SECTION 2

WATER QUALITY IMPROVEMENT TECHNIQUES EVALUATED AT THE WORKSHOP

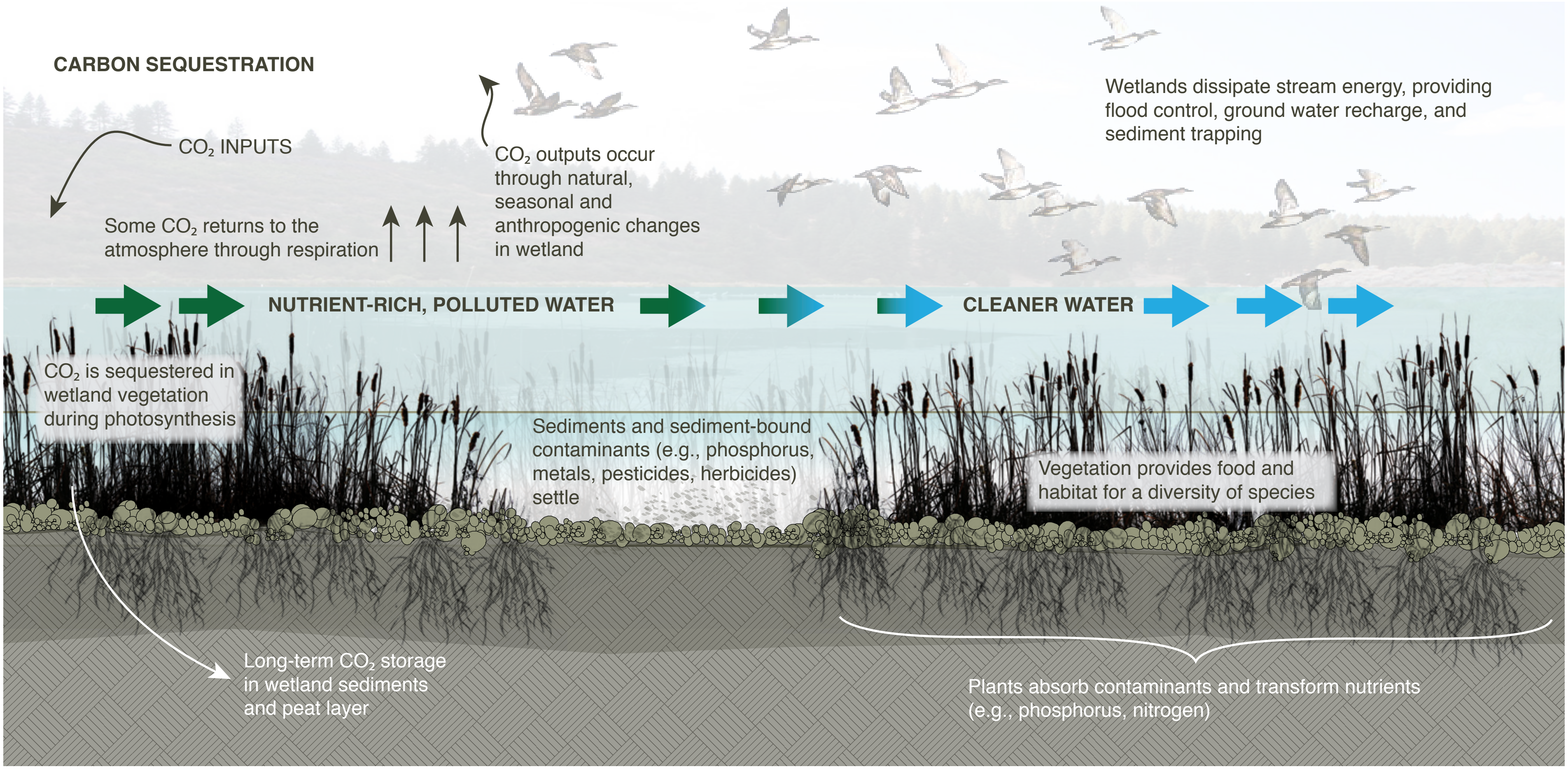


Fig. 2.1 (Above) Wetland functions, including carbon sequestration.

Fig. 2.2 (Right) Treatment Wetlands at Macintosh Park, Plant City, Florida. Photo: City of Plant City, Engineering Division.

Fig. 2.3 (Far right) Carbon sequestration in the peat layers of constructed tule wetlands is being investigated as a mitigation strategy for agricultural soil oxidation, greenhouse gas emissions, and land subsidence elsewhere in California, including the Sacramento-San Joaquin River Delta. Photo: U.C. Davis.

WETLAND REHABILITATION

Wetlands are ecotones between terrestrial and aquatic ecosystems that serve many important functions in the landscape, including flood control, groundwater recharge, nutrient transformation, support of food and habitat for numerous species of fish and wildlife, and sequestration of carbon dioxide, a potent greenhouse gas, through build-up of peat (Figure 2.1).[1] Many of the ecosystem functions provided by wetlands in the U.S. and other parts of the world have been lost as humans have drained or otherwise negatively impacted millions of acres of these natural systems.[2] In the Klamath Basin as a whole, approximately 80% of natural wetlands have been lost to other land uses, including agriculture. Increasing the extent of wetlands in the Klamath Basin is a recommended strategy for increasing resiliency to climate change in the built environment, the economy, and human systems.[3]

GOALS AND CAPABILITIES

Wetland *rehabilitation* refers to the reparation of ecosystem processes, productivity, and services and often focuses on reestablishing wetland hydrology and vegetation. The term *rehabilitation* is used rather than restoration, to emphasize that a return to historical conditions is not always possible, or desirable, given competing needs for water and land resources.

1 Current estimates from wetlands in the Sacramento-San Joaquin River Delta, California, indicate that, compared to existing agricultural practices, managed wetlands are net reducers of greenhouse gas emissions (Merrill et al. 2010).
2 Mitsch and Gosselink 2007
3 Barr et al. 2010

SIMILAR APPLICATIONS

Due to its proven pollutant reduction behavior, relatively low maintenance cost, simplicity of operation, and aesthetic and ecological value, wetland rehabilitation is increasingly common in a variety of settings, including agricultural and urban areas. There are numerous examples of treatment wetlands that have been used for nutrient and organic matter removal in the United States, including systems associated with a large river diversion and/or treatment at scales relevant to the Upper Klamath Basin, such as the following:

- Arcata Marsh and Wildlife Sanctuary, Arcata, CA
- Albany-Millersburg Integrated Treatment Wetlands System, OR
- Prado Wetlands, Santa Ana River, CA
- New River Wetlands Project, Salton Sea, CA
- Des Plains River Wetlands Demonstration Project, IL
- Everglades Construction Project, FL
- Mississippi-Ohio-Missouri Basin Nutrient Control Implementation Initiative, NCII

Additional information about these example systems can be found in *Approaches to Water Quality Treatment by Wetlands in the Upper Klamath Basin* (CH2M Hill 2012). There are also numerous examples of natural wetlands that are managed for water resources and/or wildlife habitat, and possess the secondary goal of water treatment, including large agency-managed projects and smaller projects spearheaded by private landowners in the Klamath Basin (Table 2.1 and Figure 2.6).

Fig. 2.4 Albany-Millersburg Integrated Treatment Wetlands, Albany, Oregon. Photo: City of Albany.

Wetlands can be rehabilitated for a variety of reasons, including improving habitat, water treatment, flood control, water storage, or some combination of the above. Wetlands have been shown to effectively remove a wide range of point and non-point source pollutants from incoming water including:

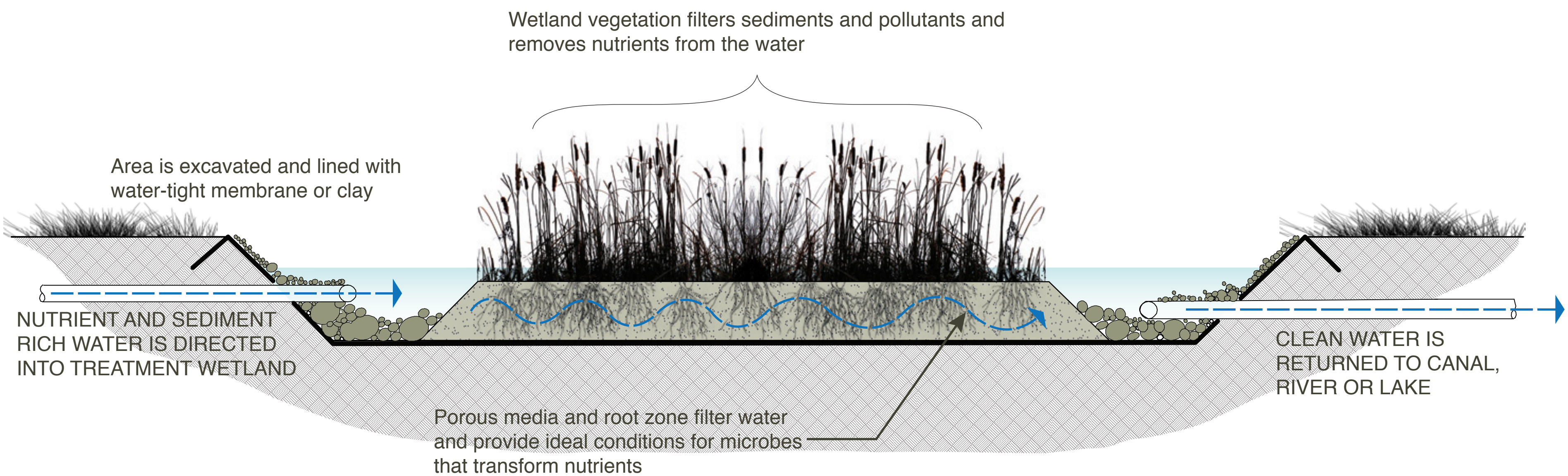
- Total suspended solids
- Nutrients such as nitrogen and phosphorus
- Metals
- Trace organic compounds such as pesticides and herbicides
- Bacteria and pathogens

Wetland projects can be small-scale (1 acre to 10s of acres), large-scale (100s to 1,000s of acres) or in-between, depending on resource management needs. Projects can be located in downstream portions of the watershed to capture pollutants before they leave the system or are discharged into a receiving waterbody, or they can be scattered throughout the watershed to provide on-site treatment and habitat (see text box on page 18).

Workshop attendees were asked to consider three different types of wetland projects, including habitat-focused wetland restoration, water quality treatment wetlands, and diffuse source (decentralized) treatment wetlands. Many participants determined that the differentiation in wetland project types is not useful. In light of the distinction between rehabilitation and restoration discussed at the workshop, many participants preferred to consider the use of all forms of wetlands, including riparian zones, in a broader, landscape sense.

Accordingly, the following section describes wetland rehabilitation in general terms, combining habitat-focused and treatment wetlands, but considering diffuse source (decentralized) treatment wetlands separately because they operate at a smaller scale and are dispersed throughout the watershed (see text box on page 15). Rankings for each of the three wetland project types are presented individually, as they were originally framed at the workshop. However, the conceptual designs related to wetlands in Section 3 combine habitat-focused and treatment wetlands, consistent with feedback from workshop participants.

Fig. 2.5 Cross section of a typical treatment wetland cell.



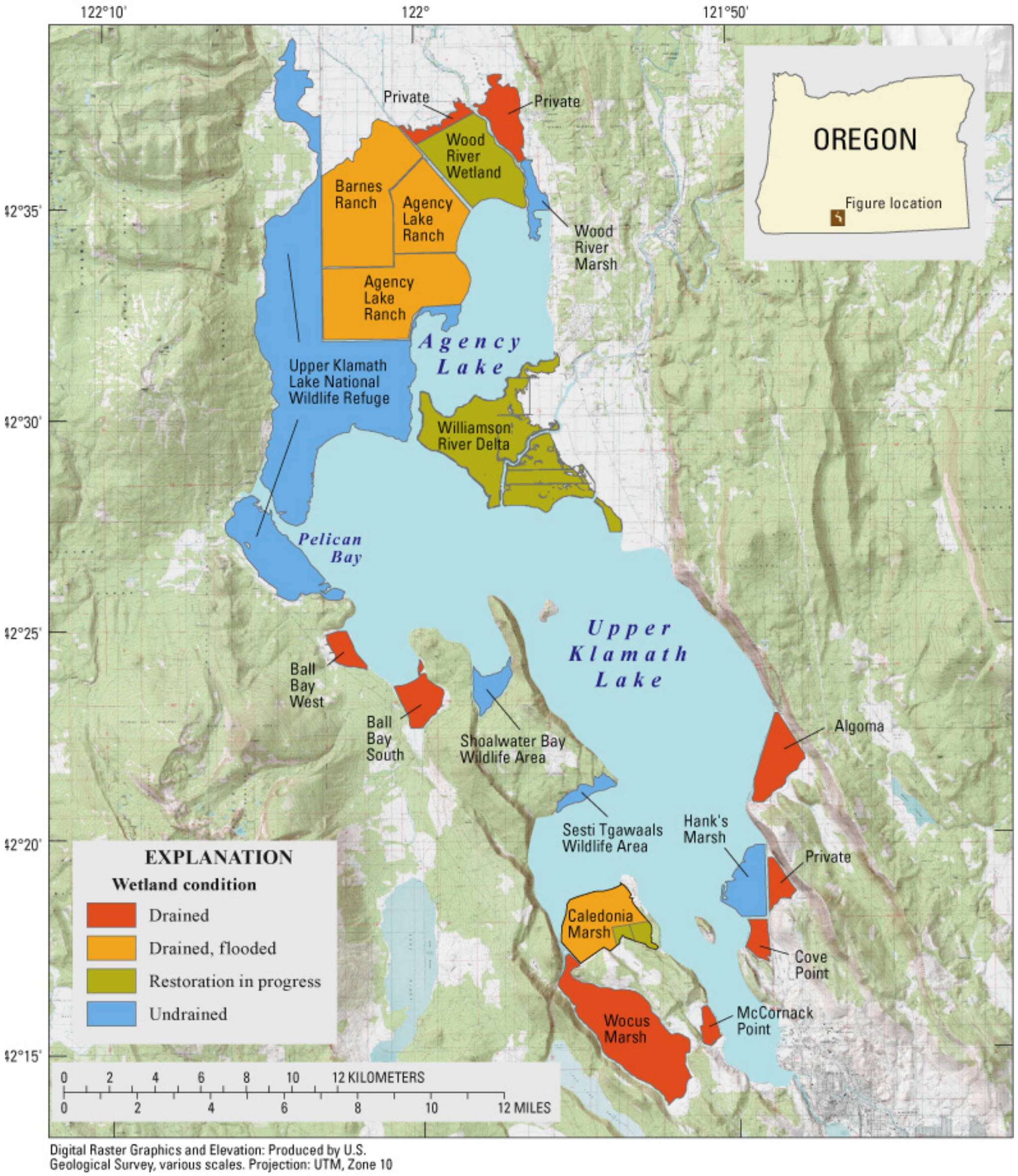


Fig. 2.6 Wetland conditions around Upper Klamath Lake. Source: USGS (Lindenburg and Wood 2009).

TABLE 2.1 - EXAMPLES OF PREVIOUSLY DRAINED AND RE-FLOODED OR NATURAL WETLANDS THAT ARE CURRENTLY MANAGED FOR WATER STORAGE AND/OR WILDLIFE HABITAT IN THE UPPER KLAMATH BASIN[4]

NAME	ACRES	MANAGEMENT ENTITY	PRIMARY PURPOSE
Ridgeway Project	257	Private	Habitat
Sycan Marsh	30,539	The Nature Conservancy	Habitat
Williamson River Delta	7,440	The Nature Conservancy	Habitat and water storage
Upper Klamath Marsh National Wildlife Refuge	13,021 (emergent) 1,008 (open water) 13,889 (meadow)	U.S. Fish and Wildlife Service	Habitat
Wood River Wetlands	3,200	BLM	Habitat and water storage
Upper Klamath Lake National Wildlife Refuge	15,000	U.S. Fish and Wildlife Service	Habitat
Barnes and Agency Lake Ranches	9,884	U.S. Fish and Wildlife Service	Water storage
Circle 5 Ranch	1,011	Private	Habitat
Lower Klamath Lake National Wildlife Refuge	21,500 (seasonal) 1,008 (emergent) 13,889 (open water)	U.S. Fish and Wildlife Service	Habitat
Tule Lake National Wildlife Refuge	1,700 (seasonal) 2,000 (emergent) 10,500 (open water)	U.S. Fish and Wildlife Service	Habitat
Miller Island Wildlife Refuge	1,420	Oregon Department of Fish and Wildlife	Habitat

4 This table is not a comprehensive summary of wetlands in the Upper Klamath Basin. Some of the examples presented in this table do not appear in Figure 2.6, and some of the parcels shown in Figure 2.6 do not appear in this table (due to a lack of readily available data).

DIFFUSE SOURCE (DECENTRALIZED) TREATMENT WETLANDS (DSTWs)

Wetland water treatment can occur throughout a watershed, rather than at the bottom or just prior to discharge into a large receiving water body. Design and implementation of networks of small-scale diffuse source (decentralized) treatment wetlands (DSTWs) can achieve the benefits of wetland ecosystem functioning in multiple locations throughout a watershed.

The goals for DSTWs are generally the same as for other types of wetlands, but the functionality occurs in relatively smaller pockets and has the advantage of on-site treatment and habitat.

Rather than being sized based on treatment efficiency, DSTWs are designed to accommodate an estimated amount of stormwater runoff from the landscape or a particular hydraulic residence time given adjacent agricultural canal flow. Specific design elements allow these systems to function at smaller scales such as natural low points in pastures and agricultural fields or areas directly adjacent to small drainage ditches (see Section 3, pages 41-50). These systems can also be used to treat wastewater and runoff from small-to medium-sized housing developments.

There are relatively few requirements and hence, relatively low costs, for building DSTW systems (see Table 2.2 on page 19). Unlike larger-scale habitat and treatment wetlands, land acquisition may be unnecessary as the wetlands can be located on a fraction of an existing parcel by an individual landowner.

Fig. 2.7 (Above) Restored wetland at San Joaquin Marsh and Wildlife Sanctuary, Irvine Ranch and Water District, Irvine, CA. Photo: Kim Trimiew.

Fig. 2.8 (Left) Treatment wetlands improving quality of irrigation tailwaters before entering the San Joaquin River. Photo: University of California.

BASIC DESIGN ELEMENTS

Wetland rehabilitation designs must be tailored to local conditions and constraints. General design criteria for wetland rehabilitation include the following:

- Water inundation or saturation for some portion of the growth season
- Topography and configuration that support a slow-moving, tortuous flow path for water
- Varied depth to support a variety of vegetation types and habitats
- Inlet and outlet structures, if hydrology is managed

Wetlands designed with the primary goal of removing or deactivating pollutants are generally referred to as *treatment wetlands* and have specific design and operation criteria that maximize water treatment. These systems are typically sized based upon treatment efficiency and *hydraulic residence time*, or the average amount of time that water spends in the wetland. These systems can also provide high quality wildlife habitat. While wetlands that are designed and operated with the primary goal of habitat or water storage do not necessarily rely upon a known or constant hydraulic residence time, they can also provide pollutant removal functions.

WORKSHOP EVALUATION[5]

In general, wetland rehabilitation was favorably ranked by workshop attendees for several criteria. Although habitat-focused, treatment, and DSTWs were considered separately for the ranking exercise (Figures 2.9-2.11), there was general agreement among workshop participants that the distinction was unnecessary. There was also general agreement that wetlands are effective at nitrogen and phosphorus removal, they possess a high degree of synergy with other restoration projects and techniques being considered in the Klamath Basin, and they exhibit a low degree of infrastructure challenges and energy use. For DSTWs, the Wood and Sprague river valleys were identified as priority locations given current land use practices and a perceived capacity for additional wetland rehabilitation.

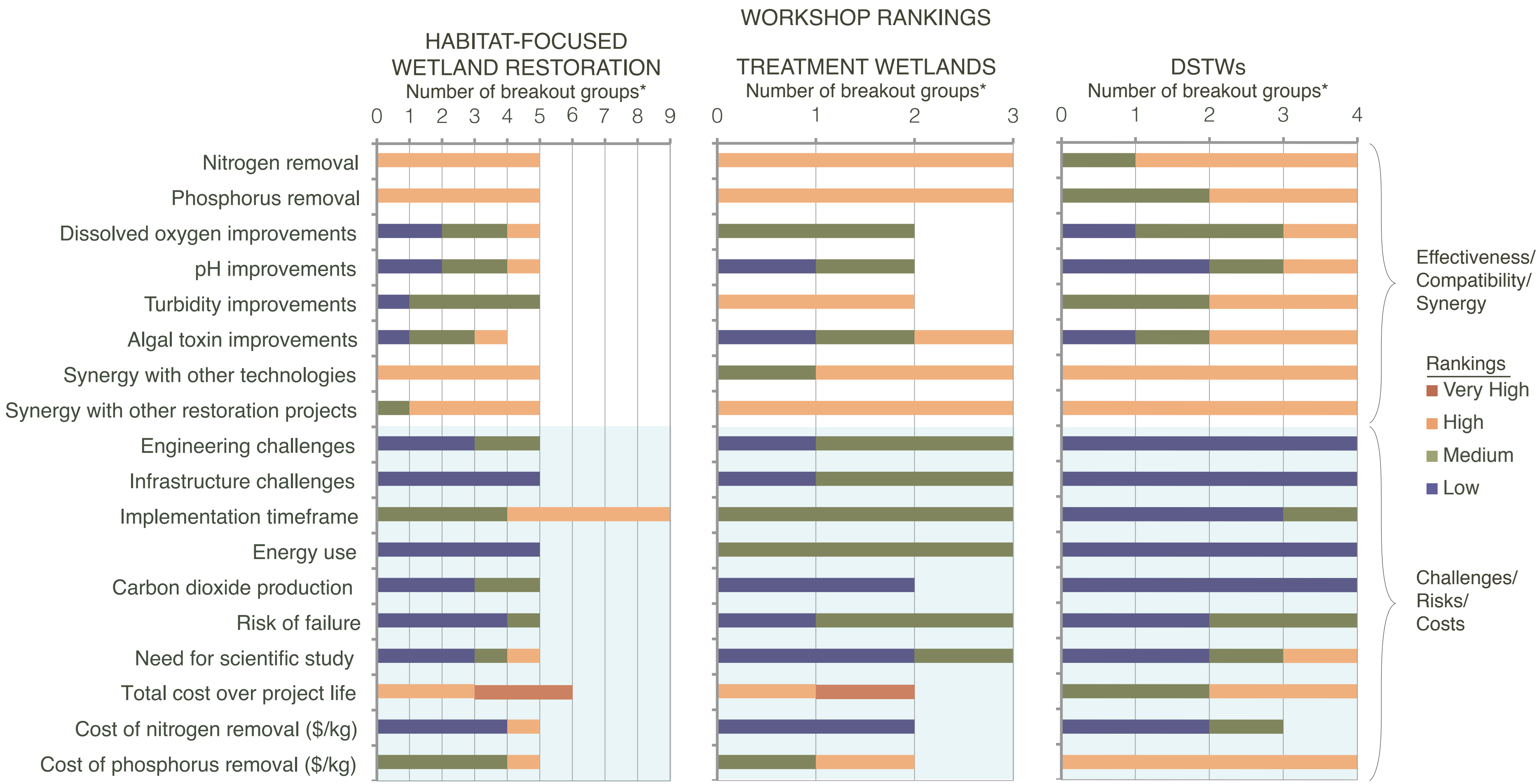
Workshop attendees ranked the potential for improvements in other water quality parameters such as dissolved oxygen, pH, turbidity and algal toxins. Rankings ranged from low to high, depending on how and where wetlands are built. Total costs for large-scale habitat and treatment wetland projects were ranked from high to very high based on land acquisition and operation and maintenance costs, whereas costs for diffuse source (decentralized) treatment wetlands were ranked as low (Figures 2.9-2.11).

TABLE 2.2 - WETLAND REHABILITATION COST ESTIMATES CONSIDERED BY WORKSHOP PARTICIPANTS[6]

	HABITAT/WATER STORAGE WETLAND	TREATMENT WETLAND	DIFFUSE SOURCE TREATMENT WETLAND
Acreage	3,200	1,600	5-10 acres
Project life	50 yrs	50 yrs	15 yrs
Project cost	$30M - $150M	$17M	$30K-$50K
Nitrogen removal ($ per kg TN)	$1 - $15	$10 - $48	$2-$3
Phosphorus removal ($ per kg TP)	$30 - $500	$47 - $162	$84-$103

5 Detailed documentation of the workshop evaluations, including the quantitative ranges used for the high, medium, and low rankings for project evaluation criteria, is presented in the workshop notes (Appendix A).

6 Assumptions for cost estimates presented at the workshop are detailed in Stillwater Sciences et al. (2012).



*The number of workshop breakout groups that ranked each pollutant reduction technique varies. Some groups ranked three techniques in the time allotted for the exercise, while other groups ranked just one or two techniques. Some groups used all of the suggested criteria in their rankings, while other groups did not.

Fig. 2.9 Workshop breakout group ranking: Wetland restoration with a habitat focus.

Fig. 2.10 Workshop breakout group ranking: Treatment wetlands (water quality focus).

Fig. 2.11 Workshop breakout group ranking: DSTWs.

ALGAL FILTRATION

GOALS AND CAPABILITIES

When algae die, organic material contained within individual cells is broken down rapidly by bacteria in the water column and sediments, using up available oxygen needed by fish and aquatic invertebrates. Algal decomposition releases a pulse of nutrients which can fuel subsequent blooms. Removal of algal cells from water bodies before they die and decompose would reduce the potential for this undesirable oxygen demand and decrease the concentration of nitrogen and phosphorus in the water column. Filtration physically removes algal biomass from the water column, for example, by capturing live cells on screens that are pulled through the water column. While nutrients can still be present in lake sediments and waters flowing into the system, the continued filtration of algal biomass from the water column is a direct approach to decreasing oxygen demand and nutrients in the system. Further, removal of toxin-producing blue-green algae such as *Microcystis aeruginosa* reduces a potential source of cyanotoxins.

BASIC DESIGN ELEMENTS

Several design elements are common to algal filtration options:

- Targeting of areas with concentrated algal blooms (i.e., “hot spots”)
- Specified filter size for capturing multiple species of algae
- Barriers to prevent accidental capture of endangered aquatic species or debris during filtration

Fig. 2.12 Aerial view of a land-based screen filtration operation. Photo: Google Earth.

- Mitigation of algal toxin release during filtration
- Dewatering of algal biomass
- Storage and transportation of biomass, followed by utilization and/or disposal

SIMILAR APPLICATIONS

Land-based and barge-based screen filtration have been used by private industry on or near Upper Klamath Lake to harvest *Aphanizomenon flos aquae* for refinement and sale as a human dietary supplement. Currently, private industry harvesting is conducted only intermittently using barges, when conditions are optimal to produce a near monoculture of algae that minimizes undesirable species. Increased utilization of these existing assets may provide a cost-effective opportunity. Expansion of land-based and barge-based screen filtration to include all forms of algae for a variety of uses (see text box) would presumably increase the amount of time spent harvesting and the associated nutrient removal and improvements to water quality and support of beneficial uses.

USES FOR ALGAL BIOMASS

Techniques that remove both algal biomass and the associated nutrients include land-based filtration, land-based separation, and in-lake techniques. Once removed from the water, algal material may be available for other uses such as:

- Dietary supplement (human or animal)[7]
- Biofuels production (biodiesel, methane, or combustion for electricity)
- Soil amendment (may need to be tested for algal toxins prior to soil application)
- Composting/landfill

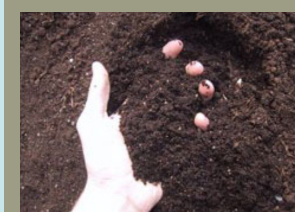


Fig. 2.13 (Above) Algal material used as a soil amendment. Photo: University of Idaho.

Fig. 2.14 (Above left) Blue-green algae converted into biofuel. Photo: matternetwork.com.

Fig. 2.15 (Above right) Blue-green algae dried for use as a dietary supplement. Photo: purebulk.com.

7 N. Simon, USGS, personal communication, May 2013.

WORKSHOP EVALUATION[8]

Algal biomass filtration was ranked by workshop attendees as being generally effective at nitrogen and phosphorus removal, having a high degree of synergy with other restoration projects and techniques being considered in the Klamath Basin, and exhibiting a low degree of engineering challenges and costs associated with nitrogen removal. Workshop attendee evaluations were mixed regarding potential improvements to other water quality parameters such as dissolved oxygen, pH, turbidity, and algal toxins, ranging from low to high depending on whether barge-based or land-based filtration was used and to what degree filtration could remove large amounts of biomass from the lake (Figure 2.16). Some groups expressed a need for further scientific studies regarding the amount of algal removal required in Upper Klamath Lake to positively affect water quality, disposal or reuse options for toxin-producing algae, and potential impacts to suckers due to screens and filtration equipment.

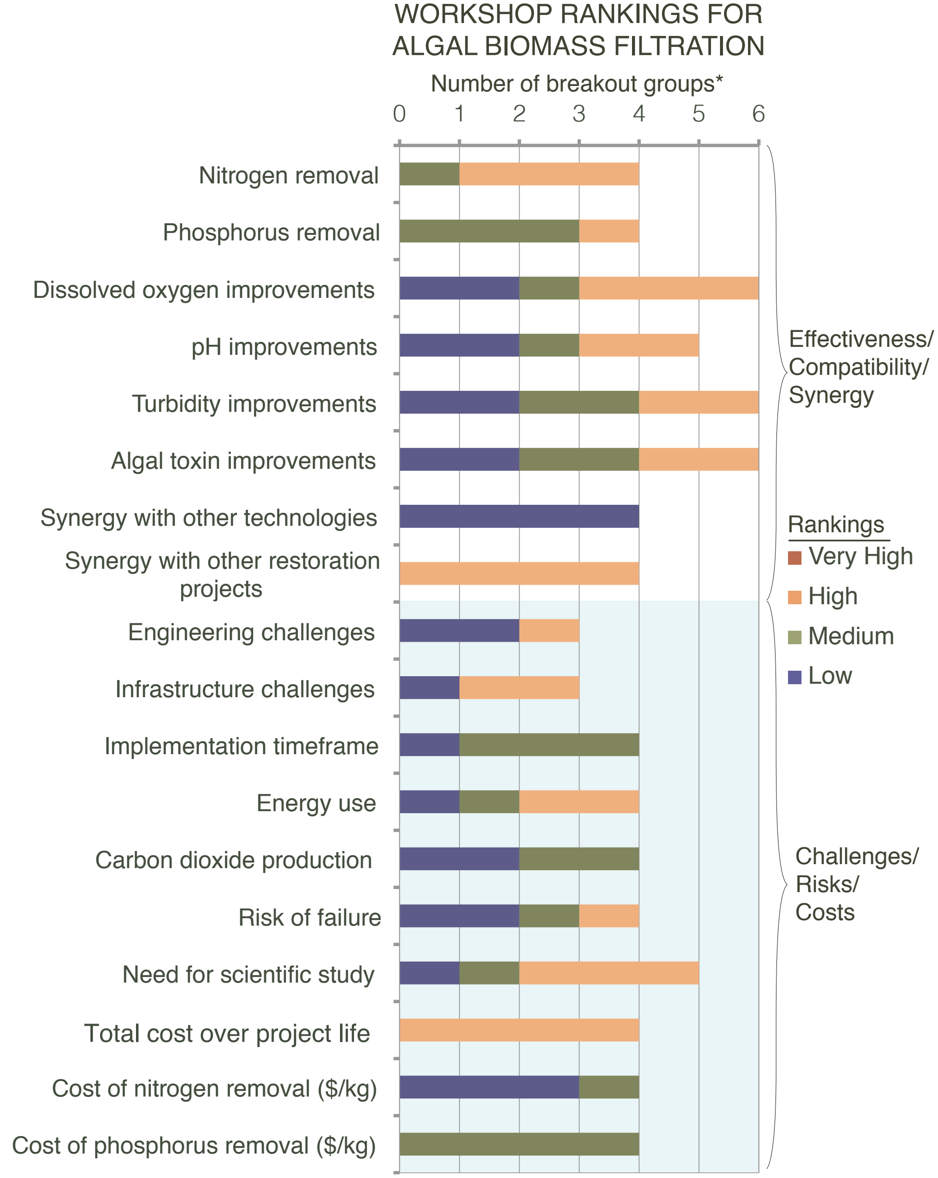
The total cost for barge-based algal biomass filtration was rated as high due to estimated maintenance, fuel, and personnel costs over the lifetime of the barge. Cost estimates were not available at the workshop for land-based algal biomass filtration.

TABLE 2.3 - BARGE-BASED ALGAL FILTRATION COST ESTIMATES CONSIDERED BY WORKSHOP PARTICIPANTS[9]

Size	1 Barge
Project life	10 yrs
Project cost	$3.7M
Nitrogen removal ($ per kg TN)	$7
Phosphorus removal ($ per kg TP)	$53

8 Detailed documentation of the workshop evaluations, including the quantitative ranges used for the high, medium, and low rankings for project evaluation criteria, is presented in the workshop notes (Appendix A).

9 Assumptions for cost estimates presented at the workshop are detailed in Stillwater Sciences et al. (2012).



*The number of workshop breakout groups that ranked each pollutant reduction technique varies. Some groups ranked three techniques in the time allotted for the exercise, while other groups ranked just one or two techniques. Some groups used all of the suggested criteria in their rankings, while other groups did not.

Fig. 2.16 Workshop breakout group ranking: Algal biomass filtration.

ALGAL FILTRATION PILOT PROJECT

There is currently momentum for implementing a pilot project for algal filtration in Upper Klamath Lake and/or the Keno Impoundment (see also Figures 2.27 and 2.28 on page 32). At least one project is in the planning stage and others may be developed. The USGS recently developed a water quality model for the "Link to Keno reach" of the Klamath River and used the model to simulate the downstream effects of removing varying amounts (25%, 50% and 90%) of blue-green algae and particulate organic matter at Link River Dam near the outlet of Upper Klamath Lake. The results indicate that the greater the amount of particulate material removed, the greater the resulting improvement in riverine dissolved oxygen concentrations. To improve dissolved oxygen in the river enough to meet water quality standards and thereby help support fish during the summer season, an extremely large percentage (approximately 90%) of blue-green algae and particulate organic matter would have to be removed.[10] Determination of whether or not existing land- and barge-based algal harvest techniques could achieve removal of such large quantities of biomass is currently limited by knowledge gaps in harvest efficiency and the basic properties of harvested biomass.

Fig. 2.17 Link River Dam. Source: Google Earth.

10 Sullivan et al. 2013

Further, given that development of viable re-use and disposal options for such large quantities of algal biomass is still ongoing, this technique has not been selected for development of a conceptual design for this report. However, this decision is not a reflection of disinterest in the technique at other scales, since algal filtration has the potential to focus treatment where and when water quality is a concern, to re-use algal material for a beneficial purpose, and to directly reduce the source of oxygen demand and particulate nutrients in the Keno Impoundment. Continued development of re-use options along with knowledge gained during proof-of-concept projects may allow this technique to be considered for future large-scale application. It would be particularly informative if the proof-of-concept project(s) addressed the following basic questions regarding algal filtration in Upper Klamath Lake and/or the Keno Impoundment:

What is a realistic/achievable mass of algae removed (wet weight) per area screen per harvest operation time (i.e., lbs wet algae/square feet/hr)?

Is there a standard conversion between wet weight and dry weight for biomass, total nitrogen (TN), and total phosphorus (TP) content? Does the conversion vary based on operating procedures like screening properties or the algal de-watering approach?

What permits would be required to implement the various types of algal removal systems under consideration?

Are there post-processing constraints on use or disposal of algal biomass?

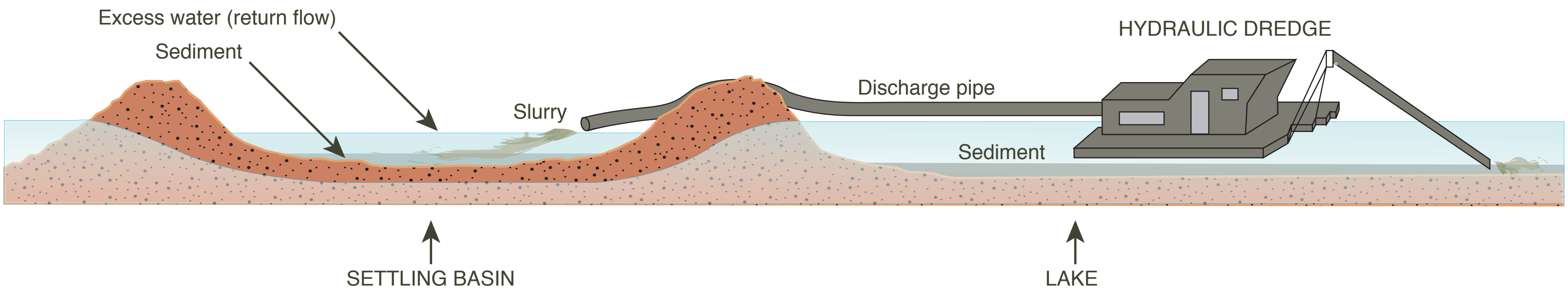


Fig. 2.18 Sediment is removed from the water and deposited in a settling basin. Once the sediment settles in the basin, excess water can be returned to the waterbody.

SEDIMENT REMOVAL (DREDGING)

GOALS AND CAPABILITIES

Dredging is the physical removal of accumulated sediments from lakes or other waterbodies in order to improve water quality, recreation, and navigation, or support other uses. Dredging can improve water quality by directly removing pollutants, nutrient-rich sediments and decomposing organic plant matter, from a lake or waterway. An entire lake bottom can be dredged or specific zones can be targeted where dredging may be most beneficial, such as areas with the thickest sediment layer or greatest concentration of pollutants.

There are two primary methods used for lake dredging: mechanical dredging and hydraulic (i.e., suction) dredging. Mechanical dredging can be either "dry" or "wet" and involves earthmoving equipment, such as bulldozers, scrapers, backhoes, draglines, and/or grab buckets to scoop sediment and transport it to a disposal site. Hydraulic dredging is a "wet" method and is the preferred method for dredging lake sediments, because it is faster than mechanical dredging, creates less turbidity in the surrounding water and can effectively remove loose, watery sediments.

Once removed, sediments are dewatered for re-use or disposed in a variety of ways based on their physical and chemical characteristics. Sediments can be re-used as agricultural soil amendments, as fill and/or subsidence reversal for planned projects or, they can be landfilled if contaminated.

BASIC DESIGN ELEMENTS

Once the area to be dredged has been identified, the appropriate dredging methodology, the fate of the dredged material (i.e., re-use or disposal), and transportation requirements must be considered. Sediment composition, contaminant levels, and possible presence of debris that could interfere with dredge machinery also need to be investigated. Hydraulic dredging requires dewatering of the sediment and water mixture or "slurry", often accomplished by piping the slurry to a settling basin (Figure 2.18). Sediments settle from the water column in the settling basin, so design of this feature requires determination of the sediment settling rate. In some cases excess water from the sediment slurry can be removed prior to being transported to the settling basin, which significantly decreases the amount of land area required for settling. After settling (and treatment, in some cases), the water can be pumped back into the lake and the sediments left in the basin to dry. An alternative to settling basins is geotextile tubes. The slurry is pumped through the tubes, allowing the filtered water to drain through the tubes' openings and the sediment to dry within. Geotextile tubes require a lined dewatering area, similar to settling basins.

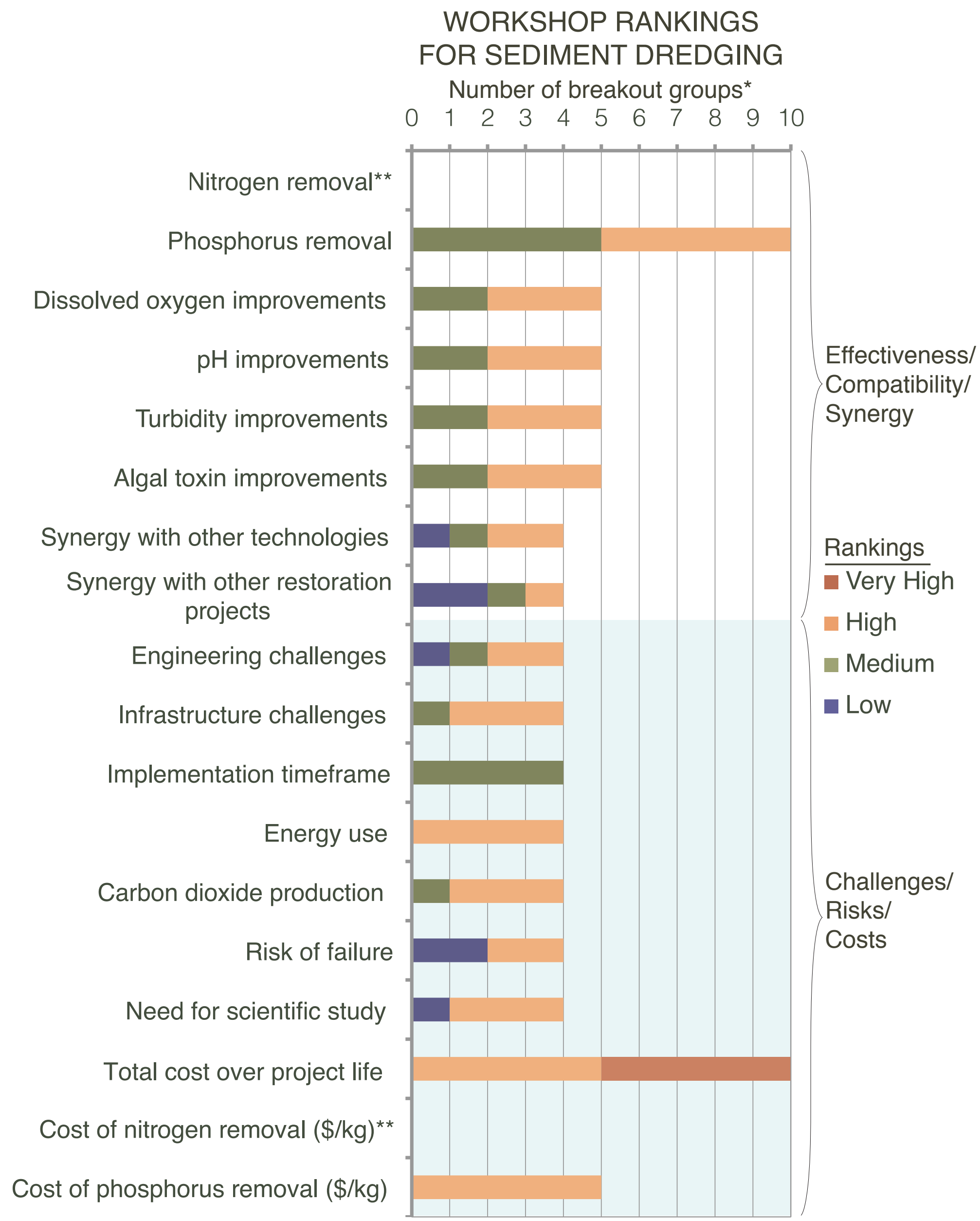
There are potential ecological and environmental impacts associated with dredging, including effects such as accidental capture or mortality and temporarily impaired water quality. Impacts to sensitive aquatic species can be avoided by selecting a dredge type that reduces or avoids their accidental capture and/or temporarily relocating less mobile organisms during dredging. Impacts to organisms and aquatic vegetation that live in or on the dredged sediments are unavoidable; however, polluted sediments often do not provide suitable habitat for desired species, and nearby organisms typically recolonize the dredged area following operations. While adult fish generally avoid areas where dredging is taking place, dredging operations should be designed to avoid certain windows of time when fish are performing critical life history functions such as spawning. Temporary water quality impacts can be lessened by using equipment that includes turbidity barriers like silt curtains and selectively targets specific sediment layers. Noise and other disturbances to wildlife are unavoidable, but are temporary in nature.

WORKSHOP EVALUATION[11]

Dredging was ranked by workshop attendees as being generally effective at phosphorus removal and supporting medium to high levels of improvements to other water quality parameters such as dissolved oxygen, pH, turbidity, and algal toxins (Figure 2.19). Evaluations of synergy with other restoration projects and techniques being considered in the Klamath Basin were mixed, ranging from low to high. The same was true of potential engineering and infrastructure challenges, with rankings ranging from low to high depending on re-use and disposal options. Energy use and CO_2 loading, although directly linked in the case of dredging, were ranked somewhat differently from one another, ranking as high for energy use, and medium to high for CO_2 loading. Some groups expressed a need for further scientific studies related to re-use and disposal, as well as long-term effectiveness related to control of nutrient sources from the surrounding watershed.

The total cost for dredging was rated as high to very high based on typical dredging costs of $5–15/yd^3 applied to the entire Upper Klamath Lake and that of the Keno Impoundment at a dredging depth of approximately 30 centimeters. However, it was generally acknowledged that identification of phosphorus hotspots and targeted dredging would be considerably more cost effective for these two water bodies in the Upper Klamath Basin.

11 Detailed documentation of the workshop evaluations, including the quantitative ranges used for the high, medium, and low rankings for project evaluation criteria, is presented in the workshop notes (Appendix A).



*The number of workshop breakout groups that ranked each pollutant reduction technique varies. Some groups ranked three techniques in the time allotted for the exercise, while other groups ranked just one or two techniques. Some groups used all of the suggested criteria in their rankings, while other groups did not.

**Nitrogen is not typically associated with sediments, so dredging was not evaluated using nitrogen removal criteria.

Fig. 2.19 Workshop breakout group ranking: Sediment removal (dredging).

SIMILAR APPLICATIONS

There have been numerous lake hydraulic dredging operations in recent years in the United States and Canada that are potentially applicable to conditions in Upper Klamath Lake. For example, Lake Trafford, a shallow, 1,600-acre lake in Immokalee, Florida, was dredged to remove muck that had accumulated as a result of high nutrient inputs and decomposing exotic plant material. Dredging was implemented in three phases in 2006, 2007 and 2010 using a hydraulic dredge to remove sediments from the central deeper part of the lake and the shallow littoral zone around the lake's edges. A total of 6.3 million cubic yards of sediment were removed and pumped to a disposal facility one mile north of the lake. In 2002, a pilot dredging project was conducted for Lake Okeechobee, a large 467,200-acre lake in south-central Florida, to determine the feasibility of removing over 261 million cubic yards of nutrient-laden sediments. Hydraulic dredging was used to successfully remove sediment slurry using an innovative approach of isolated "lanes" of dredging to minimize sediment re-suspension. Approximately 6,000 cubic yards of dredge material were relocated to a disposal facility along the shore of the lake and treated to remove phosphorus.

Past lake dredging projects have provided valuable lessons for prospective projects including the following:

- Pilot dredging operations are critical for maximizing success of full-scale projects.
- Equal or greater benefits may be obtained at a lower cost by targeting areas where pollutants are greatest.
- Control of external nutrient sources is needed to fully address impacts.
- Well-planned operation and maintenance (O&M) activities after dredging will ensure long-term benefits.

Fig. 2.20 Lake Trafford dredged sediment settling area. Photo: Atkins.

Fig. 2.21 Lake Panosofkee dredged sediment settling area. Photo: Atkins.

Fig. 2.22 A typical hydraulic dredging operation. Photo: www.naplesnews.com.

TABLE 2.4 - COST ESTIMATES FOR DREDGING OF THE ENTIRE UPPER KLAMATH LAKE, AS CONSIDERED BY WORKSHOP PARTICIPANTS[12]

Size	30.5 M/yd^3
Project life	5 yrs[13]
Project cost	$460 M
Nitrogen removal ($ per kg TN)	Not applicable
Phosphorus removal ($ per kg TP)	$330

SEDIMENT SEQUESTRATION OF PHOSPHORUS AND AERATION/ OXYGENATION

As water quality management tools, sediment sequestration of phosphorus and aeration/ oxygenation of the water column share common or complementary goals and are often used

12 Assumptions for cost estimates presented at the workshop are detailed in Stillwater Sciences et al. (2012).

13 Based on a dredge rate of 6.6 million cy/year, assuming dredge is operating 24 hours per day, 7 days per week, with a 15% downtime (from Lake Okeechobee, Florida, Pilot Dredging Project Report). This estimate is for dredging time only and does not include time for construction of settling basin/dewatering area, water treatment, etc.

in combination. At the workshop, sediment sequestration was considered for Upper Klamath Lake, and sediment sequestration with aeration/ oxygenation was considered for the Keno Impoundment.

GOALS AND CAPABILITIES

Sediment Sequestration Using Alum

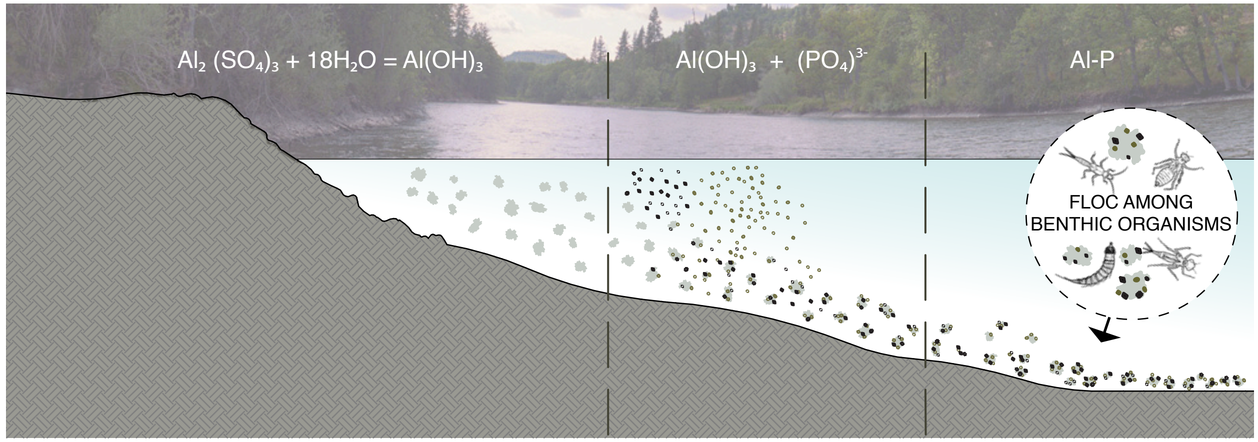


Fig. 2.23 Process of sediment phosphorus sequestration (inactivation) using alum.

Alum is a chemical compound containing aluminum and sulfate that when added to water forms a semi-solid matrix commonly referred to as “floc”. Alum floc is made up of aluminum hydroxide, which is heavier than water and sinks through the water column, collecting phosphorus as it settles (Figure 2.23). The settled material sinks into the existing sediments where the phosphorus remains bound over time. This process does not form a sediment cap and is not a biological barrier; benthic organisms live amongst the floc particles as they would other sediments.

One of the advantages of alum application is that phosphorus remains bound in the floc even during seasonal periods of low dissolved oxygen in the sediments and/or water column when phosphorus would otherwise be released and support algae growth. The main precaution associated with alum use is the presence of free aluminum at low pH (< 6.0), which can be toxic to aquatic life (see text box on page 28). To maintain the appropriate pH, alum treatments must be chemically buffered. This is common practice for environmental alum applications and would also be relevant for the relatively low alkalinity waters of the Klamath Basin.

Treatment effectiveness and longevity of sediment phosphorus inactivation using alum was evaluated in 21 lakes in 1999.[14] Reduction in sediment phosphorus release rate (internal loading) initially averaged about 70 to 85% depending on whether the lake water column was well mixed during summer months. Summer total phosphorus concentration in the water was reduced by about 50% in all lakes, and chlorophyll and cyanobacteria decreased similarly. The longevity of treatments varies, but typically about 10 years can be expected in lake systems with effectiveness waning over time as the alum floc layer sinks and new sediment with un-bound phosphorus settles and covers the alum layer.

Alum is the most widely used technique to inactivate sediment phosphorus and reduce internal phosphorus loading in lakes. There were 150 recorded alum treatments to lakes by 2005 and most of these occurred in the United States.[15] There have been many more since and many more have presumably gone unrecorded. Alum is also used to remove phosphorus from wastewater and suspended solids from drinking water. Alum treatments have increased over the past four decades, such that the procedure is now considered to be routine and one of the most commonly used methods of lake treatment. Monitoring of pH and dissolved oxygen at frequent intervals following application has indicated that these constituents remain in ranges safe to aquatic life and aluminum does not occur in its toxic form. Therefore, there is widespread consensus among lake scientists that alum is effective and safe at sequestering and inactivating phosphorus.[16]

14 Cooke et al. 2005
15 Welch and Gibbons 2005
16 Osgood et al. 2011

POTENTIAL FOR ALUM TOXICITY

Aluminum is one of the most abundant elements on earth. It is constantly solubilized from soil and bedrock through weathering. Some inorganic forms of aluminum can be toxic to aquatic animals at high and low pH; however, the insoluble and non-toxic form of aluminum prevails in the environment under typical conditions, where calcium and magnesium are also naturally weathered and produce alkalinity and pH ranges in waters (pH 6-8) that render aluminum non-toxic.

While early laboratory tests of alum treatment demonstrated toxic effects at aluminum concentrations from 1 to a few milligrams per liter and pH near 7, [17] these tests were performed without dissolved natural organic matter, which would be present in eutrophic waters and would chemically bind with aluminum making it unavailable to biota. Buffered alum treatments ranging from 5 to 26 milligrams per liter, in which fish and aquatic life were studied before and after treatment, have shown very few negative, and usually positive effects, to aquatic biota.[18] This is due to the following:

- Residual free aluminum concentrations remaining in the water column are relatively low (0.1–0.2 milligrams per liter).
- pH remains above 6, due to chemical buffering.
- Only a fraction of a given waterbody is treated each day allowing avoidance of the immediately treated area by fish and other non-benthic aquatic species.
- Any residual free aluminum is likely to be chemically complexed with dissolved organic matter, which is abundant in eutrophic lakes, rendering the aluminum non-bioavailable and non-toxic.

None of the studied alum treatments resulted in fish kills. Effects on benthic animals were usually beneficial, increasing diversity and abundance, because oxygen levels increased as a result of lower phosphorus and algal-produced oxygen demand. A thorough review of alum effects on the treated aquatic environment is given in Cooke et al. (2005).

Fig. 2.24 Alum treatment, Fremont Lake, Dodge County Nebraska. Photo: Hab Aquatics.

17 USEPA 1988
18 Pilgrim, K.M. and P.L. Brezonik 2005

Alum has been directly injected into inflows to lakes or into stormwater retention ponds on a continual basis in several states. Injecting alum through an aeration system, creating a continuous micro-alum floc during certain times of the year, can be more effective at distributing alum to sediments throughout the lake while simultaneously inactivating phosphorus in the water column carried into the lake from external sources.

Basic Design Elements

Basic design elements for phosphorus sequestration using alum include the following:

- Size of water body to treat
- Alum dose required (typically 50-100 grams of alum per square meter of lake surface area)
- Application strategy
- Logistical constraints posed by alum volume required and proximity to supply
- Availability/location of application staging area

Aeration/Oxygenation of Sediments and Water Column

Aeration/oxygenation techniques have also been widely applied to lakes and reservoirs throughout the world for over sixty years. Cooke et al. (2005) lists 51 cases of artificial circulation that were studied, mostly in the 1960s and 1970s, and 28 of hypolimnetic aeration in the 1970s to 1990s. However, most aeration applications have gone unreported in the peer reviewed literature.

There are two principal techniques used to increase dissolved oxygen in lakes and reservoirs; 1) complete circulation that mixes dissolved oxygen throughout

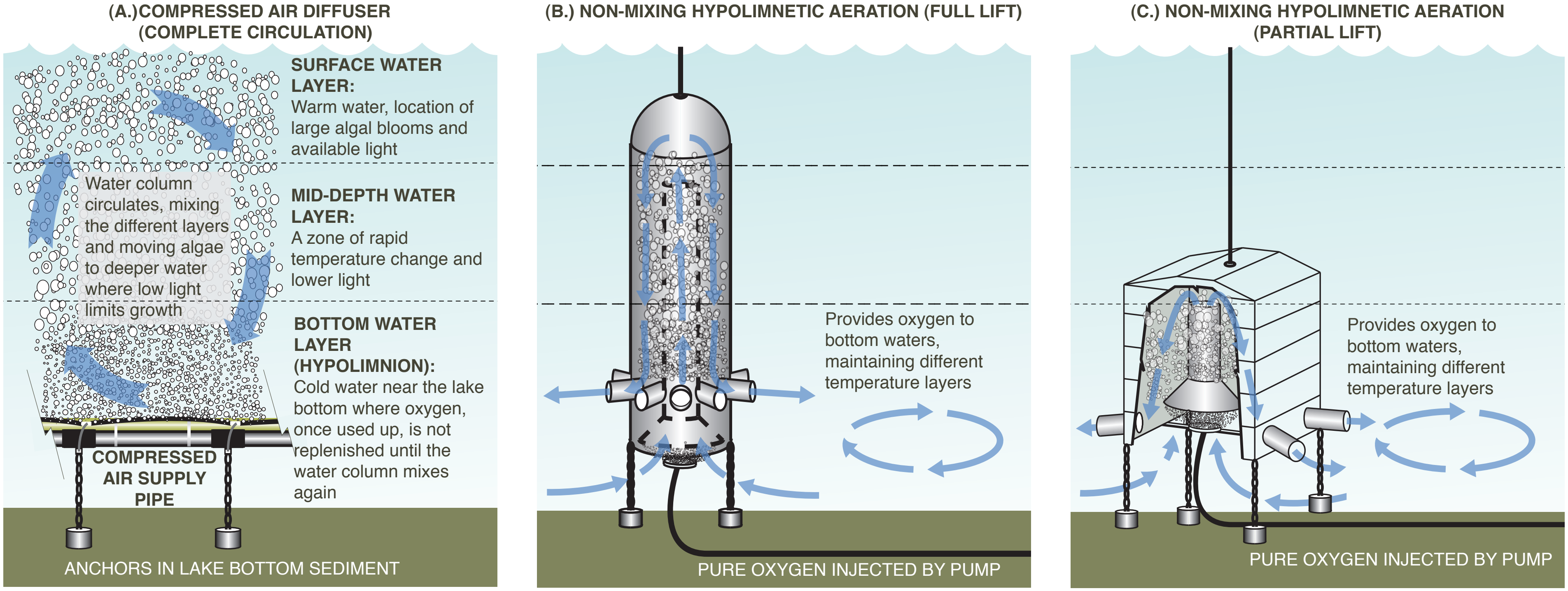


Fig. 2.25 Aeration schematics for complete circulation (A) and non-mixing hypolimnetic aeration (B and C).

the water body, and 2) aeration/oxygenation of a portion of the lake, typically the bottom waters, but can also be a longitudinal segment of the water body.[19]

The most frequently used aeration technique in lakes and reservoirs is the addition of compressed air through diffuser hoses placed along the bottom sediments (Figure 2.25 A). The resulting plume of air bubbles rises through the water column causing the water to circulate throughout the lake. Oxygenation occurs when the rising water mass is exposed to oxygen in the atmosphere. If air flow rates are sufficient, complete circulation can reduce algae by moving them out of the surface waters where light is plentiful and into deeper waters where low light limits growth. For blue green algae, this is particularly important because normally these algae optimize their position in the water column allowing them to outcompete other algae species. Circulation has also been successfully achieved with pumps or jets.

Hypolimnetic aeration/oxygenation can provide oxygen to bottom waters while maintaining cool-water habitat for fish and a daily refuge from predation for zooplankton. Hypolimnetic aeration/oxygenation is achieved through either full or partial air lift units (Figure 2.25 B and C), by injecting pure oxygen at depth with a pump, or by injecting oxygen into water pumped through a down-flow bubble contact system. Also, hypolimnetic water can be pumped to the surface, where it obtains air bubbles, and is then pumped back to the hypolimnion. Naturally oxygenated epilimnetic water can also be pumped into the hypolimnion to provide the needed oxygen.

Internal phosphorus loading from anoxic sediments is typically reduced (see also Figure 1.18, page 9) with oxygenation if sufficient iron is available to bind with the phosphorus.

Basic Design Elements

Basic design elements for water column aeration/oxygenation include the following:

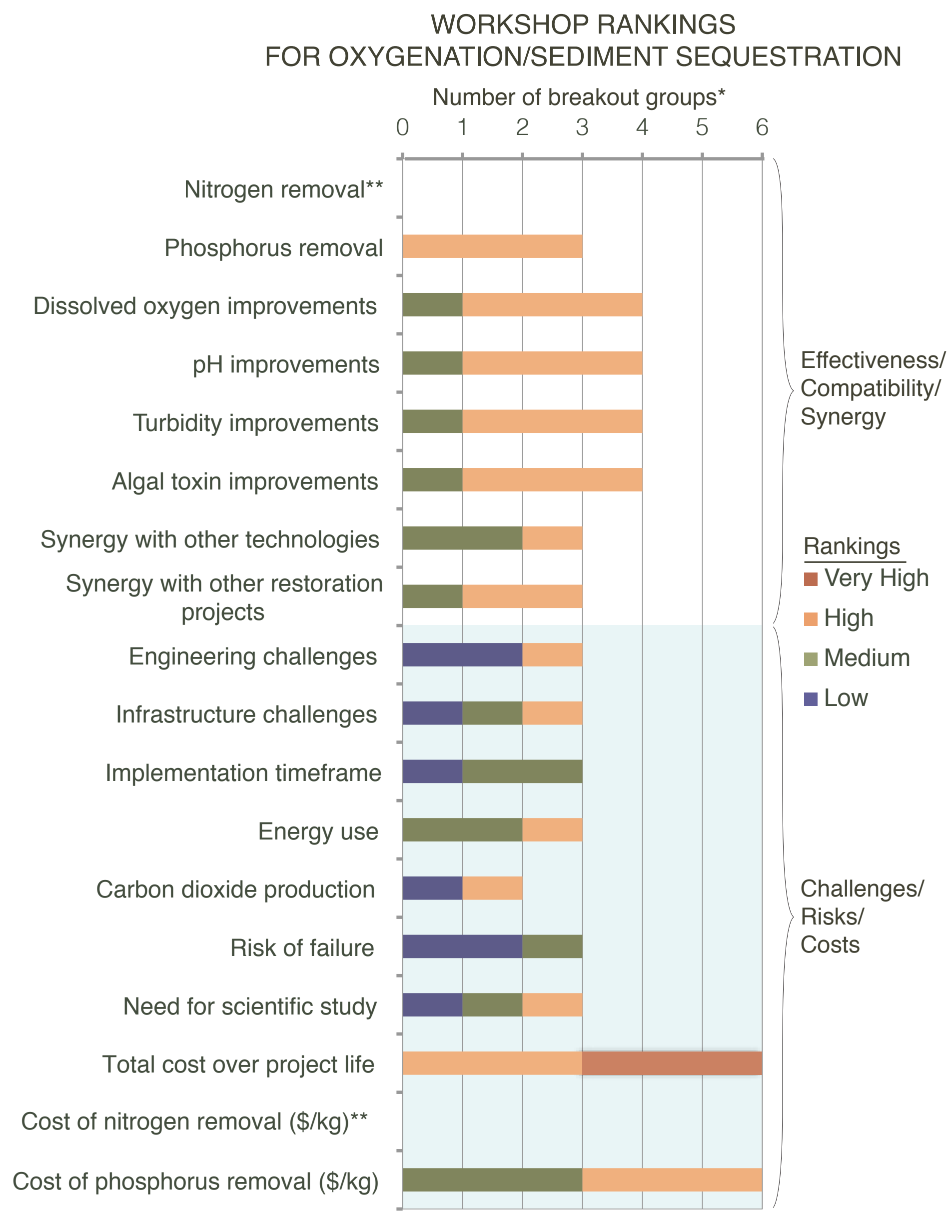
19 Cooke et al. 2005

- Compressed air capacity for complete circulation method
- Dissolved oxygen demand within the sediments and water column for hypolimnetic aeration/oxygenation
- Hose length and pore size for air transport
- Dissolved oxygen demand for hypolimnetic aeration/oxygenation and air/oxygen needed to exceed that rate
- Choice of air/oxygen injection device

WORKSHOP EVALUATION[20]

Sediment sequestration of phosphorus using alum and aeration/oxygenation appeared to be the least familiar technique to many workshop attendees, potentially affecting perceptions of implementation challenges. Despite this, these techniques were ranked by workshop attendees as being generally effective at phosphorus removal and supporting medium to high levels of improvements to other water quality parameters such as dissolved oxygen, pH, turbidity, and algal toxins. Workshop attendees felt that these techniques possess a medium to high degree of synergy with other restoration projects and techniques being considered in the Klamath Basin. The evaluations of potential engineering and infrastructure challenges were mixed, ranging from low to high depending on whether whole-lake dosing options were used or treatment was limited to portions of the Keno Impoundment. As with dredging, the energy use ranking ranged from medium to high and from low to high for CO_2 loading. Workshop attendees generally expressed a need for further scientific studies related to potential toxicity and efficacy of alum in the low alkalinity and seasonally

20 Detailed documentation of the workshop evaluations, including the quantitative ranges used for the high, medium, and low rankings for project evaluation criteria, is presented in the workshop notes (Appendix A).



*The number of workshop breakout groups that ranked each pollutant reduction technique varies. Some groups ranked three techniques in the time allotted for the exercise, while other groups ranked just one or two techniques. Some groups used all of the suggested criteria in their rankings, while other groups did not.

**Nitrogen is not typically treated using oxygenation/sediment sequestration, so nitrogen removal criteria were not applied.

Fig. 2.26 Workshop breakout group ranking: Oxygenation/ sediment sequestration.

TABLE 2.5 - COST ESTIMATES CONSIDERED BY WORKSHOP PARTICIPANTS[21]

	SEDIMENT SEQUESTRATION USING ALUM FOR THE ENTIRE UPPER KLAMATH LAKE	ALUM INJECTION/ OXYGENATION FOR KENO IMPOUNDMENT
Size	66,000 acres	790 MGD
Project life	8-15 years	20 yrs
Project cost	$180 M	$86 M
Nitrogen removal ($ per kg TN)	Not applicable	Not applicable
Phosphorus removal ($ per kg TP)	$260	$48

21 Assumptions for cost estimates presented at the workshop are detailed in Stillwater Sciences et al. (2012).

high pH waters of the Upper Klamath Basin, with particular concern regarding potential short-term and long-term effects of alum floc on sediment-dwelling organisms and protected fisheries.

The total cost for these linked techniques was rated as high for a combined oxygenation and alum treatment in the Keno Impoundment to very high for a whole-lake treatment of Upper Klamath Lake. However, it was generally acknowledged that whole-lake treatment for a lake as large as Upper Klamath Lake is not feasible. Instead, treatment of the Keno Impoundment, where dissolved oxygen is very low during summer months, could be a useful approach in the short-term.

SUMMARY OF WATER QUALITY IMPROVEMENT TECHNIQUES EVALUATED AT THE WORKSHOP

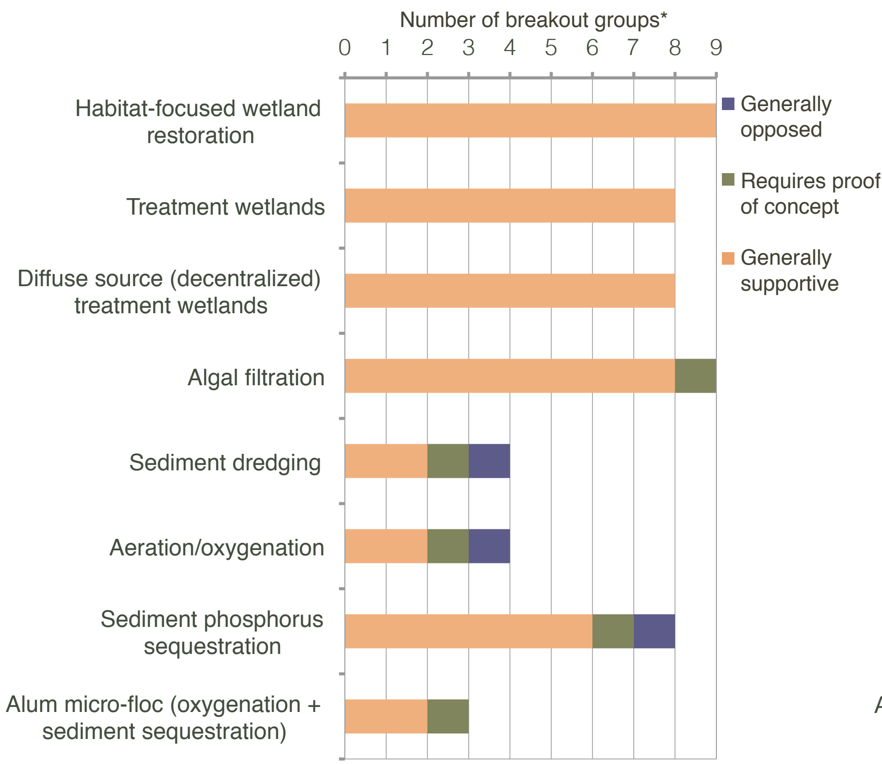
Workshop participants were generally supportive of algal filtration and wetland rehabilitation, the latter including habitat-focused wetlands, treatment wetlands, and diffuse source (decentralized) treatment wetlands (Figure 2.27). Participants recognized that these water quality improvement strategies provided substantial nutrient reduction benefits at a relatively low cost and were generally compatible with other techniques and restoration projects being considered in the Klamath Basin. Participants were supportive of all three wetland project types due to their capacity to treat the *source* of water quality problems (i.e., excessive phosphorus and nitrogen loading) rather than just the *symptoms* (i.e., algal blooms, low dissolved oxygen, high pH). Wetlands also provide wildlife habitat, use low amounts of energy, are sustainable in the long-term, and offset climate change effects through uptake of carbon dioxide (Figures 2.9 through 2.11, Table 2.6).

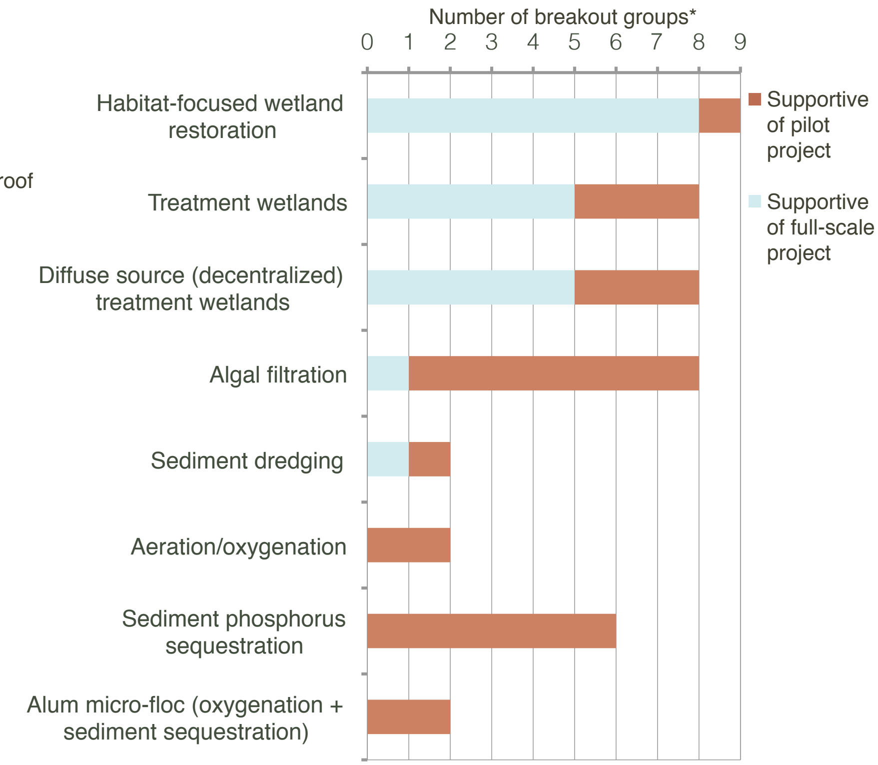
Workshop participants were also intrigued by algal filtration because of the spatial and temporal responsiveness and the economic potential as a potential by-product of this technique. While algal filtration only treats the *symptoms* of water quality problems, this strategy provides the opportunity to focus treatment where and when water quality is a concern and to re-use algal material for a beneficial purpose. Algal filtration was also recognized as a way to directly address both dissolved oxygen and nutrient concerns in the Keno Impoundment by removing the source of oxygen demand and particulate nutrients (i.e., decomposing algal biomass) (Figure 2.16, Table 2.6). Two breakout groups felt that proof of concept is needed before algal filtration could be further considered as a large-scale water quality improvement technique in the Upper Klamath Basin (see text box on page 23).

Sediment dredging, aeration/oxygenation, and sediment phosphorus sequestration were generally supported by several breakout groups, but each received one generally opposed ranking (Figures 2.19 and 2.26). For each approach, at least one breakout group felt that proof of concept is needed before the approach could be further considered for use in large-scale water quality treatment in the Upper Klamath Basin (Figure 2.27). Even though these strategies were recognized for their potential to provide substantial water quality benefits at a time scale shorter than that of wetlands, all were discounted for focusing on a single symptom of water quality problems rather than multiple symptoms and/or the sources of the problems. Sediment dredging and sediment phosphorus sequestration were further scrutinized for potential effects to bottom-dwelling organisms and high carbon dioxide production related to high energy use. When combined with oxygenation, using an alum micro-floc injection, sediment phosphorus sequestration was generally supported by three breakout groups (Figure 2.27) for use in the Keno Impoundment because this approach would add dissolved oxygen to the water column while keeping phosphorus from being released by reservoir sediments. One breakout group required proof of concept for this approach. The need for further understanding and scientific studies related to potential toxicity and efficacy of alum use in Upper Klamath Basin waters was identified by multiple breakout groups.

Further breakdown of the generally supportive rankings is shown in Figure 2.28. Approximately two-thirds of the wetland rankings supported full-scale implementation of all three types of wetlands, with roughly one-third supporting pilot projects first. The

WORKSHOP BREAKOUT GROUP OVERALL RANKING





*The number of workshop breakout groups that ranked each pollutant reduction technique varies. Some groups ranked three techniques in the time allotted for the exercise, while other groups ranked just one or two techniques.

Fig. 2.27 (Above left) Workshop breakout group overall ranking: Generally opposed, generally supportive, and requiring proof of concept.

Fig. 2.28 (Above right) Workshop breakout group overall ranking: Of the groups supportive of a project type, those supportive of full scale implementation and those supportive of pilot scale implementation.

preference for wetland pilot studies was based on uncertainties with respect to water rights, variable water quality improvements depending on location, potential for invasive species management problems, and the potential for bioaccumulation of contaminants such as mercury. Pilot studies were supported for algal filtration, where the pilot efforts would quantify the amount of algae removal required in Upper Klamath Lake to improve water quality, the potential capacity of removal operations, disposal or reuse options for toxin-producing algae, and potential impacts to suckers from screens and filtration equipment. Pilot studies were recommended for sediment dredging, sediment phosphorus sequestration, and aeration/oxygenation projects. Uncertainties to be resolved with sediment dredging and sediment phosphorus sequestration included potential effects on aquatic species, including bottom-dwelling organisms. For sediment removal, some groups expressed a need for scientific studies related to re-use and disposal of dredged sediments.

A summary of pros, cons, and identified uncertainties for each of the pollutant removal techniques evaluated at the workshop is presented in Table 2.6. The techniques are organized into two groups: those that treat the symptoms of poor water quality (e.g., seasonally low dissolved oxygen, high pH, large algal blooms) and those that treat the causes of poor water quality (e.g., excessive phosphorus and nitrogen inputs). Additional consideration of treating the symptoms versus the causes of poor water quality is presented in Section 4.

TABLE 2.6 SUMMARY OF PROS AND CONS IDENTIFIED BY WORKSHOP BREAKOUT GROUPS AND THE PROJECT STEERING COMMITTEE

PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT CAUSES				
WETLAND RESTORATION/ TREATMENT WETLANDS	Nutrient Removal & Water Quality Improvements	Provides fish and wildlife habitat while decreasing external sources of nutrients to Upper Klamath Lake and the Keno Impoundment	Internal sources of phosphorus to Upper Klamath Lake are not directly addressed in the short-term	Potential for invasive species (aquatic/terrestrial) management problems and bioaccumulation potential (e.g., mercury)
		Nutrient removal for project life: Nitrogen removal is high (>100 metric tons over 50 years) Phosphorus removal is high (>10 metric tons over 50 years)	Longer timeframe to effectiveness (3-5 years). To support high phosphorus removal capacity, wetland may have to be enhanced with low impact chemical dosing (LICD) (see text box on page 49) or dredged periodically	None identified
		Total suspended solids removal is medium to high	None identified	Improvements to dissolved oxygen, pH, chl-a/algal toxins variable, dependent on location
	Cost	Nitrogen removal costs low (<$10 per kilogram)	Phosphorus removal costs high (>$100 per kilogram) and initial project costs may be high ($1M to $100M) due to intensive land requirements and land acquisition cost	None identified
	Engineering/ Implementation	Engineering and infrastructure challenges are low to medium	Requires water right acquisition and/or transfer of existing water right to wetland use	Klamath Adjudication process for over-allocated water rights in Oregon has recently been completed and may affect water availability for wetland use
	Energy Use / CO_2 Production	Energy use is low to medium (if pumping required) and there is negative carbon dioxide loading (wetlands uptake carbon dioxide)	Some greenhouse gas production (CO_2 from pumping, and nitrous oxide, methane from natural wetland processes)	None identified
	Synergy/ Compatibility	Highly compatible/synergistic with other large-scale techniques/ approaches and ongoing restoration projects - if phased in over time, Upper Klamath Lake wetland restoration would be compatible with medium-term agricultural operations that also remove nutrients from soil, such as intensive haying	Potential loss of agricultural land	None identified

TABLE 2.6 (CONTINUED) SUMMARY OF PROS AND CONS IDENTIFIED BY WORKSHOP BREAKOUT GROUPS AND THE PROJECT STEERING COMMITTEE

PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT CAUSES				
DIFFUSE SOURCE TREATMENT WETLANDS	Nutrient Removal & Water Quality Improvements	Provides wildlife habitat and nutrient removal throughout the watershed	Internal cycling of phosphorus in Upper Klamath Lake is not directly addressed in the short-term	Potential for unintended consequences (i.e., invasive species, mosquitos, nutrient export, creation of jurisdictional wetlands)
		Overall nutrient removal over project life assuming 50 or more wetlands distributed throughout the landscape: Nitrogen removal medium to high (10 to >100 metric tons over 50 years) Phosphorus removal medium to high (1 to >10 metric tons over 50 years)	Nutrient removal in individual wetlands is relatively low and installation of numerous wetlands throughout a tributary is required	Improvements to dissolved oxygen, pH, chl-a/algal toxins variable, dependent on location
		On-site total suspended solids removal is medium to high	None identified	None identified
	Cost	Individual systems are generally affordable for individual landowners Nitrogen removal cost is low to medium (<\$10 per kilogram to \$15 per kilogram)	Phosphorus unit removal cost is relatively high (>\$100 per kilogram)	None identified
	Engineering/ Implementation	Engineering and infrastructure challenges are low because individual systems are small	None identified	Systems adjacent to canals may require consideration of water loss due to evapotranspiration and effects on downstream water users
		Implementation timeframe for individual systems is low (1-2 years)	None identified	None identified
	Energy Use / CO_2 Production	Energy use is relatively low and there is negative carbon dioxide loading (wetlands uptake carbon dioxide)	Some greenhouse gas production (nitrous oxide, methane from natural wetland processes)	None identified
	Synergy/ Compatibility	Highly compatible/synergistic with other large-scale techniques/ approaches considered	None identified	None identified

TABLE 2.6 (CONTINUED) SUMMARY OF PROS AND CONS IDENTIFIED BY WORKSHOP BREAKOUT GROUPS AND THE PROJECT STEERING COMMITTEE

PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT SYMPTOMS				
ALGAL BIOMASS FILTRATION	Nutrient Removal & Water Quality Improvements	Directly removes oxygen demand from decaying algae, reducing nutrients (e.g., nitrogen, phosphorus) in the water column	External sources of nutrients are not addressed necessitating continuous operation over the long-term	May release algal toxins to water column during harvesting
		Nutrient removal for project life: Nitrogen removal is high (>100 metric tons over 10 years) Phosphorus removal is medium (10 to 100 metric tons over 10 years)	None identified	None identified
	Cost	Nitrogen removal costs relatively low (<$10 per kilogram)	Total cost for project life (10 yrs) relatively high ($1M to $100M)	Costs for land-based operations
		Harvested algal biomass may be useful as soil amendment, energy source (biofuel), or may have possible pharmaceutical uses, offsetting operational costs	Large amounts of harvested algal biomass require disposal or other use, potentially increasing costs	Persistence of algal toxins in harvested biomass is unknown, potentially affecting re-use options and operational costs
	Engineering/ Implementation	Can be spatially (barge-based) and temporally (barge-based, land-based) responsive to seasonal algal blooms	Extremely high rate of filtration likely needed to produce a measurable effect on water quality, especially in Upper Klamath Lake	Rate of filtration needed to produce a measurable effect on water quality in Upper Klamath Lake and the Keno Impoundment
		Engineering and infrastructure challenges are low to medium since private harvest operations already exist in Upper Klamath Lake, albeit at a smaller scale	None identified	At a larger scale, infrastructure needs for biomass disposal or other uses are uncertain
	Energy Use / CO_2 Production	Carbon dioxide loading is low to medium, depending on whether barges or land-based systems are used	Scaling up the operation to remove additional biomass produces more carbon dioxide	None identified
	Synergy/ Compatibility	Highly compatible/synergistic with other large-scale techniques/ approaches and ongoing restoration projects	Land-based screening systems can inadvertently capture small fish	None identified

TABLE 2.6 (CONTINUED) SUMMARY OF PROS AND CONS IDENTIFIED BY WORKSHOP BREAKOUT GROUPS AND THE PROJECT STEERING COMMITTEE

PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT SYMPTOMS				
SEDIMENT REMOVAL (DREDGING)	Nutrient Removal & Water Quality Improvements	Direct removal of sediment decreases internal loading, a primary source of phosphorus to Upper Klamath Lake and the Keno Impoundment	External sources of nutrients are not addressed necessitating repeated dredging events over the long-term	The amount of phosphorus that must be removed from sediments to affect the whole-lake phosphorus equilibrium is currently unknown
		Phosphorus removal for project life (1 to >10 metric tons over 5 to 8 years) for full-scale dredging or dredging of hot spots in Upper Klamath Lake and/or the Keno Impoundment		
		Dissolved oxygen, pH, total suspended solids, chl-a/algal toxin improvements in Upper Klamath Lake and the Keno Impoundment medium to high due to removal of primary source of phosphorus for internal loading	Localized, short-term increases in total suspended solids and water column nutrients due to physical disturbance of sediments	None identified
	Cost	None identified	Total cost of full-scale dredging or dredging of hot spots in Upper Klamath Lake and/ or the Keno Impoundment for project life is high to very high (>$1 M to >$100M) and does not include re-use costs	Cost of sediment de-watering/ drying operation
	Engineering/ Implementation	Dredging logistics and equipment needs are fairly well understood	Engineering and infrastructure challenges in the Upper Klamath Basin area medium to high for sediment re-use	None identified
	Energy Use / CO_2 Production	None identified	Energy use and carbon dioxide production of dredge equipment and sediment transport equipment is high	None identified
	Synergy/ Compatibility	Compatible/synergistic with wetland restoration/rebuilding: dredged sediments deposited in subsided areas adjacent to Upper Klamath Lake could be used to rebuild wetlands and balance cut-and-fill costs at wetland project sites. This may provide opportunities for agricultural enhancements (soil enhancement) compatible with medium-term agricultural operations that remove nutrients from sediments over time (e.g., nutrient harvest and export)	Not compatible/synergistic with sediment sequestration Potential impacts to benthic organisms and special status fish species	

TABLE 2.6 (CONTINUED) SUMMARY OF PROS AND CONS IDENTIFIED BY WORKSHOP BREAKOUT GROUPS AND THE PROJECT STEERING COMMITTEE

PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT SYMPTOMS				
SEDIMENT SEQUESTRATION (ALUM APPLICATION) & AERATION/ OXYGENATION	Nutrient Removal & Water Quality Improvements	Direct treatment of sediment decreases internal loading, a primary source of phosphorus to Upper Klamath Lake and the Keno Impoundment	External sources of nutrients are not addressed necessitating continuous treatment or linkage to other techniques to reduce nutrient inputs in the long-term	Uncertainty in the efficacy of alum treatment in Upper Klamath Basin waters (i.e., low alkalinity, high seasonal pH), including consideration of re-suspension potential for shallow Upper Klamath Lake
		Can combine oxygenation and phosphorus sequestration using alum micro-floc	None identified	
		Phosphorus removal for project life medium to high (1 to >10 metric tons over 8 to 20 years)	Widespread concern regarding potential aquatic toxicity of alum	
		Dissolved oxygen, pH, total suspended solids, chl-a/ algal toxin improvements in Upper Klamath Lake and the Keno Impoundment medium to high due to addition of oxygen and removal of primary nutrient source		
	Cost	None identified	Phosphorus removal costs of oxygenation and alum treatment relatively high (>$100 per kilogram)	None identified
	Engineering/ Implementation	Logistics and equipment needs are well understood	Alum must be transported to the project site, so dosing levels are linked to transportion logistics	None identified
	Energy Use / CO_2 Production	None identified	Energy use and carbon dioxide production of oxygenation methods medium to high	Potential for use of solar energy source for oxygenation methods
	Synergy/ Compatibility	Generally compatible/synergistic with other large-scale techniques/approaches and ongoing restoration projects	Not compatible/synergistic with dredging	Permitting related to potential impacts to benthic organisms and special status fish species