ffg_xyl	AVG Daily DO delta (mg/L)	21	*	(*, *)	*

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_burrow	AVG Daily DO delta (mg/L)	21	-0.119	(-0.525, 0.331)	0.607

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_climb	AVG Daily DO delta (mg/L)	21	0.217	(-0.242, 0.596)	0.345

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_climbcling	AVG Daily DO delta (mg/L)	21	0.116	(-0.333, 0.523)	0.615

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_cling	AVG Daily DO delta (mg/L)	21	0.070	(-0.373, 0.488)	0.762

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_sprawl	AVG Daily DO delta (mg/L)	21	-0.567	(-0.815, -0.145)	0.007

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_habit_swim	AVG Daily DO delta (mg/L)	21	0.331	(-0.130, 0.674)	0.143

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_burrow	AVG Daily DO delta (mg/L)	21	0.217	(-0.242, 0.597)	0.345

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_climb	AVG Daily DO delta (mg/L)	21	0.034	(-0.404, 0.459)	0.884

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_climbcling	AVG Daily DO delta (mg/L)	21	0.169	(-0.287, 0.562)	0.464

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_cling	AVG Daily DO delta (mg/L)	21	0.242	(-0.219, 0.614)	0.291

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_sprawl	AVG Daily DO delta (mg/L)	21	-0.453	(-0.750, -0.004)	0.039

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_swim	AVG Daily DO delta (mg/L)	21	0.133	(-0.319, 0.535)	0.566

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_habit_burrow	AVG Daily DO delta (mg/L)	21	-0.001	(-0.432, 0.431)	0.998

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_habit_climb	AVG Daily DO delta (mg/L)	21	0.237	(-0.223, 0.611)	0.301

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value

pt_habit_climbcling	AVG Daily DO delta (mg/L)	21	0.309	(-0.152, 0.660)	0.173

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_habit_cling	AVG Daily DO delta (mg/L)	21	0.229	(-0.231, 0.605)	0.319

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_habit_sprawl	AVG Daily DO delta (mg/L)	21	-0.664	(-0.864, -0.281)	0.001

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_habit_swim	AVG Daily DO delta (mg/L)	21	0.391	(-0.066, 0.713)	0.079

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_habit_cling_PlecoNoCling	AVG Daily DO delta (mg/L)	21	0.239	(-0.221, 0.612)	0.297

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_volt_multi	AVG Daily DO delta (mg/L)	21	0.181	(-0.276, 0.570)	0.434

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_volt_semi	AVG Daily DO delta (mg/L)	21	-0.532	(-0.795, -0.098)	0.013

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_volt_uni	AVG Daily DO delta (mg/L)	21	-0.264	(-0.629, 0.197)	0.248

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_volt_multi	AVG Daily DO delta (mg/L)	21	0.197	(-0.260, 0.583)	0.391

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_volt_semi	AVG Daily DO delta (mg/L)	21	-0.055	(-0.475, 0.387)	0.814

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_volt_uni	AVG Daily DO delta (mg/L)	21	-0.122	(-0.527, 0.328)	0.598

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_volt_multi	AVG Daily DO delta (mg/L)	21	0.504	(0.064, 0.780)	0.020

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_volt_semi	AVG Daily DO delta (mg/L)	21	-0.468	(-0.759, -0.020)	0.033

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_volt_uni	AVG Daily DO delta (mg/L)	21	-0.256	(-0.624, 0.205)	0.263

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom01	AVG Daily DO delta (mg/L)	21	0.282	(-0.179, 0.641)	0.216

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom02	AVG Daily DO delta (mg/L)	21	0.166	(-0.289, 0.560)	0.471

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom03	AVG Daily DO delta (mg/L)	21	0.108	(-0.341, 0.516)	0.642

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom04	AVG Daily DO delta (mg/L)	21	0.018	(-0.417, 0.446)	0.938

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom05	AVG Daily DO delta (mg/L)	21	0.006	(-0.426, 0.437)	0.978

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom06	AVG Daily DO delta (mg/L)	21	0.052	(-0.389, 0.473)	0.823

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom07	AVG Daily DO delta (mg/L)	21	0.049	(-0.391, 0.471)	0.832

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom08	AVG Daily DO delta (mg/L)	21	0.096	(-0.351, 0.508)	0.679

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom09	AVG Daily DO delta (mg/L)	21	0.123	(-0.327, 0.528)	0.594

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pi_dom10	AVG Daily DO delta (mg/L)	21	0.151	(-0.303, 0.549)	0.515

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Becks	AVG Daily DO delta (mg/L)	21	-0.630	(-0.848, -0.231)	0.002

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Becks3	AVG Daily DO delta (mg/L)	21	-0.758	(-0.908, -0.436)	0.000

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_HBI	AVG Daily DO delta (mg/L)	21	0.571	(0.150, 0.817)	0.007

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_HBI2	AVG Daily DO delta (mg/L)	21	0.590	(0.175, 0.827)	0.005

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_NCBI	AVG Daily DO delta (mg/L)	21	0.590	(0.175, 0.827)	0.005

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Shan_e	AVG Daily DO delta (mg/L)	21	-0.065	(-0.483, 0.378)	0.780

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Shan_2	AVG Daily DO delta (mg/L)	21	-0.065	(-0.483, 0.378)	0.780

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Shan_10	AVG Daily DO delta (mg/L)	21	-0.065	(-0.483, 0.378)	0.780

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_D	AVG Daily DO delta (mg/L)	21	-0.174	(-0.566, 0.282)	0.451

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_D_G	AVG Daily DO delta (mg/L)	21	-0.117	(-0.523, 0.333)	0.614

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_D_Mg	AVG Daily DO delta (mg/L)	21	-0.104	(-0.514, 0.344)	0.654

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
x_Evenness	AVG Daily DO delta (mg/L)	21	-0.160	(-0.555, 0.295)	0.489

Pairwise Spearman Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
nt_oneind	AVG Daily DO delta (mg/L)	21	-0.246	(-0.617, 0.215)	0.283

Pairwise Spearman Correlations

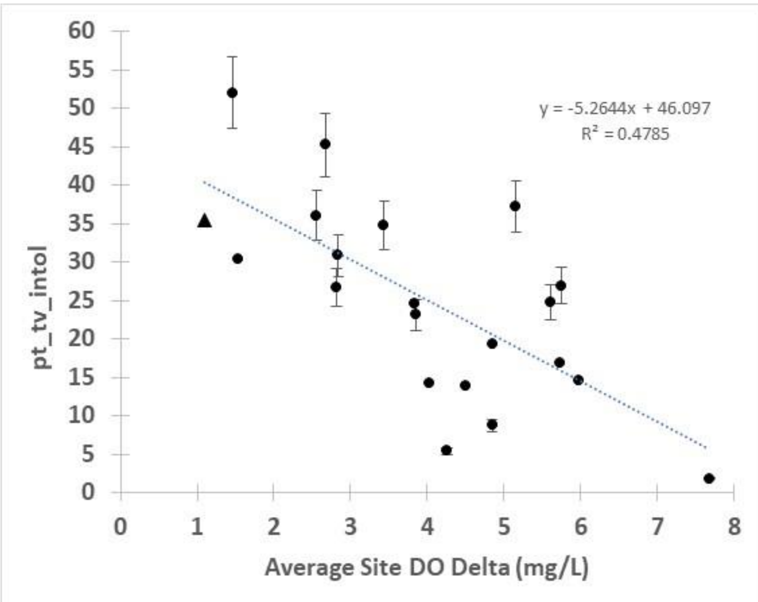
Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
pt_oneind	AVG Daily DO delta (mg/L)	21	-0.194	(-0.580, 0.264)	0.401

Pairwise Spearman Correlations

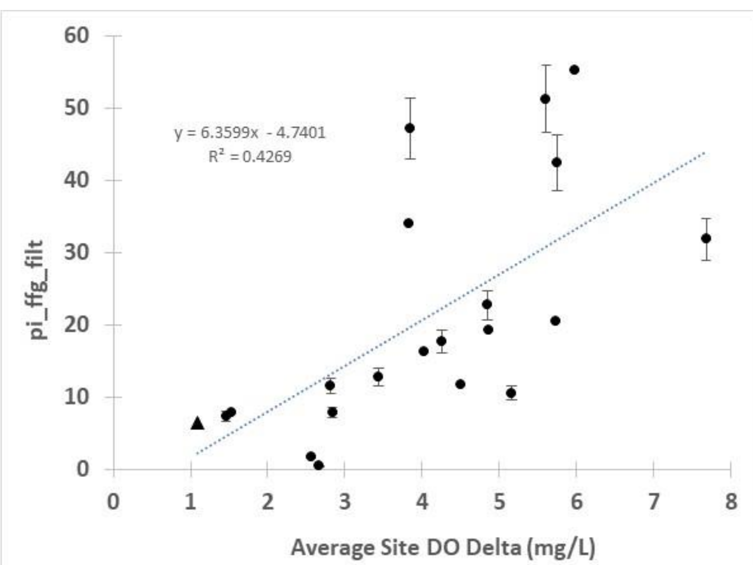
Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
BPJ_Eutrophication_Rating	AVG Daily DO delta (mg/L)	21	0.827	(0.568, 0.937)	0.000

APPENDIX G: THREE SIGNIFICANT SCATTERPLOTS WHICH WERE NOT CARRIED FORWARD TO CHANGE-POINT ANALYSIS

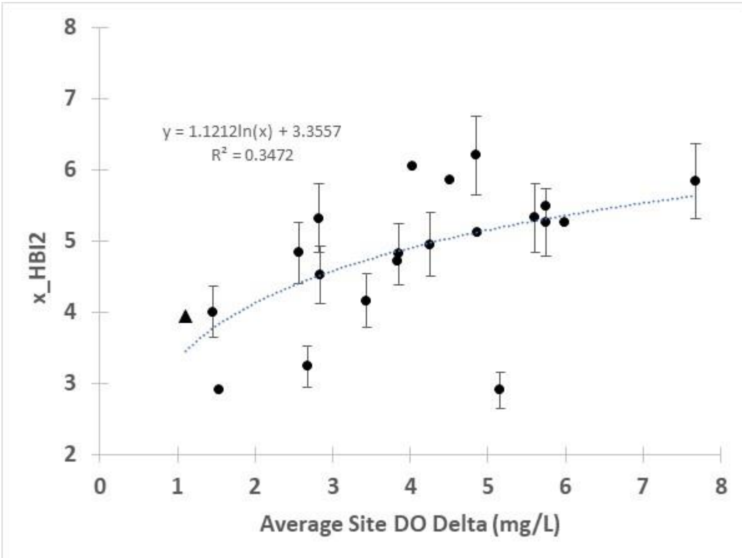
See **Section 2.4** of **Part IA** for explanation of the scatterplot's error bars.



Scatterplot of DO Δ vs. pt_tv_intol (percent of taxa with tolerance value ≤ 3). This is a metric comprising intolerant taxa. **Reason for Exclusion**: Linear relationship.



Scatterplot of DO Δ vs. pi_ffg_filt (percent individuals that are collector-filterers). This is a metric comprising generalist taxa. **Reason for Exclusion**: Linear relationship, behavior of the metric under perturbation is described as variable (Barbour et al., 1999).



Scatterplot of DO Δ vs. x_HBI2 (Hilsenhoff Biotic Index version 2). Curvilinear relationship. **Reason for Exclusion**: Redundant information to x_HBI; the plot is nearly identical to **Figure 3-7**.