Arnold Schwarzenegger
Governor

ASSESSMENT OF ECOLOGICAL IMPACTS OF HYDROPOWER PROJECTS ON BENTHIC MACROINVERTEBRATE ASSEMBLAGES: A REVIEW OF EXISTING DATA COLLECTED FOR FERC RELICENSING STUDIES

PIER FINAL PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Environmentally Preferred Advanced Generation
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- Renewable Energy Technologies
- Transportation

Assessment of Ecological Impacts of Hydropower Projects on Benthic Macroinvertebrate Assemblages: A Review of Existing Data Collected for FERC Relicensing Studies is the final report for the Bioassessment for Hydropower Evaluations project (contract number 500-03-017) conducted by the California Department of Fish and Game California Aquatic Bioassessment Laboratory. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

Several hydroelectric projects in California have conducted bioassessments using benthic macroinvertebrates (small but visible invertebrates that live on stream bottoms) to evaluate ecological and water quality conditions associated with hydropower facilities and to explore the potential for using biological data as an adaptive management tool. However, there is little guidance on interpreting datasets produced by the hydroelectric industry. In this study, existing data from nine studies were combined to provide a more comprehensive context for the interpretation of BMI responses to the effects of hydropower facilities than is possible through analysis of any single dataset. An ad hoc multi-metric index that is sensitive to the cumulative effects of hydropower operations on streams was developed, first by screening potential reference sites from a pool of 49 sites using quantitative geographical information systems landscape analysis, and then by screening 77 candidate metrics for inclusion in the multi-metric index based on three criteria: sufficient range for scoring, good discrimination between reference sites and below-dam sites, and minimal correlation with other discriminating metrics. The final multi-metric index was based on five metrics and showed good discrimination between above-dam reference sites and sites below reservoirs. Most sites below diversion dams did not differ significantly from reference sites. Fifty percent of downstream reaches within 0.4 miles of a reservoir had multi-metric index scores at least two standard deviations below the mean reference score and were considered to be in poor biological condition. Results presented here are compared with numerous published studies and recommendations for future sampling are made.

Keywords: Bioassessment, benthic macroinvertebrates, hydropower dams, multi-metric index, rivers, streams, California

Executive Summary

Introduction

More than 50 hydropower projects in California will undergo relicensing by the Federal Energy Regulatory Commission (FERC) over the next 15 years. Operation of these facilities can adversely affect water quality and aquatic life such as the small but visible invertebrates that live on stream bottoms, known as benthic macroinvertebrates. Benthic macroinvertebrates are an important element of the aquatic foodchain, and they also serve as an excellent indicator of the overall health of a stream or river. This is because they reside in the water for most or all of their lives, often live for more than one year, have limited mobility, are easy to collect, and differ in their tolerance to stressors. These reasons make them ideal for evaluating ecological conditions and recovery from short-term and chronic perturbations in localized or general areas. Because benthic macroinvertebrates provide a sensitive measure to characterize the effects of hydropower facilities on streams and rivers, the State Water Resources Control Board has requested that benthic macroinvertebrate-based bioassessments be conducted as part of the FERC relicensing process.

Purpose

This study reviewed, combined and analyzed existing data that have been collected as part of hydropower relicensing projects in California, to better inform relicensing evaluations and hydropower operations.

Project Objectives

This study had two main objectives:

- Gather physical habitat and benthic macroinvertebrate data files from hydroelectric relicensing projects that collected benthic macroinvertebrate data as part of their relicensing procedure and standardize those data.
- Conduct statistical analyses of those data to better characterize the effects of hydropower operations on benthic macroinvertebrates.

Project Outcomes

The research team developed a multi-metric index—a measurement of important characteristics of the benthic community—that was sensitive to the cumulative effects of hydropower operations on streams; first by screening potential reference sites from a pool of 49 sites using quantitative geographical information systems (GIS) landscape analysis, and then by screening 77 candidate metrics for inclusion in the multi-metric index. A geographical information system is a database tied to specific geographical locations. Inclusion of metrics in the multi-metric index was based upon three criteria: sufficient range for scoring, good discrimination between reference sites and below-dam sites, and minimal correlation with other metrics.

Conclusions

Based upon this study, researchers reached the following conclusions:

- Metrics that were responsive to hydropower operations in this study were also responsive to cumulative effects of non-point source pollution in other California regions (in other studies), suggesting that indices developed for ambient surface water monitoring could also be used for water quality monitoring downstream of hydropower plants.
- The final multi-metric index showed good discrimination between above-dam reference sites and sites below reservoirs.
- Most sites below diversion dams did not differ significantly from reference sites.
- Fifty percent of downstream reaches within 0.4 miles of a reservoir were considered to be in poor biological condition.

Recommendations

The authors recommended the following actions for future research:

- Assess specific responses of benthic macroinvertebrate assemblages to various types of alterations in thermal regimes caused by surface release versus deep release hydroelectric dams.
- Improve the qualitative physical habitat data collected in association with benthic macroinvertebrate samples, to better support analyses of benthic macroinvertebrate responses to specific hydropower-associated stressors.
- Improve understanding of benthic macroinvertebrate responses to adverse changes in stream conditions that most govern their distributions, to help establish habitat suitability criteria for water quality indicator organisms. Further, combine these criteria with organism-specific optima and tolerances for habitat parameters and flow velocity, to supply stream regulators with additional management options.

Benefits to California

By collecting and analyzing disparate research on the effects of hydropower operations on benthic macroinvertebrates, this study provides regulators and facility operators with a much more detailed view of water quality and ecological health downstream of hydropower facilities. It also advances the knowledge necessary to use benthic macroinvertebrate habitat criteria to inform hydropower river management strategies.

1.0 Introduction

In recent years, state and federal water quality regulators have increasingly emphasized the protection of biological integrity in the nation's rivers, streams, lakes, and reservoirs. *Bioassessment* is an analytical technique that evaluates the biological health of aquatic ecosystems by comparing the composition and diversity of indicator assemblages (such as fish, algae, and benthic macroinvertebrates [BMIs]) at potentially impaired sites with the composition and diversity of those same assemblages expected in the absence of human disturbance. Aquatic organisms are exposed to local physical and chemical conditions for most or all of their life cycles, and thus integrate the cumulative effects of environmental disturbance over time, providing a direct measure of ecological condition.

As part of water quality evaluations for California hydropower facilities undergoing relicensing by the Federal Energy Regulatory Commission (FERC), the State Water Resources Control Board (SWRCB) has requested that BMI-based bioassessments be conducted using the California Stream Bioassessment Procedure (CSBP). Hydropower operation may adversely affect water quality and BMI assemblages through a variety of mechanisms, including alteration of water temperature, sediment loads, nutrient transport, discharge volume and timing (Armitage 1984). Bioassessments of hydropower facilities not only provide a general indicator of ecological health, but may also be useful in diagnosing specific mechanisms causing changes to communities downstream of a dam. For example, the presence, absence or change in abundance of certain species or feeding guilds may indicate specific alterations to the flow regime, and it may be possible to use this information to determine how a hydropower facility could change its operations to improve ecological integrity (Poff and Ward 1989; Hart and Finelli 1999; Lytle and Poff 2004).

Since 1999, at least 12 hydroelectric projects have used the CSBP to evaluate ecological and water quality conditions associated with hydropower facilities and to explore the potential for using biological data as an adaptive management tool. More than 50 hydropower projects will undergo FERC relicensing in California during the next 15 years, and it is anticipated that each will require bioassessment as part of the relicensing process. However, there has been very little guidance on how to interpret the datasets that have been produced by the hydroelectric industry thus far. Most data have been collected piecemeal through studies that were limited in scope, had poorly defined objectives, and made no explicit attempt to objectively characterize minimally disturbed (reference) conditions, although the authors acknowledge that reference conditions are difficult to define on larger-order rivers. Moreover, interpretation of results has been limited or absent in every report generated to date by various agencies and consulting firms that have conducted these studies, especially in the broader context of an extensive literature base that has repeatedly documented specific biological and physical responses to hydrologic alteration in rivers worldwide (e.g., Cushman 1985; Voelz 1994; Richter et al. 1996; Richter et al. 1997; Céréghino and Lavandier 1998; Richter et al. 1998; Cazaubon and Giudicelli 1999; Rader and Belish 1999; McDonnell 2000; Sheldon et al. 2000; Brunke et al. 2001; Gore et al. 2001; Stanford and Ward 2001; Bunn and Arthington 2002; Céréghino et al. 2002; Lessard and Hayes 2003; Tharme 2003; Camargo et al. 2004; Robinson et al. 2004a; Robinson et al. 2004b).

In response to the limitations of previous studies, the California Energy Commission (Energy Commission) contracted the California Aquatic Bioassessment Laboratory (ABL) to review, combine and analyze existing data that have been collected as part of hydropower relicensing projects in California to more thoroughly characterize BMI responses to the presence of hydropower-related stream alterations. Combination of all (or most) data that have been collected to date provides a much more comprehensive context for interpretation of BMI response signatures to the generalized effects of hydropower facilities than is possible through analysis of any single dataset. The results of these analyses are presented here and are compared with findings documented in numerous published studies of the effects of altered flow regimes on aquatic biodiversity.

2.0 Methods

2.1. Data Acquisition and Management

Physical habitat and BMI data files were solicited from every hydroelectric relicensing project that was determined to have collected BMI data as part of the relicensing procedure. BMI data were uploaded into CalEDAS, an MS Access® database that facilitates standardization of benthic counts, taxonomic level of effort and the calculation of metrics based on BMI assemblages observed at each site. All BMI sampling for hydroelectric relicensing projects to date has followed the CSBP (Harrington 1999). Three targeted riffle transects were sampled per reach and were processed as separate samples. Three hundred BMIs were subsampled from each sample in the laboratory (= 900 per reach) and were identified to various levels of standard taxonomic resolution depending on the skills and specific protocols of the various labs that performed identifications. In some studies, 10 qualitative measures of channel and riparian physical habitat were estimated at each reach using the U.S. Environmental Protection Agency's (EPA's) Rapid Bioassessment Protocols (Barbour et al. 1999), and visual estimates of substrate composition were taken at most sites. Specific conductance, water temperature, pH and dissolved oxygen concentration were recorded at most sites using a YSI 600XL portable water quality meter.

The CSBP is no longer in general use, and has been replaced by a similar targeted riffle method that has been used extensively in statewide bioassessments in which a single composite sample is taken per reach and 500 BMIs are subsampled from that composite. Thus, benthic samples from pre-existing hydropower projects were composited and standardized to 500 individuals per reach using a randomized rarefaction technique. Seventy-seven metrics were generated at ABL "Level I" Standard Taxonomic Effort (www.dfg.ca.gov/cabw/camlnetste.pdf) for all samples.

2.2. Data Analysis

Two types of analyses were conducted after combining existing hydropower bioassessment datasets. In studies where sampling sites were arranged serially downstream of dams, visual inspection of bivariate scatter plots and linear regression were used to evaluate responsiveness of BMI metrics to linear distance downstream of dams, qualitative measures of reach-scale stressors and water chemistry variables. Downstream distance of sampling reaches from dams varied from 0.14 miles to 16.7 miles, so responsiveness was evaluated using (1) all downstream reaches, (2) only reaches within 8 miles of dams, and (3) only reaches within 4 miles of dams to determine if metric responsiveness varies with spatial scale. Pearson correlations were calculated between all physical habitat measurements, water chemistry variables and downstream distance of sampling reach.

In studies where the sampling design targeted sampling stations above and below dams, an objective and quantitative reference site selection procedure was followed in which potential above-dam reference sites were screened with quantitative GIS landuse analysis. While upstream, project-specific "control" sites are not influenced by hydroelectric projects, they may be biologically impaired by other surrounding land use and do not necessarily characterize regional reference conditions expected when human influence is absent or minimal. The proportions of different landcover classes and other measures of human activity within polygons delimiting the entire watershed upstream of each above-dam sampling site were calculated. The ArcView® (v. 3.2, ESRI 1999) extension ATtILA (Ebert and Wade 2002) was used to calculate the percentage of various landcover classes (such as urban, agriculture and natural) and other measures of human activity (such as population density and road density) in each watershed. Landcover analyses were based on the multi-source California Land Cover Mapping and Monitoring Program (www.frap.cdf.ca.gov). Population data were derived from the 2000 migrated TIGER dataset (California Department of Forestry and Fire Protection, www.cdf.ca.gov). Stream layers were obtained from the U.S. Geological Survey (USGS) National Hydrography Dataset. The road network was obtained from the California Spatial Information Library (gis.ca.gov) and elevation was based on the 30-meter USGS National Elevation Dataset. Thresholds listed in Ode et al. (2005) were used to exclude sites from the reference pool. Sites were further screened from the reference pool on the basis of reach-scale (in-stream and riparian) conditions as data allowed. For example, evidence of obvious bank instability, sedimentation, significant channel alteration, or riparian disturbance was used to evaluate whether each above-dam site could be considered in reference condition.

Sites were assigned to one of three groups: (1) upstream sites that passed reference screening, (2) downstream sites below a diversion dam, and (3) downstream sites below an impoundment dam. Repeat visits to the same sampling reaches in separate years were treated as independent observations. Downstream sampling sites that were > 0.4 miles from a dam were omitted from analyses. Box-and-whisker plots and Kruskal-Wallis tests were used to evaluate BMI metrics for discrimination between above-dam reference sites and sites below both dam types. Metrics were considered to show good discrimination between groups if the median of one group did not overlap with the quartiles of at least one of the other two groups and if Kruskal-Wallis tests for differences in group means were significant at the $p < 0.05$ level.

Metrics that were responsive to downstream stressor gradients and/or that showed significant discrimination between upstream reference and sites below either dam type were further screened for inclusion in an ad hoc multi-metric index (MMI) that is sensitive to the cumulative effects of hydropower operations on streams. Candidate metrics were screened for sufficient range for scoring and redundancy with other candidate metrics. Richness metrics with range < 7 were excluded. Metrics with Pearson correlations ≥ ±0.7 were considered redundant, and the metric that best discriminated between upstream reference sites and sites below dams was chosen.

Metrics were scored on a 0–10 scale using statistical properties of the raw metric values from both upstream reference and below-dam sites to define metric ceilings and floors. For positive metrics (those that increase as disturbance decreases), any site with a metric value equal to or greater than the 80th percentile of reference sites received a score of 10; any site with a metric value equal to or less than the 10th percentile of the non-reference sites received a score of 0; these thresholds were reversed for negative metrics (20th percentile of reference and 90th percentile of non-reference). In both cases, the remaining range of intermediate metric values was divided equally and assigned scores of 1 through 9. Finally, an overall MMI score was calculated for each site by summing the constituent metric scores and adjusting the MMI to a 100-point scale.

3.0 Results

3.1. Data Acquisition and Management

Benthic macroinvertebrate and physical habitat data were acquired for 9 of 12 projects that were determined to have such data available (Table 1 and Figure1). Together, these projects represented the bulk of existing BMI/physical habitat data collected to date in California as part of hydropower relicensing projects. Attempts were made to acquire data from all agencies, but several were unresponsive even after repeated inquires.

3.2. Data Analysis

Metrics responded inconsistently to downstream proximity to dams at the 3 spatial scales investigated, and the variation in most metrics was poorly explained by proximity to dams (Table 2). Only a single metric (% Shredder Individuals) was significantly responsive (least-squares regression $p < 0.05$) at all 3 spatial scales. In addition, most metrics that were responsive at one or more spatial scales did not show good discrimination between above-dam reference sites and below-dam test sites (see below); the exceptions were % Collector-Filterer + Collector Gatherer Taxa, % Intolerant Trichoptera, # Trichoptera Taxa, Shannon Diversity, and the redundant metrics % Non-Gastropod Scrapers and % Scrapers.

Results from bivariate scatterplots were not used to screen metrics for inclusion in the MMI because of the following factors:

- Inconsistent metric response at different spatial scales.
- General disagreement between bivariate analyses and above-below analyses.
- The small number of samples at > 4 miles downstream.
- The possibility that land uses other than hydroelectric dams confounded attempts to characterize the effect of hydropower projects on sites that were not immediately below dams.
- The fact that none of the qualitative in-stream physical habitat, riparian physical habitat, or water chemistry parameters was significantly correlated with proximity to dam at any spatial scale.

Forty-four of the 49 above-dam sampling reaches were considered to be in reference condition for the above/below analyses and MMI construction. Five above-dam sampling reaches were eliminated from the reference pool due to land use in the upstream watershed. Quantitative reach-scale stressors were not measured, and qualitative reach-scale stressor measurements were either lacking or insufficient to use reliably in the reference site screening process, thus no sites were omitted from the reference pool based on reach-scale stressor measurements. Sixteen sampling reaches were below diversion dams, and 30 sampling reaches were below reservoirs. Repeat visits to sampling reaches over multiple years brought the total number of samples to 84 above-dam reference site visits, 29 below diversion dams and 50 below reservoirs.

Table 1. List of hydropower relicensing projects that collected BMI data and status of data acquisition. List does not include pulse-flow studies.

PROJECT	AGENCY	FERC #	YEAR	# STATIONS	DATA STATUS
Spring Gap-Stanislaus River	PG&E	2130	2000–2001	27	Acquired
Upper American River	SMUD	2101, 2155	2002–2003	37	Acquired
SF American River	EID	184	1999–2001	30	Acquired
Pit River 4 & 5	PG&E	233	2002	6	Acquired
NF Feather River (Poe)	PG&E	2107	1999–2002	6	Acquired
NF and MF Feather River (Rock Creek/Cresta)	PG&E	1962	2000–2001	5	Acquired 1 year
Upper NF Feather	PG&E	2105	2000–2002	30	Acquired
SF San Joaquin	SoCal Edison	2175, 67, 120, 2017	2002	96	Acquired
Bear River (Chicago Park Flume)	PG&E	2310	2002–2003	3	Acquired
SF Feather River	SF Water and Power	2088		?	did not provide data
Klamath River	Pacificorp	2082	2002–2003	6	did not provide data
Borel	SoCal Edison	382		7	did not provide data

Figure 1. Map of BMI sampling locations from hydropower relicensing projects that contributed data for use in the present analyses

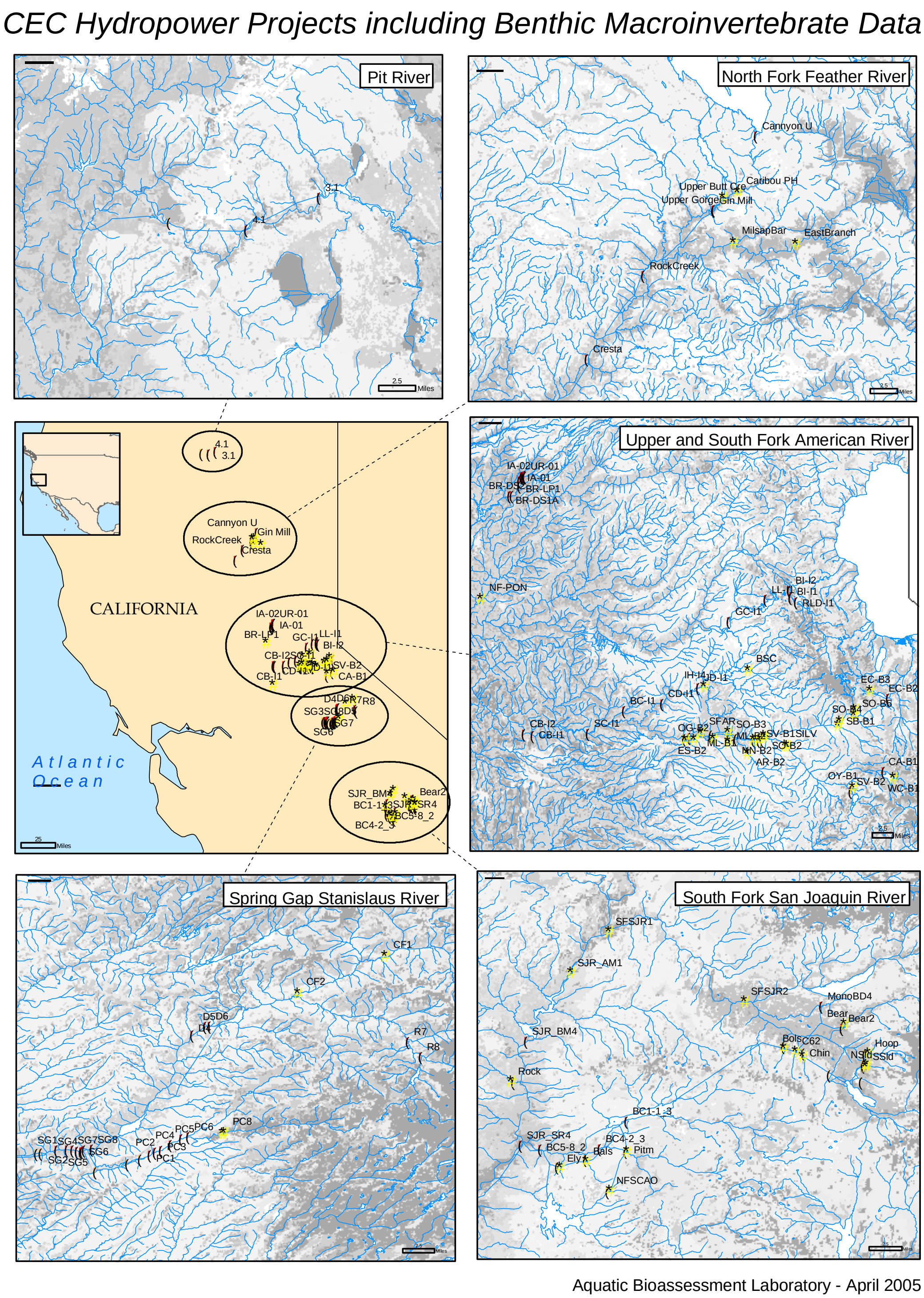


Table 2. Metrics that were significantly related (least-squares regression $p \leq 0.05$) to distance downstream from reservoir dams at one or more spatial scales. Metrics with Pearson correlations ≥ ±0.7 at each scale are marked with an asterisk.

All downstream sites (n=44)	**r^2**		**Sites ≤ 8 mi. downstream (n=38)**	**r^2**		**Sites ≤ 4 mi. downstream (n=31)**	**r^2**
% Collector-Gatherer Taxa*	0.187		% Dominant Taxon*	0.13		% Collector-Filterer Individuals	0.134
% Diptera Taxa	0.143		% Elmidae	0.112		% Diptera Individuals	0.116
% Plecoptera Individuals*	0.114		% Glossosomatidae	0.091		% Glossosomatidae	0.203
% Scraper Individuals*	0.185		% Scraper Individuals	0.11		% Intolerant Diptera*	0.131
% Shredder Taxa*	0.229		% Hydropsychidae Individuals*	0.126		% Hydropsychidae Individuals*	0.307
% Shredder Individuals*	0.15		% Shredder Individuals	0.127		% Shredder Individuals	0.108
% Intolerant Scrapers*	0.172		% Trichoptera Individuals*	0.13		% Trichoptera Individuals*	0.438
% Non-Gastropod Scrapers*	0.187		% Non-Gastropod Scrapers	0.113		% Trichoptera Taxa*	0.106
% Collector Filterer + Collector-Gatherer Taxa*	0.139		Shannon Diversity*	0.083		% Intolerant Trichoptera Individuals*	0.176
# Shredder Taxa*	0.201					% Non-*Hydropsyche*/ *Cheumatopsyche* Trichoptera Individuals*	0.181
						# Trichoptera Taxa*	0.185
						# Collector-Filterer + Collector Gatherer Taxa*	0.122
						# Collector-Gatherer Taxa*	0.099

Twenty-four metrics showed good discrimination (Kruskal-Wallis $p < 0.0001$ in all cases) between above-dam and below-dam sites (Figure 2 and Table 3). In almost all cases, sites below diversion dams had metrics scores similar to reference sites, i.e., the best discrimination was between above-dam sites and sites below reservoirs. The only notable exceptions were the redundant metrics "% of Ephemeroptera that are Intolerant" and "% Intolerant Ephemeroptera" which scored lower below both dam types than in reference sites. Sites below diversion dams were omitted from MMI construction because of their overlap with the reference distribution. Fifty-three metrics were excluded from the MMI due to insufficient range for scoring and/or poor discrimination between above-dam and below-dam sampling reaches (Figure 3 and Table 3). Seventeen metrics were eliminated because of biological and/or statistical redundancy with other responsive metrics. The remaining five responsive, least-correlated metrics (EPT Taxa Richness; Coleoptera Taxa Richness; % Collector-Gatherer+Collector Filterer Individuals; % Non-Gastropod Scraper Individuals; % Tolerant Taxa) produced a preliminary MMI that showed good discrimination between above-dam reference sites and sites below reservoirs (Table 4 and Figure 4). Final metric scores were multiplied by 2 to adjust the MMI to a 100-point scale. The boundary between "fair" and "poor" biological condition was set at two standard deviations below the mean of reference (adjusted MMI score =32); the scoring range above 32 was divided into two equal condition categories: 0–32 = "poor"; 33–66 = "fair"; and 67–100 = "good." Under these scoring criteria, 50% of stream reaches ≤ 0.4 miles below a reservoir were in poor biological condition, 40% were in fair condition, and 10% were in good condition. By contrast, 58% of stream reaches above dams were in good biological condition, and only 4% were in poor biological condition.

Figure 2, part 1. Boxplots of 24 BMI metrics that showed good discrimination between above-dam reference reaches (n=84), reaches below diversion dams (n=29), and reaches below reservoir dams (n=50). Repeat visits to the same sampling reaches in separate years were treated as independent observations. Metrics are arranged alphabetically within two broad categories: richness metrics and proportional metrics.

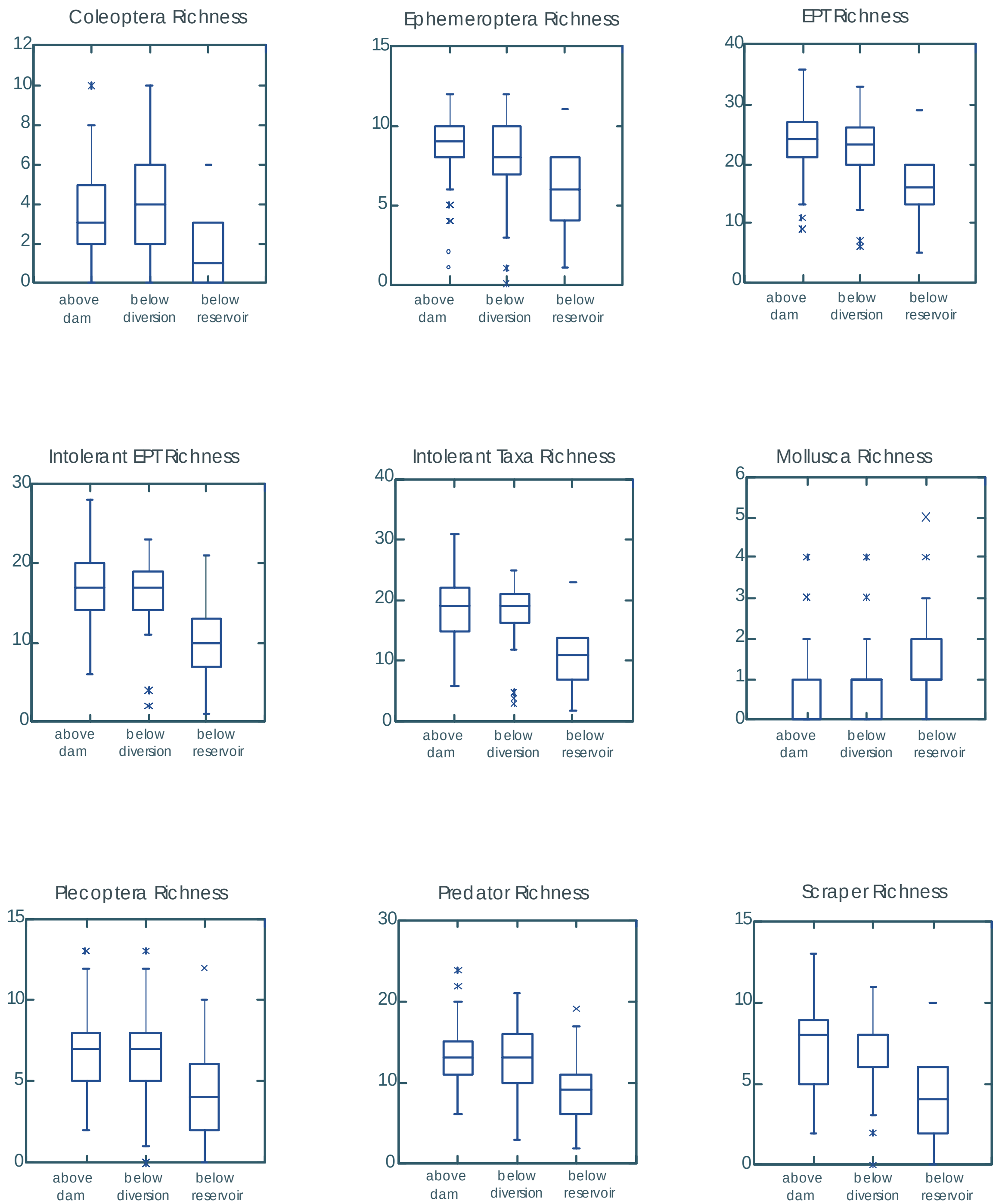


Figure 2, part 2.

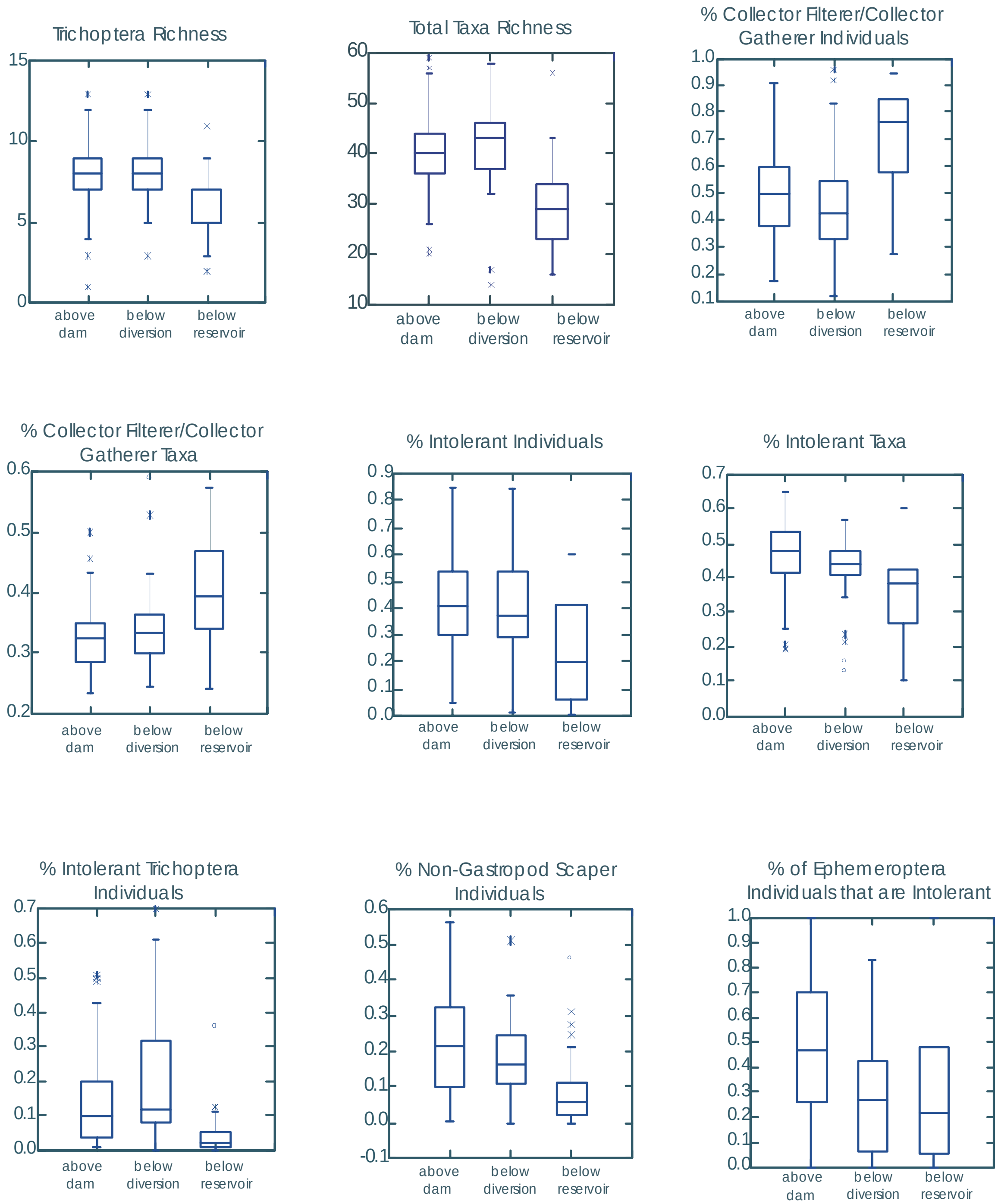


Figure 2, part 3.

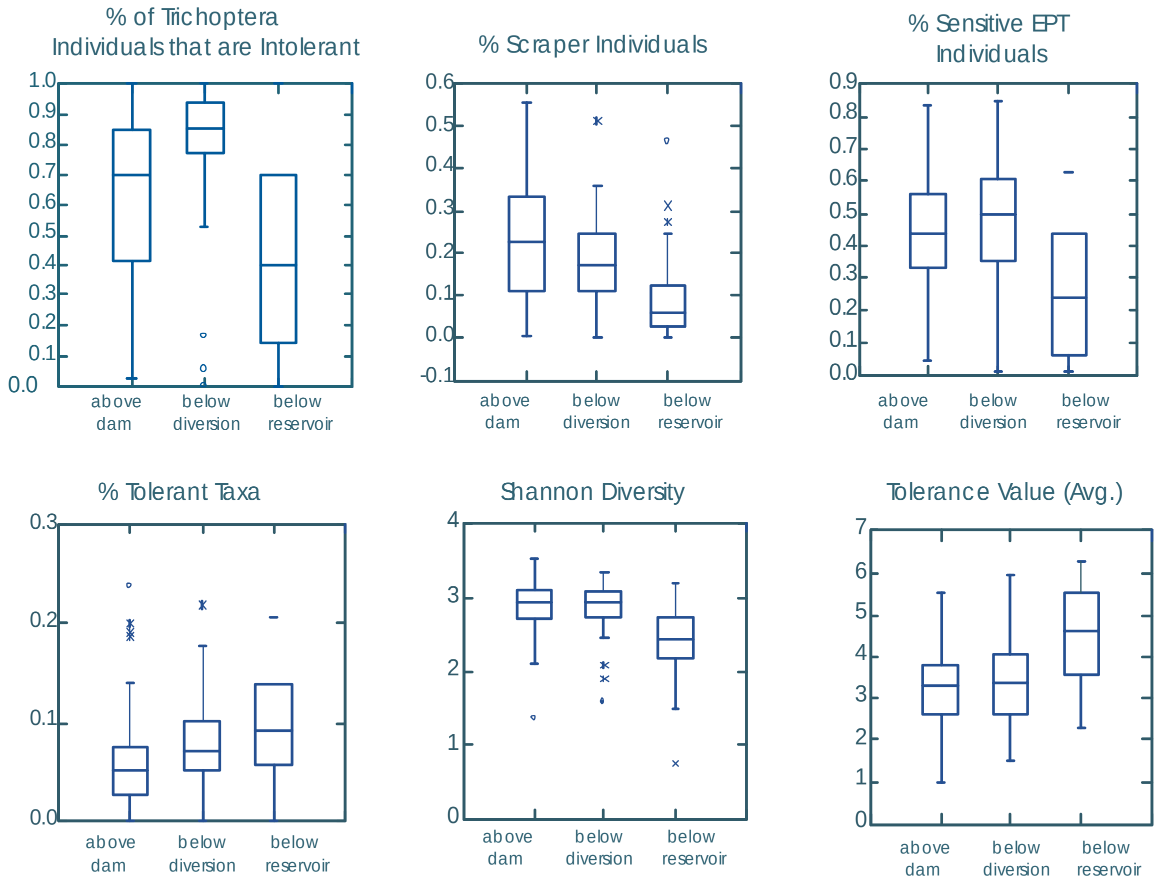


Figure 3, part 1. Boxplots of 53 BMI metrics that showed weak or poor discrimination between above-dam reference reaches (n=84), reaches below diversion dams (n=29), and reaches below reservoir dams (n=50). Repeat visits to the same sampling reaches in separate years were treated as independent observations. Metrics are arranged alphabetically within two broad categories: richness metrics and proportional metrics.

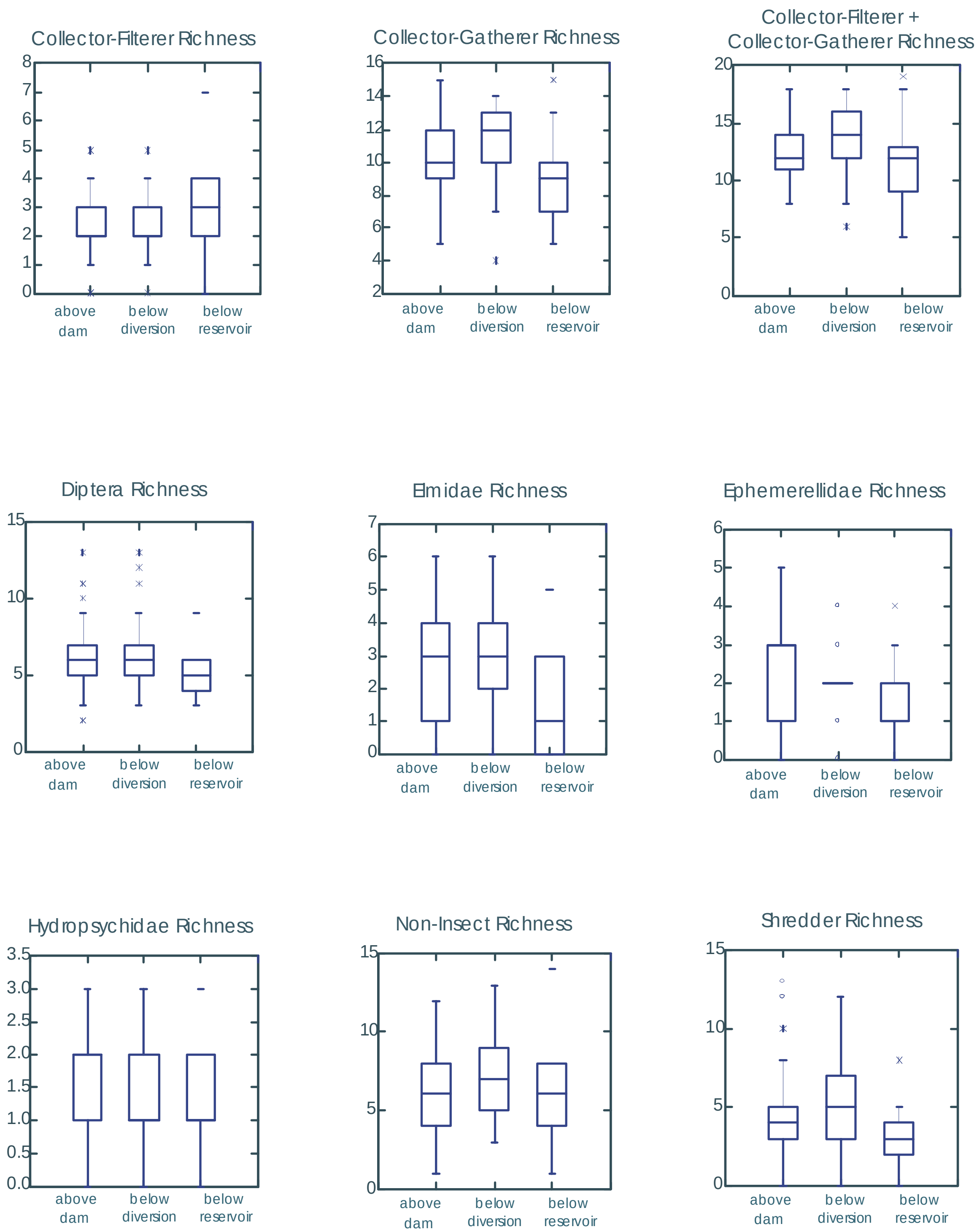


Figure 3, part 2.

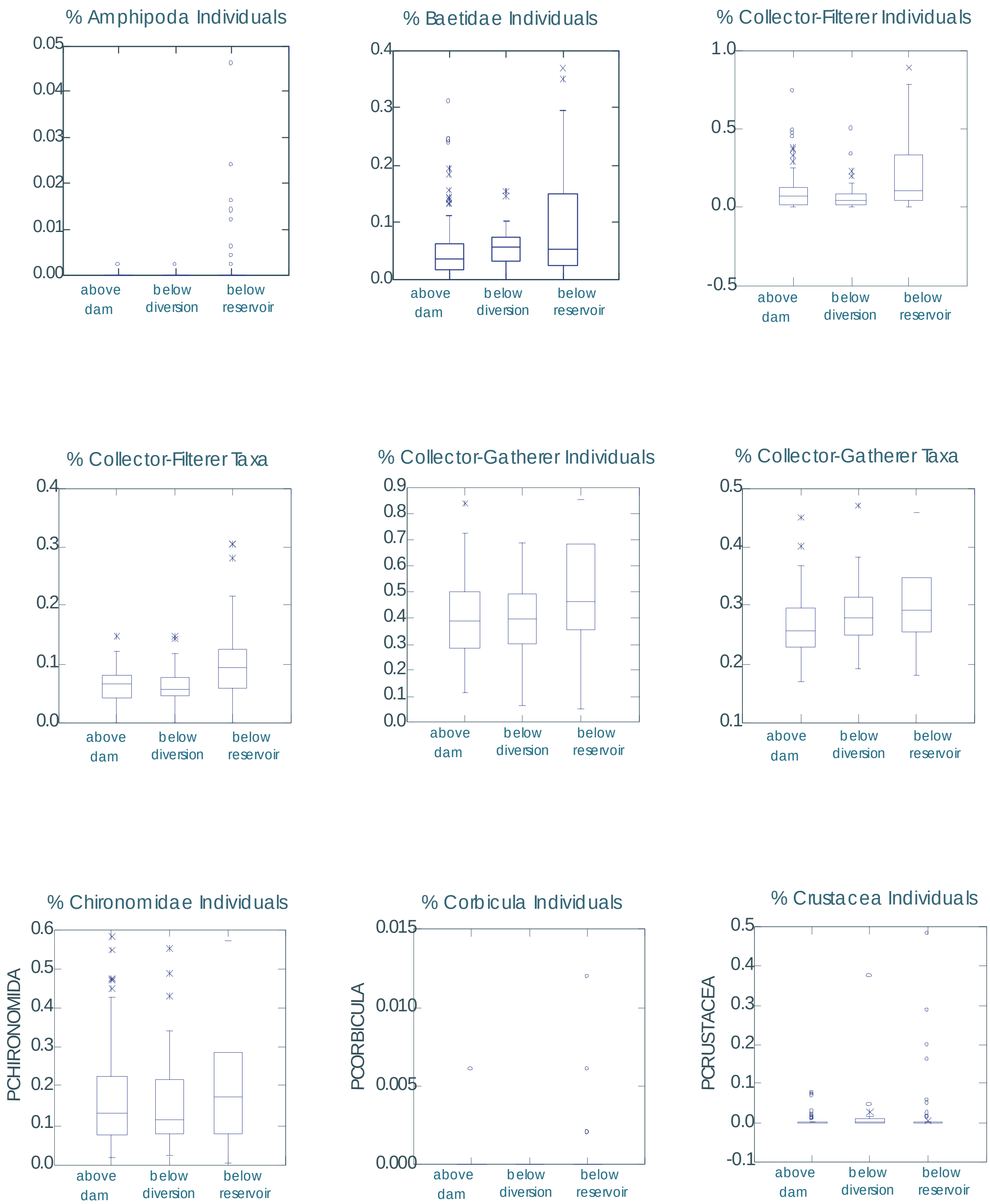


Figure 3, part 3.

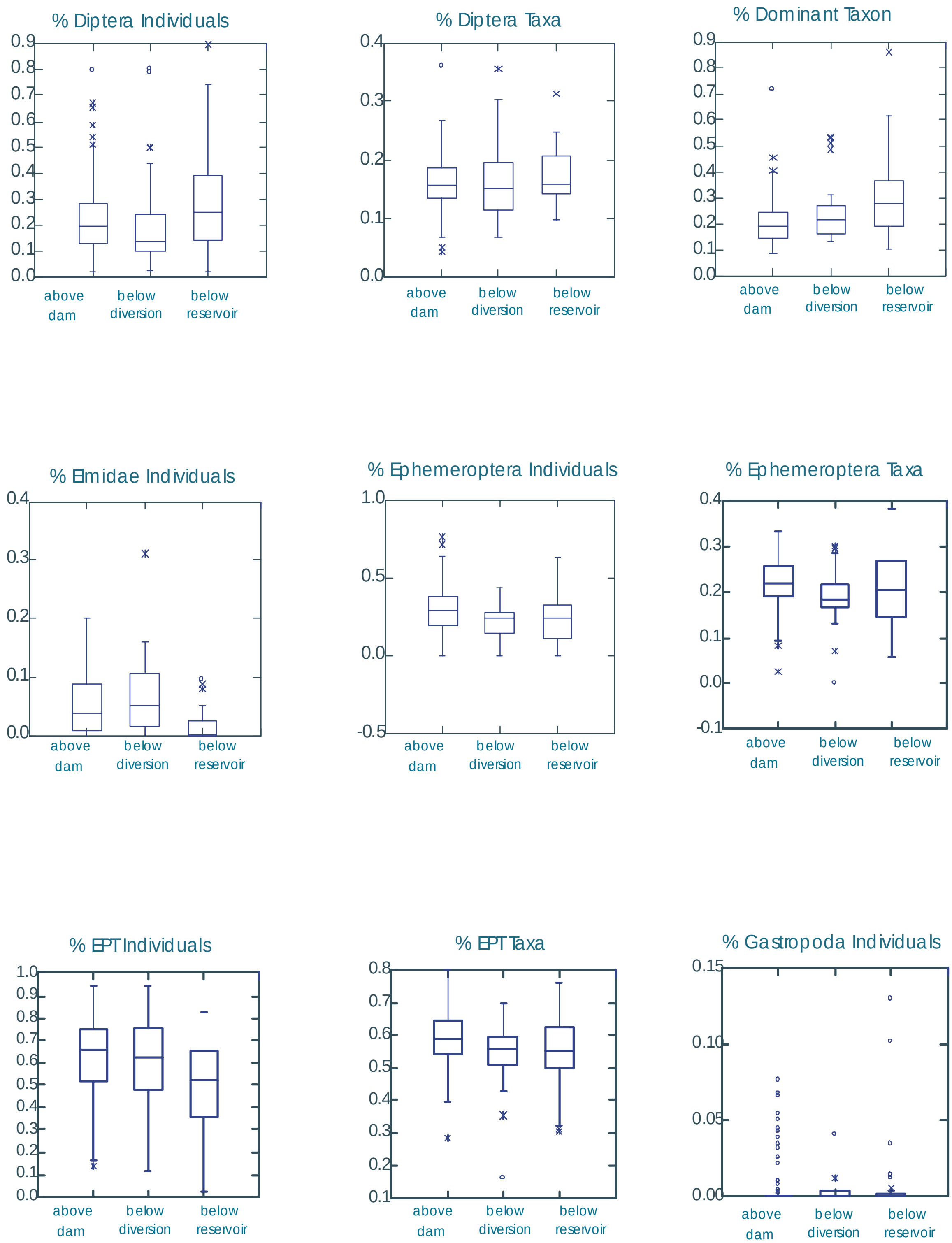
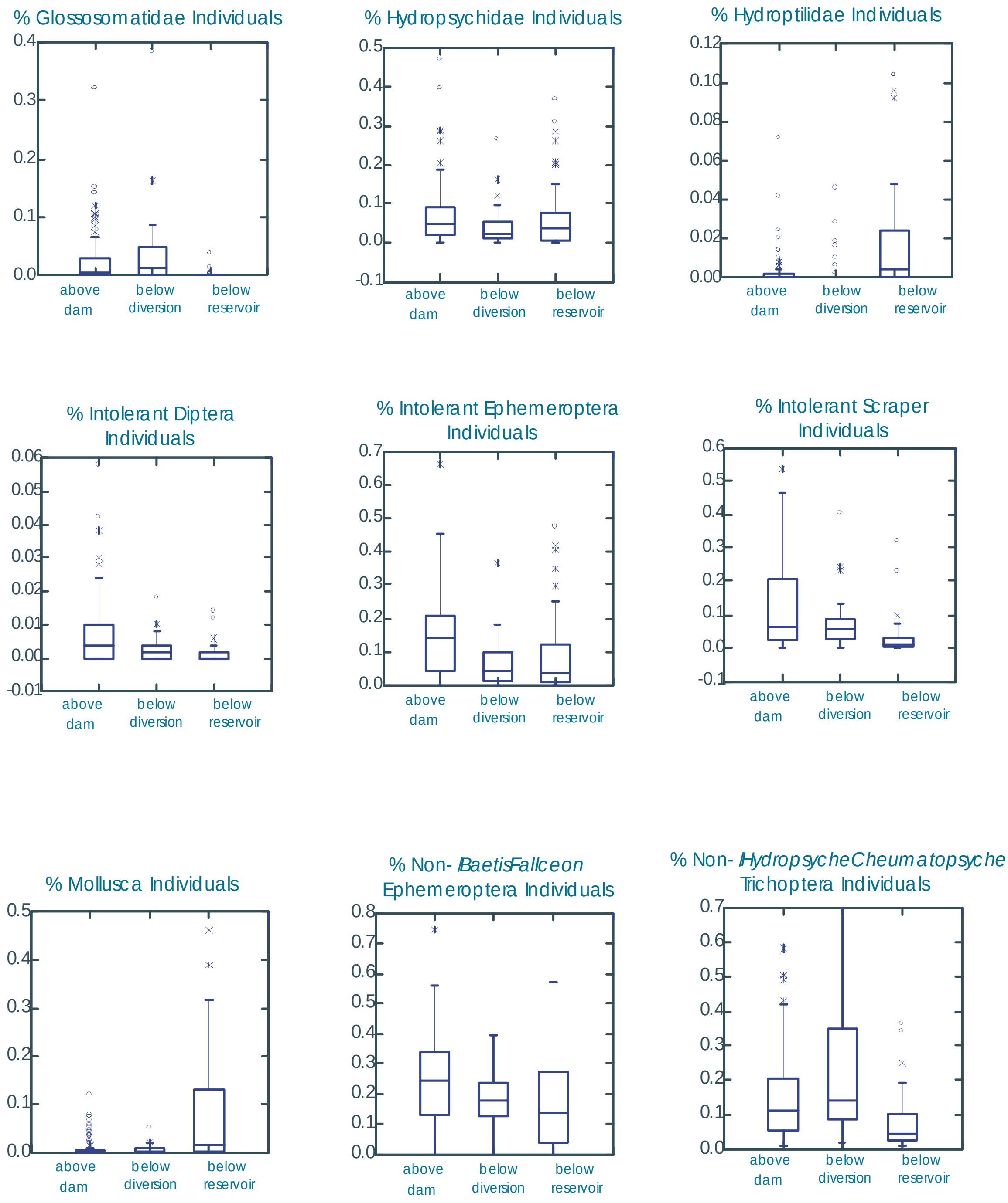


Figure 3, part 4.



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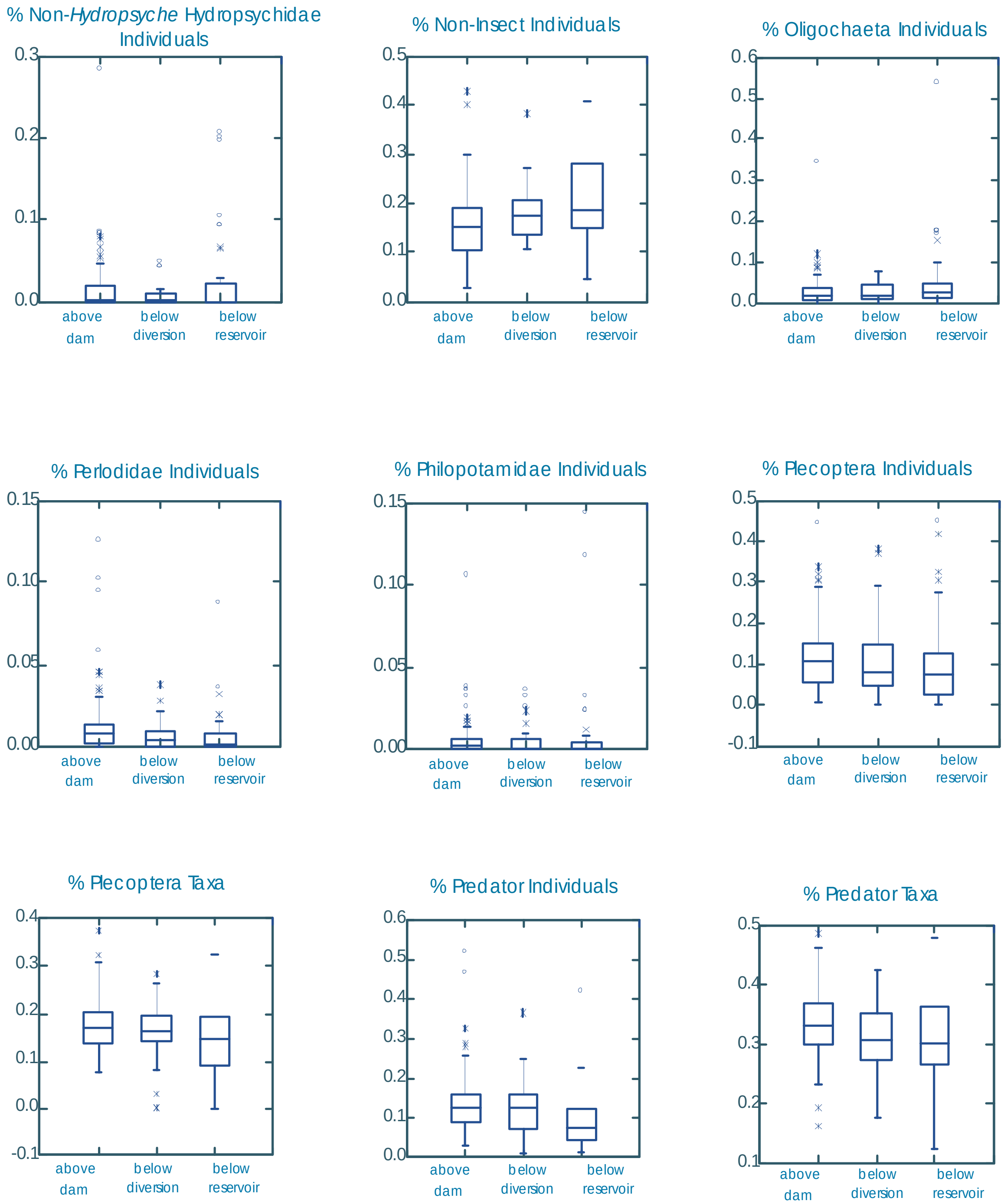


Figure 3, part 6.

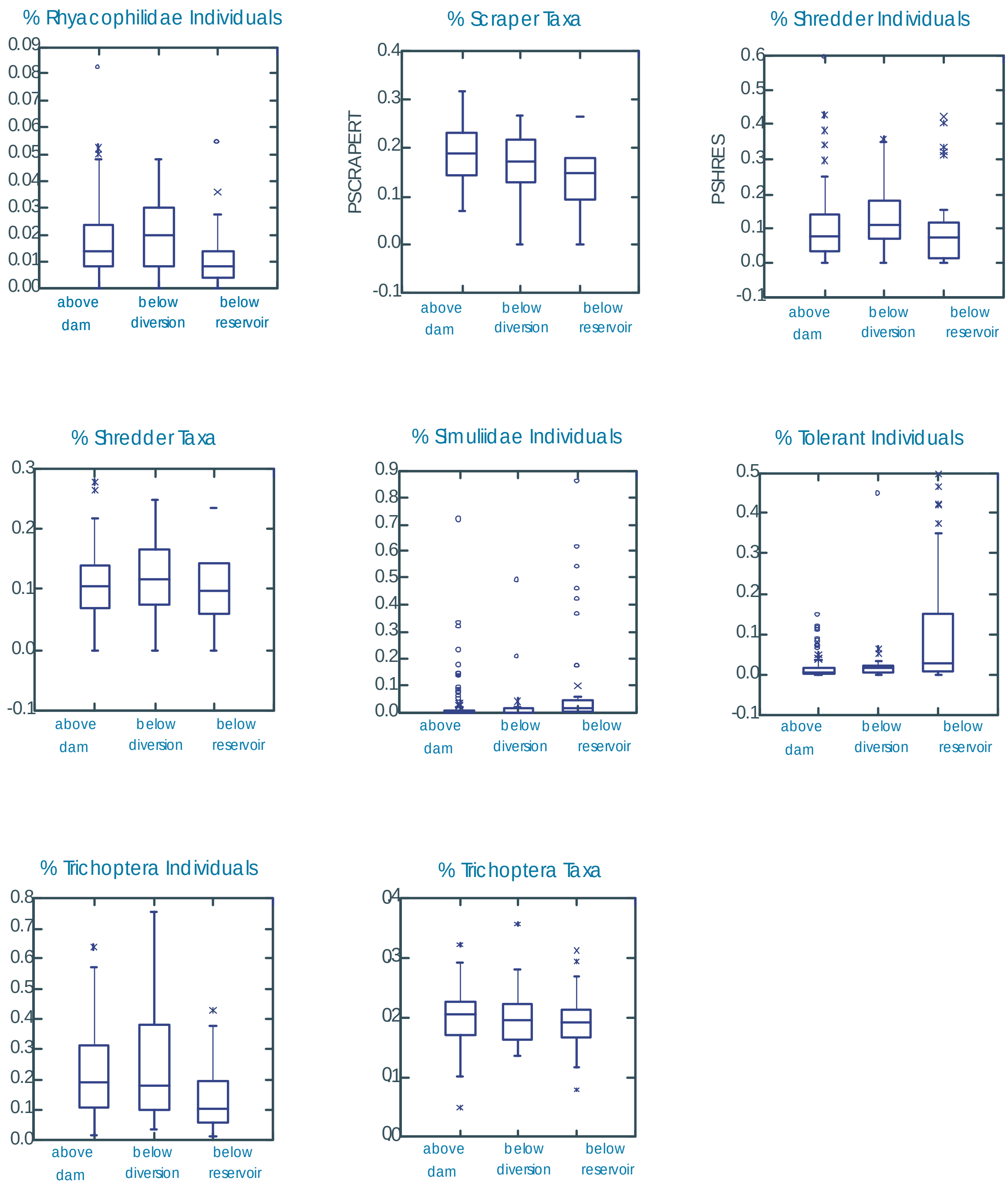


Table 3. Seventy-seven metrics evaluated for discrimination between above-dam reference sites and below-dam test sites

METRIC	REASON FOR REJECTION (if applicable)
# EPT Taxa	**Not rejected**
# CF+CG Taxa	poor discrimination
# Coleoptera Taxa	**Not rejected**
# Collector-Filterer Taxa	poor discrimination/range
# Collector-Gatherer Taxa	poor discrimination
# Diptera Taxa	poor discrimination
# Elmidae Taxa	poor discrimination/range
# Ephemerellidae Taxa	poor discrimination
# Ephemeroptera Taxa	redundant with EPT
# Hydropsychidae Taxa	poor discrimination
# Intolerant EPT Taxa	redundant with EPT
# Intolerant Taxa	redundant with EPT
# Mollusca Taxa	range
# Non-insect Taxa	poor discrimination
# Plecoptera Taxa	redundant with EPT
# Predator Taxa	redundant with EPT
# Scraper Taxa	biologically redundant with %Non-Gastropod scrapers, which omits snails
# Shredder Taxa	poor discrimination/range
# Trichoptera Taxa	redundant with EPT
% Amphipoda Individuals	range
% Baetidae Individuals	poor discrimination
% CF+CG Individuals	**Not rejected**
% CF+CG Taxa	biologically redundant with %CF+CG Individuals
% CF Taxa	poor discrimination
% CG Taxa	poor discrimination
% Chironomidae Individuals	poor discrimination
% Collector-Filterer Individuals	poor discrimination
% Collector-Gatherer Individuals	poor discrimination
% Corbicula Individuals	range
% Crustacea Individuals	range
% Diptera Individuals	poor discrimination
% Diptera Taxa	poor discrimination
% Dominant Taxon	poor discrimination, but about the same as %TolerT
% Elmidae Individuals	range
% Ephemeroptera Individuals	poor discrimination
% Ephemeroptera Taxa	poor discrimination
% EPT Individuals	poor discrimination
% EPT Taxa	poor discrimination
% Intolerant EPT Individuals	redundant with lots of other more responsive metrics
% Gastropoda Individuals	range

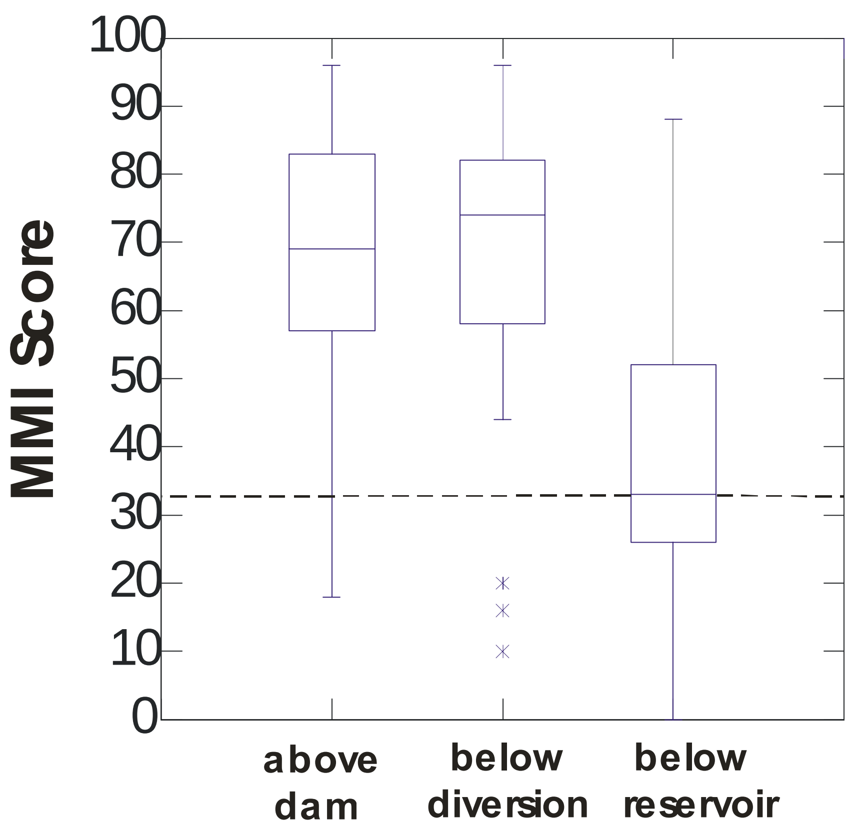
Table 3, continued

METRIC	REASON FOR REJECTION (if applicable)
% Glossosomatidae Individuals	poor discrimination/range
% Hydropsychidae Individuals	poor discrimination
% Hydroptilidae Individuals	poor discrimination/range
% Intolerant Individuals	redundant with %CFCG Individuals
% Intolerant Diptera Individuals	poor discrimination/range
% Intolerant Ephemeroptera Individuals	poor discrimination
% Intolerant Scraper Individuals	poor discrimination
% Intolerant Taxa	redundant with EPT
% Intolerant Trichoptera Individuals	biologically redundant with EPT, and "% of Trichoptera that are intolerant" is better
% Mollusca Individuals	poor discrimination/range
% Non-*Baetis* or *Fallceon* Ephemeroptera Individuals	poor discrimination
% Non *Hydropsyche* or *Cheumatopsyche* Trichoptera Individuals	poor discrimination
% Non-Gastropoda Scraper Individuals	**Not rejected**
% Non-*Hydropsyche* Hydropsychidae Individuals	poor discrimination/range
% Non-Insect Taxa	poor discrimination
% of Ephemeroptera that are Intolerant	biologically redundant with EPT
% of Trichoptera that are Intolerant	biologically redundant with EPT
% Oligochaeta Individuals	poor discrimination/range
% Perlodidae Individuals	poor discrimination/range
% Philopotamidae Individuals	poor discrimination/range
% Plecoptera Individuals	poor discrimination
% Plecoptera Taxa	poor discrimination
% Predator Taxa	poor discrimination
% Predator Individuals	poor discrimination
% Rhyacophilidae Individuals	poor discrimination
% Scraper Taxa	poor discrimination
% Scraper Individuals	redundant with %NGS
% Shredder Taxa	poor discrimination
% Shredder Individuals	poor discrimination
% Simuliidae Individuals	poor discrimination/range
% Tolerant Individuals	poor discrimination/range
% Tolerant Taxa	**Not rejected**
% Trichoptera Individuals	poor discrimination/range
% Trichoptera Taxa	poor discrimination/range
Shannon Diversity	redundant with EPT
Taxonomic Richness	redundant with EPT
Tolerance Value (Average)	redundant with EPT

Table 4. Scoring ranges for 5 component metrics in the ad hoc hydropower MMI

Score	# EPT Taxa	# Coleoptera Taxa	% CF+CG Individuals	% Non-Gastropoda Scrapers	% Tolerant Taxa
0	≤ 8	0	≥ 90	0	≥ 19
1	9–10		84–89	1–4	18
2	11–12	1	78–83	5–8	16–17
3	13–14		72–77	9–12	14–15
4	15–16	2	66–71	13–16	13
5	17–18		60–65	17–19	11–12
6	19–20	3	54–59	20–22	9–10
7	21–22		48–53	23–26	8
8	23–24	4	42–47	27–30	6–7
9	25–26	5	36–41	31–34	4–5
10	≥ 27	≥ 6	≤ 35	≥ 35	≤ 3

Figure 4. Box plots of MMI scores for above-dam reference sites, sites below diversion dams and sites below reservoirs. Dotted line shows impairment threshold two standard deviations below the mean of reference.



4.0 Discussion

The analyses presented here have characterized general responses of BMI assemblages to the cumulative effects of hydrologic alterations caused by hydropower operations and provide a preliminary context for the interpretation of BMI data being collected as part of hydropower relicensing projects in California's Sierra Nevada. Metrics that were responsive to hydropower operations in the present study also were responsive to cumulative effects of non-point source pollution in other regions of California (Ode et al. 2005; Rehn et al. 2005). This suggests that indices developed for ambient surface water monitoring in those regions could also be used for water quality monitoring downstream of regional hydropower projects.

Study designs in which targeted-riffle protocols force serial samples to be collected several miles downstream of dams limit the detection of BMI responses that often occur over much smaller spatial scales in lower order rivers. At this scale, tributaries often help to reset ecological conditions toward natural conditions as distance downstream of a dam increases (Stanford and Ward 2001). This limitation, in addition to the potential for other human land uses in study watersheds to confound detection of hydropower-specific responses, may explain the inconsistencies that were observed in metric responsiveness to distance downstream from dams at different spatial scales. Multi-habitat sampling should be considered for bioassessments of wadeable streams conducted as part of hydropower relicensing projects to avoid inconsistencies in the scale over which BMI samples are collected. The reachwide sampling method used by the EPA's Environmental Monitoring and Assessment Program (EMAP) is a systematic, objective protocol in which habitats are sampled in approximate proportion to their occurrence in streams (Peck et al. 2006). Rehn et al. (2007) found that reachwide sampling is more precise than targeted-riffle sampling, although the two methods generally produce consistent stream condition assessments in large-scale ambient programs when both methods were applied side-by-side. Boatable protocols should be considered for use on larger rivers.

Several studies have documented similar responses of BMI assemblages to flow and habitat alterations caused by hydropower operations as those presented here, especially in the relatively disturbance-intolerant insect orders Ephemeroptera, Plecoptera, and Trichoptera ("EPTs"). For example, Cushman (1985) reviewed numerous papers that documented declines in most EPT populations and increases in the proportion of tolerant taxa below hydroelectric dams. Cazaubon and Giudicelli (1999) found that BMI assemblages in regulated sections of the Durance River in southern France were characterized by lower density and diversity than similar, non-regulated sections in the same region. Rader and Belish (1999) found that BMI density and diversity was greatly reduced downstream of diversion dams that caused severe flow alteration, especially in EPT taxa. They also found that several intolerant EPT genera were extirpated downstream of severe and prolonged water diversions, but that BMIs were relatively resilient to mild flow alterations, a result similar to that shown here in which sampling reaches below most low-head, "run of the river" diversion dams supported assemblages very similar to reference reaches. Camargo et al. (2004) found similar responses in several BMI metrics as a result of nutrient enrichment caused by deep release reservoirs in headwater reaches of mountain streams in Spain, including a decline in several of the EPT metrics, % predators, % shredders and Simpson's diversity index, and an increase in % dominant taxon. However, by contrast with the present study, % scrapers increased below impoundments. Lessard and Hayes (2003) found significant reductions in EPT richness below small, surface release dams that increase downstream water temperature. Voelz et al. (1994) found that populations of several species of Trichoptera were nearly eliminated downstream of the Granby Dam on the upper Colorado River after warm surface water was released for 16 days in summer. Similarly, Fraley (1979) found a decrease in macroinvertebrate diversity directly below a surface release dam, and then increases in diversity toward upstream levels at sites further downstream.

Future analyses could assess specific responses of BMI assemblages to different types of alterations in thermal regimes caused by surface release versus deep release hydroelectric dams, although several published studies cited herein indicate that any significant thermal alteration has deleterious effects on sensitive BMI assemblages. In addition, with the possible exception of temperature measurements, the qualitative physical habitat data that are currently collected in association with BMI samples are insufficient to assess BMI responses to specific hydropower associated stressors that most affect the distribution and ecological success of lotic biota, including substrate composition, suspended sediment load, turbulence, near-bed hydraulics, channel dimensions, riffle-pool distributions, and the availability of course and fine particulate organic matter (Allan 1995; Gore et al. 2001; Bunn and Arthington 2002).

Thorough understanding of BMI responses to adverse changes in stream conditions that most govern their distributions has great potential in establishing habitat suitability criteria for water quality indicator taxa like EPT. Such criteria in combination with taxon-specific optima and tolerances for habitat parameters and flow velocity may provide additional management options to stream regulators. For example, velocity, depth, and substrate preferences for ecological indicators like EPT could be developed at the genus, family, or even order level from large datasets where physical variables were measured quantitatively, such as EMAP (Kaufmann et al. 1999). Release schedules for hydropower facilities and water abstraction rates for municipalities could be based on macroinvertebrate habitat criteria derived from these preference curves. Flow allocations required to preserve suitable habitat for BMIs are often higher than for benthic fish indicators, and loss of BMI habitat can be two or three times greater than loss of fish habitat under fluctuating flows (Gore 1989; Gore et al. 2001). As processors of allochthonous and authochthonous organic material, BMIs are a critical link in aquatic food webs and are the food base for game and forage fish. Management strategies based on BMI habitat criteria may provide the best protection of complex community structure and a greater proportion of ecological resources, especially in low order streams.

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6.0 Glossary

ABL	California Aquatic Bioassessment Laboratory
ArcView®	GIS software
ATtILA	A software extension of ArcView
BMIs	benthic macroinvertebrates
CalEDAS	An MS Access database
CSBP	California Stream Bioassessment Procedure
EMAP	Environmental Monitoring and Assessment Program
Energy Commission	California Energy Commission
EPA	U.S. Environmental Protection Agency
EPT	Ephemeroptera, Plecoptera, and Trichoptera
FERC	Federal Energy Regulatory Commission
GIS	geographic information systems
MMI	multi-metric index
SWRCB	State Water Resources Control Board
TIGER	A GIS dataset
USGS	U.S. Geological Survey