Boundary Hydroelectric Project (FERC No. 2144)

Study No. 11

Productivity Assessment

Final Report

Prepared for
Seattle City Light

Prepared by
Harry Gibbons, Robert Plotnikoff, Shannon Brattebo, Darlene Siegel, Eugene Welch, and Toni Pennington
Tetra Tech

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Study No. 11: Productivity Assessment
Final Report
Boundary Hydroelectric Project (FERC No. 2144)

1 INTRODUCTION

Study No. 11, Productivity Assessment, was conducted in support of the relicensing of the Boundary Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 2144, as identified in the Revised Study Plan (RSP; SCL 2007) submitted by Seattle City Light (SCL) on February 14, 2007, and approved by the FERC in its Study Plan Determination letter dated March 15, 2007. This is the final report for the 2007 and 2008 study efforts of the Productivity Assessment and represents completion of the study.

Primary, or photosynthetic, production is the ultimate source of energy for food webs. In aquatic systems, primary producers are phytoplankton (suspended algae), periphyton (attached algae), and aquatic macrophytes (submersed or emergent, rooted and non-rooted vascular plants). Photosynthesis is dependent on light energy and utilization of that energy as growth is dependent on primary nutrients carbon, nitrogen, and phosphorus. Productivity is the rate of growth or, in the case of primary production, the rate of photosynthesis (conversion of inorganic carbon to organic carbon). For the purposes of Study 11, productivity was not measured directly, but its potential was assessed relative to the net result of photosynthesis, standing crop or net production, as measured by chlorophyll *a* in phytoplankton and periphyton. Potential productivity of macrophytes, zooplankton, and benthic macroinvertebrates (BMI) was evaluated relative to historic operations under representative wet, dry, and average years. Relative nutrient availability and light were used in this assessment of the production of the Boundary Reservoir and specifically how Boundary Dam operations affect net production within the Reservoir.

The descriptions and criteria for Habitat Suitability Curve (HSC)/Habitat Suitability Index (HSI)[1] review the physical constraints on macrophyte and periphyton production—substrate, water velocity, and depth. These criteria set limits on the physical conditions for macrophytic plants and periphytic algae to grow and include light availability (i.e., depth). However, the

[1] The abbreviation HSI is used in this document to refer to either HSI models or HSC, depending on the context. HSI models provide a quantitative relationship between numerous environmental variables and habitat suitability. An HSI model describes how well each habitat variable individually and collectively meets the habitat requirements of the target species and lifestage, under the structure of Habitat Evaluation Procedures (USFWS 1980). Alternatively, HSC are designed for use in the Instream Flow Incremental Methodology to quantify changes in habitat under various flow regimes (Bovee et al. 1998). HSC describes the instream suitability of habitat variables related only to stream hydraulics and channel structure. Both HSC and HSI models are scaled to produce an index between 0 (unsuitable habitat) and 1 (optimal habitat). Both models and habitat index curves are hypotheses of species-habitat relationships and are intended to provide indicators of habitat change, not to directly quantify or predict the abundance of target organisms. For the Project studies, HSC (i.e., depth and velocity) and HSI (i.e., light availability, duration of inundation and dewatering) models will be integrated to analyze the effects of operations scenarios.

nutrient regime determines if and how much growth will occur. Nutrient levels in Boundary Reservoir are low, due to the low concentration entering the reservoir from upstream and the apparent lack of significant nutrient sources within the Boundary Reservoir drainage basin (Ecology 2005; SCL 2006).

The physical constraints on phytoplankton production are mixing and photic zone depths. Taken together, they determine how much light a vertically mixed phytoplankton population will receive. In a well-mixed and deep water body, light may be insufficient for net production (e.g., organic carbon produced beyond loss) to occur; one example is Lake Washington in winter. If light is sufficient, however, the biomass produced will be directly related to nutrient content, which usually is phosphorus. Again, background nutrient levels in Boundary Reservoir are not considered with the HSI approach and phytoplankton production is expected to depend on Reservoir area and light availability as factors that control growth.

Productivity is not being measured directly in this study. However, chlorophyll *a* concentration within phytoplankton is usually directly related to biomass and to productivity. Also, biomass:chlorophyll *a* ratio is typically directly related to nutrient content, e.g., total phosphorus concentration. Biomass may also be impacted by zooplankton grazing in oligotrophic water, i.e., approximately 100 percent of net productivity may be consumed (Welch and Jacoby 2004). That may not occur in short residence time environments such as Boundary Reservoir, which has a residence time of approximately 1 to 4 days.

Secondary production includes zooplankton, BMI, and fish. Zooplankton are more restricted by water residence time because their growth rates are slower. Nevertheless, environments with short residence times of 5 days or less (e.g., the Duwamish River in Seattle) produce an increase in biomass of phytoplankton (70 micrograms per liter [µg/L]) and zooplankton densities (50 organisms/L), although such environments are nutrient-rich (Welch and Jacoby 2004) when compared to Boundary Reservoir.

2 STUDY OBJECTIVES

The goal of the Productivity Assessment study was to determine the effects of current Project operations (e.g., wet, dry, and average hydraulic conditions) on primary and secondary production in Boundary Reservoir. The objective of this study was to quantify indices of primary and secondary production in reaches of the Pend Oreille River within the Project area under current (wet, dry, and average hydraulic conditions) operations. The Productivity Assessment consisted of evaluating indices of primary (nutrients, phytoplankton, periphyton, and macrophytes) and secondary (zooplankton and BMI) production. Evaluating the effects of operations scenarios was not addressed in this final report; that evaluation will occur during the Integrated Resource Analysis (IRA) and reported in the License Application (LA). The current results outline an interpretation strategy as a template that will be used to evaluate effects from other scenarios.

3 STUDY AREA

The study area encompassed Boundary Reservoir and the Boundary tailrace, or that section of the Pend Oreille River between Box Canyon Dam (Project river mile [PRM] 34.5) downstream to the confluence with Red Bird Creek (PRM 13.9) (Figure 3.0-1). The Mainstem Aquatic Habitat Model (part of Study 7, Mainstem Aquatic Habitat Modeling Study [SCL 2009a) was used to evaluate the effects of existing Project operations and will be used to evaluate the effect of various operations scenarios on aquatic habitats, biota, and production in the Pend Oreille River.

The study area was divided into the following four reaches (Figure 3.0-1):

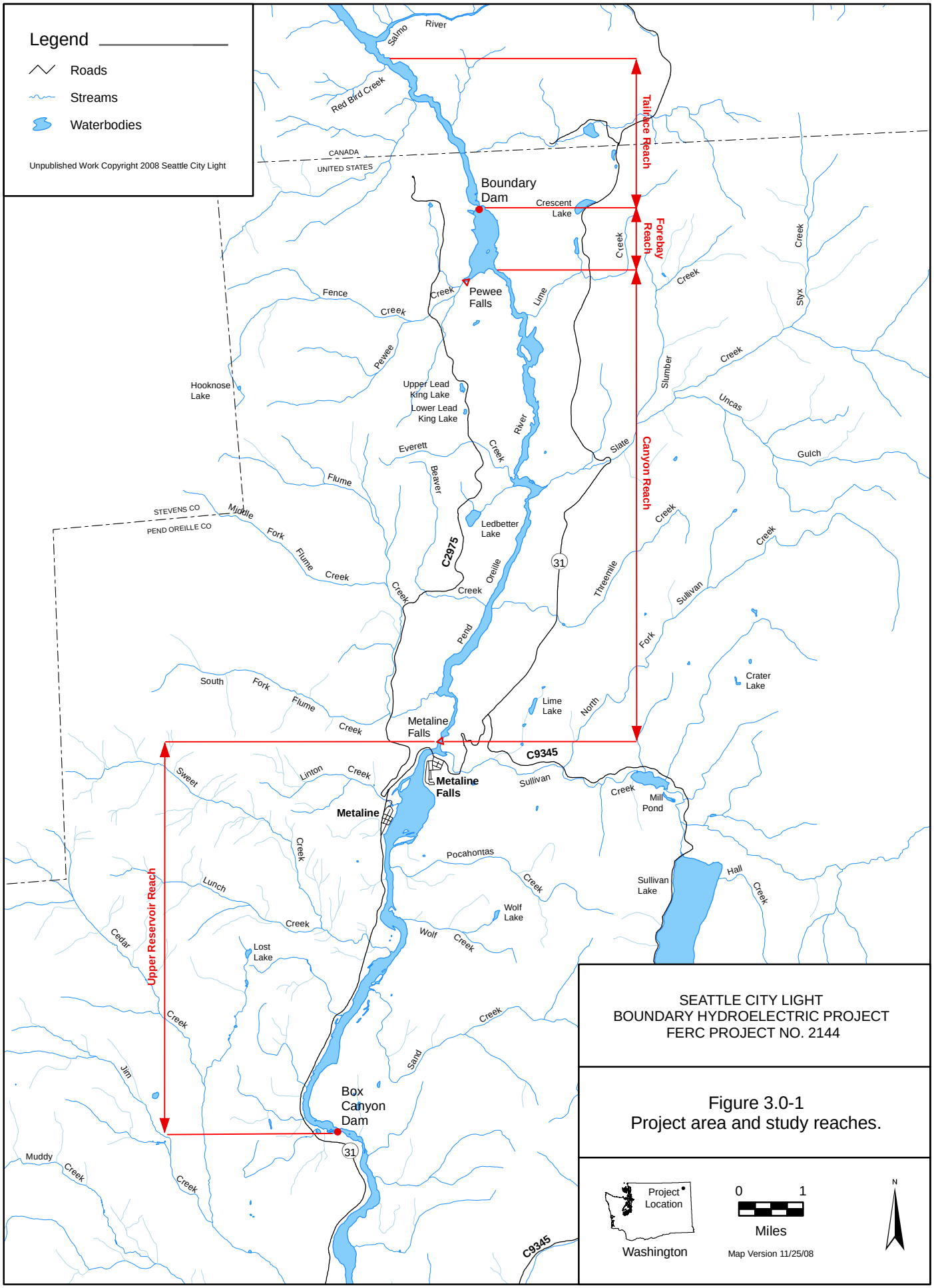
Boundary Reservoir (Above Boundary Dam)

- Forebay Reach—Boundary Dam to downstream end of Z Canyon to (PRM 17.0–18.0)
- Canyon Reach—Downstream end of Z Canyon to Metaline Falls to (PRM 18.0–26.8)
- Upper Reservoir Reach—Metaline Falls to Box Canyon Dam (PRM 26.8–34.5)

Downstream of Boundary Dam (Seven Mile Reservoir)

- Tailrace Reach—Boundary Dam downstream to Red Bird Creek confluence with the Pend Oreille River, British Columbia (PRM 17.0–13.9)

The effects of operations scenarios on aquatic habitats below Boundary Dam are influenced by Seven Mile Project operations. At low Seven Mile Reservoir water surface elevations, riverine habitat is present in the Pend Oreille River downstream to the confluence with Red Bird Creek. At high Seven Mile Reservoir water surface elevations, much of the riverine habitat above the Red Bird Creek confluence becomes reservoir habitat. The Study 7 Mainstem Aquatic Habitat Modeling effort included collecting data on up to 3.1 miles of the Pend Oreille River channel exposed for low Seven Mile Reservoir water surface elevations and performing modeling in the Tailrace Reach similar to the three reaches above Boundary Dam.



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BOUNDARY HYDROELECTRIC PROJECT
FERC PROJECT NO. 2144

Figure 3.0-1
Project area and study reaches.

4 METHODS

The effects of Project operations on aquatic productivity were assessed using six indices of production: nutrients, phytoplankton, periphyton, aquatic macrophytes, zooplankton, and BMI. No attempt was made to integrate the six indices into a measurement of total reservoir production. Each production component was assessed as a potential percent change relative to existing Project operations, and each constituent was evaluated and reported as a separate index of production. Two separate approaches were used for the assessment. The first approach was used for nutrients and planktonic fauna (phytoplankton and zooplankton). The second approach was used for the attached fauna (macrophytes, BMI, and periphyton).

Productivity for nutrients, phytoplankton, and zooplankton under existing Project operations was estimated using measurements of upper and lower bounding conditions and interpolation between those bounds. Potential changes in production will be evaluated under different operations scenarios in the IRA process. Measurements of nutrients, phytoplankton, and zooplankton were collected in Boundary Reservoir under operational and environmental conditions experienced in 2007 and 2008. The measurements of Project conditions represent one bounding condition and were compared to measurements of conditions in the Box Canyon tailrace as the other bounding condition. Box Canyon Reservoir is located immediately upstream of the Project and is exposed to a smaller range of water surface elevation fluctuation.

4.1. Tools Used for Determining Biological Production

Evaluation of habitat throughout the Boundary Reservoir and the energy transfer that promotes inhabitation of these potential areas is evaluated through estimates of weighted usable area (WUA) calculated from the Mainstem Aquatic Habitat Model (Study 7 [SCL 2009a]) and the trophic production index (TPI), respectively. The WUA predicts potential for colonization by macrophytes, periphyton, and BMI, but does not describe the existing distribution or abundance of these biological groups in Boundary Reservoir. The calculated TPI scores determine the available food base (energy) for each biological group and whether these requirements are met beginning with the lowest trophic level (i.e., periphyton). The calculated TPI scores also determine if energy flow is restricted at any of the succeeding and higher trophic levels. The WUA estimates are useful for determining the potential habitat available under various hydrologic conditions (wet, dry, and average). The TPI scores inform on whether the increase or decrease in potential habitat (estimated by the WUA) takes into account the limiting factors analysis such as community structure or quality of production based on the available energy flow upward through the trophic levels.

4.1.1. Weighted Usable Area

The WUA values predict potential for colonization by macrophytes, periphyton, and BMI and were estimated from the Mainstem Aquatic Habitat Model (see Study 7 [SCL 2009a]). Information on the response of macrophytes, BMI, and periphyton to changes in hydraulic conditions was also developed as part of the HSI component of Study 7 (see SCL 2009a). Habitat suitability information (i.e., HSI curves) represents a functional relationship between the independent variables depth, velocity, substrate, and frequency of inundation/dewatering and the

response of organisms to a gradient of the independent variable (suitability), which is expressed over a scale of 0.0 (poor) to 1.0 (best). Output from the Hydraulic Routing Model (HRM) component of Study 7 (see SCL 2009a) predicted hourly flow and water surface elevations at transects within the Project area. The HRM was used to predict depth and velocities within cells, or transect subdivisions. The HSI curves were used in the Mainstem Aquatic Habitat Model to quantify the area of Pend Oreille River channel containing potentially suitable habitat. This process was repeated to determine the WUA available in relation to flow conditions, which provided an estimate of both the quantity and quality of available species-specific habitat.

The WUA estimates for periphyton and BMI had bounding limits set as maximum water surface elevations when flows were 80,000 cubic feet per second (cfs) and greater. To prevent temporary inclusion of elevation ranges in the WUA values during water surface elevation fluctuations at which macrophytes will not be established, upper and lower elevation limits for the WUA calculations were set for macrophytes. For periphyton, only a lower limit was set. For BMI, neither an upper nor lower limit was set.

Macrophyte bounding limits for the calculation of WUA were based on the combination of the HRM and information from the depth HSI curve. The bounding limits were based on typical water surface elevations that occurred during the March and April period of the average hydrologic year (2002). The March through April timeframe corresponds to the critical period for establishment of macrophyte beds. To represent typical conditions during the critical period, the water surface elevation profile from the HRM for a median forebay elevation of 1,988 feet NAVD 88 (1,984 feet NGVD 29)[2] and a median inflow into Boundary Reservoir of 18,800 cfs were used to define the upper bounding limits (see Study 7 Final Report [SCL 2009a] for further explanation). Above the elevations defined by this profile, the model-calculated WUA was set to zero. In the Tailrace Reach, a median Seven Mile forebay elevation of 1,726 feet NAVD 88 (1,722 feet NGVD 29) and a median outflow from Boundary Dam of 24,200 cfs was used to define the upper bounding limit. Similarly, a lower bounding limit for macrophytes of 33 feet below the average hydrologic year median flow, median forebay elevation water surface profile was set based on the maximum suitable depth from the HSI curve. Below these elevations, the model-calculated WUA was set to zero. For analysis of operations scenarios, the bounding limits can be adjusted based on changes from the historic condition for the median flow and median forebay water surface elevations for the operations scenario being evaluated. The macrophyte WUA estimates used the duration of dewatering HSI curve for "established" macrophyte beds and not the "new bed" HSI curve. When an operations scenario is expected to result in expansion of the macrophyte WUA, the model will use the new bed duration of dewatering curve during March and April hourly time-step calculations and the established bed duration of dewatering curve for the remainder of the year when macrophytes are present.

The lower bounding limit for periphyton WUA was based on the combination of the HRM and information from the depth HSI curve. The bounding limits was set 54 feet below the typical

[2] SCL is in the process of converting all Project information from an older elevation datum (National Geodetic Vertical Datum of 1929 [NGVD 29]) to a more recent elevation datum (North American Vertical Datum of 1988 [NAVD 88]). As such, elevations are provided relative to both data throughout this document. The conversion factor between the old and new data is approximately 4 feet (e.g., the crest of the dam is 2,000 feet NGVD 29 and 2,004 feet NAVD 88).

water surface elevations that occurred during the March and April period of the average hydrologic year (2002). To represent typical conditions during this period, 54 feet was subtracted from the water surface elevation profile from the HRM for a median forebay elevation of 1,988 feet NAVD 88 (1,984 feet NGVD 29), and a median inflow into Boundary Reservoir of 18,800 cfs was used to define the upper bounding limits. Below the elevations defined by this profile, the model-calculated WUA was set to zero. In the Tailrace Reach, 54 feet was subtracted from the water surface profile corresponding to a median Seven Mile forebay elevation of 1,726 feet NAVD 88 (1,722 feet NGVD29) and a median outflow from Boundary Dam of 24,200 cfs was used to define the lower elevation limit for periphyton.

WUA is used in this report to develop the description of aquatic habitat for baseline conditions using the wet, dry, and average years from the historic record. WUA will be used in the IRA process to compare the effects of several operations scenarios on aquatic habitat for production for macrophytes, periphyton, and BMI under existing Project operations. This process will be completed under various operations scenarios as part of the IRA to be conducted in support of the LA.

4.1.2. Trophic Production Indices

TPIs for nutrients, phytoplankton, zooplankton, macrophytes, periphyton, and BMI were calculated in this study to account for critical factors that would promote growth or limit production of these biological groups in Boundary Reservoir.

The TPI comprised several metrics that are known to have direct influence on establishment and growth of each biological group. The individual metrics were factors known from technical literature and that were reported as influential in promoting sustained biological communities through an available food base. The combination of these metrics for each biological group describes the quality of habitat estimated from the Mainstem Aquatic Habitat Model, and whether habitat colonization predictions from WUAs reflect potential changes in production (biomass) or area of production.

4.1.3. Predicting Potential Production: Interpreting the WUA-TPI Relationship

The coupling of estimates for WUA and analysis of the proportion of habitat that can actually be expected to support the biological groups (TPI) was critical for explaining any differences between predicted habitat area and indices that describe relative production.

WUAs were calculated for each biological group (e.g., macrophytes, periphyton, and BMI) on an hourly time-step. The amount of WUA for each biological group increased and decreased based on the predictor variables (e.g., depth, velocity, substrate, duration of de-watering, and duration of inundation) as a response to water surface elevation fluctuations in the Reservoir.

The TPI scores are an aggregate of the individual biometric evaluations for each biological group. The TPI score scoring range is from 0–1 with the higher number indicative of higher potential production. The TPI scores were constructed for each biological group in order to determine if energy transfer in the form of a food base is equal to or higher than the next trophic step (e.g., primary producer to primary consumer). The TPI score ranges were compared in

pairs, food base and consumer (e.g., nutrients with phytoplankton, phytoplankton with zooplankton, zooplankton with BMI), to determine if the first group (the food base) and trophic score range was equal to or greater than the second group (the consumer base) and trophic score range. If the food base score range was smaller than the consumer base, the production of the consumer (e.g., phytoplankton, zooplankton, or BMI) base was limited by the food base (e.g., primary producer). The WUA and the TPI should change in the same direction as a response to water surface elevation fluctuations if potential available habitat (the WUA estimate) is fully available. If the TPI score is constant and remains unchanged as a response to water surface elevation fluctuation, an increase in potential available habitat (i.e., WUA) does not mean production will increase in this area of Boundary Reservoir.

TPIs were expected to respond to environmental changes in the same direction (e.g., increasing or decreasing) as WUA estimates of potential habitat. However, changes in TPI may not have been the same magnitude as WUA indicating differences in sensitivity of the two assessment tools to environmental stimuli (e.g., Project operations or natural seasonal fluctuation). Analysis of production conditions as a response to hydrologic conditions used a combination of WUA estimates and TPI scores and was guided by a basic ecological concept that describes the flow and needs of energy at each step of the "trophic ladder." Each of the biological groups (e.g., phytoplankton, zooplankton, macrophytes, periphyton, and BMI) represented each step in the trophic ladder and served as a consumable food base for the next highest step. The availability of each biological group as a food source for the next highest step was important for understanding the factor(s) limiting full production of biomass in each of the trophic steps. Specific steps for calculating macrophyte, BMI, and periphyton indices, and interpolating productivity indices for nutrients, phytoplankton, and zooplankton, are outlined in Section 4.4.

4.2. Data Collection and Compilation

Data were collected and compiled from other Project relicensing studies to be used in the productivity analyses. Data have been compiled from the following: Study 5, Water Quality Constituent and Productivity Monitoring Final Report (SCL 2009b); Study 6, Evaluation of the Relationship of pH and Dissolved Oxygen to Macrophytes in Boundary Reservoir Final Report (SCL 2009c); and the Mainstem Aquatic Habitat Model (Macrophytes, Periphyton, and Macroinvertebrates subsection) of the Study 7 Final Report (SCL 2009a). Detailed sampling methods implemented for collecting nutrient, phytoplankton, zooplankton, periphyton, benthic invertebrate, and aquatic macrophyte data are outlined in the aforementioned reports.

Data describing the physical and hydraulic characteristics of the Pend Oreille River were collected during the 2007 and 2008 field seasons along transects.

Nutrient, Secchi depth, phytoplankton, and zooplankton data were provided by Study 5 (methods are described in the Study 5 Final Report [SCL 2009b]). These data were available at eight stations by season in deep water and littoral habitats (SCL 2009b). Nutrient data are in concentration form and Secchi depth data in meters; phytoplankton abundance is presented as chlorophyll *a* concentration; and zooplankton data are in organisms per unit volume. Additional indices of zooplankton abundance, such as species composition and size, were developed as described in the Study 5 Final Report (SCL 2009b). These indices were available to supplement and interpret changes in zooplankton abundance measured as organisms per unit volume.

Nutrient data were only available in the deep water habitats, whereas phytoplankton and zooplankton data were available in the deep water habitat and littoral habitats without macrophytes. As described in the Study 5 Final Report (SCL 2009b), zooplankton was collected every 2 hours over a 24-hour cycle during the on/off-load-following to provide an indication of diurnal and drift changes in the zooplankton community. Total phosphorus and total Kjeldahl nitrogen (TKN) were representative of nutrient availability for production.

An assessment of macrophyte production was conducted under Study 7, macrophyte HSI development subsection. This information was used in the Mainstem Aquatic Habitat Model to estimate the WUA for macrophyte production under existing Project operations. Results were combined with the information under the present study to estimate aquatic productivity for macrophytes with Boundary Reservoir by reach (see Figure 3.0-1 in SCL 2009a).

Periphyton and BMI data were generated to support results from the Mainstem Aquatic Habitat Model from Study 7 (Appendix 7 and Appendix 8 in SCL 2009a). These studies provided HSI information, which was used in the Mainstem Aquatic Habitat Model to quantify the effects of Project operations on BMI and periphyton. Results were combined with the information under the present study to estimate aquatic productivity for littoral habitats by reach. The BMI data were summarized in number per unit area and periphyton data were summarized in biomass or chlorophyll *a* per unit area. A description of completed sampling in 2007 and 2008 in Boundary Reservoir and Box Canyon Reservoir is provided in Table 4.2-1.

Table 4.2-1. Summary of water quality field work completed in 2007 and 2008.

Parameters	2007		2008	
	Month/Season	**Reach**	**Month/Season**	**Reach**
Nutrients (TP, SRP, TKN)	May, June, July, August, September, November	Forebay, Canyon, Upper Reservoir, Tailrace	March	Forebay, Canyon, Upper Reservoir, Tailrace
Chlorophyll *a*	May, June, July, August, September, November	Forebay, Canyon, Upper Reservoir, Tailrace	March	Forebay, Canyon, Upper Reservoir, Tailrace
Secchi disk depth	May, June, July, August, September, November	Forebay, Canyon, Upper Reservoir, Tailrace	March	Forebay, Canyon, Upper Reservoir, Tailrace
Turbidity	May, June, July, August, September, November	Forebay, Canyon, Upper Reservoir, Tailrace	March	Forebay, Canyon, Upper Reservoir, Tailrace
Periphyton and BMI	Spring, Summer, Fall	Forebay, Canyon	Winter	Forebay, Canyon
Macrophyte Abundance and Distribution	August	Forebay, Canyon, Upper Reservoir	August	Stranding and Trapping Areas (Upper Reservoir)

Table 4.2-1, continued…

Parameters	2007		2008	
	Month/Season	Reach	Month/Season	Reach
Zooplankton	May, June, July, August, September, November	Forebay, Canyon, Upper Reservoir, Tailrace	March	Forebay, Canyon, Upper Reservoir, Tailrace
24-Hour zooplankton drift	June, August	Forebay, Tailrace	March	Forebay, Tailrace

4.3. Trophic Production Index Calculations: Nutrient Concentrations, Phytoplankton and Zooplankton Production

Indices of aquatic production were calculated for nutrients, phytoplankton, and zooplankton for three hydraulic years representing wet, dry, and average conditions under existing Project operations. Data collected in Boundary Reservoir as described in Sections 4.1 and 4.2, along with literature values and professional judgment, were used to construct indices of 2007/2008 nutrient concentrations, and phytoplankton and zooplankton production.

The 2007/2008 operations and water surface elevation fluctuations under wet, dry, and average hydrologic conditions were used to assess the relative amount of production under existing Project operations. Relative production for other scenarios can be evaluated and calculated, based on hydrologic and biological conditions under each scenario, using the aquatic production indices developed in this study.

Indices were developed for each of the trophic parameters (nutrients, phytoplankton, and zooplankton) in order to indicate production levels under existing Project operations (Appendix 1). The index developed for each trophic parameter was based upon several metrics that serve as primary factors influencing potential for production and magnitude of production. A complete list of metrics considered for inclusion in each of the final trophic production indices can be found in Appendix 2. The list for each of the biological groups and nutrients was further refined based on availability of information that enabled scoring and limited to variables where quantifiable information could be generated.

The metrics that promote or limit production of the biological groups (e.g., phytoplankton, zooplankton) considered in this study are presented in Table 4.3-1. This abbreviated list was developed from a more inclusive list of factors initially evaluated. For a complete list of metrics initially considered see Appendix 2, Table A.2-1. The level of influence of a metric on production was based on a categorical score (e.g., high, medium, or low). Each high, medium, and low ranking was assigned as score of 5, 3, or 1, respectively. A high score of 5 meant the metric had a positive influence on increasing production for a biological group. A low score of 1 meant the metric diminished the level of production for a biological group (Table 4.3-1). Depending on the rank of each metric under a trophic parameter (e.g., phytoplankton), some diminished potential production and others enhanced potential production. Multiple metrics were included to calculate each trophic parameter to acknowledge that multiple factors influence production simultaneously and should be combined to reflect reality. All of the categorical

scores (e.g., 5, 3, or 1) were multiplied by a corresponding weighting factor, summed, and divided by the highest total potential score and converted to a percentage expression. These production index scores were used to assess production for each trophic parameter. A detailed description of how and why metrics were scored is provided in Appendix 1.

Table 4.3-1. Metric index scoring system for nutrients, phytoplankton, and zooplankton in Boundary Reservoir.

Metric	Weighing Factor	Low	Medium	High
Index Scoring—Nutrients				
Inflow (µg/L)	1.00	≤12	13–20	>20
Sedimentation (Retention time, days)	0.20	>5	3–5	<2
Index Scoring—Phytoplankton				
Retention time (days)	0.75	<1.5	1.5–5	>5
Light (Secchi, m)	0.50	<2	2–4	>4
Inflow (flow, cfs)	0.90	<20,000	20,000–40,000	>40,000
Mixing Depth (ft)	0.20	>60	30–60	<30
Phosphorus (µg/L)	1.00	≤12	13–20	>20
Index Scoring—Zooplankton				
Retention time (days)	0.80	<3	3–7	>7
Inflow (flow, cfs)	1.00	<20,000	20,000–40,000	>40,000
Mixing Depth (feet)	0.20	>60	30–60	<30
Phytoplankton (µg/L Chlorophyll *a*)	0.25	<2	2–8	>8

Notes:
cfs – cubic feet per second
µg/L – microgram per liter
m – meter

4.4. Weighted Usable Area and Trophic Production Index Calculations: Macrophytes, Periphyton, and BMI

Indices of aquatic production were calculated for macrophytes, periphyton, and BMI under existing Project operations using the Mainstem Aquatic Habitat Model and additional production indices. Each estimate of aquatic production was calculated and reported separately by reach.

Using the HSI curves and information on the depth, velocity, and substrate, the Mainstem Aquatic Habitat Model identified a habitat preference for each cell of the model. Each of these cells was combined to estimate WUA for macrophytes, periphyton, and BMI. Expression of WUA was generated for each biological group (e.g., macrophytes, periphyton, and BMI) during a wet year (1997), a dry year (2001), and an average year (2002) and for each reach (Forebay, Canyon, Upper Reservoir, and Tailrace).

TPIs were developed for macrophytes, periphyton, and BMI to indicate production levels under existing Project operations. The index developed for each trophic parameter was based upon several metrics that serve as primary factors influencing potential for production and magnitude of production.

The metrics that promote or limit production of the biological groups (e.g., macrophytes, periphyton, and BMI) considered in this study are presented in Table 4.4-1. The level of influence of a metric on production was based on a categorical score (e.g., high, medium, or low). Each high, medium, and low ranking was assigned as score of 5, 3, or 1, respectively. A high score of 5 meant the metric had a positive influence on increasing production for a biological group. A low score of 1 meant the metric diminished the level of production for a biological group (Table 4.4-1). Depending on the rank of each metric under a trophic parameter (e.g., macrophytes), some diminished potential production and others enhanced potential production. Multiple metrics were included to calculate each trophic parameter to acknowledge that multiple factors influence production simultaneously and should be combined to reflect reality. All of the categorical scores (e.g., 5, 3, or 1) were multiplied by a corresponding weighting factor, summed, and divided by the highest total potential score and converted to a percentage expression. These production indices scores (0 to 1), in conjunction with the WUA estimates generated from the Mainstem Aquatic Habitat Model (SCL 2009a), were used to assess production for each of the biological groups. A detailed description of how and why metrics were scored is provided in Appendix 1.

Table 4.4-1. Metric index scoring system for macrophytes, periphyton, and BMI in Boundary Reservoir.

Metric	Weighting Factor	Low	Medium	High
Index Scoring—Macrophyte				
Direct Light (hours)	0.25	<4	4–8	>8
Light (feet)	0.50	>33 and Surface	3–17.5	17.5–33
Substrata	1.0	Bedrock	Sandy, gravel, cobble	Silt organics
Velocity (fps)	0.25	>1.6	0.3–1.6	0–0.3
Index Scoring—Periphyton				
Biograzing (Temperature, °C)	0.10	<8	8–12	>12
Burial (Velocity, fps)	0.25	<0.2	0.2–0.4	>0.4
Depth (feet)	0.50	>38 and surface	Surface to 5	5–32
Direct Light (hours)	0.50	<4	4–8	>8
Light and Season (Secchi, m)	0.80	<2	2–4	>4
Phosphorus (µg/L)	1.00	≤12	13–20	>20
Substrata	0.25	Silt or organic	Bedrock, gravel, cobble	Cobble, gravel
Velocity (fps)	0.25	>3.28	0–0.82	0.82–1.64

Table 4.4-1, continued…

Metric	Weighting Factor	Low	Medium	High
Index Scoring—BMI				
Depth (feet)	0.25	<0.3–>60	0.5–<10	10–40
Periphyton (mg chlorophyll *a*/m^2)	1.00	<20	20–60	>60
Substrata	0.50	Bedrock	Dominant-gravel, cobble, with some bedrock	Dominant-Soft substrates (sand, silt, organic matter), gravel, cobble, boulder
Velocity (fps)	0.50	>8.0	0 and 3.8–5.0	0.1–2.6

Notes:
fps – feet per second
m^2 – square meter
mg –milligram
µg/L – microgram per liter

4.5. Compilation of Results

Output from the Mainstem Aquatic Habitat Model (Study 7) reported WUA for macrophytes, periphyton, and BMI on a reach scale and for each of three hydrologic years (i.e., wet, dry, and average). The WUAs reported for these trophic parameters represented the potential for colonization and were further analyzed by comparing their TPI scores to WUA. The energy flow between trophic levels was assessed using the TPIs to determine if restrictions existed in Boundary Reservoir. By understanding the indices, potential barriers to fish production were evaluated.

Each of the production indices was assessed for its influence on higher trophic levels among wet, dry, and average years. These comparisons identified bottlenecks in food web energy transfer and determined whether Project operations had a primary effect or if other factors such as low nutrient availability controlled potential production in the reservoir from the bottom up ("bottom" of the trophic web being periphyton and phytoplankton, "up" being fish production). No attempt was made to integrate the six indices into a single measurement of reservoir productivity; neither were the number of organisms potentially produced under each of the hydraulic conditions (wet, dry, and average hydrologic years) quantified with production index values.

WUA estimates for macrophytes, periphyton, and BMI are expressed in acres and partitioned by the Forebay, Canyon, Upper Reservoir, and Tailrace reaches. The estimates for WUA are further reported on a monthly basis for each of the wet, dry, and average hydrologic years. Interpretation of these results focus on changes between hydrologic years, on a monthly basis, and between reaches to determine the primary physical factors that promote or diminish biological communities. The TPI was used to determine if a change occurred in the same direction, in an opposite direction, or remains unchanged relative to the WUA estimates for each biological group. The TPI is a unit-less number that expresses a relative level of production that exists in each of the temporal (e.g., months) and spatial (e.g., reaches) categories. The

magnitude of the TPI score and the direction of change between months or reaches reveal the extent of biological production possible once WUA estimates are described for the reach and month. This comparison generates useful information about how much of the potential WUA can realize inhabitation by macrophytes, periphyton, and BMI.

5 RESULTS

This section presents a summary of the nutrient, phytoplankton, zooplankton, macrophyte, periphyton, and BMI data collected as part of Study 5 (SCL 2009b), Study 6 (SCL 2009c), and Study 7 (SCL 2009a). A more detailed discussion of water quality, macrophyte abundance, and periphyton and BMI communities in Boundary Reservoir is provided in the studies mentioned above. This section also presents a summary of WUA calculated by the Mainstem Aquatic Habitat Model for macrophytes, periphyton, and BMI as well as the calculated TPI scores for these biological groups. TPI scores for nutrients, phytoplankton, and zooplankton are also summarized below. Production of each trophic parameter or biological group in Boundary Reservoir is discussed in detail as well as the interactions among the biological groups.

5.1. Production Estimates

Data on nutrients, phytoplankton (as measure by chlorophyll *a* concentration), zooplankton, macrophytes, periphyton, and BMI were compiled and analyzed from Studies 5, 6, and 7. Data collected in both 2007 and 2008 were used to assess relative production and trophic cascade interactions in Boundary Reservoir.

5.1.1. Nutrients

Nutrient (nitrogen and phosphorus) concentrations were measured to determine their differences between reaches (see Study 5 [SCL 2009b] for detailed methods and detailed data analysis). Extremely low phosphorus concentrations suggest that phosphorous is the limiting nutrient to overall production within Boundary Reservoir. Therefore, phosphorus was the focus for evaluating the relationship to biological response.

Soluble reactive phosphorus (SRP) is an indicator of the amount of biologically active dissolved phosphorus (orthophosphate) that is readily available for use by flora and fauna (Wetzel and Likens 1979; Welch 1992). Throughout Boundary Reservoir, the SRP concentrations were extremely low (below, at, or barely above the analytical detention level). This further indicates that phosphorus is not only limiting the primary production of phytoplankton, periphyton, and macrophytes but, by extension, organic carbon resources available for secondary and tertiary production.

Similar to SRP, the low concentrations of total phosphorus (TP) contribute to primary production limitation throughout the reservoir. Due to the low SRP concentrations throughout Boundary Reservoir, further reference to phosphorus will be to TP. The low phosphorus availability within the reservoir of either bioavailable SRP or TP is a dominate factor in controlling the potential primary production (i.e., phytoplankton and periphyton) through photosynthesis. Specifically, the summer (June through August) mean TP concentration for Boundary Reservoir was 10.3

µg/L, which indicates an oligotrophic system (or a system with low production) (Welch and Jacoby 2004). Therefore, low phosphorous concentration may be even more important in influencing the level of production than the low hydraulic retention time and light limitation.

Phosphorus available for production within Boundary Reservoir is strongly influenced by inflow and upstream concentrations. Higher inflows were associated with higher TP concentrations and the lowest TP concentrations occurred in summer and fall months, when inflow was low. In addition, TP concentrations were similar longitudinally throughout the reservoir, because no significant TP contributions were observed downstream of Box Canyon Dam.

5.1.2. Phytoplankton

Phytoplankton biomass was expressed as chlorophyll *a* concentration. In addition to nutrients, light and residence time were considered as other important limiting factors to phytoplankton production in this assessment.

Light was evaluated as a function of Secchi disk and turbidity, both of which parameters were measured in Study 5 (SCL 2009b). Light availability is a critical component in production of phytoplankton communities. Depending on physical and biological properties in the water column, light attenuation (or loss of light) will occur with increasing depth such that the rate of photosynthetic activity and hence phytoplankton production also decreases with depth.

Another important factor affecting light availability is mixing. If phytoplankton are mixed deeper than the photic zone, cells will continue to respire but will not photosynthesize and, thus, will not grow. The critical mixing depth is that depth below which cells will not show a net daily growth. Using estimates of light extinction from Secchi disk transparency (assuming the disk disappears at 15 percent of surface intensity) and equations from Oskam (1978; see Welch and Jacoby 2004, p.12)[3], critical depth estimates for Boundary Reservoir are 12 meters for May–June (standard deviation [SD] of 2 m) and 30 meters for July–August (SD of 5 m). Because depths throughout the Forebay and Canyon reaches of the reservoir are greater than 20 m and temperature profiles show the water column is completely mixed, phytoplankton growth may be limited by light as well as phosphorus, especially during spring.

There was a decrease in chlorophyll *a* concentrations from June to July throughout Boundary Reservoir. This decrease may have been due to a decline in inflow nutrient concentrations related to a decrease in flow or simply a decrease in the inflow of phytoplankton from upstream (Box Canyon Reservoir). The decrease in TP during summer (11–15 µg/L to 8–10 µg/L) is probably due to a decrease in live and dead algal cells in the inflow, i.e., fewer cells = less TP. Another reason why phytoplankton (chlorophyll *a*) may not have been growing, especially in late summer when residence time was more favorable, was the decrease in chlorophyll *a*:TP ratios in the Reservoir. The average chlorophyll *a*:TP ratio during May–June was 0.28 and 0.17 during July–August, substantially less than the 0.35 average ratio for productive, phosphorus-limited lakes suggested by Nurnberg (1996). Chlorophyll *a* concentrations in the pelagic regions of the reservoir were not different from concentrations in the littoral regions, one indication of a low

[3] A daily photo period of 10 hours and a respiration coefficient of 0.1 x maximum photosynthetic rate were assumed.

production system. Also, there was no significant change in chlorophyll *a* longitudinally in the reservoir.

Summer declines in chlorophyll *a*:TP ratio may have been due to grazing of phytoplankton by cladoceran zooplankton, which are capable of consuming 100 percent of phytoplankton productivity in oligotrophic lakes (Welch and Jacoby 2004). Cladoceran abundance in the summer (~ 5 animals/L) is considered sufficient to have affected phytoplankton levels. If grazing explains the low chlorophyll *a*:TP ratio in summer (0.17) when critical depth was greatest (30 m) and more light was available to mixed cells than in spring (critical depth = 12 m), then TP concentrations may actually be a more important factor in limiting production than light.

Residence time is another constraint on phytoplankton production that was assessed in this study. Even if the reservoir were consistently thermally stratified during late summer when transparency was greater (and critical depth was 30 m), residence time would limit the development of phytoplankton biomass. At a low inflow of 6,000 cfs (summer low flow), residence time would be approximately 5 to 8 days. At a maximum cell division rate of 1.0 per day, this is enough to increase the biomass approximately 5 to 8 times as observed in other reservoirs that have substantial biomass increase (Pridmore and McBride 1984; Soballe and Threlkeld 1985). However, biomass in Boundary Reservoir did not increase with distance; therefore, nutrients are controlling primary production (see Study 5 [SCL 2009b]).

A combination of favorable light availability (i.e., restricted mixing depth) and residence time has been shown to result in phytoplankton blooms in the Duwamish River Estuary in Seattle (Welch 1969). Phytoplankton grew at about 0.5 per day during neap tide conditions, with a mixing depth of 1 m and residence time of about 8 days, increasing biomass from 3 µg/L to 70 µg/L chlorophyll *a*. Biomass accrual was not possible during spring tide conditions, with residence time of about 3 days and a mixing depth of 4 m. The substantial difference in light availability between 1 and 4 m was because the Duwamish River was turbid from non-algal matter.

The reality in Boundary Reservoir is that, although transparency was high, the great depths (20–63 m) and complete mixing (based on uniform temperature) may marginally restrict light availability to mixed algal cells. If light were adequate, residence time for the whole reservoir volume (approximately 5 to 8 days in late summer at low flow) would have been sufficient to accrue biomass to a level restricted by TP. The fact that cladocerans became relatively abundant in summer indicates that residence time was adequate for that animal's reproduction and thus, adequate for much faster-growing phytoplankton.

Therefore, TP may well be the most limiting factor to primary productivity, despite the harsh physical constraints, in Boundary Reservoir. TP-limitation in Boundary Reservoir is also supported by low periphyton growth and biomass, which was not limited by light (substrata incubated in the photic zone) and water residence time.

Chlorophyll *a* concentrations in Boundary Reservoir suggest that the system is oligotrophic to mesotrophic (SCL 2009b; Welch and Jacoby 2004). High flows and associated detritus and nutrients are associated with higher chlorophyll *a* concentrations in May and June than in July

and August, suggesting higher transfer from upstream production during spring. During July and August, chlorophyll *a* concentrations decreased to a level below 2.8 µg/L, indicating that the reservoir is a low productivity, oligotrophic system, possibly limited by light, but more likely limited by TP (see above discussion).

5.1.3. Zooplankton

Zooplankton samples were collected and analyzed as part of Study 5; for details on methods and data including community structure and quantity, see the Study 5 Final Report (SCL 2009b). Seasonal patterns were observed in the zooplankton community structure in Boundary Reservoir and can be explained by the naturally occurring differences between seasons of the year. Individual species can dominate a community through abundance on a seasonal basis as has been well-documented in similar settings (Hynes 1970). Therefore, the seasonal zooplankton abundance is predictable and can be used as a baseline for comparison against observed results. Some of the species (e.g., cladocerans and copepods) are sensitive to physical and/or chemical stimuli and thus will have changes in abundance among seasons or may be replaced or disappear when environmental gradients change. Other groups (e.g., rotifers and nauplii) are in freshwater ecosystems like Boundary Reservoir, but only present limited diagnostic value (indicating availability of micro-organic particles and/or presence of microorganisms such as bacteria or yeast on which rotifers and nauplii feed) for determining how environmental changes affect naturally occurring zooplankton communities.

Rotifers dominated zooplankton in abundance during the spring months in both pelagic and littoral regions in Boundary Reservoir. During July and August, copepods and cladocerans were the dominant taxonomic group in both pelagic and littoral regions of the reservoir. Abundance and biomass of zooplankton were the lowest at all stations during November.

Zooplankton populations in Boundary Reservoir were determined to a large extent by entrainment from Box Canyon Reservoir inflows. In addition, low nutrient content and retention time limited zooplankton populations by restricting the available food supply (phytoplankton as primary producers) and providing inadequate time for zooplankton reproduction. These limitations on Boundary Reservoir zooplankton communities suggest that there is no correlation between pool elevation fluctuation and zooplankton population in the reservoir.

Zooplankton abundance for cladocerans in the summer in Boundary Reservoir was modestly high for oligotrophic waters, ranging from 2 to 35 organisms per liter in August (the latter number was recorded at station V7 as outflow from Box Canyon Reservoir). In contrast, copepod populations were quite low, ranging from <1 to 11 organisms per liter in August (again, the latter number was recorded at station V7). In comparison, some cladocerans in Lake Washington and Lake Sammamish (mesotrophic waters) ranged from 10 to 50 organisms per liter and copepods from 10 to 200 organisms per liter in spring, the time of maximum abundance. High flows in the spring and short retention times were probably responsible for the delay in maximum cladocerans and copepod abundance until summer in Boundary Reservoir. Zooplankton were found in much less abundance in the littoral region than in the pelagic region, possibly because littoral zooplankton were preyed upon by benthic-dwelling animals.

5.1.4. Macrophytes

Macrophyte coverage and density measurements as well as the corresponding HSI evaluations were conducted in Study 7 (SCL 2009a, see Appendix 1b and Appendix 6). Locations for macrophyte monitoring and extent of beds are described in detail in Study 6 (SCL 2009b) and Study 7 (SCL 2009a). Table 5.1-1 summarizes the macrophyte species found in Boundary Reservoir.

Table 5.1-1. Macrophyte species in Boundary Reservoir.

Scientific Name	Common Name	Status
Myriophyllum sibericum	northern milfoil	Native
Myriophyllum spicatum	Eurasian watermilfoil	Non-native invasive
Ceratophyllum demersum	Coontail	Native
Elodea canadensis	common waterweed	Native
Potamogeton crispus	curly pondweed	Non-native invasive
Potamogeton pectinatus	sago pondweed	Native
Potamogeton vaginatus	sheathing pondweed	Native
Potamogeton richardsonii	Richardson's pondweed	Native
Potamogeton zosteriformis	flat-stem pondweed	Native
Ranunculus aquatilis	white water buttercup	Native

Macrophyte beds covered 12.3 acres in the Canyon Reach and 8.4 acres in the Forebay Reach versus 202.5 acres in the Upper Reservoir Reach. Eurasian watermilfoil, pondweed species, and coontail were the dominant plant species found in Boundary Reservoir. Overall, macrophyte beds covered 12.8 percent of surface area in the reservoir.

5.1.5. Periphyton

Periphyton within Boundary Reservoir was studied and results reported under Study 7, Appendix 7 (SCL 2009a). Periphyton biomass is expressed as milligrams of chlorophyll *a* per square meter. All periphyton data collected during 2007 and 2008 were used along with results from the Hydraulic Routing Model (HRM) to calibrate literature-based HSI curves. The HRM provided information on water surface elevations, water velocities, and duration of inundation and dewatering that was used in conjunction with the site-specific periphyton data collected to validate the periphyton HSI model for Boundary Reservoir.

Average periphyton biomass during spring at vertical treatment sites ranged from 1.4 to 3.9 milligrams per square meter (mg/m^2) for all elevation intervals. Average *spring* periphyton biomass was similar at vertical treatment sites in the Canyon Reach of Boundary Reservoir and Box Canyon Reservoir. Both vertical treatment sites showed a sight decrease (48 percent and 63 percent, respectively) in *spring* periphyton biomass as the elevation interval increased from 10 to 40 feet. This decrease was not significant.

There was a larger variability in *summer* periphyton biomass at vertical treatment sites in Boundary and Box Canyon reservoirs than in spring biomass. Average *summer* periphyton biomass at vertical treatment sites ranged from 0.6 to 22.9 mg/m^2 for all elevation intervals. The highest *summer* periphyton biomass for vertical treatment sites was observed at the 5-foot elevation interval in the Canyon Reach and Box Canyon Reservoir. In addition, there was a strong downward trend (95 percent reduction) in *summer* periphyton biomass at the vertical site in the Canyon Reach below the 10-foot elevation interval.

Average *spring* periphyton biomass at shoreline sites ranged from 0.7 to 5.5 mg/m^2. Biomass at the Upper Reservoir Reach shoreline sites was slightly higher in periphyton biomass than at the Canyon Reach and Box Canyon sites at elevation intervals of 10, 15, and 25 feet. Also, biomass at the Upper Reservoir Reach and Box Canyon Reservoir shoreline sites decreased (88 percent and 74 percent reduction, respectively) with increasing depth (elevation intervals from 10 to 40 feet). *Spring* periphyton biomass was consistently low at the Canyon Reach shoreline sites deeper than the 10-foot elevation interval.

Average *summer* periphyton biomass ranged from 0.8 to 12.8 mg/m^2 for shoreline sites. Baskets with hard substrata deployed at the 2-foot elevation interval in the Upper Reservoir Reach and Box Canyon Reservoir were dewatered at the time of retrieval at the end of August, as were those at the 5-foot elevation interval in upper Boundary Reservoir.

Periphyton biomass was generally higher in the Upper Reservoir Reach where shoreline habitat was more abundant than in the Canyon Reach and Box Canyon Reservoir. Biomass peaked at the 10-foot elevation interval regardless of reach, indicating that light is a controlling factor in all the reaches at the 10-foot elevation interval and below. Light as a controlling factor in elevation intervals shallower than 10 feet was moderated by exposure of substrata with water level fluctuations.

Overall periphyton production in Boundary Reservoir was low, as expected in oligotrophic waters. The maximum biomass observed was 30 mg/m^2 at 10 feet near the shore in November 2007and 29 mg/m^2 at 10 feet in the vertical area, also in November 2007.

Generally, there was little difference in the water column mean periphyton biomass values among sites, whether shoreline or vertical. Therefore, the vertical mean (n = 5) was aggregated for each sample time to provide spring, summer, and fall grand means of 2.4 ± 1.3, 5.5 ± 5.1, and 10.4 ± 8.9 mg/m^2, respectively.

Although the two maximums observed in November 2007 (30 and 29 mg/m^2) were observed at the 10–foot elevation interval, the aggregated means at each depth during the three sample times show little difference in biomass accrual at depths from 5 to 25 feet. This further indicates phosphorus is the primary factor limiting primary production. Mean transparencies (Secchi disk depths) were 2 and 5 m in May and August, respectively, indicating greater light availability at depth in August. Those transparencies indicate that percent of surface light intensity available at 10 and 15 feet were 6 and 1.3 in May and 33 and 18 in August. These calculations assume a first order decrease in light with depth with the extinction coefficient based on the Secchi disk disappearing at 15 percent of surface intensity. Thus, greater light transmission accounts for much of the seasonal increasing biomass (doubling between sample times), and the occurrence of

the maximums in November. Nevertheless, with 24 percent surface intensity available at a 5-foot elevation interval in May, along with higher TP concentrations, a much higher mean periphyton biomass than the observed 1.9 ± 0.7 mg/m^2 would have been expected at that depth. Also, the second and third highest biomass levels in November (25 and 20 mg/m^2) occurred at 20- and 25-foot elevation intervals.

Average *summer* periphyton biomass collected from substrata in colonization baskets ranged from 0.8 to 17.0 mg/m^2 at all elevation intervals (5, 15, and 25 feet). The highest periphyton biomass was observed at the 5-foot elevation interval and after 42 days (6 weeks) of exposure. The lowest periphyton biomass occurred at the 25-foot elevation interval after only 3 days of exposure. These maximum biomass levels are on the order expected along the shore of oligotrophic lakes, i.e., < 10 to 20 mg/m^2 (Jacoby et al. 1991).

Summer periphyton colonization rates varied from 0.24 to 0.55 mg/m^2 per day for baskets at the 5-foot elevation interval, 0.11 to 0.35 mg/m^2 per day for baskets at the 15-foot elevation interval, and 0.04 to 0.27 mg/m^2 per day for baskets at the 25-foot elevation interval. Average *summer* colonization rates were 0.38, 0.23, and 0.18 mg/m^2 per day of chlorophyll *a* for baskets at 5-, 15-, and 25-foot elevation intervals, respectively. Overall, the average *summer* periphyton colonization for hard substrata in Box Canyon Reservoir was 0.26 mg/m^2 per day.

5.1.6. Benthic Macroinvertebrates

BMI density measurements as well as the corresponding HSI evaluation were conducted in Study 7 for the Forebay, Canyon, Upper Reservoir, and Tailrace reaches. The results of this study were used as evaluation elements for BMI production relative to Project operations (see Appendix 8, SCL 2009a). *Hydra* sp. was found in large numbers, in some cases, and represented a substantial portion of the biomass for a BMI sample at select depths. *Hydra* sp. is not a primary forage food of fish and, therefore, does not represent the target component of the food chain intended for examination in the BMI production estimate. The presence of *Hydra* sp. may be an artifact of the artificial substrate sampling device and represents establishment of an artificial environment in which this species would not normally colonize.

BMI samples were collected in the Canyon Reach of Boundary Reservoir and in Box Canyon Reservoir to describe the response of BMI to a range of water surface elevation fluctuations. There was no vertical cliff habitat in the upper Boundary Reservoir and sampling was limited to the vertical cliff habitat found in the Canyon Reach and Box Canyon Reservoir. The peak biomass during all seasons at the Canyon Reach vertical site was observed at the 15-foot elevation interval, whereas the lowest production was observed at the 5-foot elevation interval during all seasons. Generally, biomass in Canyon Reach on vertical sites was lowest at all elevation intervals during the winter and highest at all elevation intervals during the summer, except at the 10-foot interval. Higher production occurred at the 10-foot elevation interval during the fall than in summer.

The peak biomass during the spring and winter seasons at the Box Canyon vertical site was observed at the 2-foot elevation interval. In summer and fall, the peak biomass production in Box Canyon was observed at the 5-foot elevation interval. Generally, production appeared to be

lowest during the spring and winter seasons, except at the 2-foot elevation interval, where biomass was lowest during the summer season.

Biomass results for BMI production from shoreline hard substrates were analyzed for the Canyon Reach, Upper Reservoir Reach, and Box Canyon Reservoir. Biomass estimates for BMI at the Canyon Reach shoreline treatment sites indicated that production increased from intermediate elevation intervals (e.g., 15 feet) through the deepest elevation interval sampled (i.e., 40 feet). In the summer and fall, peak BMI production occurred at the 15-foot elevation interval. The lowest biomass produced during spring and winter was at the 10-foot interval and at the 2-foot interval during summer. Across all seasons, biomass typically appeared to be higher at lower elevations and decreased significantly above the 10-foot elevation interval.

Upper Reservoir Reach production showed that maximum biomass in spring and fall (with and without *Hydra* sp. inclusion) occurred at the intermediate elevation interval (e.g., 15 feet and 25 feet). The peak BMI production during the summer and winter seasons occurred at deeper elevation intervals (e.g., 40 feet). Overall, spring and fall were the most productive seasons for BMI in the Upper Reservoir Reach. The pattern for production of BMI at shoreline treatment sites was the same for estimates with and without *Hydra* sp. inclusion at each elevation interval. This pattern was similar to the pattern observed at the Box Canyon Reservoir vertical treatment site where depth was not a likely factor that influenced production levels of *Hydra* sp.

Production estimates for Box Canyon Reservoir shoreline treatment sites showed the same direction of change at successive elevation intervals both with and without *Hydra* sp. inclusion. Similarly, during spring and fall the BMI biomass estimates at the Box Canyon Reservoir shoreline treatment sites were higher near the shallow elevation intervals and declined at depth. However, this was not the case in the summer when peak biomass occurred at an elevation interval of 25 feet. The availability of hard substrate (e.g., vertical or shoreline) appears to be an important factor for influencing BMI production. Production estimates were greatest at upper Boundary Reservoir and Box Canyon Reservoir sites and again lowest for Canyon Reach sites (e.g., approximately 10 times less biomass at corresponding elevation intervals).

Biomass results for BMI production estimates for soft substrate sampling at the Canyon Reach, Upper Reservoir Reach, and Box Canyon Reservoir sites were 3 to 10 times lower than at hard substrate site categories. Canyon Reach soft substrate biomass estimates peaked at intermediate depths (e.g., 25 feet) and were less in the upper 10 feet of the elevation intervals sampled. The peak biomass estimates were highest at soft substrate sampling sites at the shallowest elevation interval (e.g., 2 to 10 feet) at Upper Reservoir Reach sites. The pattern of BMI biomass estimate fluctuation in soft substrates at 6 successive elevation intervals at Box Canyon Reservoir sites was the same observed for shoreline treatment sites.

5.2. Weighted Usable Area Calculations: Macrophytes, Periphyton, and BMI

The overall production of aquatic macrophytes, periphyton, and BMI was evaluated using WUA as calculated in the habitat model developed in Study 7 (SCL 2009a) and a TPI developed as a relative measure of production potential within the reservoir for each group (Appendix 1).

The Mainstem Aquatic Habitat Model calculated WUA for macrophytes, periphyton, and BMI for each reach within Boundary Reservoir. The WUA was calculated for each cell of the Mainstem Aquatic Habitat Model and was based on the HSI curves and information on the depth, velocity, and substrate and existing Project operations. Expression of WUA was generated for each biological group (e.g., macrophytes, periphyton, and BMI) during a wet year (1997), a dry year (2001), and an average year (2002), and for each reach (e.g., Forebay, Canyon, Upper Reservoir, and Tailrace).

A brief discussion is presented below on WUA estimates for macrophytes, periphyton, and BMI. Summary statistics were calculated using only WUA estimates for flows less than 80,000 cfs. The Mainstem Aquatic Habitat Model has an upper bounding condition of 80,000 cfs and therefore all WUA estimates calculated by the model for flows more than 80,000 cfs were removed from the analysis. For a more detailed discussion of WUA estimation see Sections 5.6, 5.7, and 5.8 in the Study 7 Final Report (SCL 2009a) as well as appendices 6, 7, and 8. Study 7 presents detailed graphics of macrophyte, periphyton, and BMI WUA as well as an analysis of WUA and water surface elevations for specific two-week periods in May, July, and September.

Tables 5.2-1 through 5.2-4 summarize the monthly WUA for macrophytes calculated by the Mainstem Aquatic Habitat Model by reach. Figures 5.2-1 through 5.2-4 display the WUA for macrophytes for wet, dry, and average hydrologic conditions. Estimates of WUA for macrophyte beds were highest in the Upper Reservoir Reach when compared to other areas within and below the Boundary Reservoir. The WUA for macrophytes in the Upper Reservoir Reach were consistently lower scores during the spring runoff period of May and June, and sometimes into July. Even though macrophyte beds are already established in Boundary Reservoir prior to these months, suitability for macrophytes was diminished by several factors during this time of year (i.e., higher velocities, higher turbidity, and deeper water). The Canyon Reach had only one-fifth the WUA estimates for macrophytes as those calculated for the Upper Reservoir Reach. Variability of WUA for macrophytes in the Canyon Reach was much lower than observed in the Upper Reservoir Reach indicating that limitations other than dewatering due to water surface elevation fluctuations influenced macrophyte habitat. This limitation of macrophyte WUA in the Canyon Reach could be attributed to greater depths and less suitable substrate. The Upper Reservoir Reach had the highest WUA estimates for macrophytes during dry hydrologic conditions whereas the Canyon Reach had the highest WUA estimates for macrophytes during average hydrologic conditions, although there was little difference between the three hydrologic conditions in the Canyon Reach.

The Forebay and Tailrace reaches of Boundary Reservoir had the least amount of macrophyte WUA. WUA estimates for macrophytes were slightly higher in the Forebay Reach than in the Tailrace Reach. Estimates for WUA were also relatively uniform in the Forebay Reach over all three hydrologic (wet, dry, and average). The Tailrace Reach had the lowest overall WUA estimates for macrophytes of all the reaches. This reach had higher velocities and coarse substrate, both presenting conditions that were not considered optimal for established macrophyte beds. The highest average WUA for macrophytes in the Tailrace Reach was estimated for the dry hydrologic year. This pattern for WUA (lowest WUA in wet and average years) indicates that velocity and frequency and duration of dewatering events have a larger impact on suitability scores during higher flow conditions than lower flow conditions.

Table 5.2-1. Summary of monthly macrophyte WUA (acres) in the Forebay Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	--	--	--	--	--	--	--	--	--	--	--	--
February	--	--	--	--	--	--	--	--	--	--	--	--
March	11.2	13.4	8.0	1.0	10.8	13.5	8.8	1.0	11.2	13.6	7.6	1.3
April	10.9	13.5	8.6	1.0	11.0	13.7	8.6	1.1	10.9	13.6	6.4	1.5
May	10.0	10.7	9.2	0.3	9.9	13.3	5.6	1.6	10.2	13.2	7.1	1.2
June	11.2	12.4	10.2	0.5	10.8	13.5	7.7	1.4	11.0	11.8	10.1	0.4
July	11.5	13.4	9.2	0.9	11.0	13.5	8.2	1.2	11.6	13.7	8.9	1.0
August	11.3	13.5	8.3	1.2	11.2	13.5	9.0	0.9	11.1	13.5	8.8	1.2
September	11.4	13.5	8.8	1.2	11.2	13.7	7.9	1.2	11.0	13.5	8.9	1.0
October	11.3	13.6	7.5	1.4	10.9	13.5	7.2	1.4	11.3	13.7	9.0	1.2
November	--	--	--	--	--	--	--	--	--	--	--	--
December	--	--	--	--	--	--	--	--	--	--	--	--

Note:
-- – No viable macrophyte habitat during the winter months in Boundary Reservoir.

Table 5.2-2. Summary of monthly macrophyte WUA (acres) in the Canyon Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	--	--	--	--	--	--	--	--	--	--	--	--
February	--	--	--	--	--	--	--	--	--	--	--	--
March	33.4	41.0	21.1	4.3	37.7	41.7	31.8	2.2	33.1	39.0	20.8	3.0
April	30.0	38.7	22.3	4.2	37.4	41.7	30.5	2.5	30.5	39.0	18.2	5.2
May	24.0	26.3	21.2	0.9	25.2	39.2	9.1	6.5	26.9	38.6	16.4	4.0
June	28.5	32.4	25.0	1.7	30.2	35.4	21.3	2.7	26.8	29.5	23.6	1.6
July	33.7	40.9	24.7	3.5	35.7	41.7	23.5	3.4	33.2	39.0	25.7	3.1
August	36.7	41.3	29.8	2.4	38.3	41.4	32.3	2.0	37.6	41.4	31.9	2.3
September	37.2	41.3	32.4	2.2	34.7	41.5	23.0	4.1	38.0	41.7	32.3	2.3
October	32.5	40.4	20.8	3.1	34.9	41.6	21.4	4.2	37.9	41.7	32.7	2.3
November	--	--	--	--	--	--	--	--	--	--	--	--
December	--	--	--	--	--	--	--	--	--	--	--	--

Note:
-- – No viable macrophyte habitat during the winter months in Boundary Reservoir.

Table 5.2-3. Summary of monthly macrophyte WUA (acres) in the Upper Reservoir Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	--	--	--	--	--	--	--	--	--	--	--	--
February	--	--	--	--	--	--	--	--	--	--	--	--
March	155	198	117	22.0	229	258	164	19.2	169	214	109	18.5
April	129	165	53.7	30.1	206	248	117	21.6	161	222	115	18.4
May	72.4	81.7	39.1	7.7	166	223	142	12.1	130	186	44.8	41.5
June	98.7	130	41.3	22.0	169	206	146	12.6	70.5	90.1	45.6	12.5
July	148	192	104	23.2	204	251	145	27.2	148	215	52.9	32.4
August	180	240	136	14.3	222	255	149	18.5	200	242	158	16.8
September	182	218	153	11.1	179	256	80	53.0	209	249	156	16.4
October	171	205	146	10.6	178	220	139	16.0	194	245	159	15.6
November	--	--	--	--	--	--	--	--	--	--	--	--
December	--	--	--	--	--	--	--	--	--	--	--	--

Note:
-- – No viable macrophyte habitat during the winter months in Boundary Reservoir.

Table 5.2-4. Summary of monthly macrophyte WUA (acres) in the Tailrace Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	--	--	--	--	--	--	--	--	--	--	--	--
February	--	--	--	--	--	--	--	--	--	--	--	--
March	5.2	13.1	2.8	1.6	9.2	13.2	4.0	2.0	6.7	12.2	3.5	2.4
April	4.0	7.4	2.3	0.9	7.3	12.7	3.3	2.2	5.3	12.4	2.6	2.0
May	3.1	3.7	2.8	0.2	5.7	12.3	3.1	2.3	4.0	11.3	2.6	1.4
June	3.8	4.8	2.8	0.6	5.8	11.5	2.9	2.4	3.2	3.7	2.9	0.2
July	4.8	9.7	3.1	1.0	7.2	12.0	3.5	2.2	5.0	11.3	2.9	1.6
August	7.0	13.2	3.6	2.4	8.6	12.8	3.4	2.2	7.5	12.7	3.0	2.4
September	5.9	11.8	3.1	2.1	9.3	13.1	5.5	2.1	7.4	12.7	4.1	2.0
October	6.1	12.6	3.2	2.5	7.5	13.0	3.9	2.4	7.3	13.0	3.2	2.4
November	--	--	--	--	--	--	--	--	--	--	--	--
December	--	--	--	--	--	--	--	--	--	--	--	--

Note:
-- – No viable macrophyte habitat during the winter months in Boundary Reservoir.

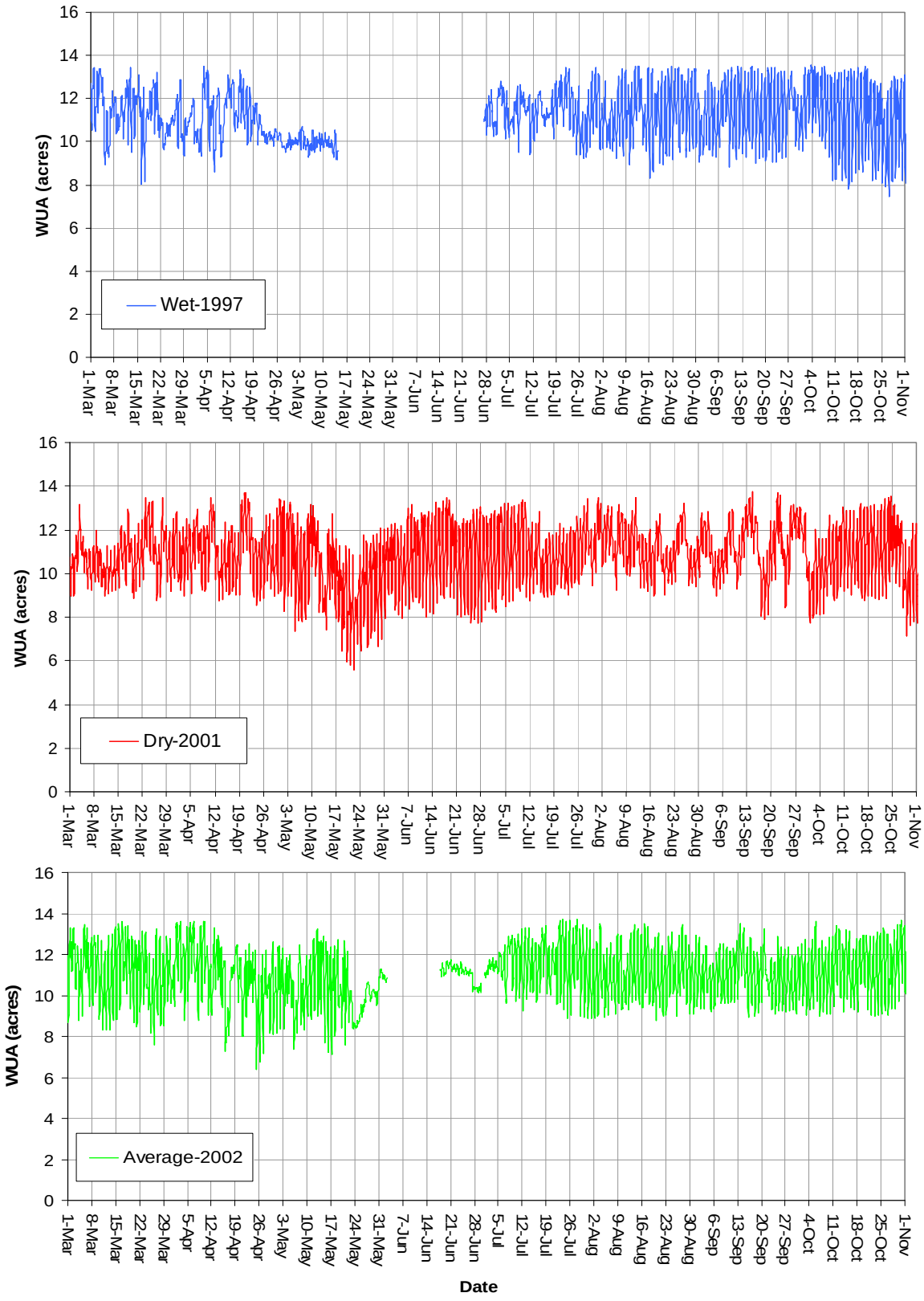

Figure 5.2-1. Macrophyte WUA in the Forebay Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

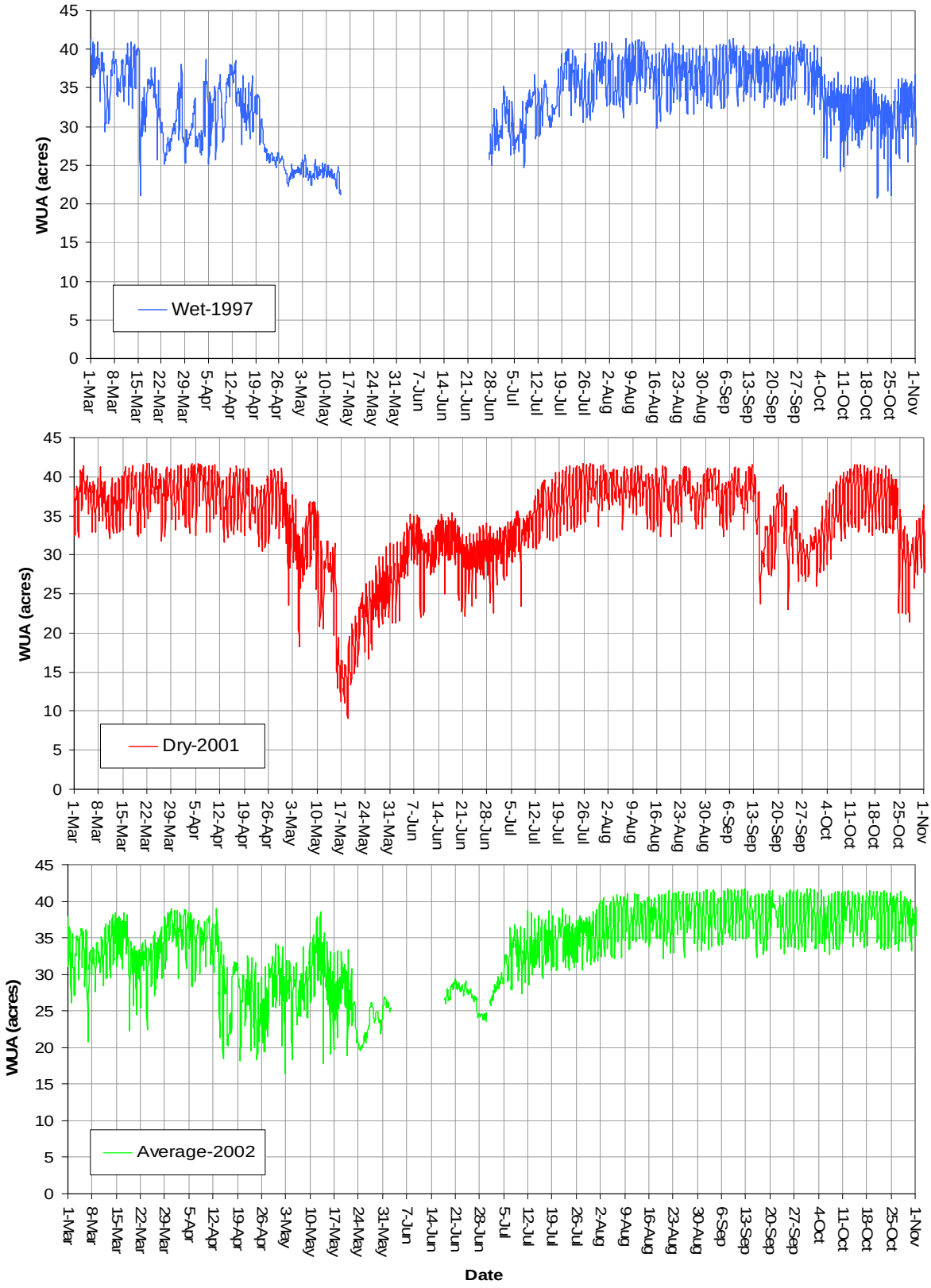

Figure 5.2-2. Macrophyte WUA in the Canyon Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

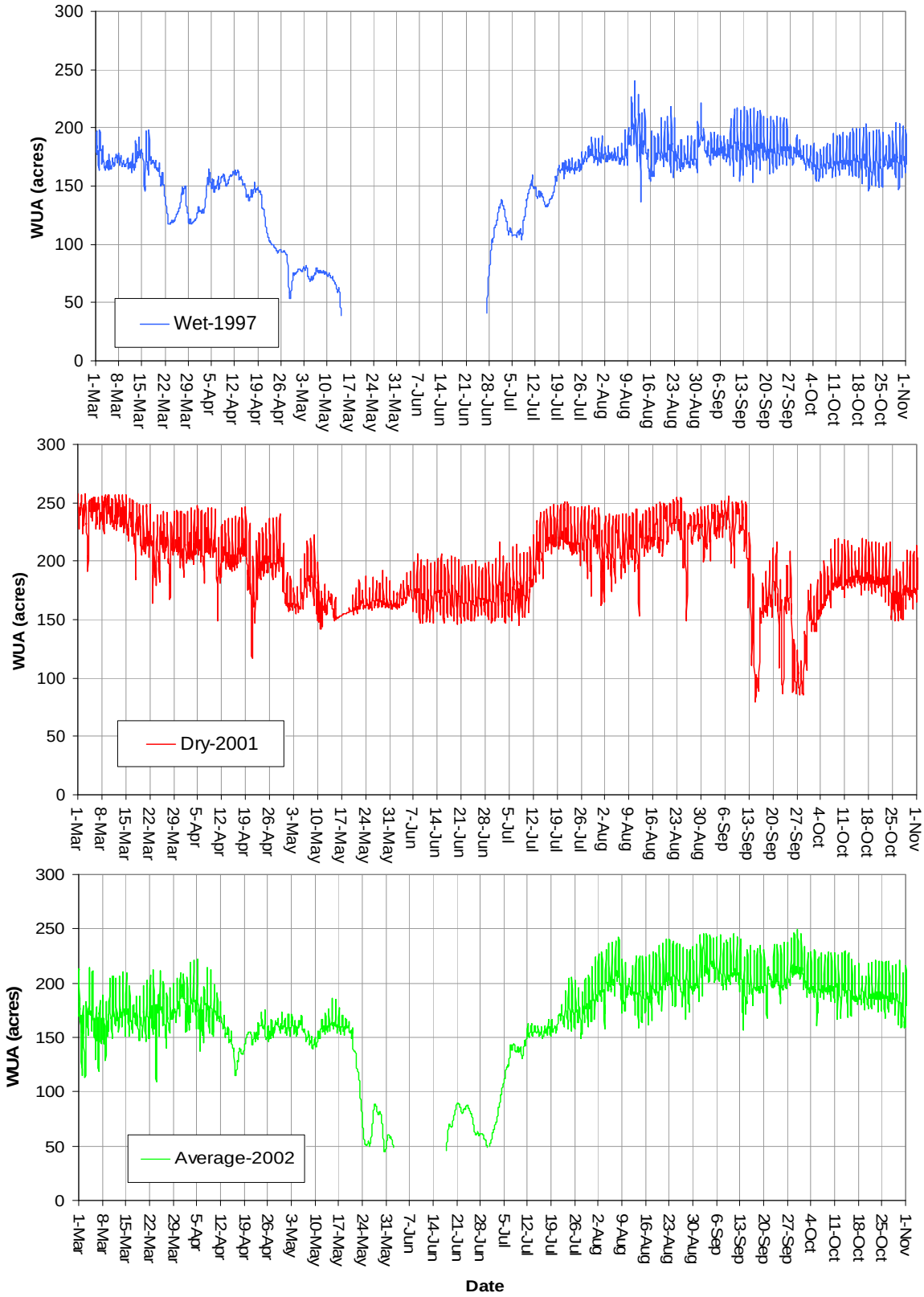

Figure 5.2-3. Macrophyte WUA in the Upper Reservoir Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

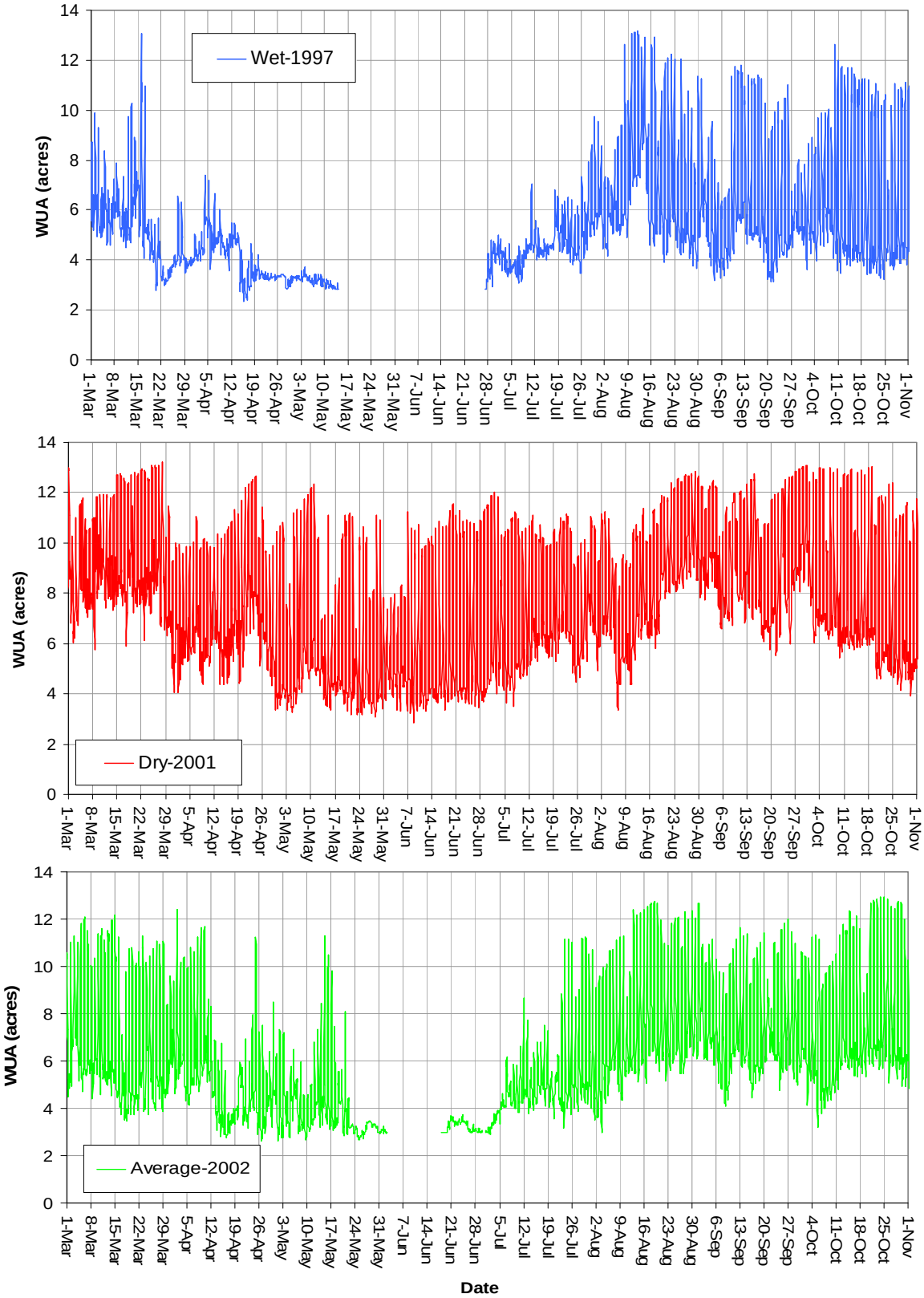

Figure 5.2-4. Macrophyte WUA in the Tailrace Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

Tables 5.2-5 through 5.2-8 summarize the monthly WUA for periphyton calculated by the Mainstem Aquatic Habitat Model by reach. Figures 5.2-5 through 5.2-8 display the WUA for periphyton for wet, dry, and average hydrologic conditions. Estimates for periphyton WUA in the Upper Reservoir Reach showed similar seasonal patterns between all hydrologic years. Periphyton WUA in the Upper Reservoir Reach for all hydrologic years was lowest during May and June when high flows from spring runoff increased water depth, turbidity, and absolute velocity of water moving over potential areas where periphyton could be established.

Periphyton WUA estimates in the Canyon Reach were significantly lower than those in the Upper Reservoir Reach. The physical setting of the Canyon Reach does not have the same type of colonizable habitat found in the Upper Reservoir Reach. Water depths are greater, especially along most of the shoreline, and other factors that promote growth of periphyton communities like photoperiod are absent due to the narrow channel bounded by canyon rock walls. Although substrate may be good relative to habitat type in the Canyon Reach, pool elevation fluctuation, light availability, and vertical nature of the substrate diminish effective colonization. WUA estimates for periphyton in the Canyon Reach were similar for all of the three hydrologic years indicating that one or more of the factors comprising the suitability index are uniform throughout this reach and do not promote the highest quality habitat available in the reservoir for periphyton production.

The lowest WUA periphyton estimates occurred in the Forebay Reach during the spring runoff period and during a dry hydrologic year; however, lower seasonal fluctuations were estimated in the Forebay Reach than for the Upper Reservoir Reach. Water surface elevation fluctuations are greatest in the Forebay Reach compared to reaches upstream of Boundary Dam. This continuous disturbance of suitable habitat through some frequency of dewatering depressed periphyton WUA estimates for all hydrologic years in the Forebay Reach and diminished the amplitude for seasonal WUA estimates described for the Upper Reservoir Reach. Estimates for periphyton WUA in the Tailrace Reach were similar to WUA estimates for periphyton in the Canyon Reach, but were more variable, similar to conditions in the Forebay Reach. The higher variability indicated that pool elevation fluctuation was a primary factor that suppressed WUA estimates in the Tailrace Reach. There was relative uniformity in periphyton WUA estimates in the Tailrace Reach among seasons, as also observed in the Canyon Reach.

Table 5.2-5. Summary of monthly periphyton WUA (acres) in the Forebay Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	3.8	4.4	2.2	0.4	3.1	4.0	1.8	0.4	2.6	3.6	1.4	0.4
February	3.8	4.6	2.2	0.5	4.7	5.4	3.4	0.5	2.5	3.2	1.3	0.4
March	3.4	4.6	1.4	0.6	4.8	5.6	2.7	0.5	2.1	2.7	1.3	0.3
April	3.3	4.7	1.8	0.7	4.3	5.2	2.2	0.6	2.0	2.9	1.2	0.3
May	5.1	5.6	4.5	0.3	1.6	3.9	0.7	0.7	2.0	3.3	1.2	0.6
June	3.9	4.9	2.4	0.6	1.6	1.8	1.1	0.2	3.5	4.3	2.7	0.4
July	3.8	4.4	2.2	0.4	2.8	4.1	1.5	0.8	3.3	4.5	2.0	0.5
August	3.8	4.5	2.5	0.4	3.9	4.7	2.7	0.4	3.6	4.4	2.3	0.4
September	3.8	4.4	2.5	0.4	3.1	4.8	1.4	1.1	4.3	4.9	2.6	0.4
October	2.3	4.4	1.4	0.5	3.0	4.1	1.3	0.7	4.3	4.9	2.2	0.5
November	2.3	2.9	1.8	0.2	2.7	3.3	1.7	0.3	4.0	4.6	2.0	0.4
December	2.8	3.5	1.8	0.3	3.9	4.7	1.6	0.6	3.5	4.6	1.4	0.8

Table 5.2-6. Summary of monthly periphyton WUA (acres) in the Canyon Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	68.8	81.4	57.6	4.8	66.8	85.4	52.7	6.7	66.1	85.8	47.9	8.0
February	71.4	80.4	59.3	4.2	70.5	76.4	61.1	3.1	66.9	89.6	49.1	8.4
March	66.6	87.7	50.5	7.9	73.2	80.7	63.4	2.8	65.6	89.9	45.8	9.9
April	60.8	79.4	49.9	6.5	71.3	81.4	58.1	4.7	64.2	86.6	39.9	10.7
May	59.3	61.3	56.5	1.3	64.1	89.4	32.7	14.0	54.8	84.6	36.8	12.3
June	60.5	64.1	54.2	2.4	61.6	84.6	41.6	11.7	51.6	55.2	45.3	2.7
July	67.8	79.6	54.0	5.3	63.8	86.2	45.9	7.6	66.6	81.9	51.6	7.0
August	70.3	80.7	56.0	5.5	69.8	78.3	59.7	3.8	68.2	81.2	55.5	5.6
September	70.6	81.1	58.6	5.4	70.7	88.7	50.4	7.8	70.6	80.8	60.2	4.1
October	67.7	87.3	45.9	10.2	65.4	88.8	45.7	8.3	72.3	81.5	61.6	4.5
November	64.1	83.9	46.7	9.0	62.9	84.9	47.7	7.5	70.4	82.7	59.1	4.8
December	65.4	84.6	47.5	7.9	69.2	87.2	55.6	5.4	70.4	88.7	53.5	6.4

Table 5.2-7. Summary of monthly periphyton WUA (acres) in the Upper Reservoir Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	245	335	127	50.4	314	337	237	19.7	275	337	163	45.5
February	248	324	186	29.2	337	346	326	4.1	276	322	207	25.5
March	187	296	105	53.2	336	347	303	6.3	253	311	172	34.7
April	140	200	79.4	33.1	323	339	178	22.7	191	306	98.9	65.0
May	94	97.7	82.7	2.7	196	312	154	39.3	142	248	69.2	45.2
June	110	143	80.5	17.1	218	283	165	28.6	84.6	93.4	72.2	5.9
July	178	299	106	50.8	307	343	187	43.2	182	320	79.3	57.1
August	261	347	185	38.1	332	340	311	5.1	316	338	248	19.4
September	262	313	210	23.4	305	340	228	27.4	329	343	277	10.1
October	223	291	180	26.4	260	297	181	26.4	300	339	225	22.0
November	232	319	178	31.6	291	338	191	33.2	307	334	218	22.0
December	267	330	190	30.9	315	341	218	23.1	287	333	205	33.5

Table 5.2-8. Summary of monthly periphyton WUA (acres) in the Tailrace Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	57.2	91.1	30.2	13.8	75.1	94.1	48.3	12.0	57.3	91.8	21.1	16.8
February	61.8	90.3	37.1	11.9	76.8	92.7	55.4	7.4	61.0	89.3	34.5	14.8
March	48.8	92.3	25.9	15.3	77.0	90.0	48.9	7.5	60.4	88.8	29.6	16.3
April	35.7	66.4	23.8	8.3	65.7	84.3	29.6	11.4	47.4	85.4	22.9	17.5
May	28.9	31.6	27.0	0.8	49.1	86.7	24.2	19.1	34.6	86.8	19.2	15.4
June	35.5	43.3	28.6	4.9	51.3	86.1	27.6	19.4	26.8	30.8	22.8	2.2
July	47.6	89.9	30.1	10.4	65.4	87.4	33.1	13.9	45.1	83.2	27.2	13.2
August	63.5	93.2	38.7	16.0	71.6	87.5	49.2	8.6	64.9	90.1	37.2	13.2
September	52.5	87.0	31.2	14.4	78.2	91.6	56.5	7.8	63.6	89.5	43.8	10.8
October	51.6	85.8	27.9	18.2	66.1	92.8	34.8	15.2	59.2	87.7	33.5	12.4
November	51.6	86.7	28.9	17.0	66.5	91.0	40.6	14.5	60.7	86.9	36.5	12.5
December	58.1	89.1	36.1	16.9	66.1	87.6	40.6	10.6	60.8	87.0	38.5	13.8

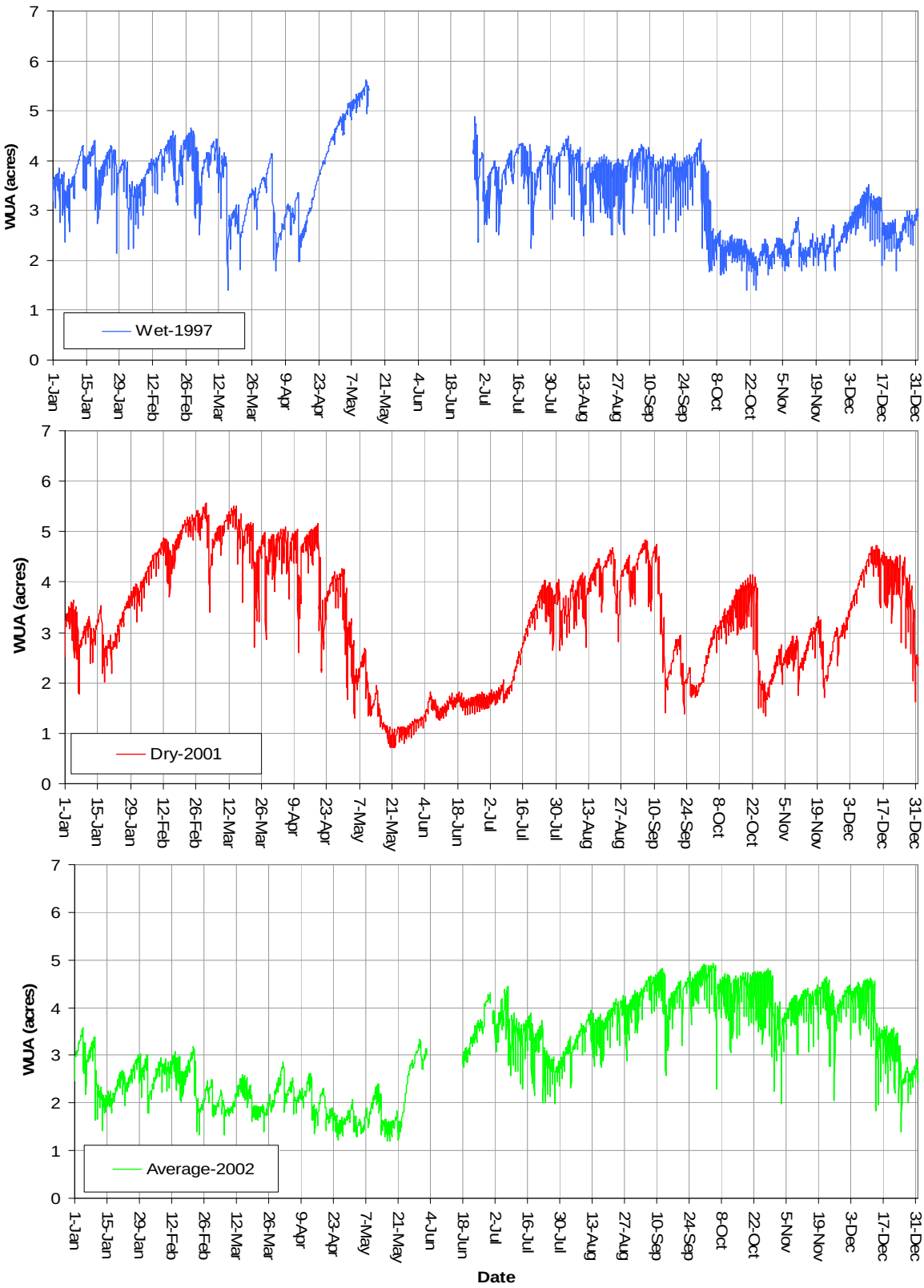

Figure 5.2-5. Periphyton WUA in the Forebay Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

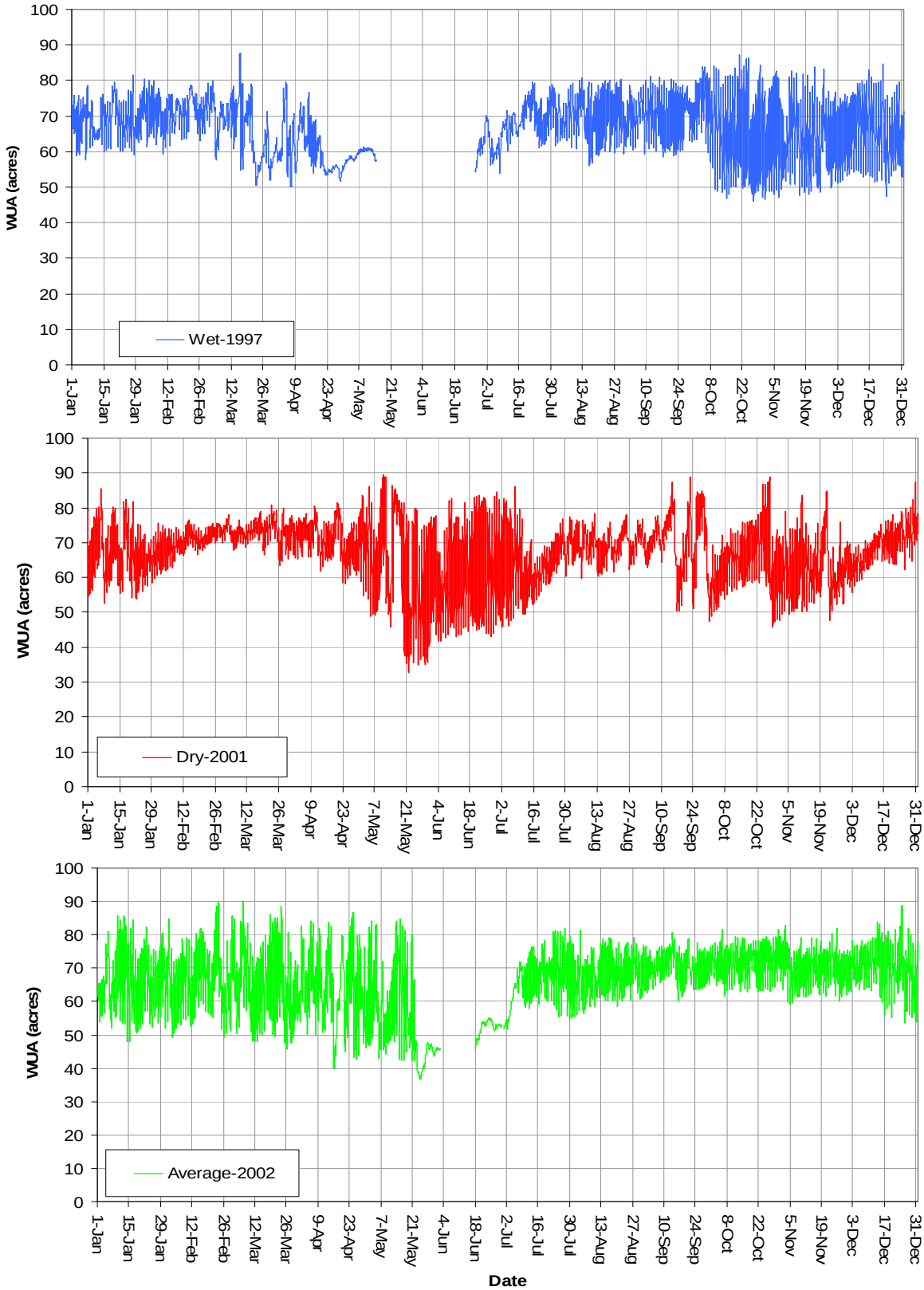

Figure 5.2-6. Periphyton WUA in the Canyon Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

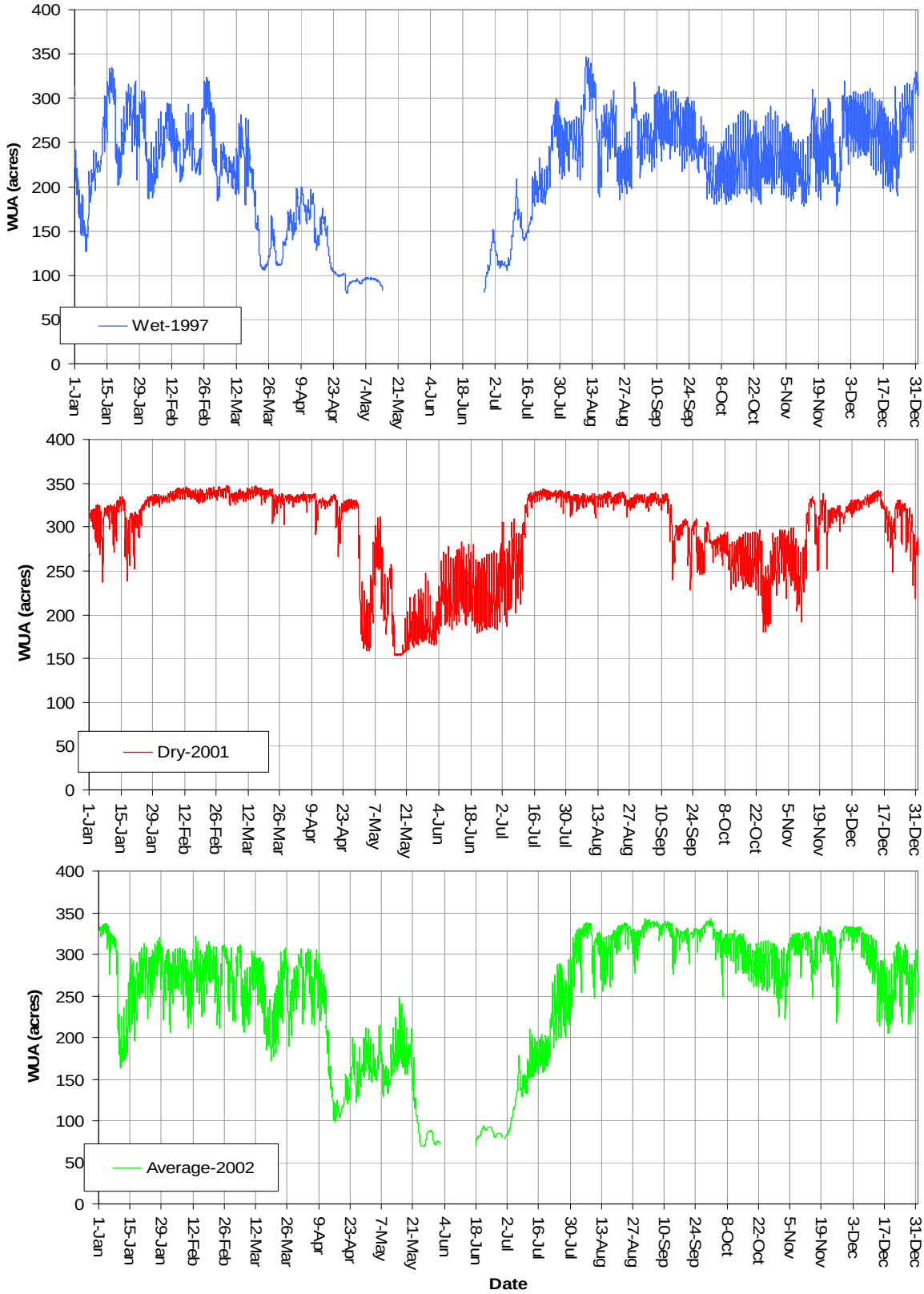

Figure 5.2-7. Periphyton WUA in the Upper Reservoir Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

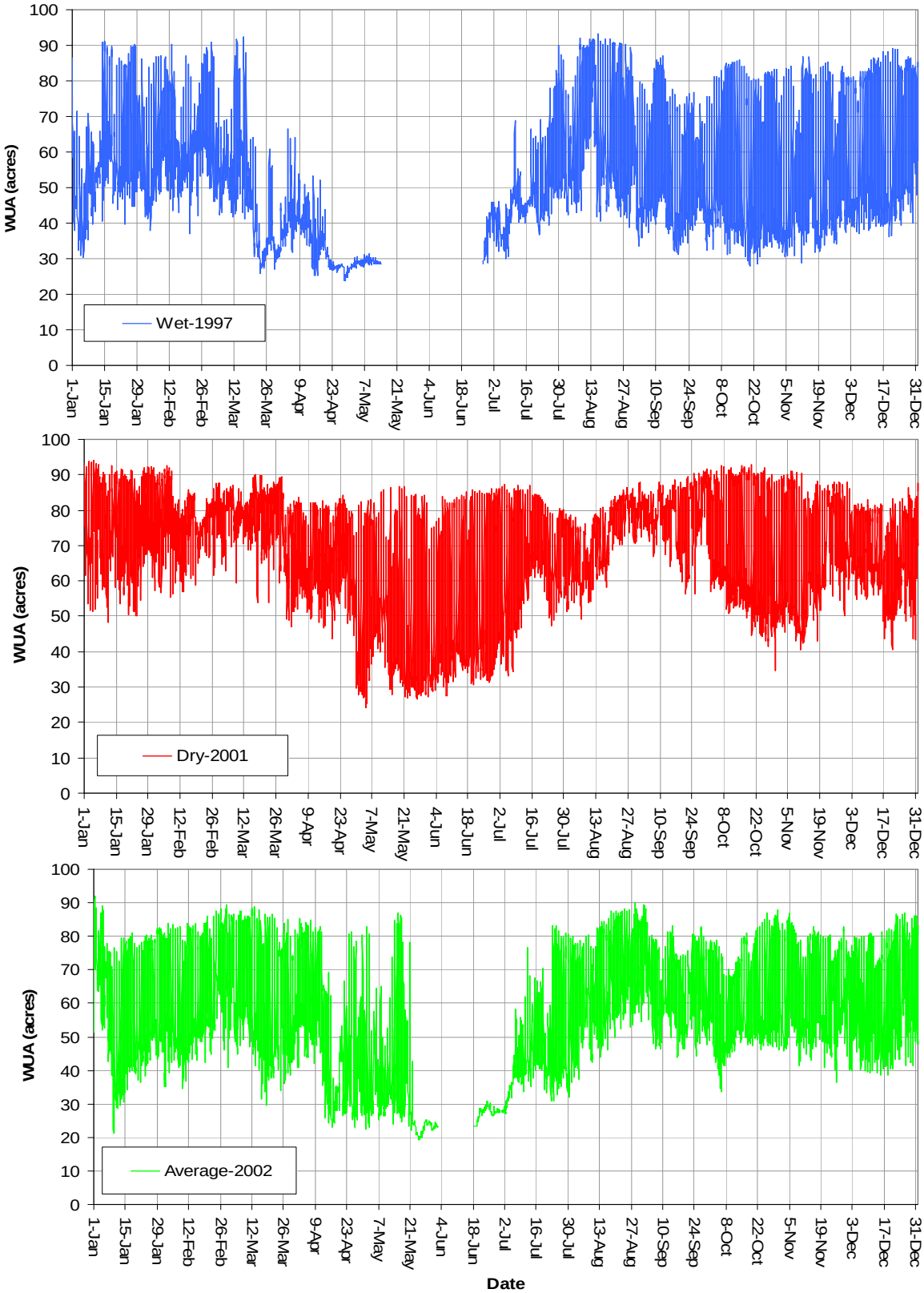

Figure 5.2-8. Periphyton WUA in the Tailrace Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

Tables 5.2-9 through 5.2-12 summarize the monthly WUA for BMI calculated by the Mainstem Aquatic Habitat Model. Figures 5.2-9 through 5.2-12 display the WUA for BMI for wet, dry, and average hydrologic conditions. BMI WUA was the highest in the Upper Reservoir Reach compared to other reaches within Boundary Reservoir and downstream of Boundary Dam. Estimates for WUA for BMI in the Upper Reservoir Reach were relatively similar over the period of one year with little or no identifiable seasonal variation for all reaches and all hydrologic conditions (wet, dry, and average). The lowest BMI WUA estimates in the Upper Reservoir Reach occurred during the dry and average hydrologic years for portions of September and February, respectively, when water surface elevations are generally lower. The relative WUA estimates for BMI reflected less available habitat under more stable water surface elevations and lower flow volumes during this time of the year (September). Variability of BMI WUA estimates during the annual cycle for other hydrologic years reflects the sensitivity of BMI to water surface elevation fluctuation in the Upper Reservoir Reach.

The Canyon Reach had the second highest BMI WUA estimates among all reaches in and below (Tailrace Reach) the Boundary Reservoir. Unlike with periphyton WUA estimates, depth in this reach did not appear to have as great an influence on suitability for colonization of BMI. WUA estimates for BMI in this reach were higher during all hydrologic years than those for periphyton, even though both of these biological groups were collected from the same locations and from the same substrates. The low variability in BMI WUA in the Canyon Reach was similar to that found in the Tailrace Reach. WUA for BMI in the Canyon Reach during the wet hydrologic year was very stable indicating that more water may result in better conditions for inhabitation by BMI even though water surface elevation fluctuations was greater in this reach than in the Upper Reservoir Reach.

Seasonal variation was minimal for WUA estimates for BMI in the Forebay Reach. This reach experienced the highest water surface elevation fluctuations among those within the Boundary Reservoir. The highest WUA estimates for BMI in the Forebay occurred during May and June during a wet hydrologic year, indicating that high flows during spring runoff contributed to greater relative BMI WUA. The variation in BMI WUA estimates was fairly small, but reflected the lower amount of relative habitat available for BMI colonization in the Forebay Reach.

The WUA estimates for BMI in the Tailrace Reach were greater than for the Forebay Reach, indicating a similar disturbance of BMI communities by dewatering that may explain part of the difference in BMI communities in the Upper Reservoir and Canyon Reaches. However, the slightly higher BMI WUA estimates in the Tailrace Reach may have been due to more suitable velocities. The small variation in BMI WUA within each year (January through December) and among hydrologic years (wet, dry, and average) indicated slightly better habitat suitability in the Tailrace Reach than in the Forebay Reach.

Table 5.2-9. Summary of monthly BMI WUA (acres) in the Forebay Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	30.5	32.9	24.6	1.7	27.8	31.5	23.9	2.3	28.0	32.1	22.9	2.5
February	30.5	33.0	26.6	1.2	27.7	31.3	24.5	1.8	27.7	31.0	22.2	2.5
March	31.1	32.8	23.6	1.4	28.5	31.9	25.6	1.9	26.6	30.2	21.0	2.4
April	31.7	33.8	28.6	1.0	28.9	32.8	24.7	2.2	27.6	30.8	20.4	2.0
May	34.3	35.4	33.4	0.4	26.3	32.7	17.1	3.3	27.9	31.0	20.3	1.8
June	33.6	35.1	32.3	0.9	24.7	28.6	18.7	2.6	31.6	33.0	30.6	0.6
July	31.9	33.8	27.4	1.1	25.4	28.8	20.2	2.3	30.6	33.1	23.7	1.9
August	30.0	32.4	24.4	2.0	27.0	29.7	23.7	1.8	28.5	31.4	23.9	2.3
September	30.1	32.2	24.7	2.1	26.9	30.3	22.7	2.0	28.8	32.0	24.9	2.1
October	28.9	32.5	22.4	2.6	27.7	31.4	21.3	2.5	29.8	32.5	25.3	2.3
November	28.5	31.2	22.4	2.3	26.5	30.0	21.4	2.4	29.3	32.1	24.9	2.2
December	28.3	31.2	23.0	2.6	27.8	31.6	23.2	2.2	29.0	32.3	23.7	2.4

Table 5.2-10. Summary of monthly BMI WUA (acres) in the Canyon Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	113	127	92.9	6.0	103	119	81.7	8.9	105	124	82.5	9.8
February	114	124	102	4.7	101	115	84.4	7.7	104	121	80.8	9.3
March	115	125	90.5	4.7	106	120	89.1	7.9	102	123	73.8	10.3
April	114	126	101	4.1	108	123	85.4	8.3	107	127	78.9	10.3
May	122	125	118	2.2	104	132	66.7	15.9	104	128	79.2	9.3
June	123	126	117	2.8	96.1	119	69.9	12.2	112	115	105	2.5
July	119	127	105	4.6	95.3	118	75.2	9.5	115	124	87.7	6.9
August	113	124	86.6	6.8	100	113	84.4	7.4	105	119	83.8	8.0
September	113	122	92.7	6.6	102	116	78.0	8.4	107	119	87.8	7.3
October	110	125	83.7	10.1	103	122	77.2	9.8	112	122	94.8	7.1
November	106	124	81.9	9.3	98.2	122	76.0	9.2	110	122	92.9	7.2
December	105	122	80.0	9.4	103	121	76.9	9.2	109	123	86.3	8.0

Table 5.2-11. Summary of monthly BMI WUA (acres) in the Upper Reservoir Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	553	585	494	20.7	496	530	423	19.4	508	546	422	20.8
February	554	590	502	19.7	494	526	451	13.1	507	548	416	26.3
March	536	588	473	27.9	495	527	432	16.2	485	521	421	22.5
April	532	582	470	26.7	504	541	422	19.9	485	542	436	23.6
May	503	510	490	5.3	498	553	440	28.3	506	575	439	36.4
June	526	565	484	22.5	518	566	464	25.2	477	492	450	11.7
July	564	616	516	26.6	510	561	439	21.4	548	613	472	31.2
August	543	607	431	33.4	478	510	401	18.1	535	572	474	19.1
September	542	570	487	17.5	436	499	336	38.6	524	549	454	15.5
October	533	579	478	25.3	474	521	412	23.2	535	564	472	16.9
November	542	578	475	23.1	492	543	357	32.9	531	559	463	15.1
December	544	578	462	22.0	495	541	429	21.6	522	560	417	23.3

Table 5.2-12. Summary of monthly BMI WUA (acres) in the Tailrace Reach determined by the Mainstem Aquatic Habitat Model for Boundary Reservoir.

Month	Wet Year 1997				Dry Year 2001				Average Year 2002			
	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.	Mean	Max.	Min.	Stdev.
January	64.1	72.4	52.7	3.8	67.7	77.4	51.5	5.8	55.6	71.1	41.2	5.0
February	67.9	75.5	58.3	3.3	62.6	77.2	45.5	7.2	58.0	68.0	48.3	4.1
March	63.8	78.8	49.2	6.9	62.8	73.3	42.7	6.9	58.4	66.9	42.1	4.0
April	56.9	72.4	43.9	5.3	58.0	65.8	41.9	4.8	55.7	66.6	42.7	5.6
May	52.7	57.3	49.1	1.5	54.9	66.3	42.2	5.3	50.3	68.0	38.1	7.3
June	61.0	70.1	52.1	5.7	54.7	64.8	43.9	4.3	47.6	53.0	41.7	3.2
July	68.6	82.4	55.3	4.9	57.0	65.3	42.6	4.3	60.0	80.2	45.0	6.9
August	66.0	75.6	46.3	4.6	56.5	67.8	41.7	6.2	60.2	70.9	45.0	4.7
September	55.7	67.6	39.9	4.9	61.6	70.6	47.2	6.5	57.5	69.6	43.9	4.7
October	55.1	66.5	45.7	4.1	65.0	75.2	51.3	4.7	57.0	67.6	42.4	4.8
November	56.0	66.3	41.7	3.9	61.5	72.0	42.5	4.6	55.9	64.4	43.3	3.9
December	56.9	66.9	41.4	4.3	58.7	67.7	43.5	4.8	57.1	67.8	43.6	4.3

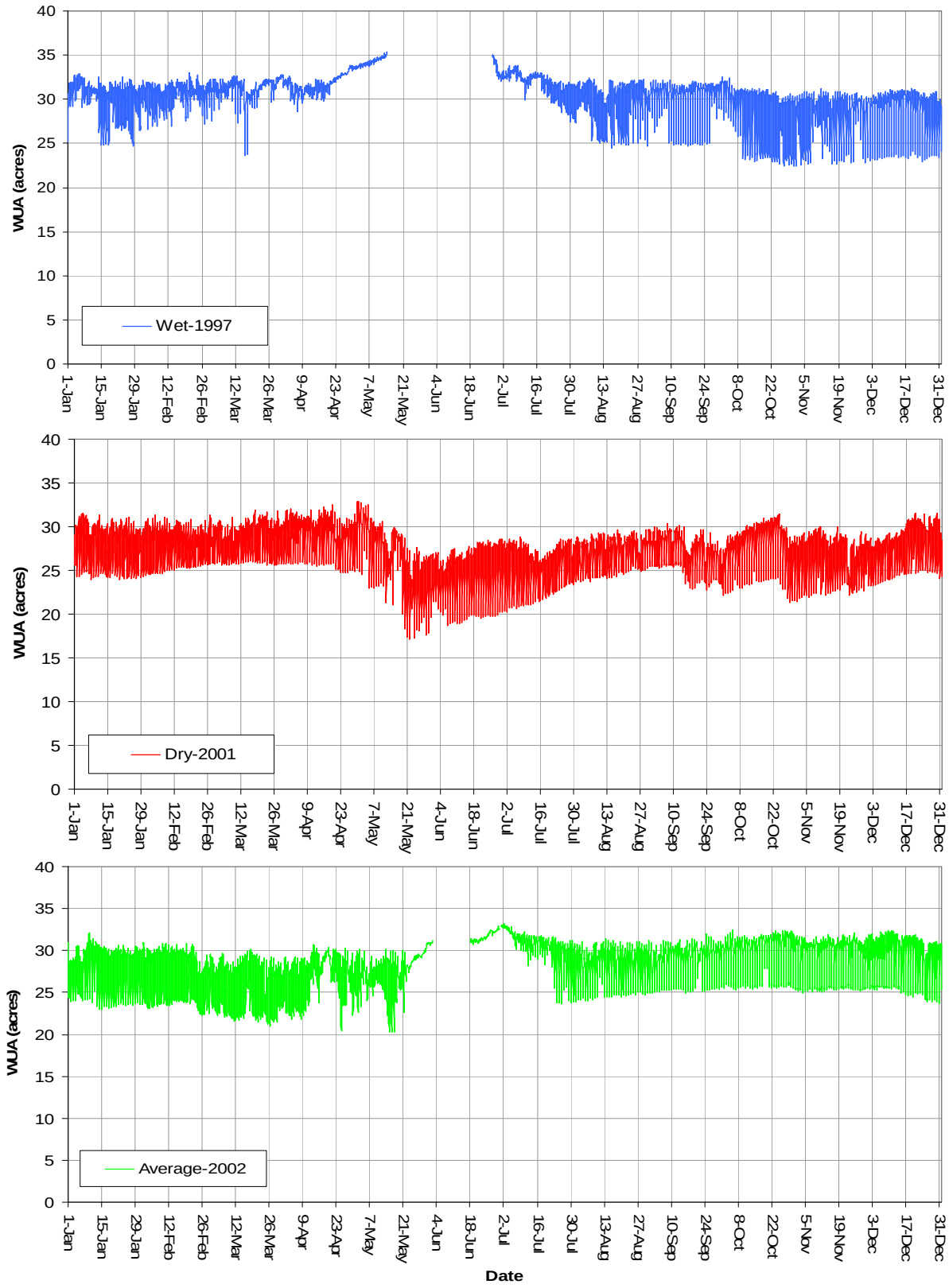

Figure 5.2-9. BMI WUA in the Forebay Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

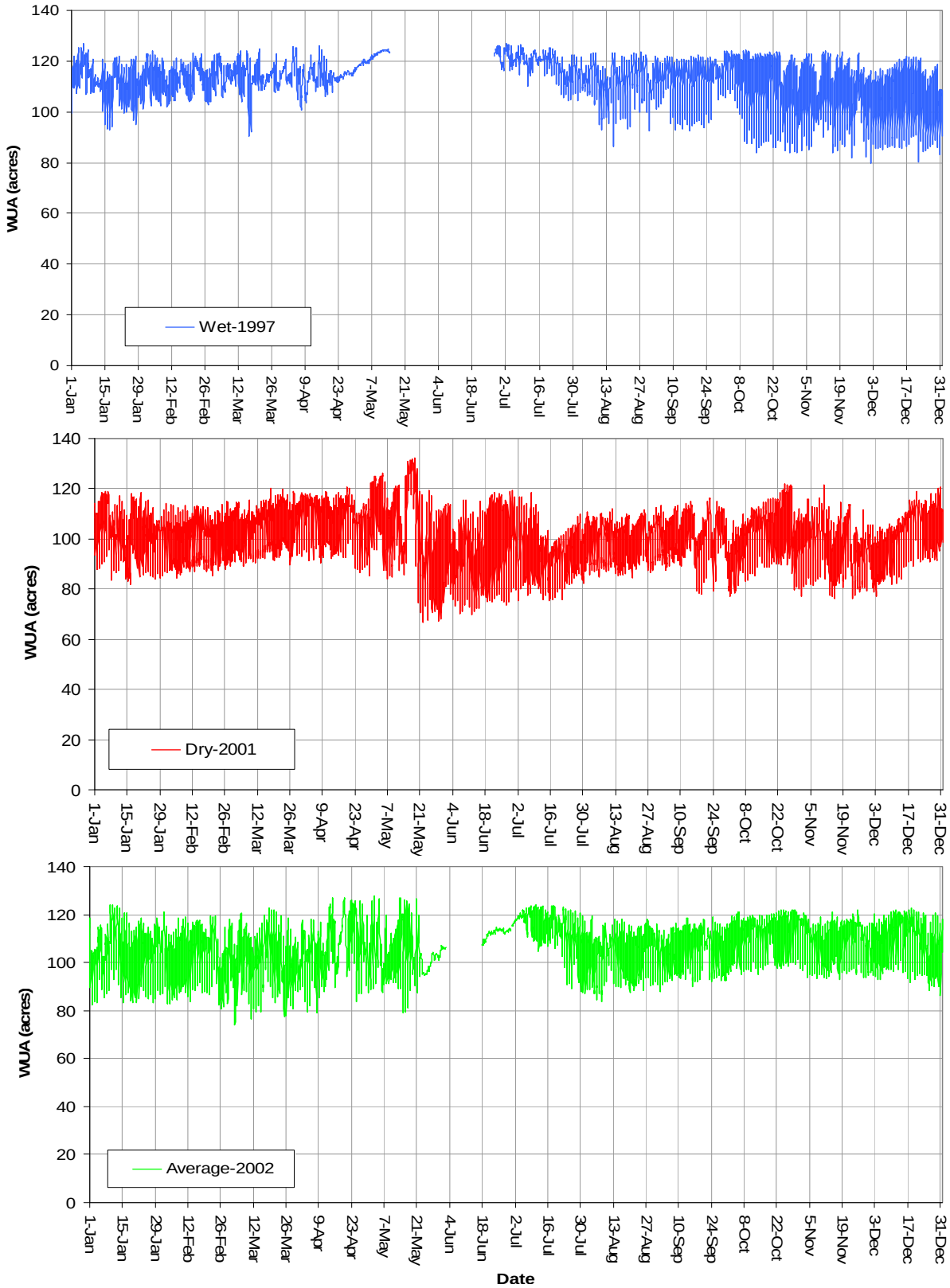

Figure 5.2-10. BMI WUA in the Canyon Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

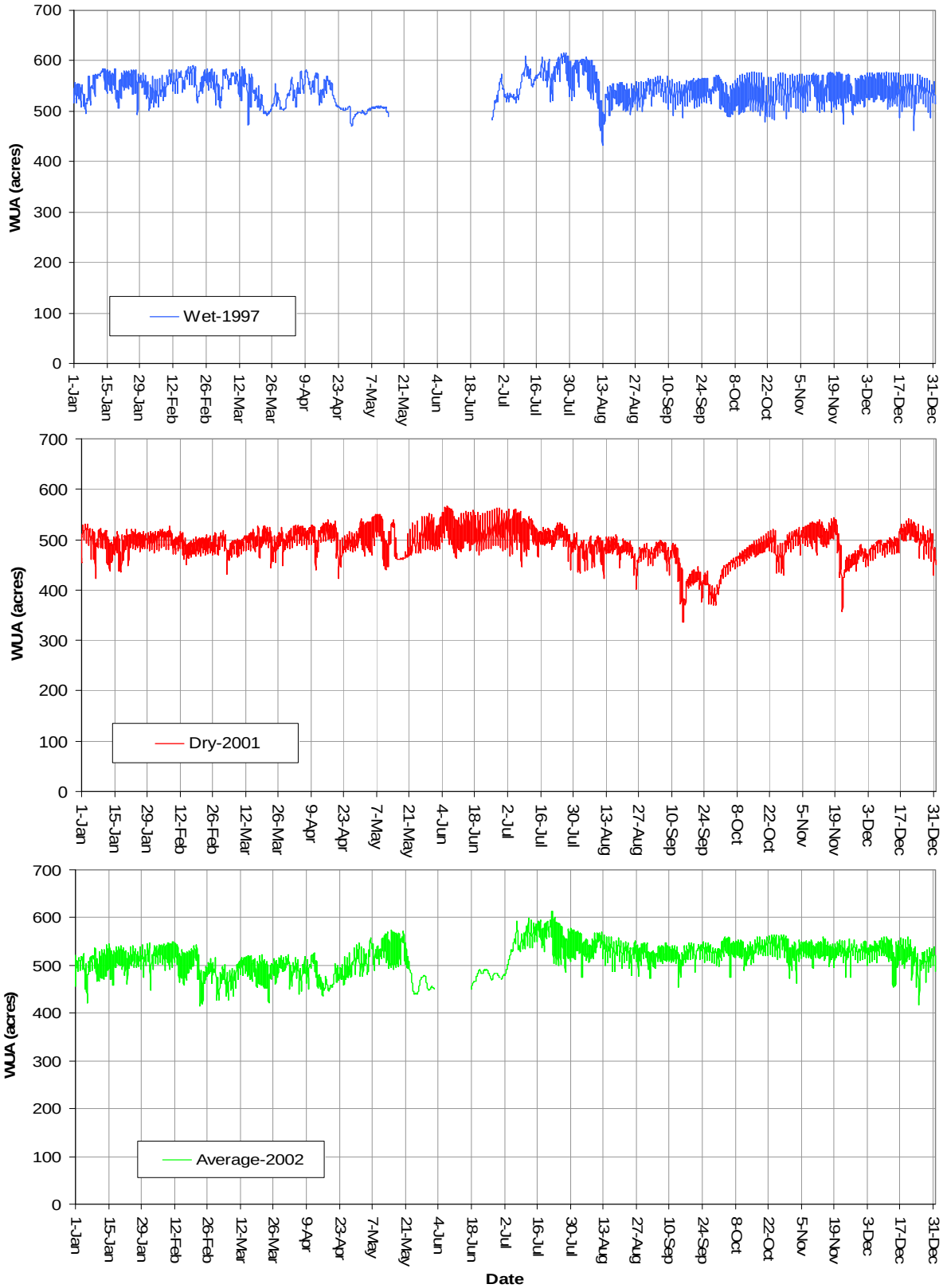

Figure 5.2-11. BMI WUA in the Upper Reservoir Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

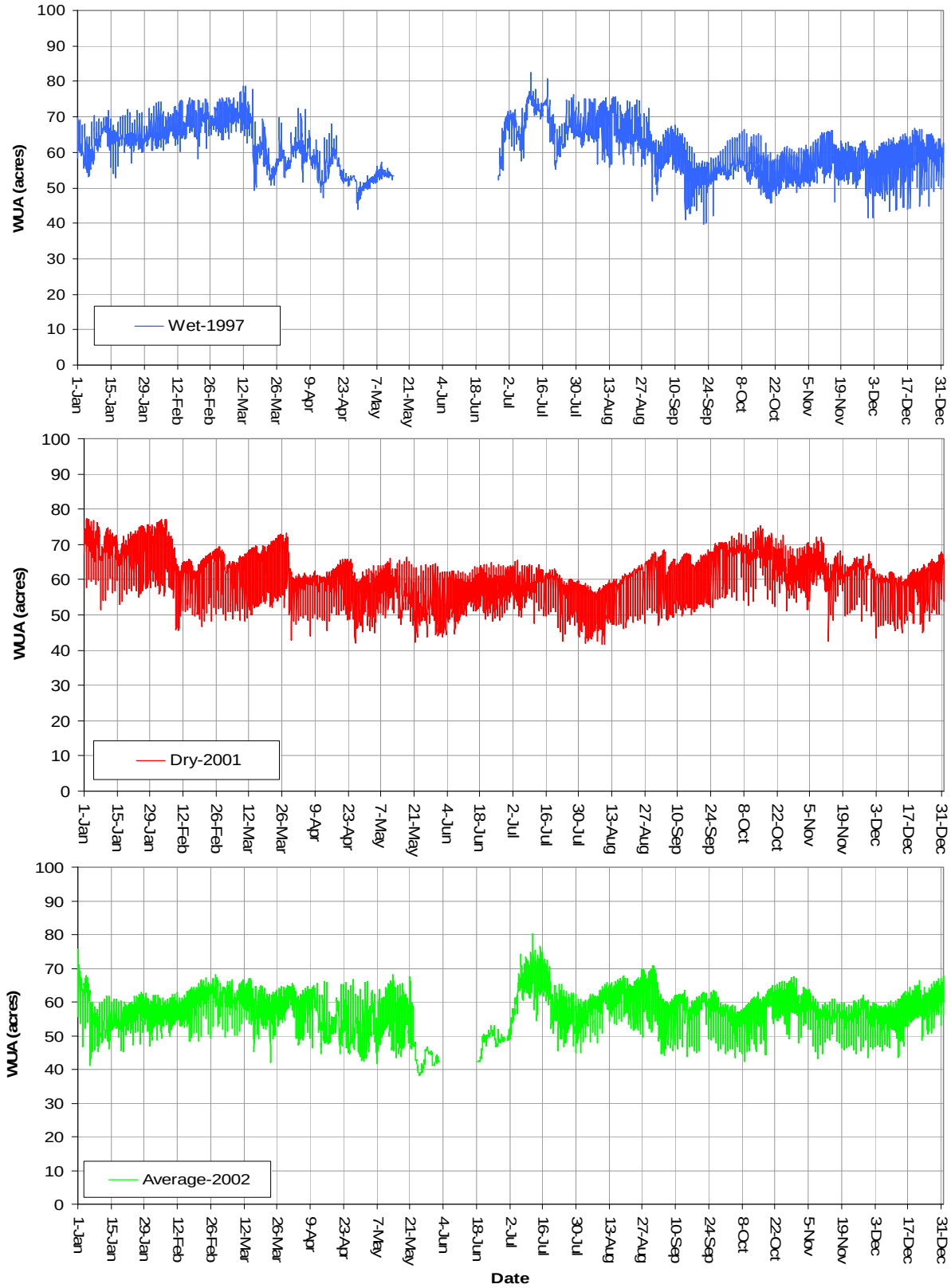

Figure 5.2-12. BMI WUA in the Tailrace Reach for wet, dry, and average hydrologic conditions in Boundary Reservoir.

5.3. Trophic Production Index

Indices of aquatic production were calculated for nutrients, phytoplankton, zooplankton, macrophytes, periphyton, and BMI for three hydraulic years representing wet, dry and average conditions under existing Project operations. Data collected in Boundary Reservoir as described in Sections 4.1 and 4.2, along with literature values and professional judgment, were used to construct indices of 2007/2008 nutrient concentrations, and phytoplankton and zooplankton production. TPIs were also constructed for macrophytes, periphyton, and BMI using data collected in Boundary Reservoir during 2007/2008, along with literature values and professional judgment.

5.3.1. Trophic Production Indices for Nutrients, Phytoplankton and Zooplankton Production

TPIs were developed, as part of this study, for nutrients, phytoplankton, and zooplankton to indicate production potential under existing Project operations similar to the WUA and TPIs for macrophytes, periphyton, and BMI. Interpretation of the TPI allows understanding of the energy flow from primary to secondary production in Boundary Reservoir, through a limiting factor analysis, such as nutrient availability that may control primary and secondary production. The index developed for each trophic parameter was based upon several metrics that serve as primary factors influencing potential for production and magnitude of production. TPI values range from 0 to 1.0 with 1.0 indicating high production, 0.5 medium production, and 0.1 low production. A detailed discussion of the methods and reasoning used in scoring the various metrics within each trophic parameter can be found in Appendix 1. Tables 5.3-1 through 5.3-4 summarize the TPI values for nutrients, phytoplankton, and zooplankton calculated as part of this study.

Total phosphorus concentrations within Boundary Reservoir are dependent on flow and phosphorus concentrations upstream in Box Canyon Reservoir. There are no significant inputs of phosphorus downstream from Box Canyon Reservoir to Boundary Dam; that is, phosphorus concentrations are similar throughout Boundary Reservoir (see the Study 5 Final Report [SCL 2009b] for a more detailed discussion). Due to the relationship between total phosphorus concentrations and flow, there will be higher phosphorus concentrations in wet hydrologic years than average years and lower phosphorus concentrations in dry years. This is shown in the calculated TPI scores for nutrients (Tables 5.3-1 through 5.3-4) as well as in the observed data (see Study 5 [SCL 2009b]). Trophic production index scores for nutrients ranged from 0.13 to 0.40 in the Upper Reservoir Reach, 0.13 to 0.27 in the Canyon Reach, 0.08 to 0.27 in the Forebay Reach, and 0.13 in the Tailrace Reach. The Canyon and Forebay reaches have lower trophic scores for nutrients due to slightly longer retention times than the Upper Reservoir Reach and the sedimentation of phosphorus. Overall, Boundary Reservoir has relatively short retention times, varying from 2 to 5 days depending on season, so if sedimentation of phosphorus occurred it would be in the deeper portions of the reservoir and very small. The total phosphorus in the Tailrace Reach has a direct relationship with phosphorus concentrations in the Forebay Reach (see Study 5) and may not be accurately described in the TPI model developed for this study.

Table 5.3-1. Trophic production index scores for nutrients, phytoplankton, zooplankton in the Forebay Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Nutrients	0.27	0.08	0.11
Phytoplankton	0.40	0.28	0.32
Zooplankton	0.36	0.29	0.32

Table 5.3-2. Trophic production index scores for nutrients, phytoplankton, zooplankton in the Canyon Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Nutrients	0.27	0.13	0.13
Phytoplankton	0.40	0.23	0.32
Zooplankton	0.36	0.21	0.24

Table 5.3-3. Trophic production index scores for nutrients, phytoplankton, and zooplankton in the Upper Reservoir Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Nutrients	0.40	0.13	0.27
Phytoplankton	0.41	0.31	0.34
Zooplankton	0.40	0.33	0.28

Table 5.3-4. Trophic production index scores for nutrients, phytoplankton, zooplankton in the Tailrace Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Nutrients	0.13	0.13	0.13
Phytoplankton	0.40	0.18	0.27
Zooplankton	0.36	0.21	0.24

The low calculated TPI scores for nutrients are consistent with the observed concentrations of total phosphorus in Boundary Reservoir during the 2007 and 2008 field seasons. Observed concentrations of total phosphorus were all below 16 µg/L, which would be considered oligotrophic to mesotrophic conditions, or low production conditions. The TPI scores calculated for total phosphorus were all 0.30 or below, with the exception of the Upper Reservoir Reach during the wet year, which corresponded to low production.

Phytoplankton TPI scores followed a similar trend as the nutrient TPI scores. The highest TPI scores for phytoplankton occurred during the wet hydrologic year for all reaches, with the Upper Reservoir Reach having the highest score of 0.41. Trophic production index scores for phytoplankton ranged from 0.31 to 0.41 in the Upper Reservoir Reach, 0.23 to 0.40 in the Canyon Reach, and 0.28 to 0.40 in the Forebay and Tailrace reaches. All scores indicate that phytoplankton production in Boundary Reservoir is low.

Phytoplankton production in Boundary Reservoir is very limited by the amount of available nutrients (phosphorus). Mixing depth and retention time have a small influence on phytoplankton production within Boundary Reservoir, but not to the extent of phosphorus. A smaller mixing depth may be one reason why there is slightly more production of phytoplankton in the Upper Reservoir Reach than there is in the other reaches of Boundary Reservoir and downstream of Boundary Dam. The Tailrace Reach has the lowest amount of phytoplankton production, most likely due to such short retention times and fast moving water.

Zooplankton populations within Boundary Reservoir also follow the same trend as nutrients and phytoplankton because they too are, in part, dependent on flow. Trophic production index scores for zooplankton were the highest in the wet hydrologic year, with the Upper Reservoir Reach having the highest score of 0.40. Trophic production index scores for zooplankton in the Upper Reservoir Reach ranged from 0.28 to 0.40, 0.21 to 0.36 in the Canyon Reach, 0.29 to 0.36 in the Forebay Reach, and 0.21 to 0.36 in the Tailrace Reach. Similar to phytoplankton, the TPI scores calculated for zooplankton indicate low zooplankton production within Boundary Reservoir.

Production of zooplankton in Boundary Reservoir is dependent on flow directly and indirectly. Directly, zooplankton is dependent on flow for the continuous inflow of populations from upstream in Box Canyon Reservoir. The highest numbers of zooplankton were observed in the Box Canyon Tailrace during field seasons 2007 and 2008 (see Study 5 [SCL 2009b]). Zooplankton populations are indirectly dependent on flow for their food supply or phytoplankton production.

In order to verify the performance of our TPI model developed for this study, trophic state index (TSI) values were calculated for Boundary Reservoir for phosphorus and chlorophyll *a* based on Carlson's equations (Carlson 1977). A TSI is an established method for measuring trophic status in lakes and reservoirs that was applied to the conditions of Boundary Reservoir for further interpretation of potential production. These TSI values were calculated using the 2007 summer mean (June-August) phosphorus and chlorophyll *a* concentrations for Boundary Reservoir which were determined in Study 5 (SCL 2009b). The calculated TSI value for phosphorus for Boundary Reservoir was 37.9, which indicates an oligotrophic system, or a low production system. The TPI value calculated for an average year in this study for nutrients (phosphorus)

ranged from 0.11 to 0.27. TPI values nearer the lower end of the index range (e.g., 0.1) are considered nutrient-poor or oligotrophic and are reflected by the results in the TPI. The Carlson TSI corresponds with the evaluation of current conditions in the Boundary reservoir using the TPI developed for this study. The calculated TSI value for chlorophyll *a* for Boundary Reservoir was also indicative of an oligotrophic or low productive water body. In comparison, the TPI value for chlorophyll *a* calculated for this study ranged from 0.27 to 0.34, which categorizes trophic status of the reservoir the same as Carlson's TSI value.

5.3.2. Trophic Production Indices for Macrophytes, Periphyton, and BMI

TPIs were developed, as part of this study, for macrophytes, periphyton, and BMI to indicate production potential under existing Project operations. The TPI for each trophic parameter describes the available food base (i.e., energy) for each TPI and whether energy flow is enhanced or impeded. The calculated TPI scores also determine if production is restricted at any trophic level. The TPI developed for each trophic parameter was based upon several metrics that serve as primary factors influencing potential for production and magnitude of production. TPI values range from 0 to 1.0 with 1.0 indicating high production, 0.5 medium production, and 0.1 low production. A detailed discussion of the methods and reasoning used in scoring the various metrics within each trophic parameter can be found in Appendix 1. Tables 5.3-5 through 5.3-8 summarize the TPI values for macrophytes, periphyton, and BMI calculated for each study reach. Annual values, rather than seasonal values, can be used to assess differing alternate operations.

Table 5.3-5. Trophic production index scores for macrophytes, periphyton, and BMI in the Forebay Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Macrophytes	0.28	0.33	0.28
Periphyton	0.24	0.24	0.26
BMI	0.36	0.31	0.39

Table 5.3-6. Trophic production index scores for macrophytes, periphyton, and BMI in the Canyon Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Macrophytes	0.13	0.20	0.13
Periphyton	0.24	0.24	0.26
BMI	0.16	0.29	0.36

Table 5.3-7. Trophic production index scores for macrophytes, periphyton, and BMI in the Upper Reservoir Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Macrophytes	0.40	0.50	0.43
Periphyton	0.35	0.32	0.36
BMI	0.31	0.46	0.46

Table 5.3-8. Trophic production index scores for macrophytes, periphyton, and BMI in the Tailrace Reach under existing Project operations and three different hydrologic conditions (wet, dry, and average years).

Trophic Parameter	Trophic Production Index Score		
	Wet Year (1997)	Dry Year (2001)	Average Year (2002)
Macrophytes	0.20	0.30	0.30
Periphyton	0.29	0.30	0.32
BMI	0.19	0.29	0.24

According to the TPI developed for this study, macrophytes have the highest production in the Upper Reservoir Reach of Boundary Reservoir. This is consistent with the distribution of macrophytes observed during the field seasons of 2007 and 2008 and with WUA estimates from the Mainstem Aquatic Habitat Model. The Upper Reservoir Reach has the most suitable habitat for macrophyte production (substrate, velocity, depth, and hours of direct light) than other reaches in Boundary Reservoir or downstream of Boundary Dam. Trophic production index scores for macrophytes in the Upper Reservoir Reach ranged from 0.40 to 0.50, indicating medium levels of production. The highest production for macrophytes was determined to be during dry hydrologic conditions when depth and velocities are low. Trophic production index scores for macrophytes were the lowest in the Canyon Reach, ranging from 0.13 to 0.20. These index scores indicate low macrophyte production within the Canyon Reach, which is consistent with observed macrophyte bed coverage. Most likely the primary reason for low macrophyte production within the Canyon Reach is the limited amount of direct light (due to high canyon walls) and the lack of suitable substrata.

Trophic production index scores for macrophyte production were similar in the Forebay and Tailrace reaches. Scores in these reaches were less than those in the Upper Reservoir Reach but higher than in the Canyon Reach. Macrophyte TPI scores ranged from 0.28 to 0.33 in the Forebay Reach and 0.20 to 0.30 in the Tailrace Reach. These scores indicate low macrophyte production within these reaches, even though they are slightly higher than scores in the Canyon Reach. The Forebay and Tailrace reaches have slightly better conditions for macrophyte growth in terms of direct light, substrata, and depth than the Canyon Reach.

Periphyton TPI scores were highest in the Upper Reservoir Reach compared to other reaches within Boundary Reservoir and the Tailrace Reach. This is consistent with results from the hard substrata artificial sampling conducted in 2007 and 2008 (see Study 7, Appendix 7 [SCL 2009a]) and the WUA estimates for periphyton from the Mainstem Aquatic Habitat Model. Periphyton TPI scores ranged from 0.32 to 0.36 in the Upper Reservoir Reach indicating low production, even though the Upper Reservoir Reach has the most suitable conditions for periphyton growth (substrata, hours of direct light, shallowest depths). The low production scores for periphyton in the Upper Reservoir Reach indicate that nutrient availability (phosphorus) may be the limiting factor in periphyton production. Periphyton production in the Canyon and Forebay reaches was also low, with TPI scores ranging from 0.24 to 0.26 in both reaches. Scores in the Canyon and Forebay reaches are lower than in the Upper Reservoir Reach most likely due to the amount of suitable substrata available for colonization, as well as greater depths and less light. The lack of nutrients available for growth also limits the amount of periphyton production in these reaches.

The Tailrace Reach had TPI scores for periphyton that were slightly higher than those calculated for the Canyon and Forebay reaches. Trophic production index scores for periphyton ranged from 0.29 to 0.32 in the Tailrace Reach, indicating low production, as seen in all the other reaches. Periphyton production is slightly higher in the Tailrace Reach as compared to the Canyon and Forebay reaches because there is more suitable substrata for periphyton colonization and more hours of direct light. However, during wet and average hydrologic years higher velocities in the Tailrace Reach may inhibit periphyton growth.

Similar to macrophytes and periphyton, BMI TPI scores were highest in the Upper Reservoir Reach, ranging from 0.31 to 0.46. These scores indicate that BMI production can range from low to medium depending on the hydrologic conditions (higher scores were calculated for the average and dry years). The Upper Reservoir Reach has the most suitable substrata available for BMI colonization as well as the most periphyton production for consumption as compared to other reaches in Boundary Reservoir and downstream of Boundary Dam. BMI TPI scores were similar in the Canyon and Forebay reaches, ranging from 0.16 to 0.36 to 0.31 to 0.39, respectively. The low TPI score of 0.16 in the Canyon Reach was for wet hydrologic conditions when velocities were the highest and depth the greatest.

Tailrace Reach TPI scores for BMI ranged from 0.19 to 0.29, which were lower than scores calculated for all other reaches in Boundary Reservoir, except for the Canyon Reach during a wet hydrologic year. The scores for BMI in the Tailrace Reach, similar to all other reaches, indicate low production. Although there is more suitable substrate for BMI production in the Tailrace Reach, the high velocities, which at times are extremely variable, and low amount of periphyton available for consumption inhibit BMI production.

5.4. Compilation of Results

This section presents a comparison between WUA estimates from the Mainstem Aquatic Habitat Model, TPI scores developed as part of this study, and any data collected as part of studies 5 and 7 (SCL 2009b and 2009a, respectively). This section also discusses the limiting and controlling factors of production with Boundary Reservoir and the potential effects of Project operations on production.

5.4.1. Discussion of WUA, TPI, and Existing Conditions

For nutrients, phytoplankton, and zooplankton, calculated TPI scores were compared to observed concentrations (nutrients and phytoplankton) and biomass to determine whether patterns in TPI scores were similar to existing conditions in Boundary Reservoir. Figures 5.4-1 through 5.4-3 show the comparisons between TPI scores and observed conditions for nutrients, phytoplankton, and zooplankton in Boundary Reservoir.

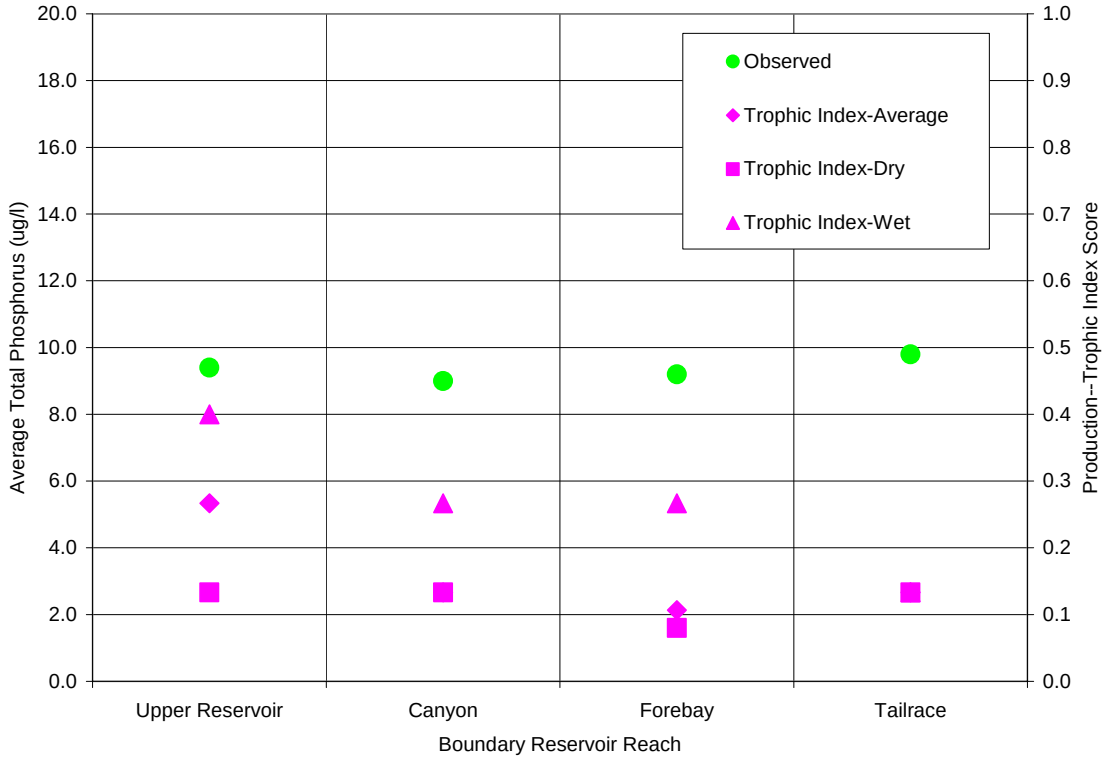

Figure 5.4-1. Total phosphorus observed concentrations compared to calculated trophic production index scores in Boundary Reservoir.

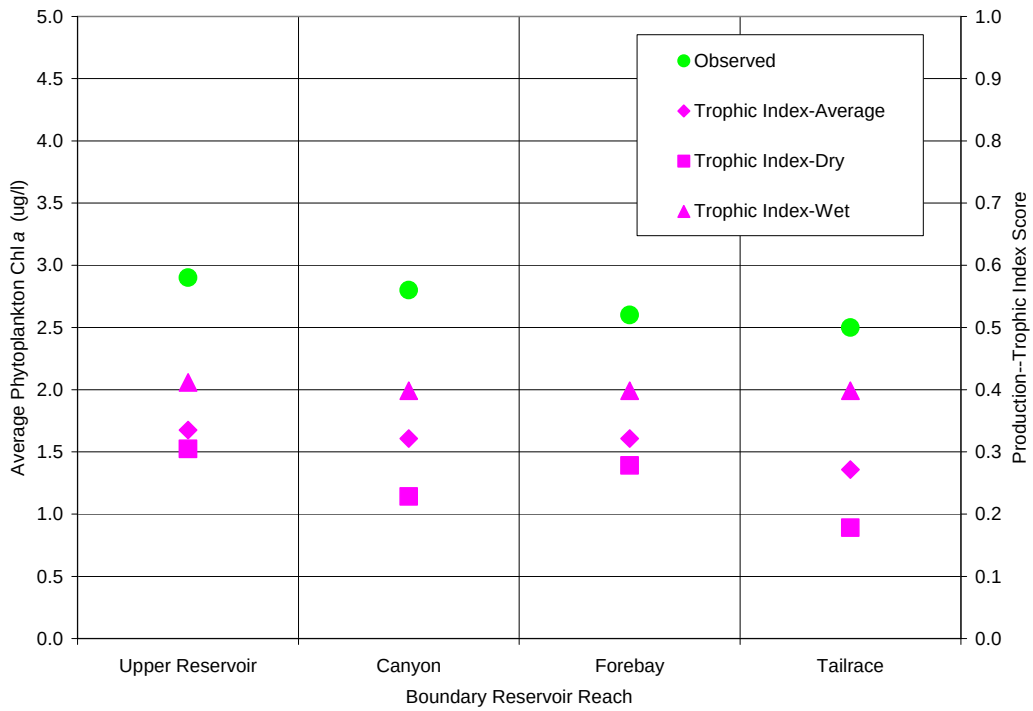

Figure 5.4-2. Phytoplankton (chlorophyll *a*) observed concentrations compared to calculated trophic production index scores in Boundary Reservoir.

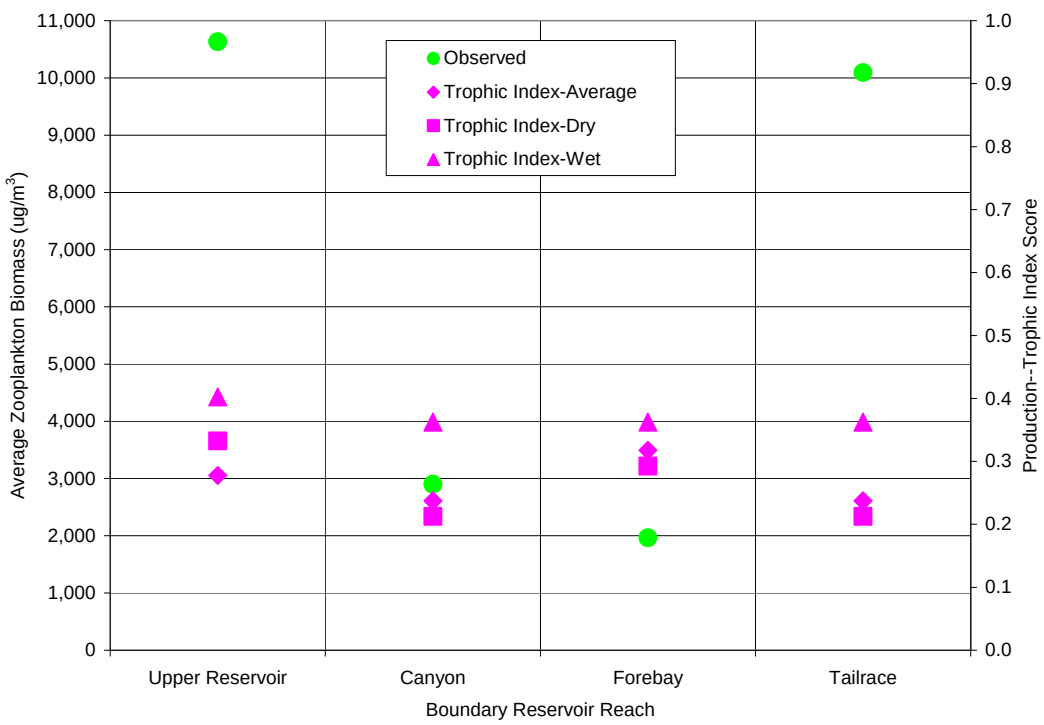

Figure 5.4-3. Zooplankton observed biomass compared to calculated trophic production index scores in Boundary Reservoir.

Total phosphorus TPI scores follow a similar pattern as observed TP concentrations within Boundary Reservoir. There is little difference between the TPI scores for TP across the reaches in Boundary Reservoir. The two exceptions to this are the higher TPI score for TP for the wet hydrologic year in the Upper Reservoir Reach and the TPI scores calculated for the Tailrace Reach. The TP in the Tailrace Reach has a direct relationship with TP concentrations in the Forebay Reach (see Study 5 [SCL 2009b]) and may not be accurately described in the TPI model developed for this study, hence the difference in pattern from the other reaches in Figure 5.4-1.

Phytoplankton TPI scores calculated for Boundary Reservoir follow the same pattern as observed phytoplankton (chlorophyll *a* concentrations) (Figure 5.4-2). Average chlorophyll *a* concentrations remain fairly consistent from reach to reach with a very slight decrease from the Upper Reservoir Reach to the Tailrace Reach. Calculated TPI scores for phytoplankton also remain consistent from reach to reach for the wet hydrologic year and slightly decrease from upstream to downstream for the average hydrologic year. Trophic production index scores for phytoplankton calculated during a dry hydrologic year vary just slightly from the pattern of observed concentrations in that the Canyon Reach has a lower TPI score than the Forebay Reach, which is not the case for the other hydrologic years or the observed conditions. However, this slightly lower TPI score for phytoplankton in the Canyon Reach is for only one hydrologic condition and does not mean that the TPI model developed for phytoplankton is invalid.

Predicted zooplankton production potential varied slightly among reaches during the wet hydrologic year. Minor differences among reaches were predicted from TPI scores during the dry and average hydrologic years (Figure 5.4-3). The observed zooplankton biomass values were more similar to the TPI scores for the Canyon and Forebay reaches than for the Upper Reservoir and Tailrace reaches. The difference between observed zooplankton biomass estimates in the Upper Reservoir and the Tailrace reaches did not follow the same pattern as TPI scores calculated for the same reaches. Both the Upper Reservoir and Tailrace reaches had similar velocity characteristics, depths, and substrata that differed from the Canyon and Forebay reaches. Vertical tows in each reach were used to estimate zooplankton biomass per unit volume of water with total volume estimated from vertical distance and size of opening in the zooplankton net. However, the water velocity in both the Upper Reservoir and Tailrace reach samples was much greater than in the other reaches and likely resulted in an underestimation of water volume filtered therefore inflated zooplankton density. This logistical issue may have resulted in observed estimates for zooplankton density higher than would have been determined in lacustrine settings (e.g., Canyon and Forebay reaches) with similar velocity and depth characteristics. The primary indicator for zooplankton production potential (i.e., TPI score) is a better representation of responses to hydrologic years based on determinations from index metrics that evaluate larger scale characteristics of each reach and are not influenced by variability associated with environmental sampling error. Another important consideration is the estimate of zooplankton density versus the aerial biomass estimate. Given the flow dynamics within the reservoir that result in insignificant loss of zooplankton due to direct settling, expressing the effect of density dilution on biomass in the Canyon and Forebay reaches on a per unit volume basis gives a greater value than by expressing the effect per unit area. If the latter were used, the seeming difference in observed versus TPI scores would be less.

WUA values for macrophytes, periphyton, and BMI are based on physical predictor variables such as depth, velocity, substrata, duration of dewatering, and duration of inundation. These physical parameters are influenced by operations and are the basis for the Mainstem Aquatic Habitat Model (see Study 7 [SCL 2009a]). The TPIs are based on physical, chemical, and biological parameters that promote or restrict production for each of the six elements (i.e., nutrients, phytoplankton, zooplankton, macrophytes, periphyton, and BMI). The limiting factors included in the generation of TPI scores (Table 4.3-1) are interrelated by the carbon (or energy) flow between trophic levels from primary to secondary production. The bases of the trophic cascade are the primary limiting factors for photosynthesis, which are nutrients and light availability. Study 5 (SCL 2009b) showed that phosphorus was the limiting factor for primary production or photosynthesis; therefore, phosphorus has a direct and indirect impact on all six TPIs.

TPI scores calculated for macrophytes, periphyton, and BMI were compared to estimated WUA to determine whether similar patterns were observed between the two measures of production. For this comparison, TPI scores for macrophytes, periphyton, and BMI were multiplied by the available area for production in each reach. For macrophytes, the TPI score was multiplied by the surface area of each reach for depths less than 30 feet. For periphyton, TPI scores were multiplied by the surface area of each reach for depths less than 50 feet, and for BMI, TPI scores were multiplied by the total surface area for each reach. Reach surface areas were calculated as part of Study 7 (see Study 7 Final Report, Section 5.2.2 [SCL 2009a]). In the case of macrophytes, observed macrophyte coverage was also compared to the TPI score acreage and WUA. Figures 5.4-4 through 5.4-6 show the comparisons between WUA, acreage calculated by the TPI scores, and observed conditions for macrophytes.

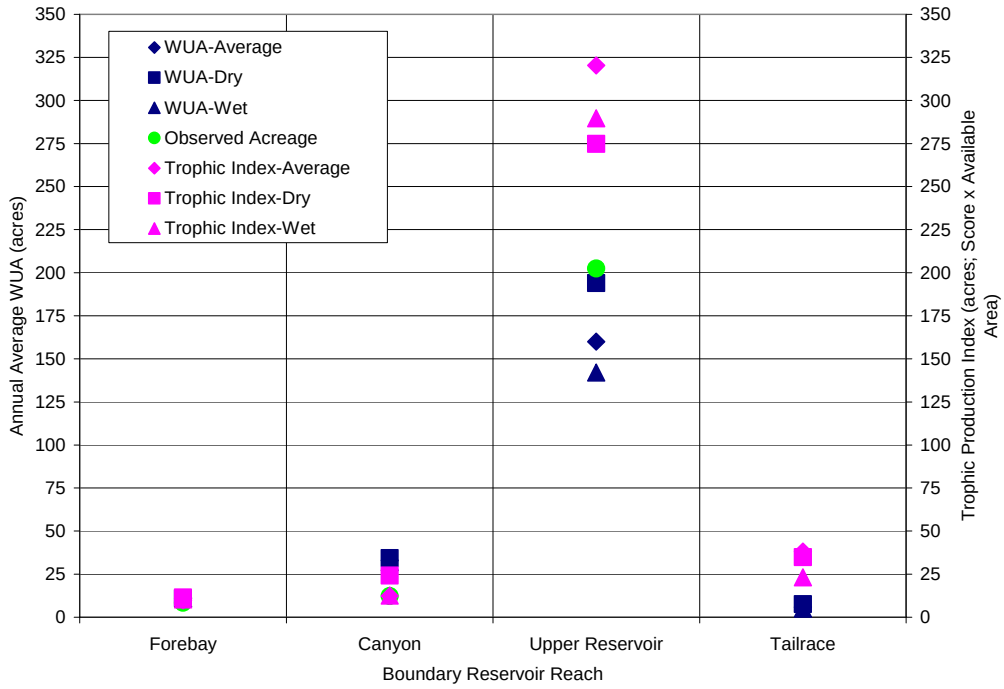

Figure 5.4-4. Macrophyte WUA and acres predicted by calculated trophic production index scores compared to observed macrophytes within Boundary Reservoir.

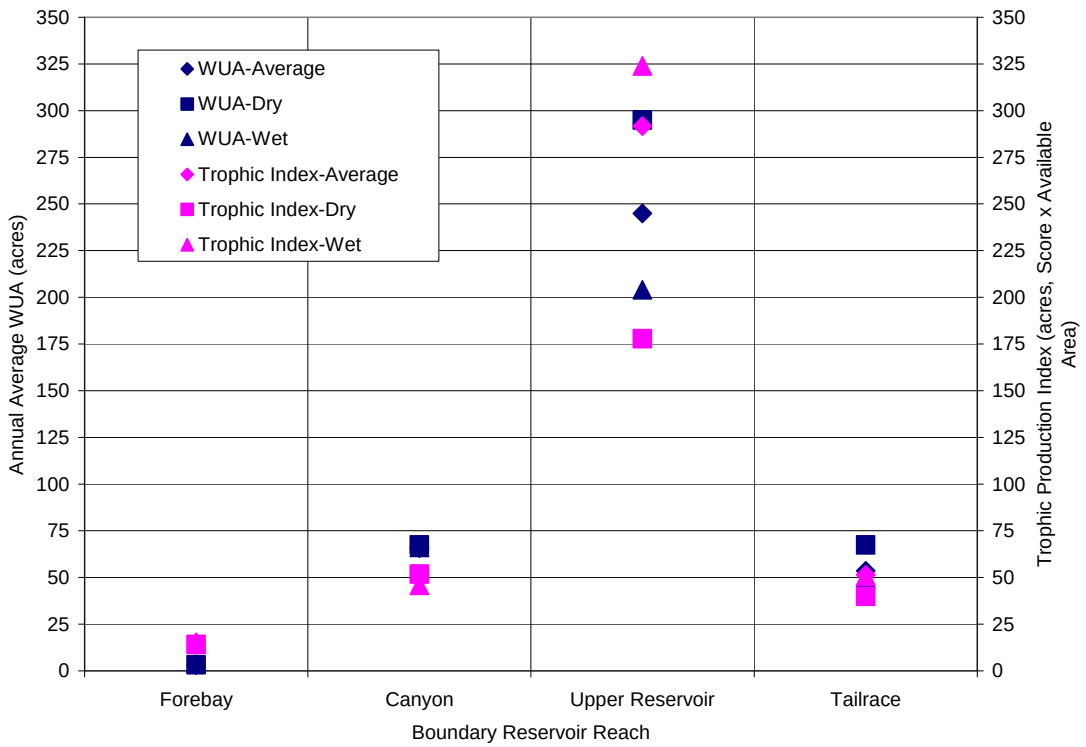

Figure 5.4-5. Periphyton WUA compared to areas predicted by calculated trophic production index scores in Boundary Reservoir.

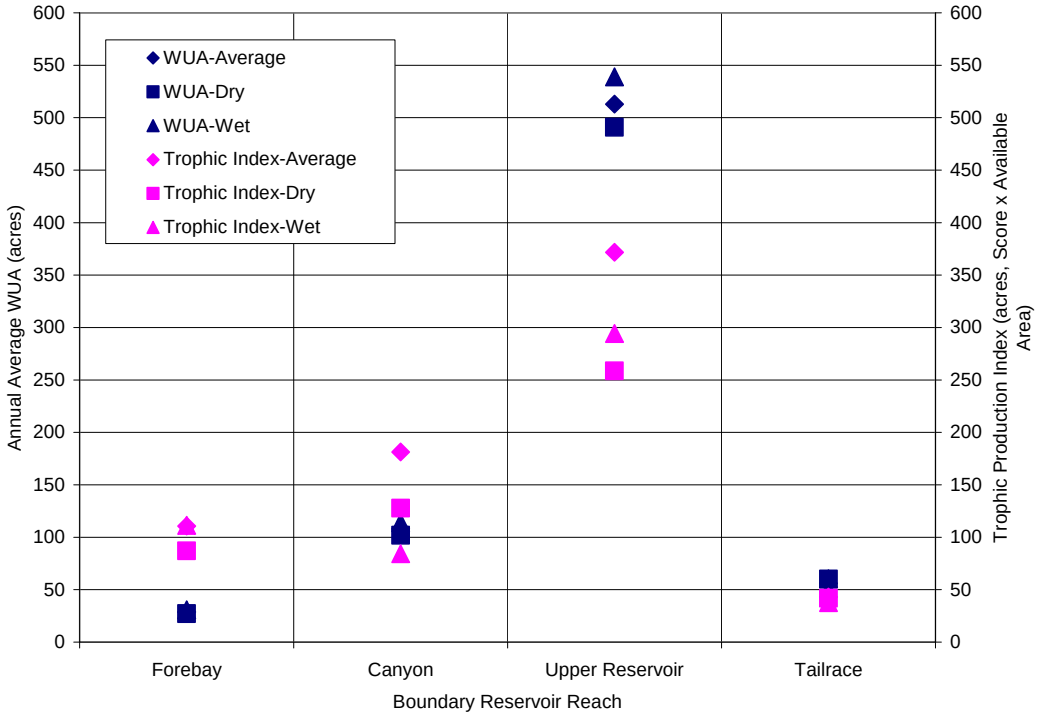

Figure 5.4-6. BMI WUA compared to areas predicted by calculated trophic production index scores in Boundary Reservoir.

TPI scores calculated for macrophytes, when multiplied by the surface area at depths less than 30 feet, follow similar patterns as WUA estimates and observed macrophyte acreage. The exception to this is in the Upper Reservoir Reach where TPI scores predict a higher number of acres for macrophyte production than the WUA. In the Upper Reservoir Reach the WUA estimates for macrophytes are very similar to the existing macrophyte coverage observed in Boundary Reservoir during 2007 and 2008. For the Canyon and Forebay reaches, both the WUA and TPI scores match up with observed acres of macrophytes. No data were available for existing macrophyte coverage in the tailrace (field studies were only conducted to the U.S. border and do not represent the entire Tailrace Reach) but TPI scores and WUA estimates for macrophyte coverage area were similar.

WUA estimates for periphyton and calculated TPI scores, as area, were very similar for the Canyon, Forebay, and Tailrace reaches. They differed in the Upper Reservoir Reach where WUA estimates were highest for the dry hydrologic year and TPI scores predicted more periphyton production for the wet hydrologic year. The difference in WUA and predicted area by TPI score may be the result of WUA only representing a relative amount of suitable colonizeable area by periphyton or it could be related to the Mainstem Aquatic Habitat Model not accounting for hours of direct light or depth of light (transparency). In general, the magnitude of the variability in TPI score was in part due to the increase in sensitivity of the index as more optimum production conditions were attained.

WUA estimates for BMI are higher in the Upper Reservoir Reach than the area predicted for BMI production by the TPI scores. This could be because WUA is only representative of a portion of the habitat that could be colonized by BMI and may not represent the actual area of BMI habitat. For the other three reaches, WUA estimates for BMI are fairly similar to areas calculated from the TPI scores for BMI. There is a slight difference between WUA and TPI area in the Forebay Reach but it is not significant.

5.4.2. Energy Flow of Trophic Levels

Potential energy flow from one trophic level in Boundary Reservoir can be examined in two ways: as enabling production or controlling (i.e., limiting) production. Factors involved in enabling production include the inflow of phosphorus, phytoplankton, and zooplankton, as well as the amount and quality of light in the water column. Factors involved in controlling production are the amount and availability of phosphorus inflow to the reservoir; the hydrology and hydraulic characteristics, retention time, and morphology of each reach (including depth); and Boundary Reservoir mixing patterns.

5.4.2.1. Enabling Production

As indicated above, phosphorus concentration and inflow and therefore bio-availability within the Upper, Canyon, and Forebay reaches are directly related to inflow concentration and flow magnitude from Box Canyon Reservoir. In short, phosphorus is the key limiting nutrient to primary production in Boundary Reservoir, and the vast majority of the phosphorus entering the reservoir comes from the inflow through Box Canyon Dam. As discussed in Study 5 Final Report (SCL 2009b) the concentration of phosphorus is low and characteristic of a low

production system. Thus, primary production of phytoplankton, periphyton, and aquatic macrophytes is largely dependent upon the inflow of phosphorus. Similarly, the inflow of phytoplankton and zooplankton from Box Canyon Reservoir plays an extremely large role in the observed biomass within Boundary Reservoir. Although there is production of phytoplankton and zooplankton within Boundary Reservoir, it appears that this net production is only equal to the losses from grazing, predation, and sedimentation. As previously discussed, given the observed growth patterns and characteristics of the reservoir, light is not the primary limiting factor in the reservoir. Nevertheless it is an important factor, although perhaps more of a controlling factor for grazing, predation, and primary production.

5.4.2.2. Controlling Production

As the bio-availability of phosphorus enables primary production, the low concentration of phosphorus especially SRP limits or defines the maximum attainable level of biomass that can be produced. In Boundary Reservoir, the extremely low levels of SRP translate to a low level of organic carbon fixation through photosynthesis and a low level of primary production of phytoplankton, periphyton, and aquatic macrophytes. The Pend Oreille River basin hydrology and the Boundary Reservoir morphology combine to define both mixing characteristics and retention time, both of which are factors in controlling production. The relatively high flow rates through the reservoir and the narrow, deep bathymetry of the reservoir both physically remove organisms from the photic zone and limit the time that planktonic organisms remain in the reservoir. This effectively limits light for photosynthesis and grazing while removing both phytoplankton and zooplankton from the reservoir before they can reproduce. Hence, the three major limiting factors to production in Boundary Reservoir are low nutrients, light limitation due to mixing, and short retention time.

5.4.3. Project Effects

This section presents the evaluation of potential Project effects on primary and secondary production in the mainstem Boundary Reservoir and tailrace. The following subsections provide observations for primary and secondary production assessments developed from the 2007–2008 study period. Observations are followed by deductions made regarding the potential effects of Project operations on production in Boundary Reservoir.

5.4.3.1. Nutrients

Low concentrations of nutrients, especially phosphorus, limit primary production throughout Boundary Reservoir and this, combined with low hydraulic retention times and deep mixing, reduces overall production in the reservoir (see Section 5.4.2.1). Also, low nutrient availability (especially phosphorus, which is the dominant limiting factor to primary production) persists regardless of water surface elevation fluctuations and is a reflection of low inflow concentrations. These low levels of nutrients are expected to remain low regardless of operations scenarios because nutrient concentrations are a direct function of incoming nutrient concentrations from Box Canyon Reservoir.

5.4.3.2. Phytoplankton

Very few differences were found in chlorophyll *a* concentrations within Boundary Reservoir and between TPI scores by reach for phytoplankton. Differences were found seasonally, with the highest chlorophyll *a* concentrations measured in May, and with hydrologic year, with the highest TPI score calculated for both the wet and average years. The current study confirms observations made earlier in the Pend Oreille River by McLellan and O'Connor (2001). This seasonal and hydrologic difference in phytoplankton is the direct result of nutrient availability (higher phytoplankton production with higher nutrient concentrations). No definable Project operations effects on chlorophyll *a* were observed based on spatial and temporal measurements and there are no anticipated differences in chlorophyll *a* concentrations between operations scenarios because phytoplankton is limited by available phosphorus, which is governed by inflow and upstream conditions, not Project operations.

5.4.3.3. Zooplankton

Seasonal patterns of zooplankton community structure were observed in which larger, more desirable zooplankton consumed by fish (e.g., Cladocera) are present in greater numbers in summer and much lower densities in winter, indicative of low productive systems. Both nutrient concentrations and light availability are at the lowest levels during the winter season. Zooplankton populations were found to be relatively low in abundance and were defined by inflow populations (from Box Canyon Reservoir), low primary production based on low phosphorus availability, and seasonally dependent short retention time. McLellan and O'Connor (2001) found similar results for zooplankton density and community composition.

Sampling was performed outside of macrophyte beds, but it is suspected that macrophyte beds allow for slightly higher biomass accumulations than in open water habitat. Furthermore, the aerial extent of macrophyte beds is less than 13 percent of the total reservoir but less than 2 percent of total water volume; therefore, the beds have limited influence on zooplankton abundance as a whole within Boundary Reservoir.

The zooplankton community within Boundary Reservoir is controlled by the inflow population, low primary production, and short hydraulic retention times; thus, there was no definable impact of Project operations on zooplankton. There are no anticipated differences in low zooplankton densities or community structure between operations scenarios. Because nutrient concentrations are low throughout the year, increased light availability during the summer enhances food sources (e.g., phytoplankton) for zooplankton, which is in contrast to limited light availability during winter months; however, phosphorus limitation is still the dominant factor in food resource production for zooplankton. For example, under full pool and low flow conditions during late summer and early fall, the food resources are limited by low phosphorus concentrations that reduce potential primary production (see Study 5).

5.4.3.4. Macrophytes

Macrophyte beds are present and actively growing from May through October in Boundary Reservoir. Water surface elevations during March through April control long-term macrophyte bed distribution and coverage. Test operations during summer 2007 and 2008 resulting in

dewatering did not reduce the aerial extent of macrophyte beds. Following reservoir refill, the aerial extent of macrophyte beds resembled conditions prior to dewatering. Hence summer reservoir drawdown may cause short-term die-back of macrophytes, but without controlled and extended drawdowns, macrophyte distribution is not expected to change from conditions observed in 2007 and 2008. Specially, in order for summertime drawdown to be effective, a prolonged period of exposure without precipitation or wet of shoreline by fog would be needed (at least 45 to 60 days).

In order for a drawdown to be an effective control measure for aquatic macrophytes within Boundary Reservoir, a prolonged period of exposure that results in root crown desiccation would be needed. The best time for this to occur is March through April when the macrophytes are beginning to sprout and are most vulnerable to exposure to low air temperatures and desiccation of both emerging shouts and roots. Given the night time freezing air temperatures at that time of year it is estimated that at least 30 days without precipitation would be needed to promote hydrosoil and hence root crown desiccation. For example, at a 1,984-foot NAVD 88 (1,980-foot NGVD 29) water surface elevation at Boundary Dam, only 6 vertical feet of aquatic macrophyte beds would be exposed in the Forebay and Canyon reaches at flows ranging between 6,000 cfs and 40,000 cfs. Above Metaline Falls, aquatic macrophyte beds would only begin to be exposed at flows below 20,000 cfs and, at flows less than 10,000 cfs, only 4 to 5 vertical feet of aquatic macrophyte exposure would occur, resulting in minimal impact on aquatic macrophyte coverage and biomass. At flows of 6,000 cfs, there would only be an increase in exposure of a vertical foot.

However, by holding the Boundary Reservoir at a 1,974-foot NAVD 88 (1,970-foot NGVD 29) water surface elevation during March through April at Boundary Dam, 16 vertical feet of aquatic macrophyte beds would be exposed or approximately 50 percent of the bed area in the Forebay and Canyon reaches at flows ranging between 6,000 cfs and 40,000 cfs. Above Metaline Falls, aquatic macrophyte beds would only begin to be exposed at flows below 20,000 cfs and, at a flow of 10,000 cfs, only 6 to 8 vertical feet of aquatic macrophyte beds would be exposed (approximately 25 percent of the bed area). At flows of 6,000 cfs, an additional 2 to 3 feet of aquatic macrophyte beds would be exposed, for a maximum of 40 percent.

5.4.3.5. Periphyton

Periphyton biomass is primarily controlled by phosphorus availability and secondarily by light availability. Nutrient availability during the 2007 and 2008 study period was low throughout the year despite the influence of Project operations and was governed by upstream inflow concentrations. Relatively high (for oligotrophic systems) periphyton biomass was observed during the summer and fall months. Dewatering adversely affects periphyton biomass and production within the water fluctuation zone after 12 hours. Pool elevation fluctuations associated with Project operations will determine the loss in potential periphyton WUA. Large pool elevation fluctuations will be associated with longer dewatered habitat periods and would represent a more dramatic loss of periphyton. Periphyton production extends well beyond the water fluctuation zone to a depth of approximately 50 feet and therefore the potential loss of periphyton production within the fluctuation zone is a fraction of the total production. The primary factors affecting periphyton production are phosphorus, substrata, light availability, velocity, and then burial. Project operations principally affect light availability, burial, and

dewatering. Phosphorus availability has the same effect on stimulating periphyton growth regardless of Project operations, but the quantity of available habitat as influenced by pool elevation fluctuations is reflected in WUA periphyton estimates. Periphyton will appear in areas where water is resident for longer periods of time, but is limited by phosphorus availability. Habitat that is dewatered for longer periods of time, even though it is inundated periodically will reduce the ability of periphyton to colonize.

5.4.3.6. Benthic Macroinvertebrates

BMI biomass is controlled by habitat and food availability (periphyton production, settled seston [suspended live and dead particulate organic material] availability, and organic particle drift). Higher BMI biomass corresponds with high periphyton biomass during the summer months and suitable habitat area. Dewatering adversely affects BMI biomass and survival after 12 hours. Project operations that dewater shallow areas of Boundary Reservoir reduce the potential of the BMI community to utilize suitable habitable area. BMI colonize areas of the reservoir that are inundated for longer periods of time may be re-colonized by some species that previously existed within the dewatered habitat by drift transport through the water column. BMI are long-lived compared to periphyton and cannot regenerate as rapidly so some species will establish in deeper areas where the food base and inundation are constant. Other BMI species will be more opportunistic in colonizing temporary habitat that is frequently dewatered and will colonize during inundation periods, but with a lower production potential. Regardless of the Project operation scenario, BMI species will colonize habitat based on mobility into shallow water or if relegated to deeper water that is always inundated or nearly so.

5.4.3.7. Summary of Project Effects

There were no Project operations effects observed from the evaluation of nutrient concentrations and phytoplankton and zooplankton communities (see Study 5 [SCL 2009b]). Macrophytes are established based on spring hydrologic conditions (e.g., low flow/low pool elevation in March and April) and, as a result, operational drawdowns during an average hydrologic year would not provide the continuous extended period of dewatering required for long term macrophyte control. The degree of effect on periphyton and BMI communities is limited to areas within the water fluctuation zone. Nutrient availability controlled primary productivity, which was controlled by inflow loading characteristics to Boundary Reservoir (see Study 5 [SCL 2009b]). Dewatering reduces periphyton and BMI productivity, as indicated by the rate of recolonization during inundation (see Study 7 [SCL 2009a]).

Based on inundation and recolonization as well as drawdown characteristics, fluctuation in water surface elevation reduces available habitat for periphyton and BMI in the shallow areas of Boundary Reservoir (see Study 7, Appendix 7 and Appendix 8 [SCL 2009a]).

6 CONCLUSIONS

TPIs were developed for the phosphorus and the biological groups including the primary producers phytoplankton, periphyton, and aquatic macrophytes, as well as the secondary producers zooplankton and BMI, for each reach. The TPIs were developed to reflect not only the

current potential production under average, dry, and wet hydrologic years, but also for evaluating potential Project effects under operations scenarios. The TPIs were based on a scale of 0.1 to 1 for low to high production potential. The use of TPI demonstrates the control of phosphorus on production in Boundary Reservoir.

The TPI developed for phosphorus reflects the relatively low phosphorus concentration within Boundary Reservoir; the low phosphorus TPI in turn represents limited or low potential for stimulating production for all three hydrologic conditions (wet, dry, and average). Regardless of changes in Project operations, low phosphorus concentration entering the reservoir is the principal factor in controlling primary and, by extension, secondary production throughout Boundary Reservoir. Phytoplankton production is dictated principally by phosphorus and secondly by depth and residence time. Low secondary production by zooplankton is expected due to low phytoplankton for grazing, ultimately resulting from low phosphorus.

Periphyton, similar to phytoplankton, is principally controlled by phosphorus concentrations. In turn, BMI production is controlled by the low amount of food produced by the periphyton community and low overall production of Boundary Reservoir. In addition, both periphyton and BMI production is also affected by dewatering within the water fluctuation zone, although it is only a small proportion of total production for periphyton and BMI because of the total area that is inundated.

Macrophyte production is dictated in part by reservoir levels during late winter/early spring. Assessments of macrophyte density and aerial coverage may in part reflect non-native species dominance of the macrophyte community.

Both WUA and TPI indicate that most production for macrophytes, periphyton, and BMI occurs in the Upper Reservoir Reach. The Upper Reservoir Reach experiences less water level fluctuations than the other Project reaches, but the Upper Reservoir Reach contains more total habitat area and production than the other reaches. Conversely, there is a greater loss of potential habitat due to historic water level fluctuations associated with operations in the Canyon and Forebay reaches, but these reaches have less total habitat area and production than the Upper Reservoir Reach.

7 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

A significant variance that affects Study 11 involved evaluating operations scenarios. This Final Report presented development of WUA and TPI for historic hydrologic record for representative wet, dry, and average years. The RSP indicated that operations scenarios would be evaluated in the Final Report; however, this evaluation will occur in 2009 as part of the IRA. This is a variance from the study plan schedule as outlined in the RSP.

The IRA process will synthesize the results of individual study results across resource areas to characterize Project-related resource impacts and evaluate potential operations-related protection, mitigation, and enhancement measures. The results of Study 7, Study 8, Sediment Transport and Boundary Reservoir Tributary Delta Habitats Final Report (SCL 2009d), and

Study 11 will be integrated with the results of other resource studies such as wildlife, recreational resources, and water quality. The IRA process will also identify potential effects of operations scenarios on SCL's interests as a public power provider.

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Appendix 1: Trophic Production Index Score Sheets and Explanation

Trophic Production Index Descriptions and Summaries

Trophic production indices (TPIs) were developed for the following biological groups: phytoplankton, zooplankton, periphyton, macrophytes, and benthic macroinvertebrates (BMI) and used to express production potential characteristic of each reach of Boundary Reservoir. The TPI was constructed by including several metrics that were each weighted and then averaged for a single index score. An index was also developed for nutrient condition that served as an indicator for sources stimulating primary production in the reservoir.

The following discussion reviews the individual metrics included for calculating a TPI score for each biological group and nutrients. The reason for including individual metrics for calculating each TPI is further discussed. Scoring ranges (1=poor, 3=fair, 5=good) for each metric were expressed as thresholds that were developed from existing data in related studies (e.g., Study 7 and Study 5 [SCL 2009a, b]).

The calculation of TPI scores was based on the aggregation of metric scores and divided by the total score possible as follows:

$$Trophic_Index_Score = \frac{\sum (WeightingFactor) Metric_Scores}{5 \times (no._of_metrics)}$$

Where:

Metric Scores ~ scores for each metric are 1, 3, or 5.

No. of metrics ~ varies by trophic component (e.g., nutrients, phytoplankton, periphyton, zooplankton, macrophytes, and BMI).

Weighting Factor ~ ranked the importance of a metric relative to the most influential metric that received a score of 1.0.

Nutrient Index

Nutrients are the fuel that transfers energy upward through the trophic ladder. Nutrients directly influence production of periphyton and phytoplankton and, to a lesser extent, macrophyte beds. This index expressed the availability of nutrients in the water column and addressed the source of these nutrients in the reservoir. Nutrient condition included soluble and particulate forms and the potential of nutrients for bioavailability.

Two metrics were used to construct for the TPI for nutrients: nutrient concentration in surface water inflow and loss of nutrients to sedimentation. Nutrient concentrations used to evaluate surface water inflow were based on total phosphorus (TP) concentrations measured in Study 5 (SCL 2009b). Sedimentation was estimated based on retention time (in days) of water moving through the reservoir in each of the reaches.

Inflow of TP concentration to the reservoir was the primary source for fueling primary production. The indicator for availability of phosphorus for production in the water column was water retention time. Phosphorus tended to remain in the water column with minimum loss to

sediment if retention times were short, i.e., high inflow volume. Phosphorus tended to be lost from the water column if retention times were long. However, retention time, if too short, would not allow sufficient time for production, even if phosphorus remained in the water column.

Phytoplankton

Phytoplankton are primary producers that use photosynthesis as the process for energy production and re-generation. These organisms are free-living in the aquatic environment, have densities slightly greater than water so sink if not buoyed up by currents, and some (e.g., cyanobacteria) can migrate vertically in the water column through gas regulation. Phytoplankton serve as an important food source for primary consumers that include zooplankton and some BMI species.

An index was constructed to reflect the production status of the phytoplankton community. Five individual metrics were used to construct this index that included primary requirements for phytoplankton growth and physical conditions in the reservoir that would influence phytoplankton growth and survival. Total phosphorus was considered the primary metric influencing phytoplankton biomass (chl *a*) and growth. Influx of phytoplankton cells from the upstream Box Canyon Reservoir was considered an important factor that introduced the existing community, especially since TP concentrations are very low and restrict growth in Boundary Reservoir. Residence time of water in the reservoir directly influences the residence time for the phytoplankton community to grow and proliferate. Light availability was included and measured by using a surrogate (Secchi depth) to indicate the quantity of useable habitat in the four reaches of the reservoir. Mixing described the vertical stratification in the water column and explained, in part, volume of useable habitat in each reach and the vertical transfer of TP.

Periphyton

Periphyton algae are attached primary producers that are influenced by physical disturbances on the bottom of the Reservoir, consumption by grazing animals (e.g., benthic macroinvertebrates), light energy, and nutrients. Periphyton production is mediated by an aggregate of factors that changes on a daily and a seasonal basis. Convergence of optimal levels for each of the metrics considered important for growth and loss in the periphyton community included physical setting as well as factors that promote photosynthetic activity (e.g., light and nutrients).

Eight metrics were used to construct a TPI for periphyton and included: grazing, burial, depth, direct light, photoperiod, TP, substrata, and velocity. Grazing reflects consumption of periphyton by BMI grazers. The surrogate measure used for estimating grazing was surface water temperature as it relates to metabolic activity of BMI. An adequate grazer biomass was assumed to exist. Influence of burial on periphyton colonies was determined by using velocity with optimal score based on maintenance of sediment in suspension rather than settling on substrata in the Reservoir.

Depth of periphyton colonization covaried with effects from light penetration and daylight hours. Light transmission measured by Secchi depth (meters) was considered a more global metric that influenced photosynthetic activity throughout the reservoir with measures for direct light and

depth as having site-specific influences. Among metrics in the TPI for periphyton, depth, velocity, and substrata used thresholds that defined scoring ranges from the HSI curves. The primary metric used in the TPI for periphyton was TP concentration, the principal nutrient that stimulates algal growth in this reservoir.

Zooplankton

Zooplankton are primary consumers of particles in select sizes (e.g., phytoplankton, protozoans, and bacteria) throughout the aquatic environment of the reservoir. These organisms are free-living and mobile in the water column of the reservoir, but can use benthic habitat as refuge for food gathering and predator avoidance. The zooplankton community production is used to estimate available food for resident fish populations and is considered one of the primary indicators for viability of fish management decisions.

Factors that influence zooplankton production in Boundary Reservoir are described by four metrics as the basis for calculating the TPI describing zooplankton production status. The most influential metric use in this index is "influx" and refers to the quantity of zooplankton introduced to the Boundary Reservoir from the upstream Box Canyon Reservoir. Zooplankton production may be controlled by water retention time in the Reservoir and determines the potential for reproduction while in the Reservoir, and loss of zooplankton from the Reservoir. Phytoplankton presence is a surrogate measure for food availability. The change in phytoplankton biomass is expected to directly affect response of the zooplankton community. The fourth metric comprising the TPI for zooplankton production is vertical mixing. Mixing of the water column transports food (i.e., phytoplankton) and nutrients that would influence food production consumed by zooplankton.

Macrophytes

Macrophytes (aquatic plants) have been observed in various portions of the Reservoir and serve as habitat to a variety of biological groups. The macrophyte beds established along some of the shorelines and within the channels modify water chemical characteristics within the margins of individual beds, but have no influence on surrounding surface water chemistry in the reservoir. The cover provided by macrophyte beds is used by fish, BMI, and as substrata colonized by periphyton. Macrophyte communities have both native and introduced species within Boundary Reservoir. The introduced macrophyte species have a tendency to tolerate greater extremes in physical and other subtle and unknown environmental characteristics, and out-compete native species for space.

Four metrics were used to construct the TPI assessing potential for production of macrophytes. The most important metric for determining the potential for production of macrophytes is availability of silt and organic substrata. Macrophytes are known to respond positively to sediment organic content (if not high) and sediment texture, much like terrestrial plants. Occurrence of this soft substrata material represents optimal habitat in the reservoir. Light penetration is also an important factor promoting growth of macrophytes at greater depths. This metric was measured as a function of depth with ranges determined from the depth suitability

curve for established macrophyte beds and adopted from the HSI report in Study 7 (Appendix 6 [SCL 2009a]). Similarly, classification ranges were also adopted from the velocity suitability curve described for macrophyte bed establishment in the reservoir. The fourth metric used in construction of this index was prevalence of direct light. This metric accounted for seasonal availability of light as well as the influence of surrounding topographical relief along the reservoir on daily incidence of light. Macrophytes are high light lovers and usually are limited to the depth of visibility (~15 percent surface sunlight). Hence, shading by surrounding steep canyon walls are thought to have a negative effect.

Benthic Macroinvertebrates

BMI are secondary consumers that feed on a variety of live and dead plant and animal material. These animals are somewhat sessile in the aquatic environment, but can drift behaviorally, or by dislodging, over longer distances downstream. BMI are an important component in the energy transfer chain of the aquatic environment where they consume deposited or drifting detritus consisting of living and dead plant and animal material. BMI are the primary food source, along with zooplankton and fish fry, for most of the juvenile and adult fish species in the reservoir.

Primary metrics considered to be important for estimating production in BMI communities included the three variables used in the HSI Model (e.g., depth, velocity, and substrata). In addition, periphyton availability was considered the most important of all metrics and was reflected by the surrogate measure using chlorophyll *a*. Substrata size and velocity were secondarily important for determining the potential for BMI production. Categorical ranges were identical to those used in the HSI model development for BMI. Depth was included as the fourth metric used to calculate the BMI index value for a reach and during specific hydrologic conditions. Scoring ranges for depth was based on the HSI suitability curve developed for BMI response in the reservoir. Production of BMI was reflected by the pattern of index scores when compared among reaches were made. BMI were able to colonize deeper portions of the reservoir by feeding on settled detritus and so could yield a higher level of production than was possible if based solely on periphyton, which was light limited as a function of depth.

Table A.1-1. Nutrient (phosphorus) metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Inflow (µg/L)	5	5	1	1	3	3
Sedimentation (Retention time, days)	5	1	5	1	5	1
Index		**0.40**		**0.13**		**0.27**
Canyon						
Inflow (µg/L)	3	3	1	1	1	1
Sedimentation (Retention time, days)	5	1	5	1	5	1
Index		**0.27**		**0.13**		**0.13**
Forebay						
Inflow (µg/L)	3	3	1	1	1	1
Sedimentation (Retention time, days)	5	1	1	0.2	3	0.6
Index		**0.27**		**0.08**		**0.11**
Tailrace						
Inflow (µg/L)	1	1	1	1	1	1
Sedimentation (Retention time, days)	5	1	5	1	5	1
Index		**0.13**		**0.13**		**0.13**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
µg/L – microgram per liter
WF – weighted factor

Table A.1-2. Phytoplankton metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Retention time (days)	1	0.75	5	3.75	3	2.25
Light (Secchi, m)	3	1.5	5	2.5	3	1.5
Inflow (flow, cfs)	5	4.5	1	0.9	3	2.7
Mixing Depth (ft)	3	0.6	5	1	3	0.6
Phosphorus (µg/L)	5	5	1	1	3	3
Index		**0.41**		**0.31**		**0.34**
Canyon						
Retention time (days)	1	0.75	3	2.25	3	2.25
Light (Secchi, m)	3	1.5	5	2.5	3	1.5
Inflow (flow, cfs)	5	4.5	1	0.9	3	2.7
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phosphorus (µg/L)	5	5	1	1	3	3
Index		**0.40**		**0.23**		**0.32**
Forebay						
Retention time (days)	1	0.75	5	3.75	3	2.25
Light (Secchi, m)	3	1.5	5	2.5	3	1.5
Inflow (flow, cfs)	5	4.5	1	0.9	3	2.7
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phosphorus (µg/L)	5	5	1	1	3	3
Index		**0.40**		**0.28**		**0.32**
Tailrace						
Retention time (days)	1	0.75	1	0.75	1	0.75
Light (Secchi, m)	3	1.5	5	2.5	3	1.5
Inflow (flow, cfs)	5	4.5	1	0.9	3	2.7
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phosphorus (µg/L)	5	5	1	1	3	3
Index		**0.40**		**0.18**		**0.27**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
cfs – cubic feet per second
m – meter
µg/L – microgram per liter
WF – weighted factor

Table A.1-3. Zooplankton metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Retention time (days)	1	0.8	3	2.4	1	0.8
Inflow (flow, cfs)	5	5	3	3	3	3
Mixing Depth (ft)	5	1	5	1	5	1
Phytoplankton (µg/L chlorophyll *a*)	5	1.25	1	0.25	3	0.75
Index		**0.40**		**0.33**		**0.28**
Canyon						
Retention time (days)	1	0.8	1	0.8	1	0.8
Inflow (flow, cfs)	5	5	3	3	3	3
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phytoplankton (µg/L chlorophyll *a*)	5	1.25	1	0.25	3	0.75
Index		**0.36**		**0.21**		**0.24**
Forebay						
Retention time (days)	1	0.8	3	2.4	3	2.4
Inflow (flow, cfs)	5	5	3	3	3	3
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phytoplankton (µg/L chlorophyll *a*)	5	1.25	1	0.25	3	0.75
Index		**0.36**		**0.29**		**0.32**
Tailrace						
Retention time (days)	1	0.8	1	0.8	1	0.8
Inflow (flow, cfs)	5	5	3	3	3	3
Mixing Depth (ft)	1	0.2	1	0.2	1	0.2
Phytoplankton (µg/L chlorophyll *a*)	5	1.25	1	0.25	3	0.75
Index		**0.36**		**0.21**		**0.24**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
cfs – cubic feet per second
µg/L – microgram per liter
WF – weighted factor

Table A.1-4. Macrophyte metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Direct Light (hrs)	5	1.25	5	1.25	5	1.25
Light (ft)	3	1.5	5	2.5	3	1.5
Substrata	5	5	5	5	5	5
Velocity (fps)	1	0.25	5	1.25	3	0.75
Index		**0.40**		**0.50**		**0.43**
Canyon						
Direct Light (hrs)	1	0.25	1	0.25	1	0.25
Light (ft)	1	0.5	3	1.5	1	0.5
Substrata	1	1	1	1	1	1
Velocity (fps)	3	0.75	5	1.25	3	0.75
Index		**0.13**		**0.20**		**0.13**
Forebay						
Direct Light (hrs)	3	0.75	3	0.75	3	0.75
Light (ft)	1	0.5	3	1.5	1	0.5
Substrata	3	3	3	3	3	3
Velocity (fps)	5	1.25	5	1.25	5	1.25
Index		**0.28**		**0.33**		**0.28**
Tailrace						
Direct Light (hrs)	5	1.25	5	1.25	5	1.25
Light (ft)	3	1.5	3	1.5	3	1.5
Substrata	1	1	3	3	3	3
Velocity (fps)	1	0.25	1	0.25	1	0.25
Index		**0.20**		**0.30**		**0.30**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
fps – feet per second
WF – weighted factor

Table A.1-5. Periphyton metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Biograzing (Temperature, °C)	3	0.3	5	0.5	3	0.3
Burial (Velocity, fps)	5	1.25	1	0.25	3	0.75
Depth (ft)	3	1.5	5	2.5	3	1.5
Direct Light (hrs)	5	2.5	5	2.5	5	2.5
Light and Season (Secchi, m)	1	0.8	5	4	5	4
Phosphorus (µg/L)	5	5	1	1	3	3
Substrata	5	1.25	5	1.25	5	1.25
Velocity (fps)	5	1.25	3	0.75	5	1.25
Index		**0.35**		**0.32**		**0.36**
Canyon						
Biograzing (Temperature, °C)	1	0.1	3	0.3	1	0.1
Burial (Velocity, fps)	5	1.25	3	0.75	3	0.75
Depth (ft)	1	0.5	3	1.5	1	0.5
Direct Light (hrs)	1	0.5	1	0.5	1	0.5
Light and Season (Secchi, m)	1	0.8	5	4	5	4
Phosphorus (ug/L)	5	5	1	1	3	3
Substrata	3	0.75	3	0.75	3	0.75
Velocity (fps)	3	0.75	3	0.75	3	0.75
Index		**0.24**		**0.24**		**0.26**
Forebay						
Biograzing (Temperature, °C)	1	0.1	3	0.3	1	0.1
Burial (Velocity, fps)	3	0.75	1	0.25	1	0.25
Depth (ft)	1	0.5	3	1.5	1	0.5
Direct Light (hrs)	3	1.5	3	1.5	3	1.5
Light and Season (Secchi, m)	1	0.8	5	4	5	4
Phosphorus (µg/L)	5	5	1	1	3	3
Substrata	1	0.25	1	0.25	1	0.25
Velocity (fps)	3	0.75	3	0.75	3	0.75
Index		**0.24**		**0.24**		**0.26**

Table A.1-5, continued…

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Tailrace						
Biograzing (Temperature, °C)	1	0.1	3	0.3	1	0.1
Burial (Velocity, fps)	5	1.25	5	1.25	5	1.25
Depth (ft)	3	1.5	3	1.5	3	1.5
Direct Light (hrs)	3	1.5	3	1.5	3	1.5
Light and Season (Secchi, m)	1	0.8	5	4	5	4
Phosphorus (µg/L)	5	5	1	1	3	3
Substrata	5	1.25	5	1.25	5	1.25
Velocity (fps)	1	0.25	5	1.25	1	0.25
Index		**0.29**		**0.30**		**0.32**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
fps – feet per second
µg/L – microgram per liter
WF – weighted factor

Table A.1-6. BMI metric trophic production index scores for the Upper Reservoir, Canyon, Forebay, and Tailrace reaches during wet (1997), dry (2001), and average (2002) hydrologic years.

Metric	Wet		Dry		Average	
	Score[1]	Score x WF	Score	Score x WF	Score	Score x WF
Upper Reservoir						
Depth (ft)	5	1.25	5	1.25	5	1.25
Periphyton (mg chlorophyll *a*/m^2)	1	1	3	3	3	3
Substrata	5	2.5	5	2.5	5	2.5
Velocity (fps)	3	1.5	5	2.5	5	2.5
Index		**0.31**		**0.46**		**0.46**
Canyon						
Depth (ft)	1	0.25	3	0.75	1	0.25
Periphyton (mg chlorophyll *a*/m^2)	1	1	1	1	3	3
Substrata	1	0.5	3	1.5	3	1.5
Velocity (fps)	3	1.5	5	2.5	5	2.5
Index		**0.16**		**0.29**		**0.36**
Forebay						
Depth (ft)	1	0.25	5	1.25	3	0.75
Periphyton (mg chlorophyll *a*/m^2)	3	3	1	1	3	3
Substrata	3	1.5	3	1.5	3	1.5
Velocity (fps)	5	2.5	5	2.5	5	2.5
Index		**0.36**		**0.31**		**0.39**
Tailrace						
Depth (ft)	3	0.75	3	0.75	3	0.75
Periphyton (mg chlorophyll *a*/m^2)	1	1	1	1	1	1
Substrata	3	1.5	5	2.5	3	1.5
Velocity (fps)	1	0.5	3	1.5	3	1.5
Index		**0.19**		**0.29**		**0.24**

Notes:
1 Scores: Low = 1, Medium = 3, High = 5; Index = sum of scores ÷ total possible score (i.e., 15)
fps – feet per second
mg chlorophyll a/m^2 – milligrams chlorophyll *a* per square meter
WF – weighted factor

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Appendix 2: Metrics Considered for Construction of Each Trophic Production Index

Each trophic production index (TPI) was constructed of several metrics that directly relate to production of biomass. The original list of variables considered in construction of each TPI for nutrients, phytoplankton, zooplankton, macrophytes, periphyton, and benthic macroinvertebrates (BMI) was more extensive than the final list (Table A.2-1) used to calculate the trophic status of each group in Boundary Reservoir. The result of the extensive list is reported in the following table.

Table A.2-1. Complete list of metrics considered for construction of each trophic production index (nutrients, phytoplankton, zooplankton, macrophytes, periphyton, and BMI).

Trophic Parameters					
Nutrients	**Phytoplankton**	**Zooplankton**	**Macrophytes**	**Periphyton**	**BMI**
Inflow Concentration	Retention Time	Retention Time	Direct Light	Depth	Depth
Sedimentation	Light	Mixing Depth	Light	Biograzing	Periphyton
Groundwater	Inflow	Inflow	Substrata	Burial	Substrata
Biological Uptake	Mixing Depth	Phytoplankton	Velocity	Direct Light	Velocity
Outflow	Phosphorus Concentration	Predation	Aspect	Phosphorus Concentration	Burial
	Biograzing	Outflow	Burial	Light and Season	Seasonality
	Outflow		Grazing	Substrata	Community Structure
	Season		Nutrients	Velocity	Predation
	Sedimentation		Season		
			Species Composition		

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