Final Technical Report

Evaluation of Particulate Organic Matter Removal from Klamath River Source Water Using Stormwater Treatment Technology, 2012

Prepared for

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July 2013

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1.0 INTRODUCTION

On February 18, 2010, the United States, the States of California and Oregon, PacifiCorp, regional Native American tribes, and a number of other stakeholder groups signed the Klamath Hydroelectric Settlement Agreement (KHSA). The KHSA lays out the process for additional studies, environmental review, and a determination by the Secretary of the Interior regarding whether removal of four dams owned by PacifiCorp on the Klamath River (i.e., J.C. Boyle, Copco 1, Copco 2, and Iron Gate dams) will advance restoration of the salmonid fisheries of the Klamath Basin and is in the public interest (which includes effects on local communities and tribes).

The KHSA includes provisions for interim operation of the dams and mitigation activities prior to potential removal of the hydroelectric facilities. One such provision—titled Interim Measure 11: Interim Water Quality Improvements—emphasizes water quality improvement projects in the Klamath Basin during the interim period.

As part of Interim Measure 11, PacifiCorp contracted with Watercourse Engineering, Inc. (Watercourse) to conduct a pilot-scale study to test the feasibility of vortex separation technology to remove particulate organic matter from the Klamath River. As discussed further is this report, a prototype continuous deflective separation (CDS) particle separator was specially constructed and tested for this study. CDS separators are gravity separators consisting of a specifically-designed round vault and screen through which treated waters water travel in a circular fashion to effectively screen, separate, and trap material. CDS separators are most commonly employed in municipal stormwater treatment systems to remove coarser particulates.

Several studies have identified stormwater treatment technologies as an effective way of removing particulates and associated nutrients that potentially promote algae growth (Patel *et al*. 2004; Reddy *et al*. 2006; Perry *et al.* 2009). However, no significant work has been completed to investigate the potential of using stormwater treatment technology to directly remove algae and organic matter. The Klamath River is nutrient-enriched, due to large loads of nutrients and organic matter to the river from hypereutrophic Upper Klamath Lake (UKL) and other upstream sources (NAS 2004; Lindenberg *et al*. 2009). Reductions of seasonal algae and organic matter loads emanating from UKL could provide substantial water quality improvements in the Klamath River, and especially in Keno Reservoir, which is just downstream and experiences seasonal anoxia due to the organic matter loads from UKL (PacifiCorp 2008). Further, water quality improvements from the reductions in particulate organic matter would potentially provide important benefits for endangered suckers found in Keno Reservoir (USFWS 2001), and could also lead to lower seasonal organic matter concentrations in the Klamath River downstream of Keno Dam.

This report is organized into several sections. Section 2 includes pertinent background information, which includes a description of the hydrodynamic separation process, a brief summary of previous work, and a description of the project area. Section 3 describes methodology, including the experimental set-up and the sampling procedures employed in the study. Section 4 describes the results, followed in section 5 by a discussion of the findings based on these results. Section 6 summarizes conclusions and provides several recommendations for future consideration.

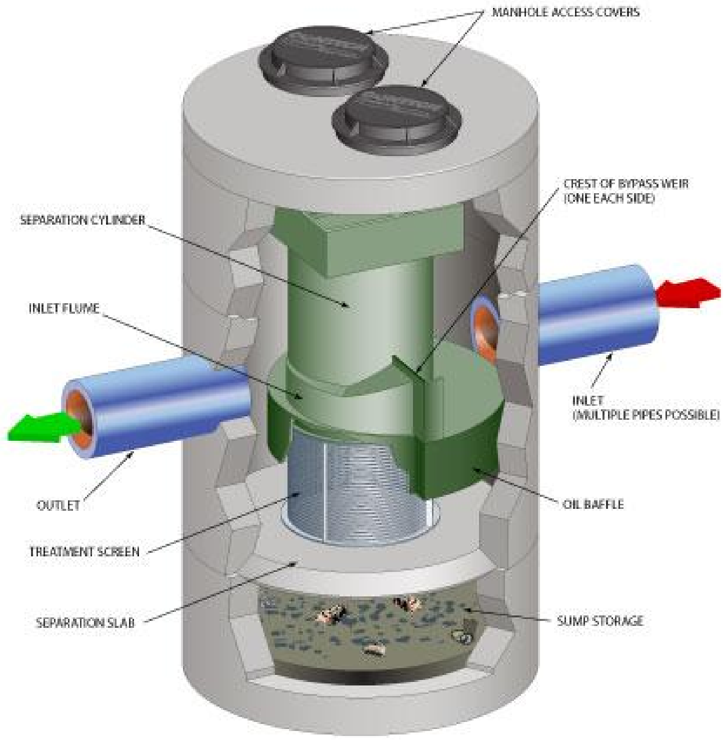
2.0 BACKGROUND

This section presents background information relevant to the study. First, the hydrodynamic vortex separation technology used in the study is discussed. Next, preliminary tests previously conducted in 2011 based on an initial prototype separator are summarized to provide context for the 2012 study. The project area for the 2012 study is also described in this section.

2.1 Hydrodynamic Separation Technology

The prototype hydrodynamic vortex separation technology used in the study is the continuous deflective separation (CDS) technology developed by CONTECH Construction Products Inc. (CONTECH) that uses hydrodynamic separation to treat stormwater. In a typical stormwater application, CONTECH’s CDS unit comprises a cylindrical manhole that houses flow and screening controls (Figure 1). Stormwater runoff enters the CDS unit at a tangent through the “inlet flume”, which brings about a vortex motion within the unit’s separation chamber. The vortex motion keeps larger particles in the middle of the chamber while pushing water outwards against a cylindrical treatment screen. The particles that were brought to the center eventually settle to the containment sump at the bottom of the unit. The perforations in the treatment screen are elongated diamond-shaped holes, which are aligned with the longer axis in the vertical direction. The size of the perforations can be specified according to performance requirements. Typically, the width of the short axis ranges from 2.4 mm to 4.7 mm. In a typical municipal application, the stormwater that has passed through the screen is essentially a pre-treated effluent that can then be sent to a treatment facility for further treatment, if necessary.

Figure 1. Three-dimensional Schematic of a CDS Unit Installed in a Municipal Setting
From www.conteches.com



For this study, it was hypothesized that vortex motion that directs particles and sediments into the rotational center while pushing water outwards can be used to remove phytoplankton and larger particulate matter from Klamath River water. Algae and organic matter loads from UKL are seasonally dominated by the biomass of the blue-green algae species *Aphanizomenon flos-aquae* (APFA). APFA has a known competitive advantage in UKL's phytoplankton community, provided in part due to its relatively large size and buoyancy characteristics compared to other species (Peterson Holm et al. 1983, Canter Lund and Lund 1995, Porat et al. 2001). APFA's prolific seasonal biomass, size, and buoyancy are factors that were hypothesized as advantageous for potential removal of these algae from the water using a CDS unit.

Like an actual CDS unit, the prototype particle separator designed for removing algae consists of two layers of cylindrical tanks concentric to each other. The inner tank is a separator screen contained within the larger outer tank. The inflow enters the separator screen tangentially into the side of the wall, generating a rotating flow that spirals around in the inner tank. The rotational motion pushes the water outwards to and through the screen, while a fraction of the particulate organic matter and algae is assumed to be trapped behind the screen. At the same time, the spinning motion brings the particulate organic matter into the middle where it is drained into a sump at the bottom of the two tanks. The sump can be set up to either be terminal (no outlet) or have an outflow. If set up with an outflow, the CDS unit essentially provides a waste stream reduction function. Water that travels through the screen and into the outer portion of the unit is considered "treated water" and contains lower concentrations of particulate material.

2.2 Previous Work

In 2011, the initial prototype particle separator was built and tested. This preliminary study indicated that operation of such a prototype unit was possible outside of the municipal setting where such stormwater systems are typically installed. While the 2011 results were inconclusive, the lessons learned through this preliminary experiment led to an improved prototype separator design for the 2012 study.

2.3 Project Area

The study was conducted near Link River just upstream of the outlet from UKL (Link Dam) in the city of Klamath Falls. The tests in 2012 relied on pumping water to the separator unit located adjacent to the river. However, the ultimate concept would be to design a system that relied on gravity. The natural drop in elevation of Link River from Link Dam to the river bed below would provide the necessary head to feed a separator system. For the 2012 field work, tests using the new prototype separator were conducted behind the fish screen in the A-Canal diversion (Figure 2). The A-Canal has a capacity of 1,150 cfs and conveys water from UKL to the U.S. Bureau of Reclamation's Klamath Project. Fish screens in the A-Canal began operation in 2003, and are designed to keep endangered suckers and other fish from being diverted into the series of canals that feeds Reclamation's Klamath Project.

Figure 2. Study Location
Google Earth

While the prototype separator system was designed to operate with a fish screen on the intake, the 2012 experiments were completed in A-Canal downstream of the A-Canal fish screens. Thus, the intake fish screen was not required, leading to reduced experiment set-up times in 2012. Further, the fish screen was also identified, in the 2011 tests, as a potential restriction to larger particulate matter and algae that would otherwise be removed by the separator unit. While the A-Canal fish screens remove a portion of the larger algae and organic matter, A-Canal waters downstream of the screens still contained notable loads of algae, so that A-Canal was considered an acceptable substitute or surrogate for the Klamath River for purposes of this study. In other words, water quality conditions and algal content of the water in A-Canal was assumed to be representative of the water quality from UKL to Link River and Keno Reservoir, such that this experiment can provide insight into the effectiveness of such a strategy in improving water quality conditions in the Klamath River in accordance with Interim Measure 11.

3.0 METHODOLOGY

The 2012 study employed a Contech-designed prototype separator (see section 2.1) that was approximately 2 feet in diameter and 4 feet in height. The study was designed to test the application of the new prototype particle separator to improve water quality conditions through particulate matter removal over a range of separator operations. The experiment was conducted on August 29, 2012.

3.1 Set-Up

The experimental set-up of the prototype separator system consisted of a variable speed trash pump (Honda WB30XT), the particle separator (separator) and sump (below the separator) and inflow and outflow piping (Figure 3). The set-up was assembled on a trailer bed so that the equipment could be conveniently transported to various test locations (Figure 4). The set-up also allowed water samples to be taken before the separator, at the separator outlet, and at the sump outlet.

Figure 3. Prototype Particle Separator and its Component Parts - Schematic

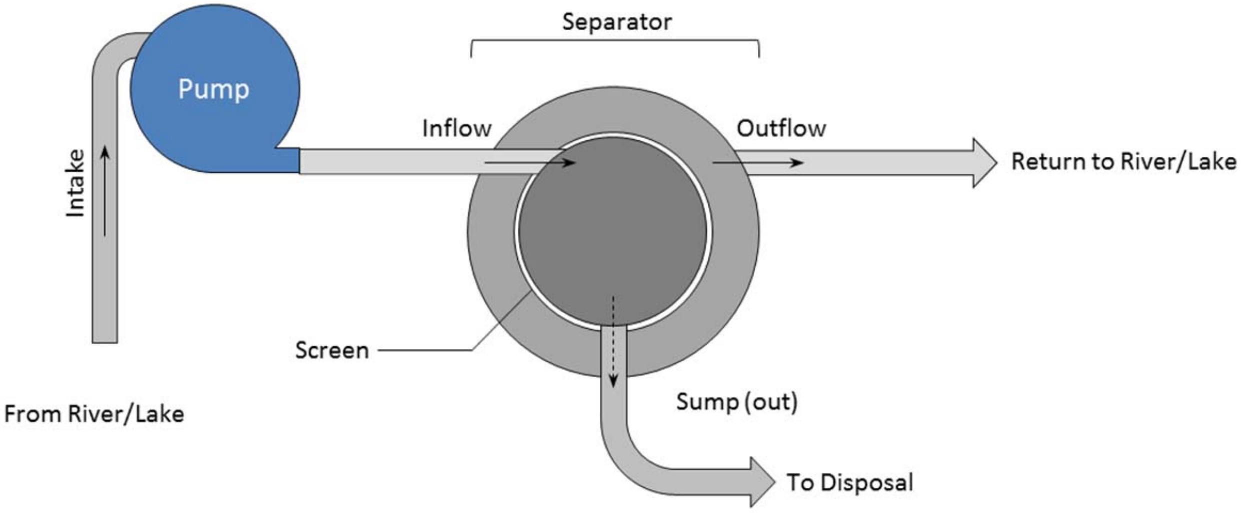


Figure 4. Prototype Particle Separator and its Component Parts – On Site Under Operation

The variable speed pump was used to draw water from A-Canal diversion channel downstream of the fish screens and feed the separator via the inflow pipe. The entrance to the separator provided the necessary head to set up the vortex within the inner annular portion of the separator. The separator creates a rotational motion of the feed water that focuses particulate material into the center while water and fine particulate material pass through the screen to the outer annular portion and ultimately to the outflow ("treated" water). The fraction of particulate material that remains in the sump is removed via the sump outlet. At the same time, the water that goes through the separator screen leaves the separator through the separator outlet. The separator is considered to be running at steady state when flow rate and outlet/sump ratios are relatively stable (Figure 5).

Figure 5. Top View of Prototype Separator with Arrows Indicating the Direction of Flow
Sump outlet occurs from bottom of inner annular portion of the separator and cannot be seen in the photo

3.2 Sampling Procedure

Samples for the study were collected at three main points in the separator system: (1) inflows to the separator that were pumped from the A-Canal diversion channel; (2) post-separator outflows; and (3) sump outflows. After going through the separator system, outflows were returned to the channel downstream of the inflow. Pre-separator samples were collected at the inflow pipeline just before the separator where a sampling port had been installed for this purpose. Post-separator and sump samples were taken at the downstream end of the outflow pipe as water was released back into the diversion channel.

Five separate experiments were conducted in which the inflow rate and outlet/sump flow ratio were varied incrementally. The experimental approach was aimed at reducing the waste stream (reducing the amount of water for disposal), which is represented by the sump outflow. Thus, the outlet/sump ratio represents fraction through each outflow, e.g., a 75/25 outlet/sump ratio translates to 75 percent of the flow through the outflow pipe and 25 percent through the sump.

Two flow rates were targeted for the tests: approximately 40 gpm and 80 gpm (actual flow rates varied somewhat as presented below). For the 40 gpm test, three outlet/sump ratios were tested, and for the 80 gpm test, two outlet/sump rations were tested. The flow and outlet/sump ratio were held stable, i.e., at steady state, throughout the duration of each individual experiment. Flow at the separator outlet and the sump outlet were calculated based on the time it takes to fill a fixed volume (i.e., a 5-gallon bucket). A table summarizing the recorded times is included in Appendix A.

For each experiment, after steady state had been attained (based on multiple measurements of sump and outlet flows), integrated water samples were collected at the three sample points; i.e., separator inflow (pre-separator), separator outflow (post-separator), and at the sump outlet. A graduated cylinder was used to collect 1-liter samples at the three points: first at the inflow, then the outflow, and then at the sump outlet. The collection of 1-liter samples at these three sample points was repeated seven times in that order – creating a 7 liter composite sample, each in individual churn sample splitters representing pre-separator, post-separator, and sump outlet samples. The graduated cylinder was triple rinsed with environmental water between each 1-liter sample collection. Following this sampling procedure, seven liters of integrated samples (in churn sample splitters) from the three points were collected for each experiment. The integrated sample from each churn sample splitter was then used to fill the respective sample bottles that would be sent for laboratory analysis. All non-preserved sample bottles were triple rinsed prior to sample collection. Between all experiments, graduated cylinders and churn sample splitters were cleaned with distilled water. Also, the separator was completely drained between experiments to avoid carryover from the previous experiment. All samples were collected consistent with PacifiCorp QAPP and SOP.

Samples were processed for particulate matter, specifically particulate carbon (PC), particulate nitrogen (PN), particulate phosphorus (PP) and particulate inorganic phosphorus (PIP), chlorophyll *a* and cyanobacteria species (including APFA). The samples were also analyzed for nutrients (total nitrogen, ammonia, nitrate+nitrite, nitrite, total phosphorus, orthophosphate, and dissolved organic carbon). Laboratory methods and related information are included in Table 1.

Table 1. Laboratory Methods, Method Detection Limits (MDL), and Reporting Limits (RL) as Applicable

Constituent	Units	Method	Preservative	MDL[a]	RL[a]	Laboratory
TN	mg/l	NEMI[b] I-4650-03	None	0.01	0.02	Biogeochemistry Laboratory, U.C. Davis
(NO3+NO2)-N	mg/l	Nitrate via V(III) reduction[c]	None	0.005	0.01	Biogeochemistry Laboratory, U.C. Davis
NO2-N	mg/l	Nitrate via V(III) reduction	None	0.002	0.01	Biogeochemistry Laboratory, U.C. Davis
NH4-N	mg/l	SM[d] 4500-NH3 F	None	0.005	0.01	Biogeochemistry Laboratory, U.C. Davis
TP	mg/l	NEMI I-4650-03	None	0.01	0.01	Biogeochemistry Laboratory, U.C. Davis
OPO4-P	mg/l	SM 4500-P E	None	0.001	0.005	Biogeochemistry Laboratory, U.C. Davis
DOC	mg/l	EPA 415.3	None	0.1	0.1	Biogeochemistry Laboratory, U.C. Davis
Chlorophyll *a*	µg/l	EPA 445.0	None	1 ppb	n/a	Biogeochemistry Laboratory, U.C. Davis
PC, PN, PP, PIP	mg/l	EPA 440.0	Filter and freeze	0.0021	n/a	Chesapeake Biological Laboratories

[a] Units are in mg/l unless otherwise specified.

[b] National Environmental Methods Index

[c] This method was developed by UC Davis Department of Land, Air and Water Resources (Doane and Horwath, 2003)

[d] Standard Methods

4.0 RESULTS

The respective flow rates and outlet/sump ratios for the five experiments are listed in Table 2. The results for the five experiments are presented in successive subsections below for particulate matter (PC, PN, PP, PIP), chlorophyll *a*, and cyanobacteria (blue-green algae) species (notably APFA). Although also analyzed, results are not presented in detail in this section for nutrients (total nitrogen, ammonia, nitrate+nitrite, nitrite, total phosphorus, orthophosphate, and dissolved organic carbon). The dissolved nutrient constituents showed no change between inflow and outflow samples because the particle separator has no effect on dissolved constituents. Total nitrogen and total phosphorus, did indicate a change, but the response was variable. While a total N and total P sample is unfiltered, the sample includes all particulate matter. Because the separator experiment focused on material that was notably larger, separator performance was more explicitly represented through the particulate matter samples (e.g., PC, PN, PP). Nutrient analysis results are included in Appendix A. Laboratory reporting information associated with each constituent is also included in Appendix A.

Table 2. Flow Rates and Outlet/Sump Ratios for Five Separator Experiments

Experiment #	Total Flow (gpm)	Outlet Flow (gpm)	Sump Flow (gpm)	Outlet/Sump Ratio
1	39	32.4	6.6	83% / 17%
2	40	28.4	11.6	71% / 29%
3	41	21.3	19.7	52% / 48%
4	80	58.4	21.6	73% / 27%
5	84	74.8	9.2	89% / 11%

Graphs of results are included in the subsections below, and are presented with ±20 percent error bars. These error bars are not formal quality assurance results, but rather are based on relative percent difference criteria[1]. The error bars are included as a guide to assist in interpretation of results, i.e., to indicate whether changes in particulate concentrations are within the typical range of laboratory uncertainty or whether results indicate systematic pre-to-post separator reductions.

4.1 Particulate Samples

PC, PN, PP, and PIP showed consistent reductions in concentrations between pre-separator inflow and post-separator outflow samples in all five experiments. Concurrent particulate concentrations in sump outflow samples were consistently higher than pre-separator inflow samples (Figure 6 through Figure 8, respectively). These results indicate that the prototype separator provided reductions – as anticipated – in particulate matter in post-separator outflow, and collection of particulates in the sump.

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[1] PC, PN, PP, PIP analyses were performed by Chesapeake Bay Laboratory (CBL). The 20 percent error bars are consistent with previous relative percentage difference (RPD) given by CBL and others (e.g., USBR 2012).

Figure 6. Summary of Particulate Carbon Levels as a Function of Variable Flow Rates and Outlet/Sump Ratios

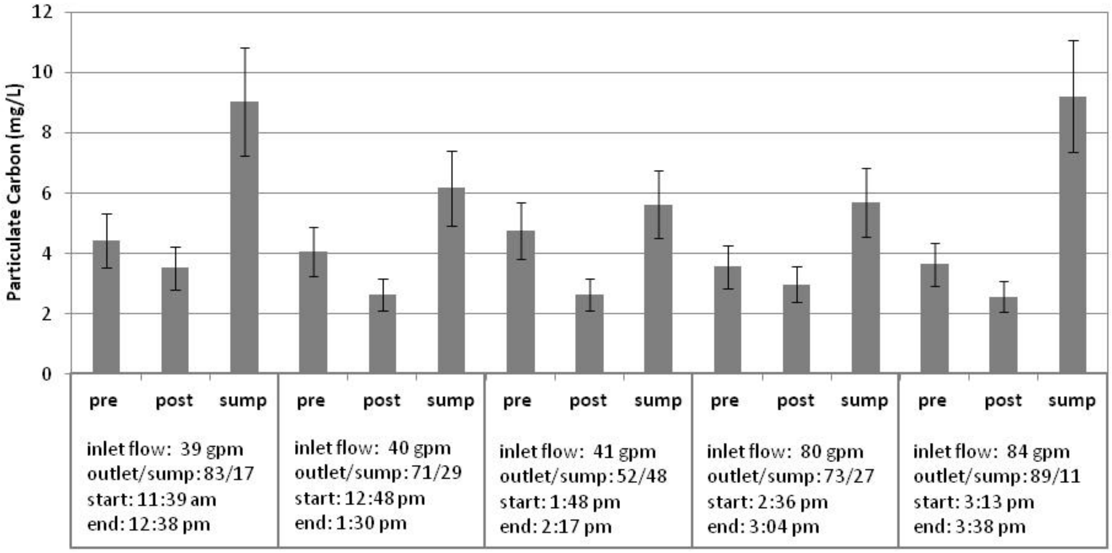


Figure 7. Summary of Particulate Nitrogen Levels as a Function of Variable Flow Rates and Outlet/Sump Ratios

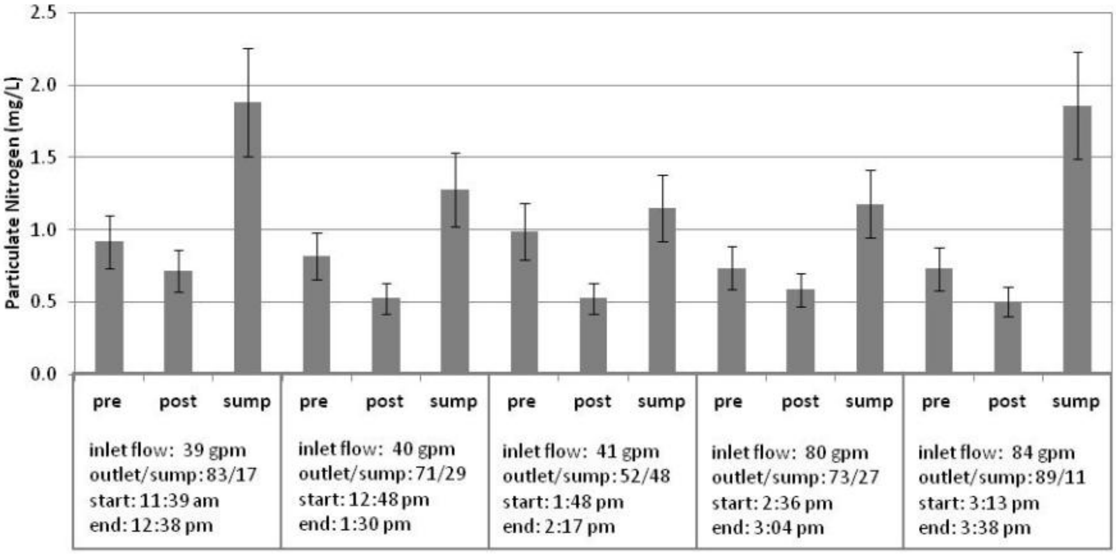
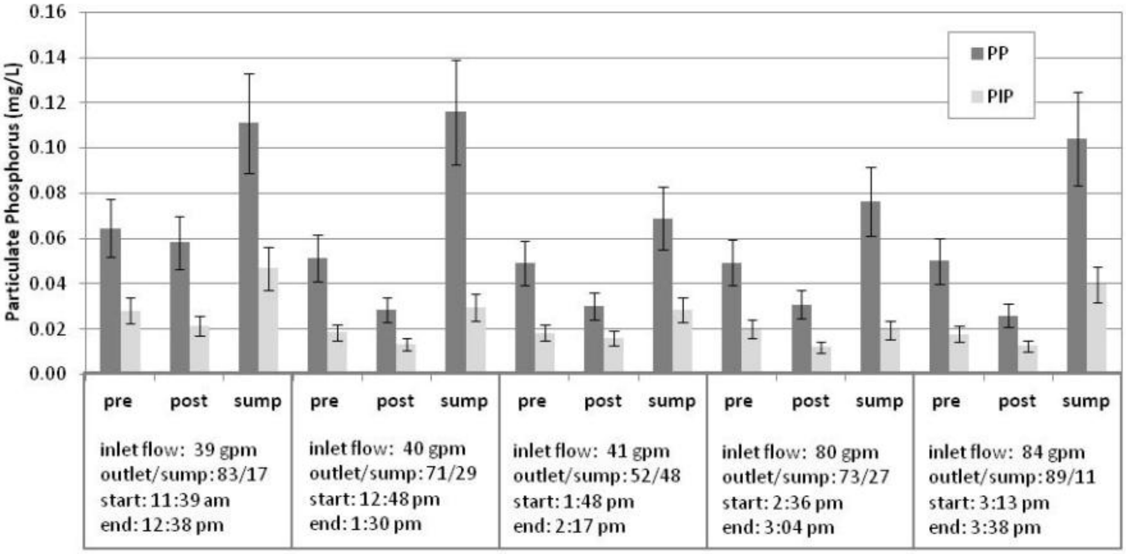


Figure 8. Summary of Particulate Phosphorus (PP) and Particulate Inorganic Phosphorus (PIP) Levels as a Function of Variable Flow Rates and Outlet/Sump Ratios



Mass reductions for PC, PN, PP and PIP in the post-separator outflow were calculated based on flow rate and concentration (Table 2). Percent reduction (in mass) was calculated and is shown in Table 4. When larger fractions of flow are shunted to the sump, removal mass and percent reduction increases in the post-separator outflow.

Table 3. Mass Reductions of PC, PN, PP, and PIP in the Post-Separator Outflow as a Function of Flow Rates (“40 gpm” and “80 gpm”) and for Different Outlet/Sump Ratios

Exp #	Total Flow gpm	Outlet/Sump Ratio	Reduction in Mass kg/d			
			PC (40 gpm)	**PN (40 gpm)**	**PP (40 gpm)**	**PIP (40 gpm)**
1	39	83%/17%	0.3228	0.0685	0.0035	0.0022
2	40	71% / 29%	0.4824	0.0965	0.0068	0.0020
3	41	52% / 48%	0.7581	0.1600	0.0075	0.0022
			PC (80 gpm)	**PN (80 gpm)**	**PP (80 gpm)**	**PIP (80 gpm)**
4	80	73% / 27%	0.6113	0.1344	0.0117	0.0049
5	84	89% / 11%	0.6234	0.1285	0.0123	0.0031

Table 4. Percent Reductions of PC, PN, PP, and PIP in the Post-Separator Outflow as a Function of Flow Rates (“40 gpm” and “80 gpm”) and for Different Outlet/Sump Ratios

Exp #	Total Flow gpm	Outlet/Sump Ratio	Percent Reduction %			
			PC (40 gpm)	**PN (40 gpm)**	**PP (40 gpm)**	**PIP (40 gpm)**
1	39	83% / 17%	34%	35%	25%	37%
2	40	71% / 29%	54%	54%	60%	49%
3	41	52% / 48%	71%	72%	68%	54%
			PC (80 gpm)	**PN (80 gpm)**	**PP (80 gpm)**	**PIP (80 gpm)**
4	80	73% / 27%	39%	42%	54%	56%
5	84	89% / 11%	37%	38%	54%	38%

4.2 Chlorophyll *a*

Chlorophyll *a* showed consistent reductions in concentrations between pre-separator inflow and post-separator outflow samples in four out of the five experiments. Concurrent chlorophyll *a* concentrations in sump outflow samples were higher than pre-separator inflow samples in all five experiments (Figure 9). Mass removed and percent reductions are shown in Table 5. Like the particulate results described above, these chlorophyll *a* results indicate that the prototype separator provided reductions in algae-related particulate matter in post-separator outflow and collection of algae-related particulate matter in the sump.

Figure 9. Summary of Chlorophyll *a* Levels as a Function of Variable Flow Rates and Outlet/Sump Ratios

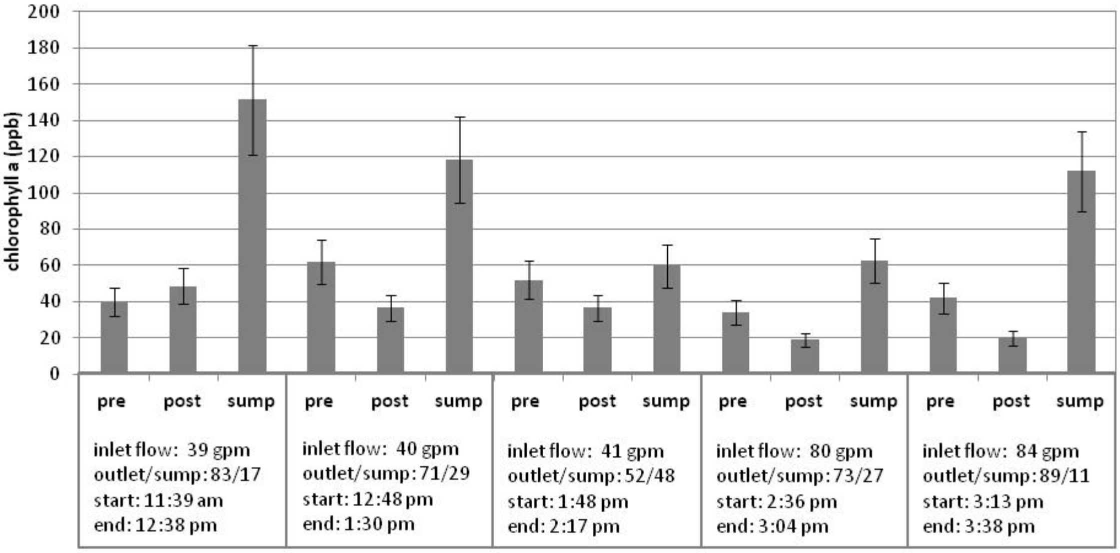


Table 5. Summary of Chlorophyll *a* Reductions (kg/d and percent reduction) as a Function of Variable Flow Rates and Outlet/Sump Ratios for each of the Five Experiments

Experiment #	Outlet/Sump	Total Flow gpm	Mass Removed kg/day	Percent Reduction %
1	83/17	39	-0.0001	-22
2	71/29	40	0.0078	41
3	52/48	41	0.0074	30
4	73/27	80	0.0090	45
5	89/11	84	0.0111	53

Note: Negative percent reduction indicates an increase in chlorophyll *a* concentration.

4.3 Cyanobacteria (Blue-Green Algae) Species

For this study, algae species enumeration was limited to cyanobacteria (blue-green algae). Algae density for APFA and other cyanobacteria species are presented below (Figure 10). As expected, the algae species enumeration in pre-separator inflow samples was dominated by APFA. Reductions in APFA occurred between pre-separator inflow and post-separator outflow samples in three (out of five) experiments. Higher APFA concentrations were consistently observed in the sump outflow samples. Mass removed and percent reductions are shown in Table 6. These results align with the chlorophyll *a* results described above, and verify that the prototype separator provided reductions in algae-related particulate matter in post-separator outflow and collection of such matter in the sump.

Figure 10. Summary of *Aphanizomenon flos-aquae* (APFA) (with 20 percent error bars) and Other Cyanobacteria Species Density as a Function of Variable Flow Rates and Outlet/Sump Ratios

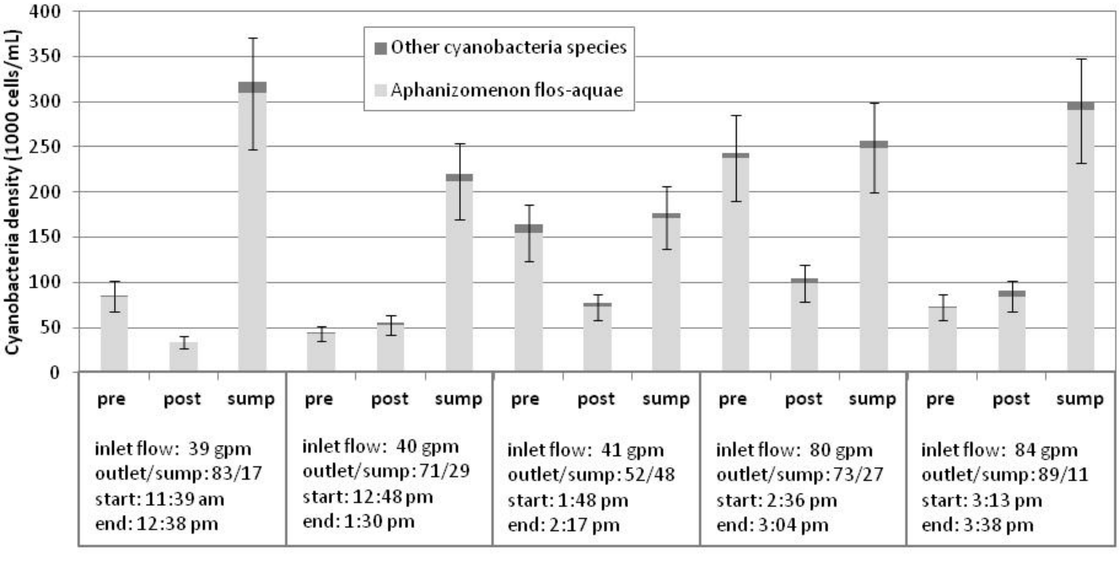


Table 6. Summary of Reductions of *Aphanizomenon flos-aquae* (APFA) as a Function of Variable Flow Rates and Outlet/Sump Ratios

Experiment #	Outlet/Sump	Total Flow gpm	Cell Count Reduction Cells/ml	Percent Reduction %
1	83/17	39	51,061	60
2	71/29	40	-9,722	-23
3	52/48	41	82,543	53
4	73/27	80	138,989	58
5	89/11	84	-11,944	-16

Note: negative percent reduction indicates an increase in APFA density.

5.0 DISCUSSION

Overall, results indicate that the prototype separator is able to reduce the amount of particulate algae/organic matter in post-separator outflow, and collect such particulate matter in the separator's sump. These observations suggest that the hydrodynamic vortex separation technology can effectively partition out a certain fractions of particulate material from the water, and can potentially be an effective technology for reducing particulate organic matter to improve water quality in the Klamath River system, particularly Link River and Keno Reservoir, which are just downstream from UKL and directly receive the large seasonal loads of particulate organic matter from the lake's outflow (Link Dam).

5.1 Particulate Matter

The separator removed a notable fraction (i.e., up to 24 percent) of particulate matter under experimental conditions. Accounting for particulate mass removal attributable simply to the diversion of water into the sump outlet, this removal percentage varied between 0 and 24 percent. As would be expected, the outlet/sump ratio was the principal factor that determined the particulate mass removal efficiencies observed from the experiments. Initial separator design and operation considered using the sump with no outflow – akin to a settling chamber. However, early experiments indicated that little material settled in the sump – even after extended operation. Without at least a minor sump outflow, removal rates were near zero since algal biomass removed into the sump was subject to resuspension into the separator outlet flow given its neutral buoyancy and the small size of the pilot scale separator. Introducing a positive outflow to the sump created a draw of water vertically along the screen and substantially improved removal efficiency of the separator. Visual inspection of filters identified notable reduction in filtered particulate residue between pre-separator and post-separator points, and marked increase in sump particulate material (Figure 11).

Figure 11. Photograph of Filtered Sample for Pre- and Post-treatment and Sump

Pre (inflow) Post (outflow) Sump

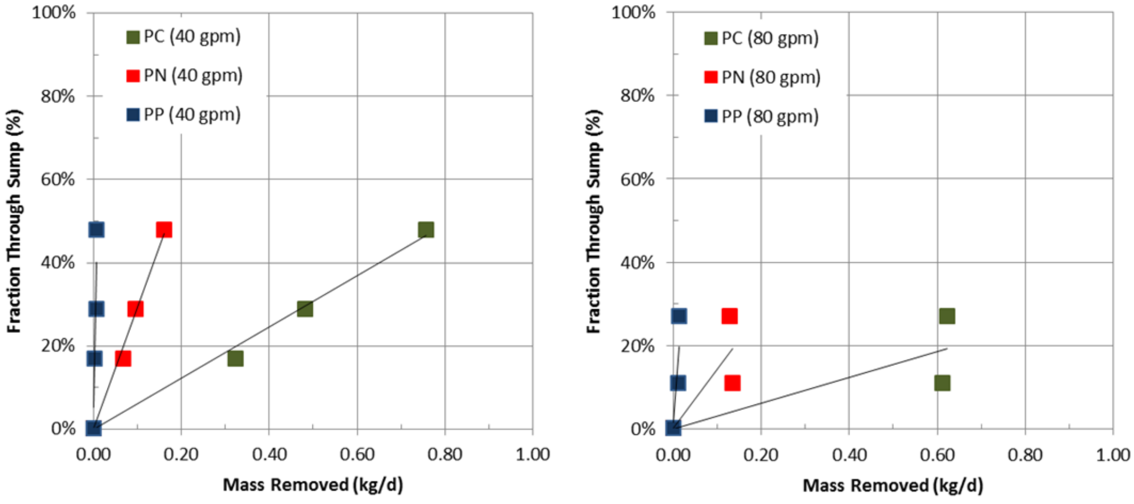
Prior to examining removal rates, a mass balance was completed to verify that the mass of particulate matter into and out of the separator was being accounted for appropriately. Flow and particulate concentrations were measured or calculated for the pre-separator inflow, post-separator outflow, and sump outflow. Using this information, a comparison of calculated and measured mass was completed for each of the particulates (i.e., PC, PN, PP, and PIP) across the five experiments. The differences (in percent) between measured and calculated mass were mostly within 10 percent, with a maximum difference of 31 percent (Table 7). The differences between measured and calculated mass of PC, PN, and PP were generally smaller than the differences for PIP. Overall, the differences for PIP were more variable than the differences for PC, PN, or PP. These results indicate that the differences were mostly within the range of typical laboratory and field measurement accuracy for these constituents. Therefore, an appropriate accounting of the mass of particulate matter into and out of the separator was provided during the experiments.

Table 7. Difference (Percent) in Measured Versus Calculated Mass for the 40 and 80 gpm Experiments for PC, PN, PP, and PIP

Experiment #	Flow gpm	PC kg/d	PN kg/d	PP kg/d	PIP kg/d
1	40	0%	0%	4%	-9%
2	40	-10%	-9%	5%	-3%
3	40	-14%	-17%	-1%	21%
4	80	4%	1%	-13%	-29%
5	80	-10%	-10%	-31%	-13%

Particulate removal efficiency in the separator was further assessed by comparing the particulate mass removed at the various flow rates and sump flow fractions (i.e., outlet/sump flow ratios). Particulate mass removed (in kg/d) versus sump flow fraction (in percent) are graphed in Figure 12 for PC, PN and PP. The Figure 12 graphs also include regressions of the data using a linear fit. The linear relationships can be used to estimate the particulate mass removed from inflow for both 40 and 80 gpm flow rates as a function of the fraction of flow passed through the sump (Figure 12).

Figure 12. Mass Removed for the (a) 40 gpm and (b) 80 gpm Experiments Versus Fraction Through Sump



(a) (b)

A discernible pattern from these linear relationships is that the removal rate of particulate carbon and nitrogen at 80 gpm[2] is approximately twice the corresponding removal rate at 40 gpm (Figure 12). This result suggests that overall flow rate may not be as critical as the sump flow fraction in determining particulate mass removal efficiency. Specifically, conservation of mass would require that twice the flow rate would result in twice the mass removal, all other conditions being static.

Figures 13 and 14 show additional relationships between particulate mass removed versus sump flow fraction at the 40 and 80 gpm flow rate, respectively. However, in these graphs the particulate mass removed is in terms of percent reduction (rather than mass removed in kg/d) between separator inflow and outflow. Figure 13 includes symbols (squares) that represent the actual sample data, and three lines to aid in the analysis of the data. The lines include: (1) a simple straight-line interpolation between the data points; (2) a polynomial fit to the sample data; and (3) a 1:1 line to identify the horizontal deviation between the experimental results and a no-treatment condition. This deviation is represents an efficiency metric that can be employed to identify an “optimal” fraction that represents the maximum possible percentage reduction in particulate matter. For example at zero and 100 percent flow through the sump, removal efficiency is zero. At some intermediate location, where the deviation of the two lines is greatest, the optimal or highest removal efficiency is achieved.

As with the previous figures, a zero flow through the sump is assumed equal to zero percent removal (or reduction). This same approach was developed for the 80 gpm flow rate. Figure 14 includes symbols (circles) that represent the actual sample data, and

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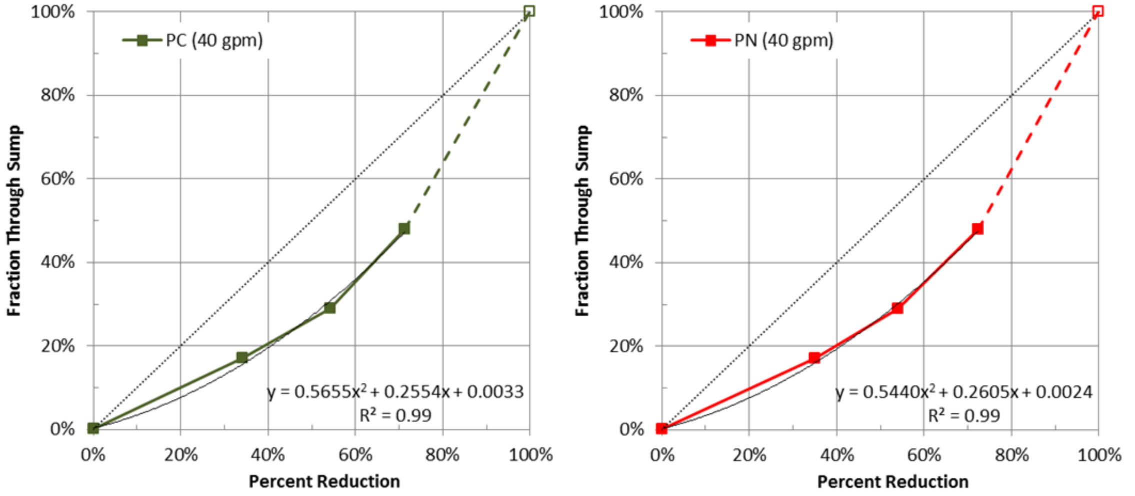
[2] It is noted the 80 gpm linear relationships are based only on three points, including two experimental points and the assumed zero removal for zero flow through sump point. This may affect the comparability of the 80 gpm linear relationships to the 40 gpm relationships.

includes the straight-line interpolation between the field data points and the 1:1 “optimal” line. However, with less sample data for the 80 gpm flow rate, a polynomial fit could not be developed.

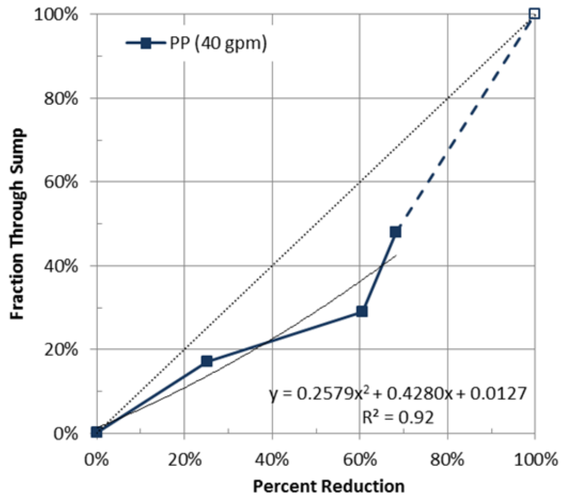
Considered altogether, Figures 12-14 are useful for identifying the optimal removal rate and mass for the prototype separator, and provides valuable information for assessing the use and potential effectiveness of vortex separation technology going forward. Using PC as an example (in Figures 12 and 13), when the fraction passing through the sump is between 30 and 40 percent, the removal efficiency is the highest (defined as the fraction through sump value that deviates furthest from the 1:1 line) at approximately 24 percent. At larger and smaller fractions through the sump, the relative removal rate is lower. While “optimal” removal rates may be desirable, Figure 13 also illustrates that for lower fractions of water passed through the sump, removal is still appreciable (e.g., at a sump flow fraction of 15 percent, removal is approximately 20 percent).

Figure 13. Percent Reduction in Mass Removed for the 40 gpm Experiment Versus Fraction Through Sump for (a) PC, (b) PN, and (c) PP

Regression included only for available data. Dashed line (open symbol) represents potential trace to 100 percent of flow through sump. 1:1 line included for reference.



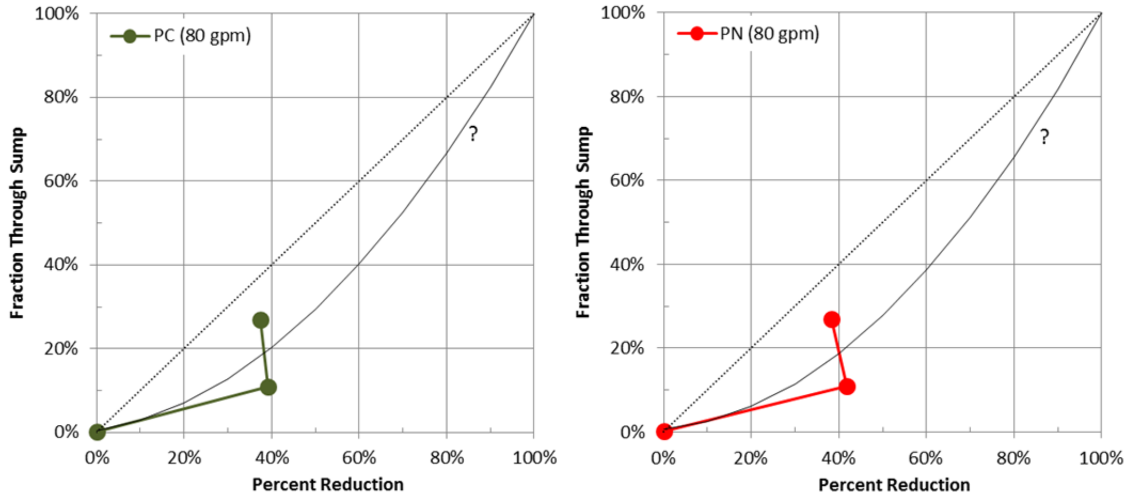
(a) (b)



(c)

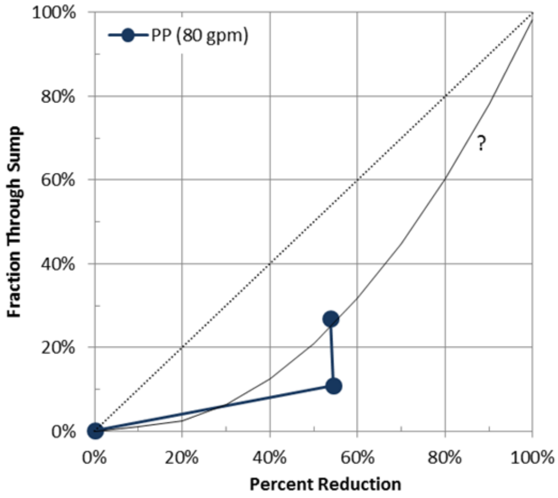
Figure 14. Percent Reduction in Mass Removed for the 80 gpm Experiment Versus Fraction Through Sump for (a) PC, (b) PN, and (c) PP

Possible trend line/relationship included only for illustrative purposes. No potential trace to 100 percent of flow through sump due to limited data.



(a)

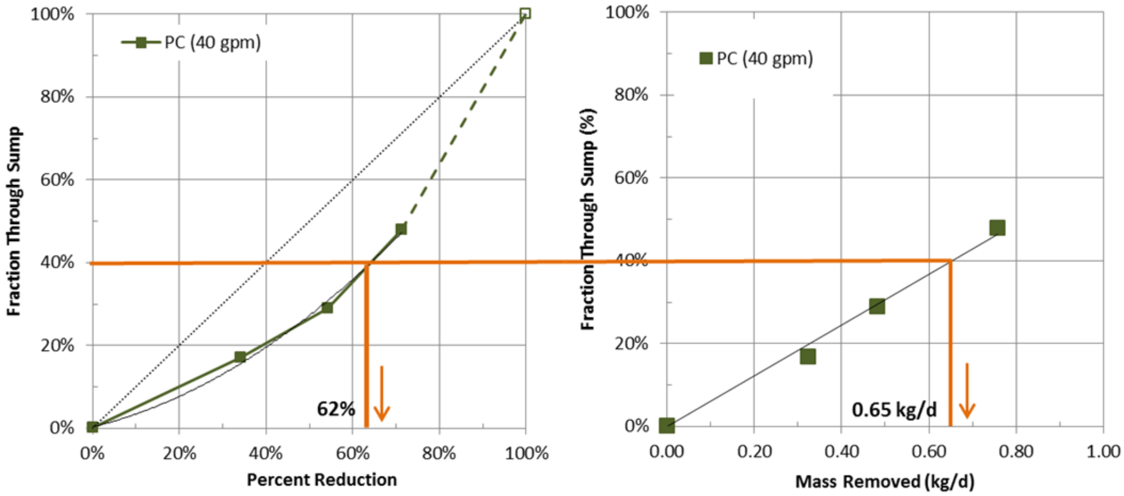
(b)



(c)

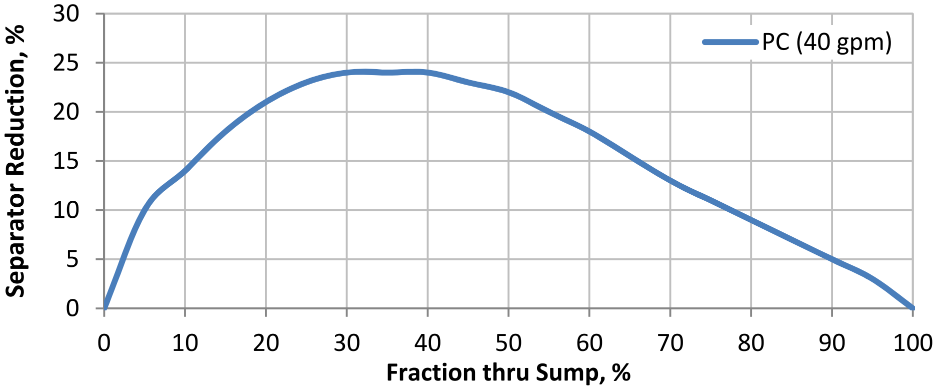
The efficiency curve (fraction through sump and percent reduction) shown in Figure 15 can be used in concert with the mass removal curve (fraction through sump and mass reduction) to identify mass removed for a desired removal efficiency. Ultimately, these sorts of analyses can help to identify the best balance between facilities construction and operations and maintenance costs, which would play a role in future decisions on the potential implementation of vortex separation technology to improve water quality in the Klamath River system.

Figure 15. PC Percent Reduction and Mass Removed Versus Fraction Through Pump, 40 gpm Case



Another way to view the mass removal percentages presented above in Figure 15 is to plot the difference between the percent reduction observed and the percent reduction that would be attributable to simply removing mass from the outlet sump (the horizontal difference between the percent reductions shown above and the corresponding percent of water discharged through the sump) for varying sump discharge fractions. This is illustrated below in Figure 16, which indicates that PC removal was most efficient (a high of 24 percent reduction) at sump discharge percentages between 30 and 40 percent.

Figure 16. PC Percent Reduction Versus Fraction Through Sump, 40 gpm Case



5.2 Chlorophyll *a* and Cyanobacteria (Blue-Green Algae) Species

Similar analyses to the particulate matter (as presented above in Figures 12-15) were not developed from the sample results for chlorophyll *a* and cyanobacteria (blue-green algae) species. Similar to the particulate matter data, the chlorophyll *a* and APFA levels generally indicate reduction through the separator. However, the sample results for the chlorophyll *a* and APFA levels were more variable than the particulate matter data. For example, there were instances when inflow concentrations or cell counts were lower than outflow values. Yet, in these instances, the sump outflow samples yielded notably higher values than either pre-separator inflow or post-separator outflow values. These more variable sample results for chlorophyll *a* and cyanobacteria (blue-green algae) species (as seen by comparing Figures 9 and 10) suggest that there is more variability in field conditions, laboratory results, or both with regards to chlorophyll *a* and algae cell counts as compared to the particulates (PC, PN, and PP).

6.0 CONCLUSIONS AND RECOMMENDATIONS

The 2012 organic matter removal experiment tested the feasibility and performance of hydrodynamic vortex separation as a potential technology for removing particulate algae and organic matter. The results of the experiment, using a prototype separator, suggest that such a technology could be effective for improving downstream water quality through the removal of algal biomass. The study results demonstrated that removal efficiency depends on flow rate and outlet/sump ratio. These parameters in turn would affect the cost of building and operating a larger-scale separator system. Therefore, further testing would be needed to better understand the range of possible removal efficiencies, which is dependent on flow and outlet/sump ratio, and the variable implementation options. Recommendations for additional testing and analysis include:

Build upon existing efficiency curves with more data points from similar experiments. More experiments with varying flow rates and outlet/sump ratios would need to be conducted to create an efficiency curve with more data points. The design improvements described above would make future experiments more efficient and wide-ranging. Completing the experiment in different months (e.g., between late May and late September) would also provide additional data important for better understanding expected removal efficiencies that could inform the conceptual design of a treatment system.

Test prototype separator at other locations. At UKL, the predominant algae species is APFA, and some degree of removal efficiency was observed in the 2012 experiment. Other algae species of concern at other locations could likewise be removed using hydrodynamic separation technology and testing at other locations would develop information on removal efficiency for other species.

Run experiment using a siphon (no pump). When water is pumped from a lake with a large algae mat, the algal colonies are separated as the water goes through the pump. Using a siphon could reduce the amount of disturbance and allow larger masses of algae to enter into the separator. The larger algal mass in an undisturbed colony would likely be more effectively removed by the hydrodynamic separation process. However, the siphoning process requires that the separator to be located below the water surface. As such, locations near the Klamath River, where such an experiment can be conducted, are limited.

Test different screen sizes. In 2012, the 2.4 micron screen appeared to have limited ability in screening out particulates. As such, only the 1.2 micron screen was tested. In future experiments, smaller screen sizes should be tested to assess potential removal efficiency improvements.

Run several prototype separators in series and in parallel. If separators were run in series, the additional hydrodynamic separation processes would likely remove more particulates and further concentrate removed algal biomass. However, running several separators in parallel could potentially have greater overall downstream water quality impacts because treatment of a larger volume of water could be treated given a fixed number of separators.

Identify scale-up issues for design consideration. Identify appropriate fractions of water to be treated and the range of flows in order to define separator capacity and/or number of separators required to achieve a specific water quality objective or design removal rate.

Identify issues related to disposal of sump water and collected algal biomass. The disposal of sump water may trigger regulatory requirements related to a potential discharge that should be identified. Additionally, the algal biomass removed by the separators may have disposal issues that should be assessed. The potential for beneficial use of removed biomass should be included in this assessment as a means to address possible disposal issues, lower disposal costs, and potentially offset project costs.

Complete a cost analysis. Complete a cost analysis that identifies design elements (separators, pumping, infrastructure, etc.), capital costs, and operations and maintenance expenses. Using these elements identify a range of conceptual designs and develop costs associated with construction and operation of such a system.

The above list of recommendations provides a guideline for future work that would add to the current understanding and guide decision makers considering the implementation of hydrodynamic separation as a water quality improvement strategy.

7.0 REFERENCES

Canter Lund, H., and J.W.G. Lund. 1995. *Freshwater Algae*. Biopress Limited. Hong Kong. 360 pp.

California Department of Public Health (CDPH). 2013. Blue-Green Algae (Cyanobacteria) Blooms. Website: http://www.cdph.ca.gov/healthinfo/environhealth/water/pages/bluegreenalgae.aspx (Assessed on January 15, 2013)

Lindenberg, M.K., G. Hoilman, and T.M. Wood. 2009. *Water quality conditions in Upper Klamath and Agency Lakes, Oregon, 2006*. U.S. Geological Survey Scientific Investigations Report 2008-5201, 54 p.

National Academy of Sciences (NAS). 2004. *Endangered and Threatened Fishes in the Klamath River Basin.* The National Academies Press, Washington D.C. 397 pp.

New Jersey Department of Environmental Protection (NJDEP). (2006). New Jersey Tier II Stormwater Test Requirements—Amendments to TARP Tier II Protocol. Trenton, New Jersey. Available online: http://www.state.nj.us/dep/dsr/bscit/NJStormwater_TierII.pdf

PacifiCorp. 2008. Application for Water Quality Certification Pursuant to Section 401 of the Federal Clean Water Act for the Relicensing of the Klamath Hydroelectric Project (FERC No. 2082) in Klamath County, Oregon. Klamath Hydroelectric Project (FERC Project No. 2082). Prepared for: Oregon Department of Environmental Quality, Portland. Prepared by: PacifiCorp, Portland, Oregon. February 2008.

Patel, D. J. Hauser, J. Johnston, and J. Curtis. 2004. “Pilot Filtration Studies for Turbidity and Nutrient Removal at Lake Tahoe.” 3rd Annual North American Surface Water Quality Conference (StormCon), Palm Desert, July 26-29, 2004.

Perry, S., J. Garbon, and B. Lee. 2009. “Phosphorus Treatment – Advanced Removal Mechanisms and Amended Design for Stormwater BMPs.” Proceedings of the 2009 Georgia Water Resources Conference. April 27–29, 2009, at the University of Georgia.

Peterson Holm, N., G.G. Ganf, and J. Shapiro. 1983. “Feeding and assimilation rates of *Daphnia pulex* fed on *Aphanizomenon flos-aquae*.” Limnol. Oceanogr., 28(4) pp 677-687.

Porat, R., B. Teltsch, A. Perelman, and Z. Dubinsky. (2001), ‘Diel Buoyancy Changes by the Cyanobacterium *Aphanizomenon ovalisporum* from a Shallow Reservoir’, J. Plankton Res., 23, 753-763

Reddy, K.R., R.H. Kadlec, and M.J. Chimney. 2006. “The Everglades Nutrient Removal Project.” *Ecological Engineering*. 27(4) pp 265-267.

Technology Acceptance and Reciprocity Partnership (TARP). (2003). The Technology Acceptance Reciprocity Partnership Protocol for Stormwater Best Management Practice Demonstrations. Harrisburg, Pennsylvania. Available online: http://www.dep.state.pa.us/dep/deputate/pollprev/techservices/tarp/pdffiles/Tier2protocol.pdf

United Stated Bureau of Reclamation (USBR). 2012. Standard Operating Procedures for Quality Assurance. Prepared by the Environmental Monitoring Branch, Revision 2012-07. July.

United States Environmental Protection Agency (USEPA). (2002). Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements (EPA-821-B-02-001). Washington, D.C. Available Online: http://epa.gov/waterscience/stormwater/montcomplete.pdf

United States Fish and Wildlife Service (USFWS). (2001). *Biological/Conference Opinion Regarding the Effects of Operations of the Bureau of Reclamation’s Klamath Project on the Endangered Lost River Sucker (Deltistes luxatus), Endangered Shortnose Sucker (Chasmistes brevirostris), Threatened Bald Eagle (Haliaeetus leucocephalus), and Proposed Critical Habitat for the Lost River/Shortnose suckers*. Klamath Falls, OR: Klamath Falls Fish and Wildlife Office.

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APPENDIX A

Supporting Data and Information

This appendix includes supporting data and information for the 2012 study to test the feasibility of vortex separation technology to remove particulate organic matter from Klamath River source water.

A.1 Field Data: Nutrients, Chlorophyll a, and Aphanizomenon flos-aquae

Table A-1. Summary of total nitrogen results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Total Nitrogen mg/l		
			pre	post	sump
1	39	83% / 17%	1.85	1.88	2.82
2	40	71% / 29%	1.82	2.18	2.47
3	41	52% / 48%	1.84	1.61	2.30
4	80	73% / 27%	1.82	1.93	2.34
5	84	89% / 11%	2.47	2.03	3.62

Table A-2. Summary of nitrate and nitrite ((NO2-NO3)-N) results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Nitrate and Nitrite mg/l		
			pre	post	sump
1	39	83% / 17%	0.049	0.045	0.036
2	40	71% / 29%	0.056	0.067	0.065
3	41	52% / 48%	0.070	0.072	0.069
4	80	73% / 27%	0.084	0.090	0.081
5	84	89% / 11%	0.091	0.095	0.078

Table A-3. Summary of ammonium (NH4-N) results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Ammonium mg/l		
			pre	post	sump
1	39	83% / 17%	0.049	0.047	0.062
2	40	71% / 29%	0.078	0.076	0.101
3	41	52% / 48%	0.087	0.092	0.053
4	80	73% / 27%	0.062	0.082	0.038
5	84	89% / 11%	0.056	0.083	0.044

Table A-4. Summary of total phosphorus results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Total Phosphorus mg/l		
			pre	post	sump
1	39	83% / 17%	0.173	0.178	0.272
2	40	71% / 29%	0.173	0.210	0.237
3	41	52% / 48%	0.178	0.160	0.223
4	80	73% / 27%	0.164	0.187	0.219
5	84	89% / 11%	0.241	0.201	0.356

Table A-5. Summary of orthophosphate (PO4-P) results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Orthophosphate mg/l		
			pre	post	sump
1	39	83% / 17%	0.024	0.026	0.037
2	40	71% / 29%	0.029	0.032	0.043
3	41	52% / 48%	0.030	0.034	0.026
4	80	73% / 27%	0.026	0.027	0.021
5	84	89% / 11%	0.021	0.024	0.020

Table A-6. Summary of dissolved organic carbon results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Dissolved Organic Carbon mg/l		
			pre	post	sump
1	39	83% / 17%	7.60	7.50	9.15
2	40	71% / 29%	7.89	7.71	9.24
3	41	52% / 48%	7.83	7.55	7.59
4	80	73% / 27%	7.52	7.47	7.72
5	84	89% / 11%	7.61	7.64	8.06

Table A-7. Summary of *Aphanizomenon flos-aquae* cell density results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	*Aphanizomenon flos-aquae* Cell Density 1000 cells/ml		
			pre	post	sump
1	39	83% / 17%	84.7	33.6	309.6
2	40	71% / 29%	43.1	52.8	211.7
3	41	52% / 48%	155.1	72.6	171.7
4	80	73% / 27%	238.0	99.0	249.0
5	84	89% / 11%	72.5	84.4	290.4

Table A-8. Summary of chlorophyll *a* results

Experiment #	Total Flow gpm	Outlet/Sump Ratio	Chlorophyll *a* ppb		
			pre	post	sump
1	39	83% / 17%	39.8	48.6	151.4
2	40	71% / 29%	61.9	36.4	118.5
3	41	52% / 48%	51.9	36.4	59.6
4	80	73% / 27%	34.2	18.8	62.6
5	84	89% / 11%	42.0	19.9	111.9

A.2 Field Data: PC, PN, PP, PIP and C:N, C:P and TP:PIP ratios

Table A-9. Field data and C:N, C:P, and TP:PIP ratios

Exp.	Loc.	Flow	#	Concentration				Ratio		
				PC mg-C/l	**PN mg-N/l**	**PP mg-P/l**	**PIP mg-P/l**	**C:N**	**C:P**	**TP:PIP**
40 gpm	Pre	39.0	201	4.44	0.918	0.0646	0.0282	4.8	68.7	2.3
	Post	32.4	202	3.52	0.718	0.0582	0.0215	4.9	60.5	2.7
	Sump	6.6	203	9.04	1.88	0.111	0.0468	4.8	81.4	2.4
40 gpm	Pre	40.0	211	4.08	0.819	0.0512	0.0185	5.0	79.7	2.8
	Post	28.4	212	2.63	0.53	0.0285	0.0132	5.0	92.3	2.2
	Sump	11.6	213	6.17	1.28	0.116	0.0298	4.8	53.2	3.9
40 gpm	Pre	41.0	221	4.76	0.99	0.0493	0.0183	4.8	96.6	2.7
	Post	21.3	222	2.63	0.527	0.0301	0.0162	5.0	87.4	1.9
	Sump	19.7	223	5.63	1.15	0.0689	0.0285	4.9	81.7	2.4
80 gpm	Pre	80.0	231	3.57	0.736	0.0494	0.02	4.9	72.3	2.5
	Post	58.4	232	2.97	0.586	0.0308	0.0121	5.1	96.4	2.5
	Sump	21.6	233	5.7	1.18	0.0762	0.0196	4.8	74.8	3.9
80 gpm	Pre	84.0	241	3.64	0.731	0.0501	0.0179	5.0	72.7	2.8
	Post	74.8	242	2.56	0.506	0.026	0.0125	5.1	98.5	2.1
	Sump	9.2	243	9.22	1.86	0.104	0.0398	5.0	88.7	2.6

A.3 Field Sampling Times

Table A-10. Summary of experiment #1 sampling times.

Experiment #1			
	Sampling Times		
Sample	**Pre (inflow)**	**Post (outflow)**	**Sump (Disposal)**
	201	202	203
1	11:39	11:41	11:42
2	11:43	11:45	11:46
3	11:48	11:49	11:51
4	11:52	11:53	11:55
5	11:57	11:58	12:00
6	12:02	12:03	12:04
7	12:06	12:07	12:09

Table A-11. Summary of experiment #2 sampling times.

Experiment #2			
	Sampling Times		
Sample	**Pre (inflow)**	**Post (outflow)**	**Sump (Disposal)**
	211	212	213
1	12:48	12:49	12:51
2	12:59	13:01	13:02
3	13:03	13:05	13:06
4	13:07	13:08	13:09
5	13:11	13:12	13:13
6	13:15	13:16	13:17
7	13:18	13:19	13:20

Table A-12. Summary of experiment #3 sampling times.

Experiment #3			
	Sampling Times		
Sample	**Pre (inflow)**	**Post (outflow)**	**Sump (Disposal)**
	221	222	223
1	13:48	13:49	13:50
2	13:51	13:52	13:53
3	13:54	13:55	13:56
4	13:57	13:58	13:59
5	14:00	14:01	14:03
6	14:04	14:05	14:06
7	14:07	14:08	14:09

Table A-13. Summary of experiment #4 sampling times.

	Experiment #4		
	Sampling Times		
Sample	Pre (inflow)	Post (outflow)	Sump (Disposal)
	231	232	233
1	14:36	14:37	14:38
2	14:40	14:41	14:42
3	14:43	14:44	14:45
4	14:46	14:47	14:48
5	14:49	14:50	14:51
6	14:52	14:53	14:54
7	14:55	14:56	14:57

Table A-14. Summary of experiment #5 sampling times.

	Experiment #5		
	Sampling Times		
Sample	Pre (inflow)	Post (outflow)	Sump (Disposal)
	241	242	243
1	15:13	15:14	15:15
2	15:16	15:17	15:18
3	15:19	15:20	15:21
4	15:22	15:22	15:23
5	15:24	15:25	15:26
6	15:27	15:28	15:29
7	15:30	15:31	15:32

Table A-15. Summary of sampling time of integrated samples.

Integrated Sample		Sampling time
201	Pre (inflow)	12:27
202	Post (outflow)	12:35
203	Sump (Disposal)	12:38
211	Pre (inflow)	12:26
212	Post (outflow)	13:28
213	Sump (Disposal)	13:30
221	Pre (inflow)	14:11
222	Post (outflow)	14:14
223	Sump (Disposal)	14:17
231	Pre (inflow)	14:59
232	Post (outflow)	15:02
233	Sump (Disposal)	15:04
241	Pre (inflow)	15:34
242	Post (outflow)	15:36
243	Sump (Disposal)	15:38