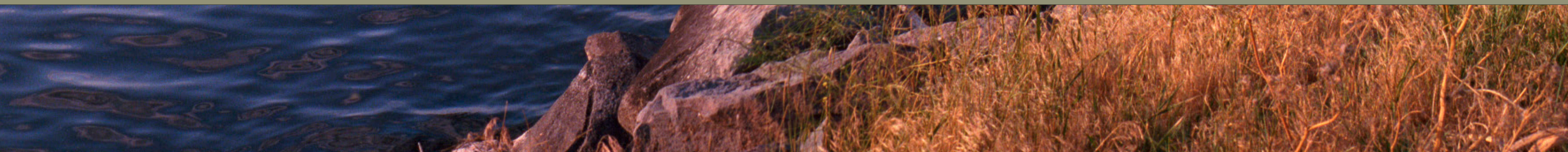
WATER QUALITY IMPROVEMENT TECHNIQUES FOR THE UPPER KLAMATH BASIN:

A TECHNICAL WORKSHOP AND PROJECT CONCEPTUAL DESIGNS

FINAL REPORT | SEPTEMBER 4, 2013



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Klamath River, Oregon & California

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State Water Resources Control Board – Training Academy

PROJECT STEERING COMMITTEE:
California State Coastal Conservancy, PacifiCorp, North Coast Regional Water Quality Control Board, State Water Resources Control Board – Training Academy, Oregon Department of Environmental Quality, U.S. Environmental Protection Agency (Region 9), U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. Fish and Wildlife Survey, Karuk Tribe, Klamath Tribes, Humboldt State University

PROJECT TECHNICAL TEAM:
Atkins, Aquatic Ecosystem Sciences (AES),
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North-facing view from the eastern shore of Upper Klamath Lake. Photo: David Garden.

CONTENTS

EXECUTIVE SUMMARY

The Klamath River Water Quality Workshop was held on September 10-13, 2012 in Sacramento, California, to evaluate large-scale techniques for improving water quality in the Upper Klamath Basin and to inform decision-making on nutrient reduction approaches. The workshop focused on upper basin projects to foster a new, healthier equilibrium condition for basin headwaters, to treat both the symptoms and the causes of elevated phosphorus and nitrogen levels, and, ultimately, to support water quality improvements in downstream reaches of the Klamath River. Workshop participants included over 100 attendees representing roughly 13 federal and state (California, Oregon) agencies, multiple tribes, and several consulting firms, academic institutions, and utilities. Six large-scale pollutant reduction techniques were evaluated at the workshop, including the following:

- Wetland restoration (habitat focus)
- Treatment wetlands (water quality focus)
- Diffuse source (decentralized) treatment wetlands
- Algal filtration
- Sediment dredging
- Sediment sequestration of phosphorus and aeration/oxygenation

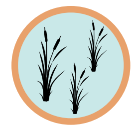
This report summarizes information presented at the workshop and, based on feedback from workshop participants and the project Steering Committee, presents conceptual designs for pilot projects to improve water quality in the Upper Klamath Basin. The report is organized into four sections, as follows.

SECTION 1 provides a summary of water quality challenges in Upper Klamath Basin; this information was also presented in a technical document given to workshop participants (Stillwater Sciences et al. 2013) and reviewed as background information at the workshop. Section 1 addresses the following topical questions:

- What are the water quality problems in Upper Klamath Lake and the Klamath River?
- What are the reasons for poor water quality?
- Where do the excessive amounts of phosphorus in Upper Klamath Lake come from?
- Can the phosphorus and algae problem be fixed?
- How do social and cultural factors influence the planning for Upper Klamath River Basin water quality improvement projects?

SECTION 2 presents an overview of the large-scale water quality improvement techniques evaluated by participants at the workshop, including goals and capabilities, basic design elements, and examples of similar applications. The results of workshop small-group evaluation sessions for each of the techniques are presented along with the generalized cost estimates considered by participants during their evaluations. Pros and cons of the different techniques are summarized at the end of Section 2, developed using feedback from workshop participants and the project Steering Committee. Detailed documentation of the workshop itself, including the agenda, participant list, and individual comments and observations of workshop participants during the small-group evaluation sessions and a design charrette, is presented as Appendix A to this report.

SECTION 3 moves beyond the workshop, presenting pilot project conceptual designs developed by the project technical team for three overarching techniques: wetland rehabilitation, sediment removal (dredging), and sediment sequestration of phosphorus with oxygenation/aeration. Briefly, the pilot project conceptual designs include the following:



Diffuse Source Treatment Wetlands (DSTWs)

Small (1 to 10s of acres), flow-through and terminal wetlands located along creeks and canals or in low-lying areas in fields within the Wood River and Sprague River valleys. These systems would require minimal earthwork, pumping, and infrastructure. A network of DSTWs would decrease external loading of phosphorus and nitrogen to Upper Klamath and Agency lakes and decrease resulting nuisance algal blooms in these waterbodies.

Large Wetlands

Large (10s to 1,000s of acres) wetlands on the margins of Upper Klamath and Agency lakes, along the Keno Impoundment, and along the Klamath Straits Drain. These systems would be designed to decrease external loading of phosphorus and nitrogen to Upper Klamath and Agency lakes and the Keno Impoundment and to provide habitat for the endangered shortnose and Lost River suckers.

Northwestern view of wetlands and fields adjacent to Upper Klamath Lake. Photo: David Garden.

Sediment Removal (Dredging)

Targeted dredging of a portion of Upper Klamath Lake just south of Goose Bay containing relatively high concentrations of phosphorus, thereby decreasing the potential for internal loading of phosphorus to the lake and subsequent nuisance algal blooms. Based on the results of pilot testing, dredged sediments would be re-deposited in adjacent areas targeted for wetland rehabilitation, as well as local agricultural areas that would benefit from subsidence reversal and soil amendment.

Sediment Sequestration of Phosphorus and Aeration/ Oxygenation

Buffered alum dosing and oxygenation in Lake Ewauna and the Keno Impoundment, predicated on the successful outcome of bench-scale water quality and toxicity tests. Alum micro-floc and oxygen would be injected into a pilot site in Lake Ewauna to reduce oxygen demand and sequester or inactivate phosphorus in the sediments and water column.

The pilot project conceptual designs described in Section 3 are "place based" to the degree possible, given available information. They are also intended to help fill information gaps related to the application of each project type in the basin. Several other creative ideas were discussed by workshop participants as possible contributors to improved water quality in the Upper Klamath Basin and, where relevant, these ideas have been incorporated into the conceptual designs. The primary design elements presented herein represent a starting point, since full implementation would, in most cases, require additional knowledge gained from the pilot projects. If one or more of the conceptual designs were to be considered for implementation funding, further development of the design elements presented in Section 3 would be necessary.

SECTION 4 presents a discussion of anticipated benefits from linking short-term projects that treat the symptoms of poor water quality in the Upper Klamath Basin, to longer-term projects that treat the causes. Additional ideas generated at the workshop that require further development are also listed in Section 4, along with a set of ongoing research needs identified by workshop participants.

IN SUMMARY, no one project or technique can solve the basin-scale water quality problems affecting Upper Klamath Lake, its tributaries, and its primary downstream waterbody, the Klamath River. This report progresses from a summary of our current understanding of upper basin water quality problems to a set of linked projects to address those problems, acknowledging along the way that a fully feasible long-term solution requires a mosaic of techniques to provide conditions that support multiple beneficial uses. The conceptual nature of the pilot project designs also acknowledges gaps in our current understanding of how each of the project types would function in the unique setting of the Upper Klamath Basin.

Ultimately, linking multiple projects in space and time represents an exciting opportunity to improve water quality in the basin. By design, the workshop was focused on evaluating six specific techniques pre-selected by the project Steering Committee. However, there was widespread agreement among workshop participants that while these six techniques could be used to accelerate water quality improvements, they should be a complement, not a substitute, for a comprehensive watershed-based approach to address the root causes of excess phosphorus. Sustainable long-term improvements to water quality will require reductions in the amount of phosphorus that runs off land and is delivered to Upper Klamath Lake through its tributaries. With continuing education, outreach, and appropriate incentives for land owners and managers, the successful implementation of water quality improvement projects, such as the ones included in this report, can be accomplished in a way that supports local social norms and cultural traditions, and builds on the existing science, to substantially improve water quality in the Upper Klamath Basin.

SECTION 1 | OVERVIEW AND BACKGROUND

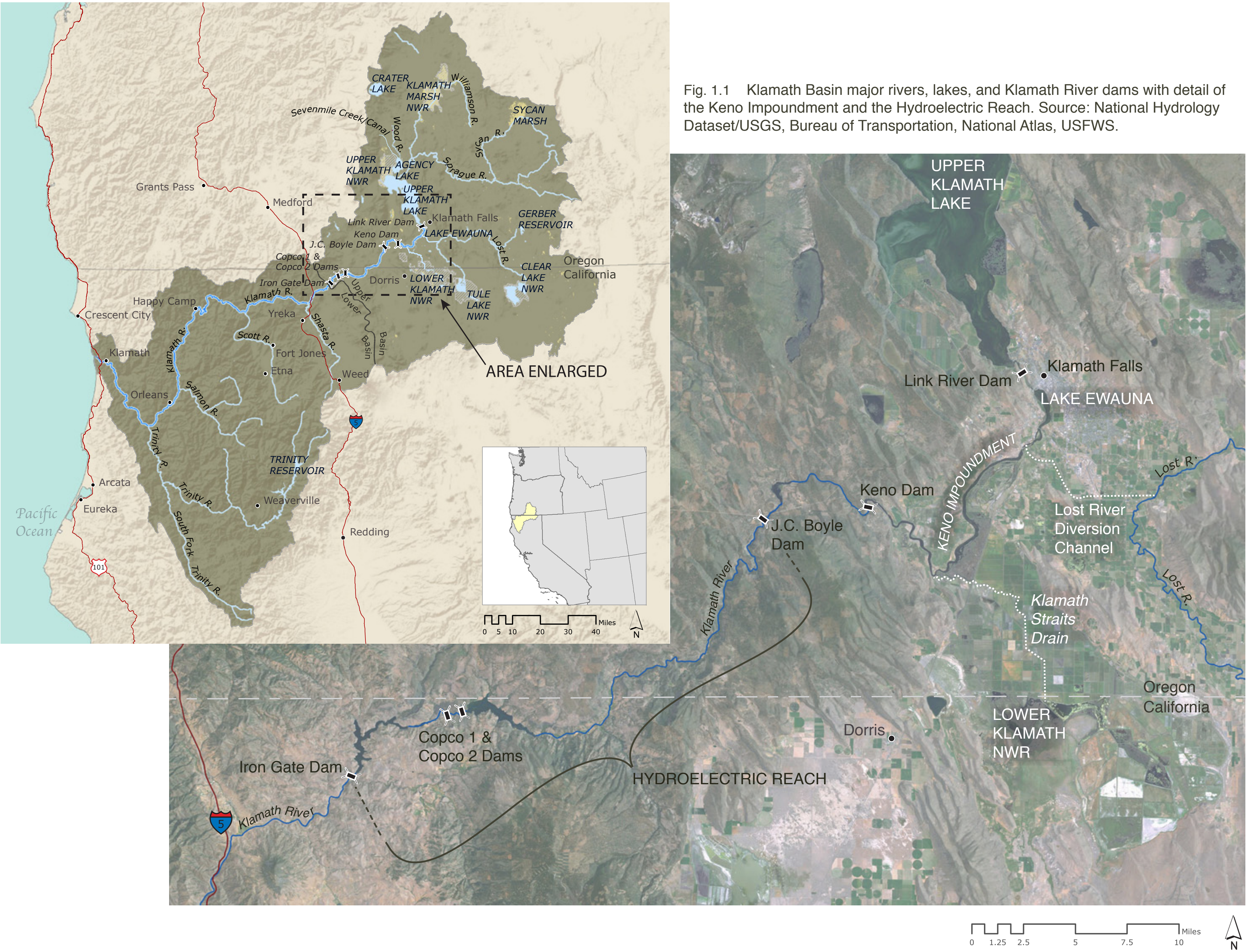


Fig. 1.1 Klamath Basin major rivers, lakes, and Klamath River dams with detail of the Keno Impoundment and the Hydroelectric Reach. Source: National Hydrology Dataset/USGS, Bureau of Transportation, National Atlas, USFWS.

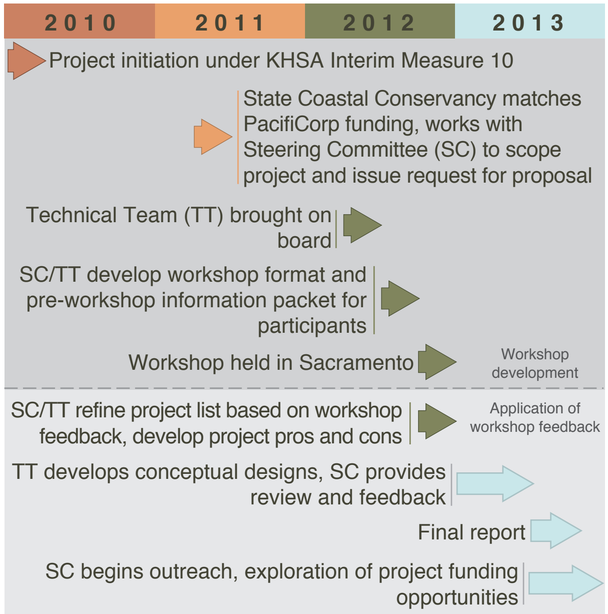


Fig. 1.2 (Far left) Klamath River Water Quality Workshop and report four-year timeline, from project initiation to post-report outreach.

Fig. 1.3 (Left) Satellite photo of Upper Klamath Lake showing typical summer lake-wide blooms of the blue-green algae *Aphanizomenon flos-aquae*. Upper Klamath Lake is broad and shallow, which affects water temperatures, circulation, and mixing patterns. Photo: NASA Earth Observatory, June 14, 2000.

OVERVIEW AND BACKGROUND

On February 18, 2010, the United States, the States of California and Oregon, PacifiCorp, tribal nations, 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 (including Iron Gate, Copco 1 and 2, and J.C. Boyle dams [Figure 1.1]) would help restore the salmonid fisheries of the Klamath Basin, and if dam removal is in the public interest.

The KHSA includes provisions for the interim operation of the dams and mitigation activities prior to removal of the dams or the termination of the KHSA. One of the provisions involved funding of the Klamath River Water Quality Workshop, which was held on September 10-13, 2012 in Sacramento, California. The purpose of the workshop was to evaluate large-scale approaches for improving water quality in the Upper Klamath Basin and to inform decision-making on nutrient reduction approaches. During the workshop, experts gave presentations on six large-scale pollutant reduction techniques or approaches that were pre-selected by the project Steering Committee. These techniques have demonstrated success in other systems challenged by nutrient pollution, including Chesapeake Bay, the Florida Everglades, and the Salton Sea in California. The six large-scale techniques evaluated by workshop participants included:

- Wetland restoration (habitat focus)
- Treatment wetlands (water quality focus)
- Diffuse source (decentralized) treatment wetlands
- Algal filtration
- Sediment dredging
- Sediment sequestration of phosphorus and aeration/oxygenation

Workshop participants then broke into groups to evaluate and rank the six different techniques as applied to water quality problems in the Upper Klamath Basin. Using results of the project evaluations, participant breakout groups designed a hypothetical 20-year program that would reduce nutrient and organic matter loads to the Upper Klamath River and improve water quality in the basin.

Outcomes of the workshop are summarized in Section 2 of this report. Detailed documentation of the workshop project evaluation sessions, including comments and observations of workshop participants, is presented in Appendix A. Lastly, a pre-workshop information packet, which was distributed to all participants prior to the workshop to provide technical information regarding the evaluation and design of water quality improvement projects, is available for download from the project website (http://www.stillwatersci.com/case_studies.php?cid=68).

WHAT ARE THE WATER QUALITY PROBLEMS IN UPPER KLAMATH LAKE AND THE KLAMATH RIVER?

Water Quality in Upper Klamath and Agency lakes and their tributaries the Wood, Williamson, and Sprague rivers (see Figure 1.1 for tributary locations), has been significantly degraded by human activities and has not met water quality standards for a

Fig. 1.4 (Above) shortnose sucker. Photo: USGS.

Fig. 1.5 (Below) Lost River sucker. Photo: USGS.

number of years.[1] Water quality is worst during the summer and early fall, with large blooms of algae and cyanobacteria[2] in Upper Klamath Lake (Figure 1.3) leading to depressed dissolved oxygen, high pH and ammonia concentrations, and problematic levels of algal toxins. Acute water quality conditions have been linked to redistribution and even large die-offs of native fish populations in the upper basin, including the shortnose sucker (*Chasmistes brevirostris*), the Lost River sucker (*Deltistes luxatus*), and the interior redband trout (*Oncorhynchus mykiss* ssp.). The endangered shortnose and Lost River suckers (Figures 1.4 and 1.5) have experienced substantial declines in the abundance of spawning fish in recent decades because an insufficient number of juvenile

1 WQST 2011

2 Cyanobacteria are photosynthetic organisms and can often be a nuisance aquatic species, occurring as large seasonal blooms that alter surrounding water quality. They are often referred to as blue-green algae, although they are actually bacteria.

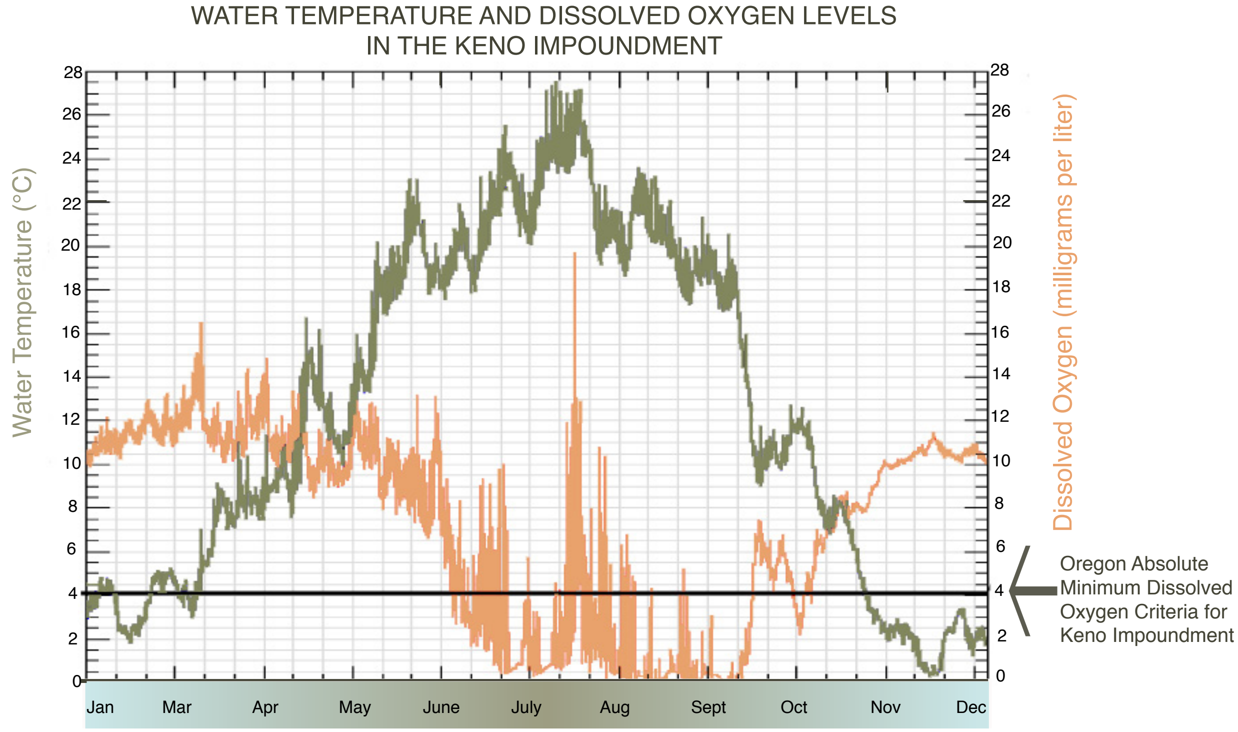


Fig. 1.6 Water temperature and dissolved oxygen concentration near the water surface at Island in the Keno Impoundment.

fish are surviving to become mature adults.[3] Overall, degraded water quality resulting from algal blooms is a significant threat to the long-term viability of the endangered suckers and other aquatic life in Upper Klamath Lake, not only because of fish-kill events, but also because of reduced fitness and long-term survival as a result of chronic stress[4] and possibly exposure to algal toxins.[5]

Water quality problems also affect fish and other aquatic species living in the Klamath River downstream of Upper Klamath Lake. Lake Ewauna and the Keno Impoundment (Figure 1.1) experience acutely low dissolved oxygen concentrations during the summer and fall (Figure 1.6). pH can also exceed water quality standards during this period, increasing potential for ammonia toxicity in this lake and reservoir. Although it is not well known how suckers utilize habitat in Lake Ewauna and the Keno Impoundment, water quality improvement in these waterbodies will help support the survival and return of a large number of juvenile suckers swept downstream of the Link River Dam each year from Upper Klamath Lake.[6]

3 Hewitt et al. 2011, Janney et al. 2009

4 ODEQ 2002

5 VanderKooi et al. 2010

6 USFWS 2008, NMFS and USFWS 2013

Further downstream, in the Hydroelectric Reach, construction of four dams (J.C. Boyle, Copco 1 and 2, and Iron Gate) (Figure 1.1) created reservoirs that slow the downstream movement of water and intercept or otherwise alter the natural transport of sediment, nutrients, and other constituents to downstream waters. When compared to free-flowing river reaches, the two larger reservoirs (Copco 1 and Iron Gate) experience large blooms of blue-green algae and exhibit altered seasonal water temperatures. Water quality in the Hydroelectric Reach and the Klamath River downstream of Iron Gate Dam does not meet applicable standards for the states of Oregon and California, with primary water quality concerns including seasonally altered water temperatures, low dissolved oxygen, high pH, and high chlorophyll-a and algal toxin concentrations.[7] Numerous fish species use the Klamath River and major tributaries downstream of Iron Gate Dam during all or some portion of their life cycle, including salmon, steelhead, lamprey, sturgeon, suckers, minnows, and sculpin. Many other species are present in the Klamath Estuary. Of the five populations of anadromous salmonid species in the Klamath River downstream of Iron Gate Dam, which include Chinook salmon, coho salmon, steelhead, and coastal cutthroat trout, all but coastal cutthroat have experienced reductions greater than 50% from historical levels.[8] Poor water quality, which contributes to incidences of fish disease downstream of the hydroelectric dams, is one important reason for the decline of fisheries in the Klamath Basin.[9]

Poor seasonal water quality also impacts cultural and recreational uses of waterbodies in both the Upper and Lower Klamath Basin. For example, known and/or perceived concerns over health risks associated with seasonal algal toxins have resulted in the alteration of traditional cultural tribal practices, such as gathering and preparation of basket materials and plants, fishing, ceremonial bathing, and ingestion of river water.[10]

7 ODEQ 2010, NCRWQCB 2010
8 Moyle 2002, Moyle et al. 1995, Ackerman et al. 2006, Leidy and Leidy 1984, Busby et al. 1994
9 Hamilton et al. 2011

Fig. 1.7 (Above left) Photo of *Aphanizomenon flos-aquae*. Photo: S. Poulson, UNR.

Fig. 1.8 (Above right) Scientists collected sediment cores in Upper Klamath Lake to determine when *Aphanizomenon flos-aquae* spores first appeared in the lake (Eilers et al. 2004). Photo: Jacob Kann.

WHAT ARE THE REASONS FOR POOR WATER QUALITY?

The relatively low topographic relief and volcanic terrain in the Upper Klamath Basin support large, shallow natural lakes and wetlands, with soils that are naturally high in phosphorus. Water quality in the basin is affected by this natural source of phosphorus as well as nonpoint sources (NPS) of pollution that result from human activities. NPS pollution is caused when runoff from rainfall, snowmelt, and irrigation moves over and through the ground, picking up and carrying natural and human-made pollutants and depositing them into lakes, rivers, wetlands, coastal waters and ground waters.[11] In the Upper Klamath Basin, phosphorus is the NPS pollutant of primary concern because this nutrient enables excessive blooms of cyanobacteria in the lake and in downstream reaches of the Klamath River.

10 USDOI and NMFS 2012

Upper Klamath Lake has historically been a highly productive or *eutrophic* lake even prior to land use by European Americans, as evidenced by 19th century accounts. However, the lake was not always dominated by high levels of the blue-green alga *Aphanizomenon flos-aquae* (Figures 1.3 and 1.7), as is the case today. Evidence from lake sediment cores (Figure 1.8) looking back approximately 1,000 years indicates that *Aphanizomenon flos-aquae* did not appear in Upper Klamath Lake until the latter part of the 19th century, increasing substantially after that time and becoming the dominant summertime algal species. Today, Upper Klamath and Agency lakes are considered to be *hypereutrophic*

Fig. 1.9 Upper Klamath Lake sucker during a fish die-off. Photo: Jacob Kann.

11 USEPA 2005

given their massive seasonal blooms of blue-green algae.[12] Such large algal blooms further exacerbate poor seasonal dissolved oxygen and pH levels in lake water, creating adverse conditions for fish and other aquatic species (Figure 1.9).

Excessive additions of phosphorus to Upper Klamath and Agency lakes from both natural sources and NPS pollution are an important reason for the current conditions. Both phosphorus and nitrogen are essential nutrients for algal growth, but *Aphanizomenon flos-aquae* can provide its own source of nitrogen through a cellular process called nitrogen fixation in which the algae removes nitrogen directly from the atmosphere and converts it into a biologically useful form. Nitrogen is present in relatively low concentrations in Upper Klamath Lake's tributary streams (although its concentrations have also increased over time due to

Fig. 1.10 Microcystis aeruginosa. Photo: Susan Corum.

12 Bradbury et al. 2004a, 2004b, Colman et al. 2004, Eilers et al. 2004

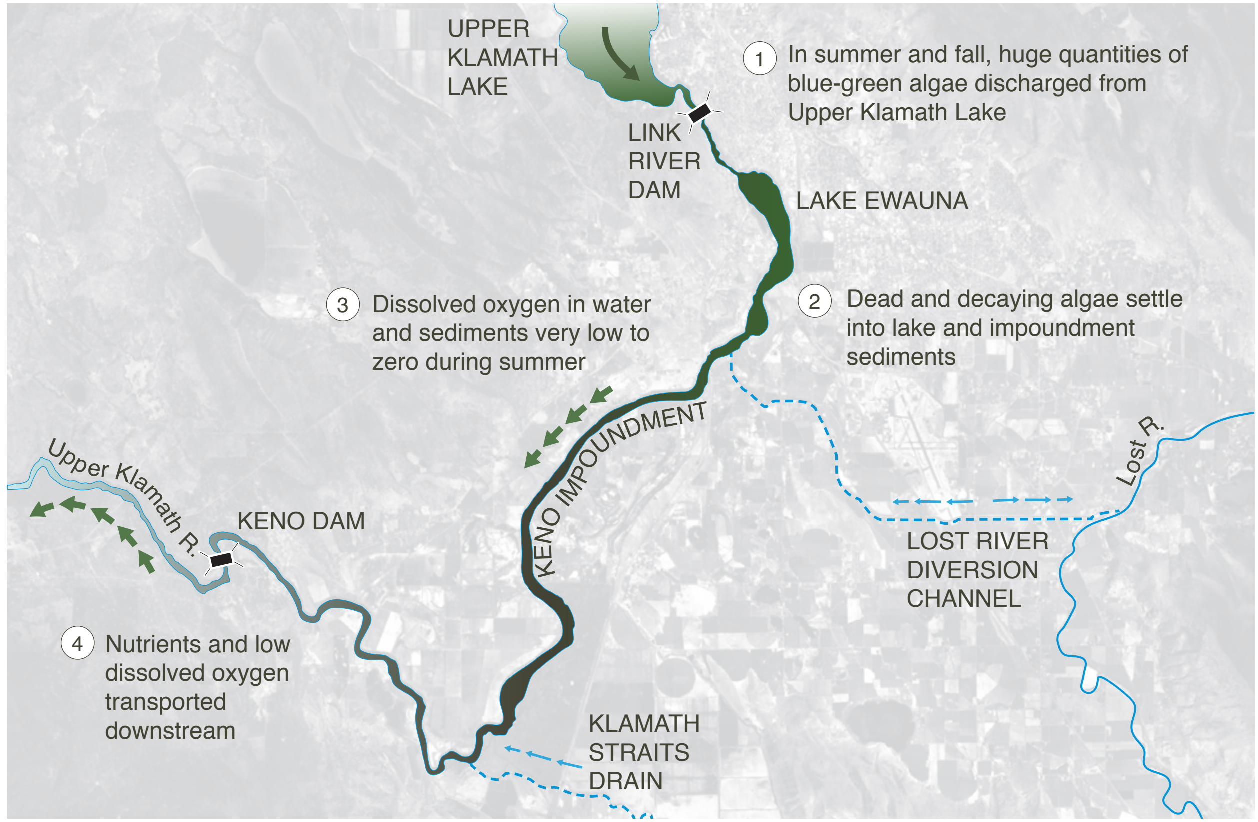


Fig. 1.11 Water quality issues downstream of Link River Dam.

human activities). High phosphorus and low nitrogen conditions give the nitrogen-fixing *Aphanizomenon flos-aquae* a competitive advantage over other algal species and allow it to dominate the algal community in the lake. When the *Aphanizomenon flos-aquae* bloom subsides, decaying algal cells release nitrogen and phosphorus that is then available to fuel growth of a another species of blue-green algae, *Microcystis aeruginosa* (Figure 1.10). Although never approaching the biomass levels of *Aphanizomenon flos-aquae* in Upper Klamath Lake, *Microcystis aeruginosa* blooms are responsible for production of a toxin (microcystin) that can cause irritation, sickness, or in extreme cases, death to exposed organisms, including humans, pets, or livestock[13] and can bioaccumulate in aquatic organisms.[14,15]

Huge quantities of algae produced in Upper Klamath Lake are discharged into Lake Ewauna and the Keno Impoundment during summer and early fall months (Figure 1.11). For reasons that are

13 WHO 1999
14 Eldridge et al. 2012
15 Kann 2008, Miller et al. 2010, Kann et al. 2011, Vanderkooi et al. 2010

Fig. 1.12 Aerial photo of *Microcystis aeruginosa* bloom in Copco Reservoir in September 2007. Photo: Jacob Kann.

unclear, algal production is not well-supported in the Keno Impoundment and algal biomass declines with increasing distance downstream of Link River Dam.[16] Particulate organic matter, derived from the upstream-generated blue- green algae, die and decay, settling to become reservoir sediments that require large amounts of oxygen to decompose (Figure 1.6). Modeling results indicate that sediment oxygen demand in the Keno Impoundment is the largest contributor to oxygen depletion in this portion of the Klamath River, followed in importance by organic matter that is suspended in the water column as both particulate and dissolved forms.[16] There are also numerous agricultural drains flowing into the Keno Impoundment including the Klamath Straits Drain (KSD), which has historically operated year-round, and the Lost River Diversion Channel, which generally diverts flow away from the reservoir during the irrigation season but discharges to the reservoir for the remainder of the year (Figure 1.11). The effects of the KSD and the Lost River Diversion Channel on the Keno Impoundment nutrient concentrations are important and variable by year,[17] depending on

16 Sullivan et al. 2011
17 Stillwater Sciences et al. 2012

Fig. 1.13 Aerial photo of *Microcystis aeruginosa* bloom in Iron Gate Reservoir in September 2007. Photo: Jacob Kann.

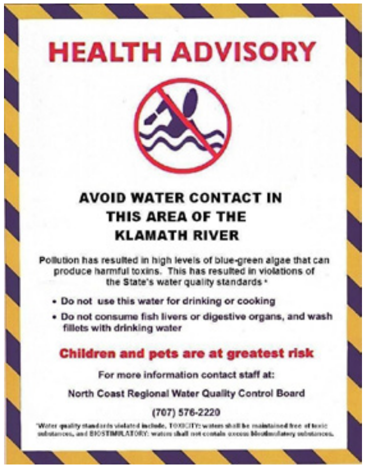
their relative flow contributions, but their effect on dissolved oxygen is substantially less than that of algae from Upper Klamath Lake.[18]

In the Upper Klamath River, downstream of the Keno Impoundment, levels of algae rapidly decline as the system changes from a lake to a turbulent river environment that is not favorable for growth of free-floating algae.[19] Nearing the Oregon-California stateline, the river and J.C. Boyle Reservoir are not impaired by algal growth, perhaps due to short residence times and generally shallow water. However, once the river reaches the larger Copco and Iron Gate reservoirs, the lake environment, with deep waters and longer residence times, supports significant levels of the toxigenic species *Microcystis aeruginosa* (Figures 1.12 and 1.13). The timing of *Microcystis aeruginosa* blooms appears to be related to an influx of a specific form of nitrogen (nitrate) that is a breakdown product of algal proteins following die-offs of *Aphanizomenon flos-aquae* blooms in Upper Klamath Lake.[20] The summer/fall blooms of *Microcystis aeruginosa* in the

18 Sullivan et al. 2009
19 Kann and Asarian 2006
20 Kann and Asarian 2007, Asarian and Kann 2011

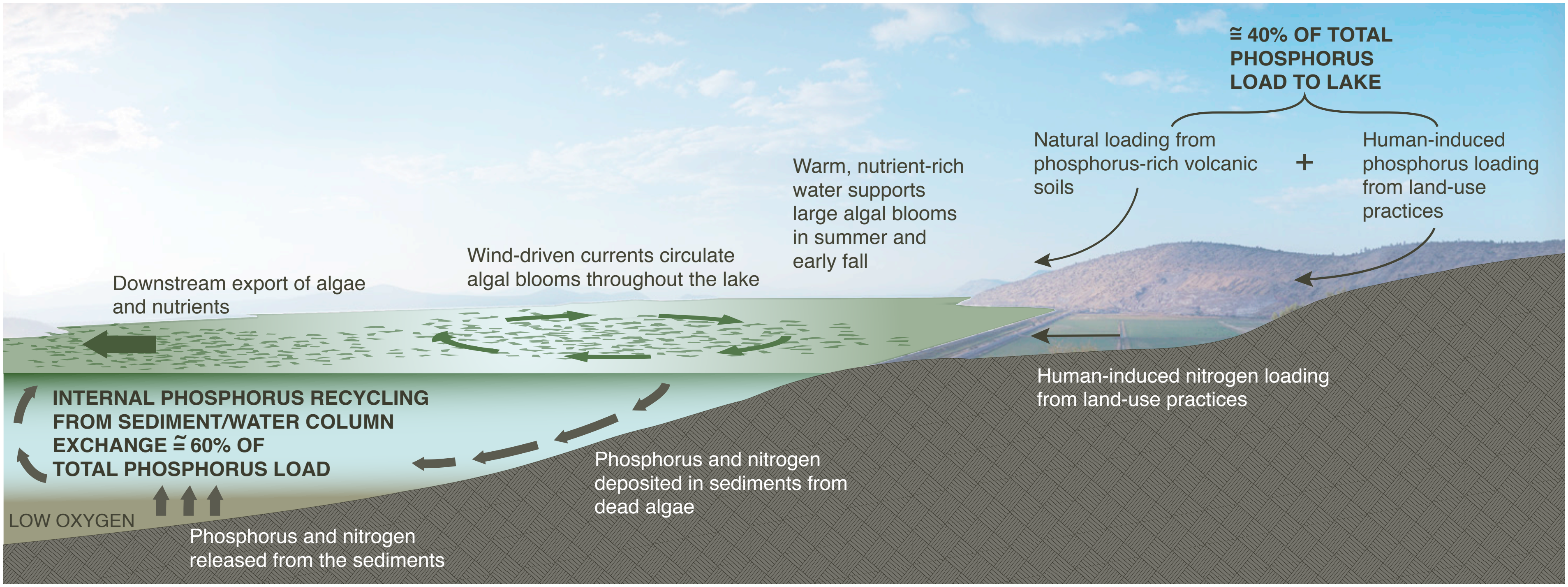
Fig. 1.14 (Above right) Farm land along the shore of Upper Klamath Lake. Photo: David Garden.

Fig. 1.15 (Below) Health advisory postings occur in June-October during intense blue-green algal blooms in Copco 1 and Iron Gate Reservoirs, and downstream reaches of the Klamath River.



reservoirs produce cell densities and microcystin toxin levels that can exceed public health guidelines (Figure 1.15) during summer and early fall within the reservoirs[21] and in the river downstream,[22] which

21 Jacoby and Kann 2007, Kann and Corum 2009, Raymond 2010a
22 Kann and Bowman 2011, Fetcho 2008



can result in the bioaccumulation of microcystin in a variety of fish species and freshwater mussels.[23]

WHERE DO THE EXCESSIVE AMOUNTS OF PHOSPHORUS IN UPPER KLAMATH LAKE COME FROM?

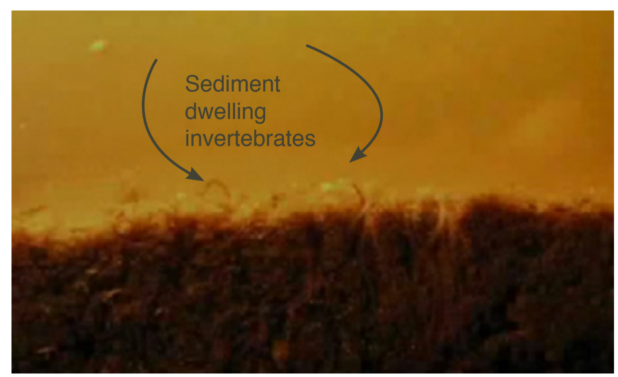
Watershed activities beginning in the late 1800s and accelerating though the 1900s, such as timber harvest, wetland draining, livestock grazing, cropland irrigation, water diversions, and stream channelization increased loading of nutrients, particularly phosphorus, to the lake. Phosphorus in Upper Klamath Lake originates from both *external* and *internally recycled* sources. An external source is one that comes from outside of the lake, such as tributaries carrying nutrients from surface runoff and erosion, or drainage pumped from lakeside farms (Figure 1.14). An internal source is one where externally loaded phosphorus retained within the lake sediments is then recycled back to the water column. Currently, external sources of total phosphorus to Upper Klamath Lake account for approximately 40% of the total phosphorus load (Figure 1.16).[24] The three major tributaries to the lake, the Wood River, Sprague River, and Williamson River, each contribute roughly a fifth of the lake's total external phosphorus load, despite their relative differences in drainage area and somewhat lesser differences in flow volume to the lake. Recent studies indicate that total phosphorus increases as water

23 Fetcho 2006, 2011; Kann 2008, et al. 2010, et al. 2011; Mekebri et al. 2009, CH2M Hill 2009a, 2009b; Prendergast and Foster 2010

24 Walker et al. 2012

Fig. 1.16 (Above) Seasonal nutrient and algae mechanisms in Upper Klamath Lake.

Fig. 1.17 (Below) Upper Klamath Lake sediments with invertebrates and bioturbation. Source: USGS, Kuwabara et al. 2007.



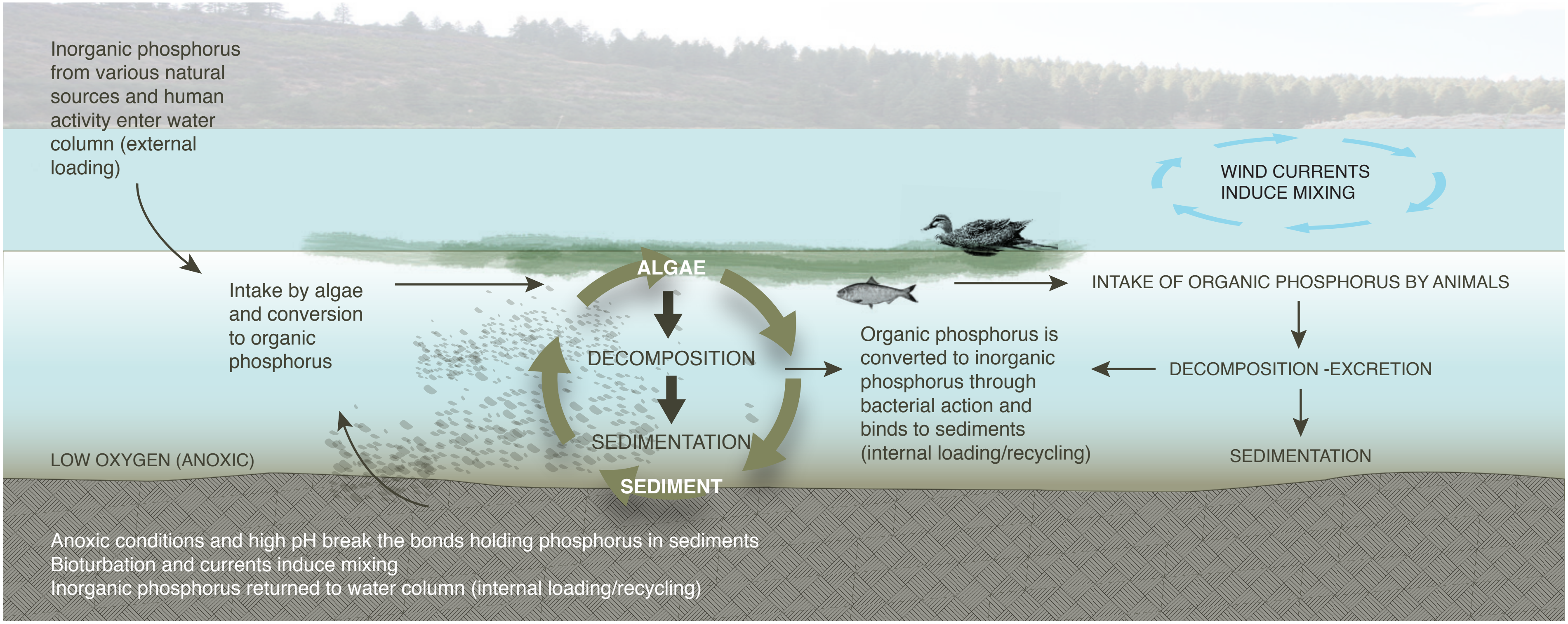


Fig. 1.18 Coupled sediment-water interactions.

moves downstream through pastures and irrigated grazing lands in each of these tributaries.[25]

The internal or recycled source of phosphorus to Upper Klamath Lake is its sediments, which release historically deposited phosphorus into the water column on a seasonal basis. During the summer and early fall when algae blooms occur, internal recycling from the sediments is the largest source of phosphorus for algae in Upper Klamath Lake, accounting for just over 60% of total loading (Figure 1.16).[26] A number of physical, chemical, and biological factors are responsible for the high rates of internal phosphorus loading. These include algal growth and decay, low oxygen conditions, processing by microbes, high pH, burrowing and/or mixing by sediment dwelling organisms (Figure 1.17), diffusion, and re-suspension of sediments by wind and/or wave action. These processes operate at varying time and spatial scales in the lake.[27] However, phosphorus in lake sediments and phosphorus in the water column are coupled, meaning that disturbing one component of the system will cause other components to adjust (Figure 1.18). Because sediment and water column phosphorus concentrations are in equilibrium, complete depletion of sediment phosphorus may not be necessary in order to see improvements in Upper Klamath Lake water quality.[28] Scientists are working to determine if there is a critical threshold for phosphorus levels in Upper Klamath Lake sediments, below which large seasonal algae blooms would no longer be supported by internal recycling rates.

CAN THE PHOSPHORUS AND ALGAE PROBLEM BE FIXED?

As part of the analyses conducted for development of the Upper Klamath Lake TMDL (see text box on page 10), utilizing extensive water quality monitoring

25 Walker et al. 2012
26 Kann and Walker 1999, ODEQ 2002

27 Barbiero and Kann 1994; Laenen and LeTourneau 1996; Kuwabara et al. 2007, et al. 2009, et al. 2012; Simon et al. 2009; Simon and Ingle 2011

28 Wood et al. 2012

TOTAL MAXIMUM DAILY LOADS (TMDLs) IN THE UPPER KLAMATH BASIN

Section 303(d) of the Clean Water Act (CWA) requires states to identify water bodies that do not meet water quality standards (objectives) and are not supporting their designated beneficial uses. These water bodies are considered to be impaired with respect to water quality. Oregon Department of Environmental Quality (ODEQ) and California North Coast Regional Water Quality Control Board (NCRWQCB) have both included the Upper and Lower Klamath Basin and specifically, the Klamath and Lost Rivers on their CWA Section 303(d) lists of water bodies with water quality impairments. For water bodies included on the 303(d) list, the state with jurisdiction over the water body must develop total maximum daily loads (TMDLs) to protect and restore beneficial uses of water. TMDLs (1) estimate the water body's capacity to assimilate pollutants without exceeding water quality standards; and, (2) set limits on the amount of pollutants that can be added to a water body while still protecting identified beneficial uses. ODEQ and NCRWQCB cooperated on the development of TMDLs for the impaired water bodies of the Upper and Lower Klamath Basin. TMDLs have been adopted for Upper Klamath Lake and its tributaries. TMDLs have also been adopted for the Klamath River in California and are pending USEPA approval for the Klamath River (and Lost River) in Oregon. Additional information regarding the Oregon TMDLs can be found on ODEQ's website (http://www.deq.state.or.us/WQ/TMDLs/klamath.htm) and for the California TMDLs on the NCRWQCB website (http://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls).

Fig. 1.19 Klamath Tribe water quality technicians measuring pumped discharge from the Wood River Ranch into Sevenmile Creek; circa 1992. Photo: Jacob Kann.

data and modeling of the phosphorus, algal bloom, and pH dynamics, the Oregon Department of Environmental Quality (ODEQ) has determined that reducing external phosphorus loads from human sources would be the most effective means of improving water quality conditions in the lake.[29]

Achieving the TMDL loading target of 109 metric tons/year of total phosphorus would require a 40% reduction in external phosphorus loads. Limiting external phosphorus contributions to the lake is anticipated to decrease the extent of early season blooms of *Aphanizomenon flos-aquae*, which would bring less available nitrogen into the water column and thus limit the extent of later season blooms of other blue-green algae, including the toxin producing *Microcystis aeruginosa*. However, since internal sediment recycling of phosphorus is currently such an important source of phosphorus to summertime algal blooms, the internal sediment release must be reduced as well. If external loads could be sufficiently reduced, the internal load would also eventually be reduced, after a period of equilibration (years to decades). It may be possible to accelerate this process by applying active management techniques to directly address the internal load.

It may not be necessary to remove all of the phosphorus in the sediments (or water column) of Upper Klamath Lake. The sediment and water column are a coupled system such that decreases in sediment levels of phosphorus would result in proportional decreases in water column phosphorus, and hence available phosphorus for algae. A new equilibrium condition would be established that is characteristic of a healthier ecosystem with fewer water quality problems in Upper Klamath Lake and in downstream reaches of the Klamath River.[30]

Multiple efforts are being undertaken by agency, county, and state entities to improve water quality in the Upper Klamath Basin. Some are ongoing while others are anticipated through the TMDL and NPS reduction programs.[31] Examples of Oregon projects anticipated to have significant benefits include water quality management plans (e.g., for City of Klamath Falls), water quality restoration plans (e.g., for Upper Klamath Lake tributaries), and land use and management plans (LRMPs) (e.g., for USFS and BLM). In California, examples include the irrigated

29 ODEQ 2002

30 T. Wood (USGS), KRWQ Workshop, September 2012

31 WQST 2011

lands discharge program (e.g., tailwater discharges, degradation of riparian areas, and destabilized stream banks), timber harvest plans (for non-federal lands), and forest management plans (for federal lands), including implementation of best management practices (BMPs).[32]

Recent data indicate that the use of BMPs on agricultural lands appears to have contributed to a decreasing trend in total phosphorus concentrations in some tributary segments upstream of Upper Klamath Lake.[33] Additionally, recent re-flooding of former lakeside wetlands has also reduced the external load to the lake.[34]

The large-scale water quality improvement approaches considered during the workshop and discussed in this report represent techniques that could be implemented at a large-scale, in concert with the continued implementation of BMPs and management plans already underway in the Upper Klamath Basin, to treat both the symptoms and causes of elevated phosphorus and nitrogen levels and substantially improve conditions in both the short- and long-term.

HOW DO SOCIAL AND CULTURAL FACTORS INFLUENCE THE PLANNING FOR KLAMATH BASIN WATER QUALITY IMPROVEMENT PROJECTS?

In addition to consideration of pollutant removal effectiveness, cost efficiency, and potential effects on aquatic dependent organisms, the successful design and implementation of basin-scale water quality improvement projects requires consideration of social and cultural factors. Fully feasible water quality improvement projects must be consistent with and support local social norms and cultural traditions within the Upper Klamath Basin.

For example, the Upper Klamath Basin is home to the Klamath Tribes who have historically depended on healthy fish populations as an important part of their diet and way of life. Agriculture is also an important part of the upper basin culture and economy with the production of alfalfa, hay, grains, potatoes, onions, and livestock (among others) producing valuable economic activity that extends beyond the substantial value of the commodities produced to support businesses and jobs in affiliated sectors.[35]

To ensure that recommended water quality improvement projects support local social and cultural traditions, Upper Klamath Basin experts on agricultural operations and tribal fisheries were invited to participate as contributing experts to the workshop and review of this report. Workshop participants included technical consultants to the Klamath agricultural community including the USDA Natural Resource Conservation Service, the Klamath Soil and Water Conservation District, and Klamath Water Users Association. Representatives of the Yurok, Karuk, and Klamath Tribes also participated in the workshop and review of the final report. Including input from agricultural engineers, conservationists, and operators as part of this project, along with tribal representatives, allows for the design of multi-objective projects. An inclusive approach is important for identifying and, ultimately, recommending projects that can be supported by local landowners and tribal members.

In addition, project evaluation criteria used at the workshop included water use/water rights considerations. Consideration of water use is critical to successful project design. It also avoids placing additional burdens on an already over-allocated water supply. Other evaluation criteria included consideration of infrastructure challenges and identifiable social or cultural impacts; these types of criteria can help ensure that project designs do not disrupt or interfere with land uses such as agricultural operations. For example, the diffuse source (decentralized) treatment wetlands (DSTWs) are small and use low-tech design features, such that they can be integrated into existing agricultural operations without additional water use, and minimal- to no-water rights permitting actions or removal of existing lands from agricultural operation.

Because of the scale of potential projects, it is important to involve local experts carefully and apply a wide range of evaluation criteria such that selected projects positively contribute to the cultural and social landscape of the Upper Klamath Basin.

32 WQST 2011
33 J. Kann, AES, personal communication, January 2013
34 Walker et al. 2012
35 WEF 2011

SECTION 2

WATER QUALITY IMPROVEMENT TECHNIQUES EVALUATED AT THE WORKSHOP

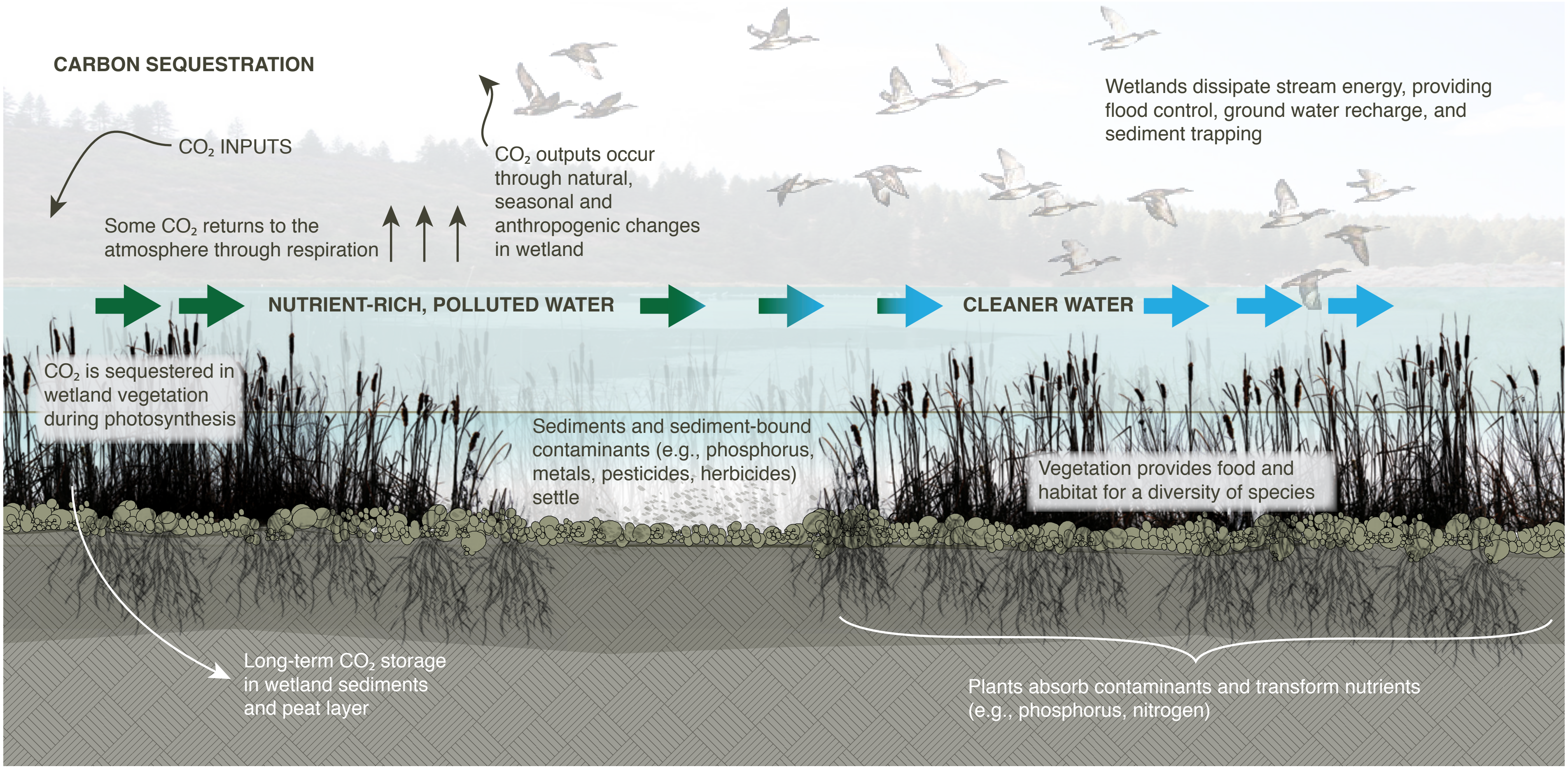


Fig. 2.1 (Above) Wetland functions, including carbon sequestration.

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.

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.

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

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:

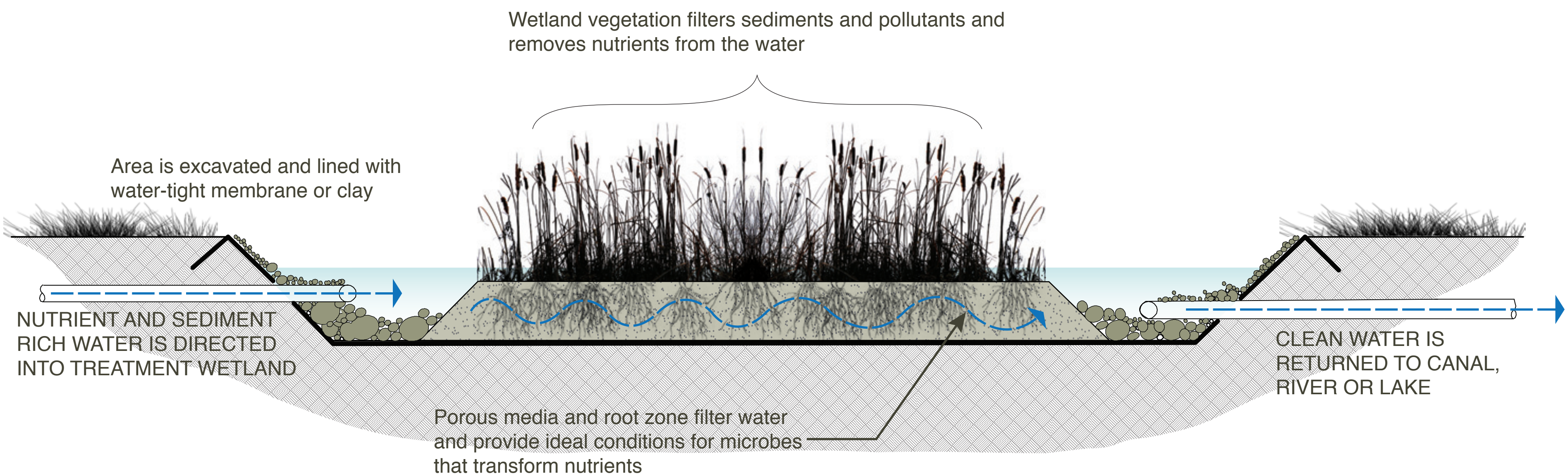
- Total suspended solids
- Nutrients such as nitrogen and phosphorus
- Metals
- Trace organic compounds such as pesticides and herbicides
- Bacteria and pathogens

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.



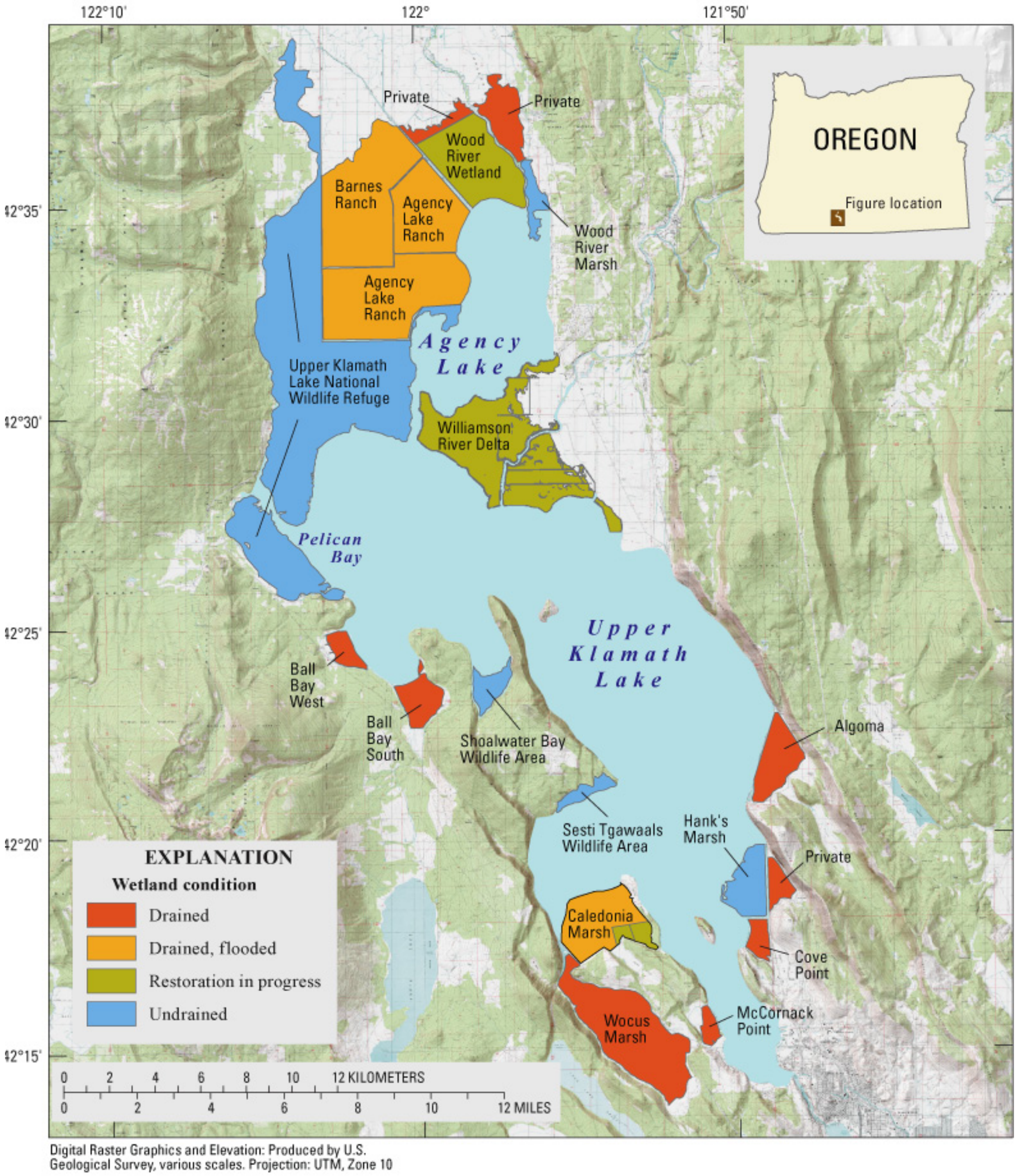


Fig. 2.6 Wetland conditions around Upper Klamath Lake. Source: USGS (Lindenburg and Wood 2009).

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.

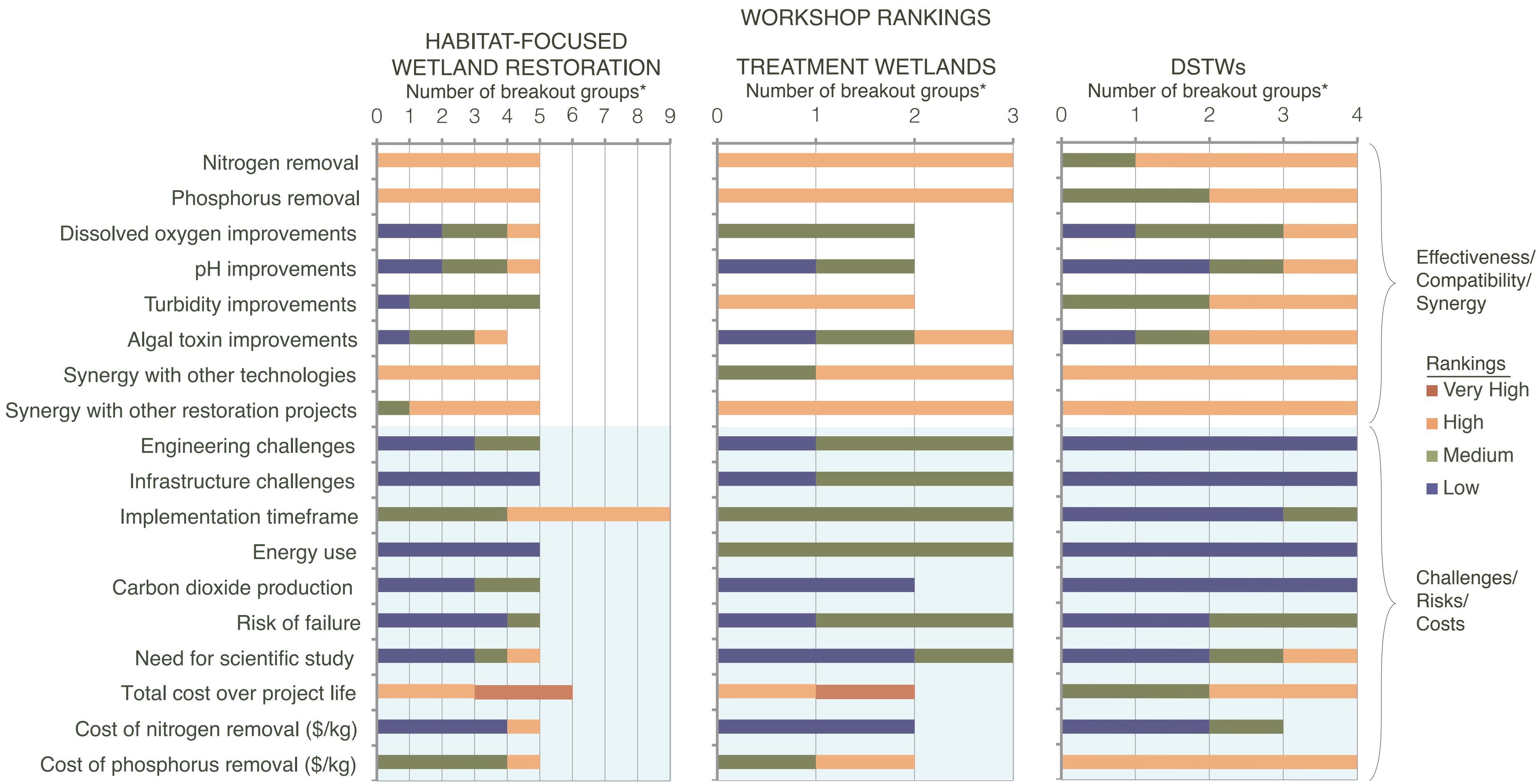
Workshop attendees ranked the potential for improvements in other water quality parameters such as dissolved oxygen, pH, turbidity and algal toxins. Rankings ranged from low to high, depending on how and where wetlands are built. Total costs for large-scale habitat and treatment wetland projects were 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

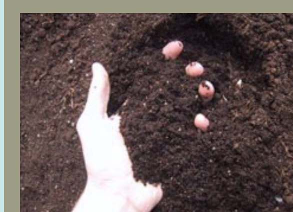


Fig. 2.13 (Above) Algal material used as a soil amendment. Photo: University of Idaho.

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.

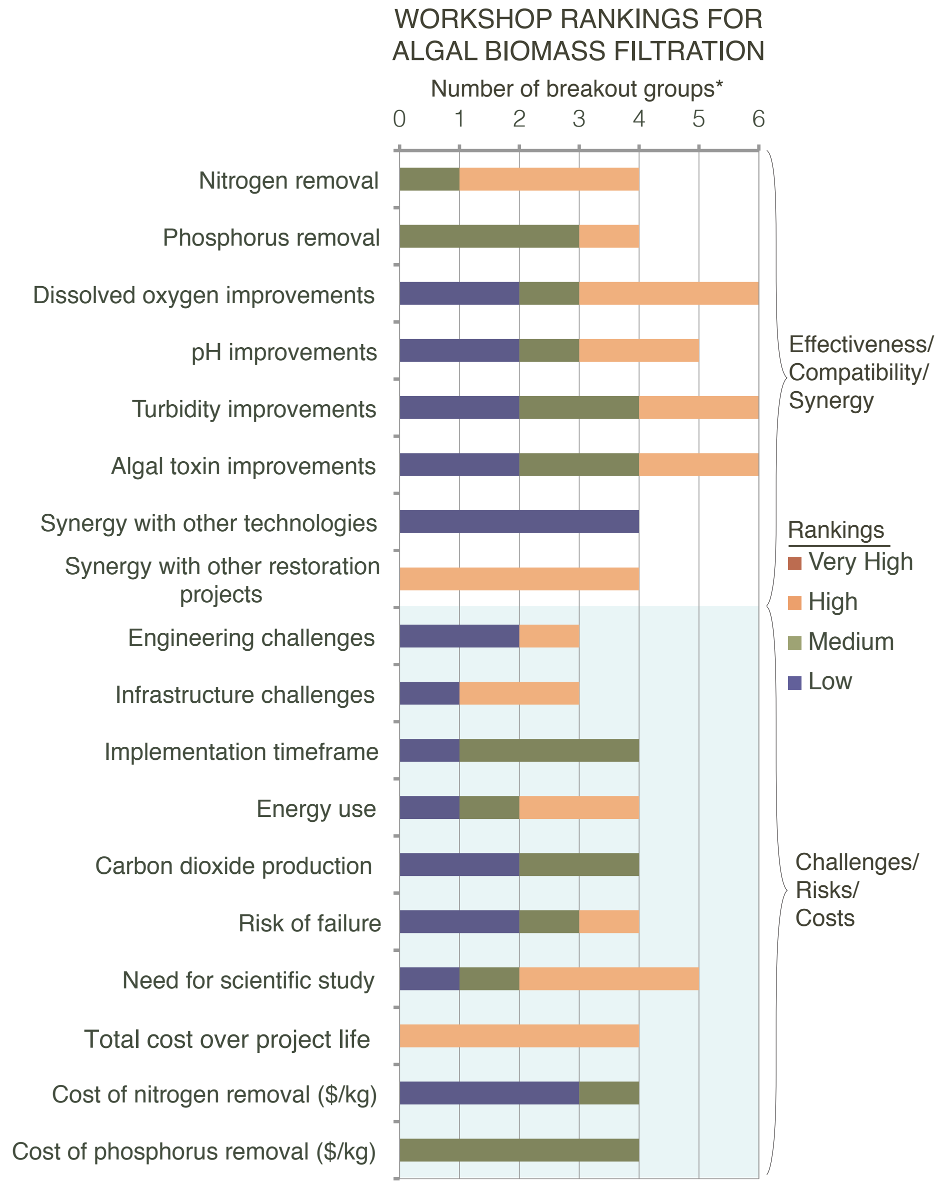
The total cost for barge-based algal biomass filtration was rated as high due to estimated maintenance, fuel, and personnel costs over the lifetime of the barge. Cost estimates were not available at the workshop for land-based algal biomass filtration.

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.

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?

10 Sullivan et al. 2013

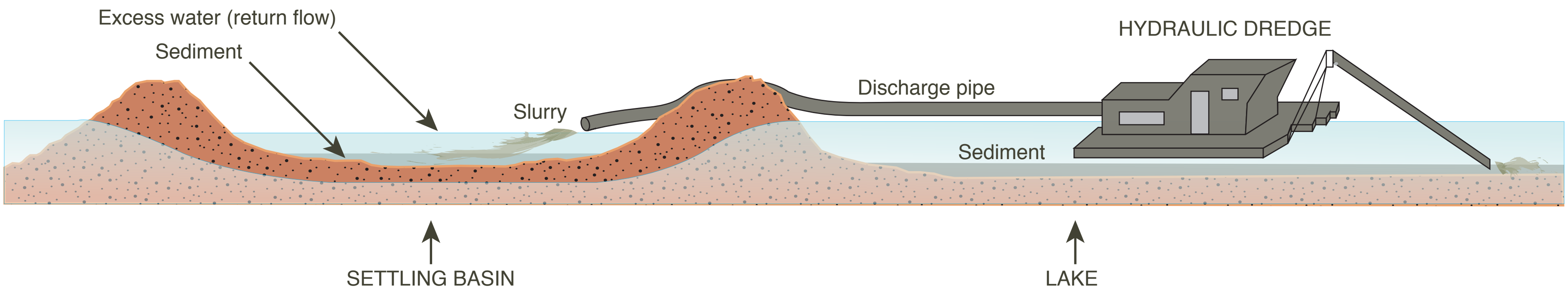


Fig. 2.18 Sediment is removed from the water and deposited in a settling basin. Once the sediment settles in the basin, excess water can be returned to the waterbody.

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

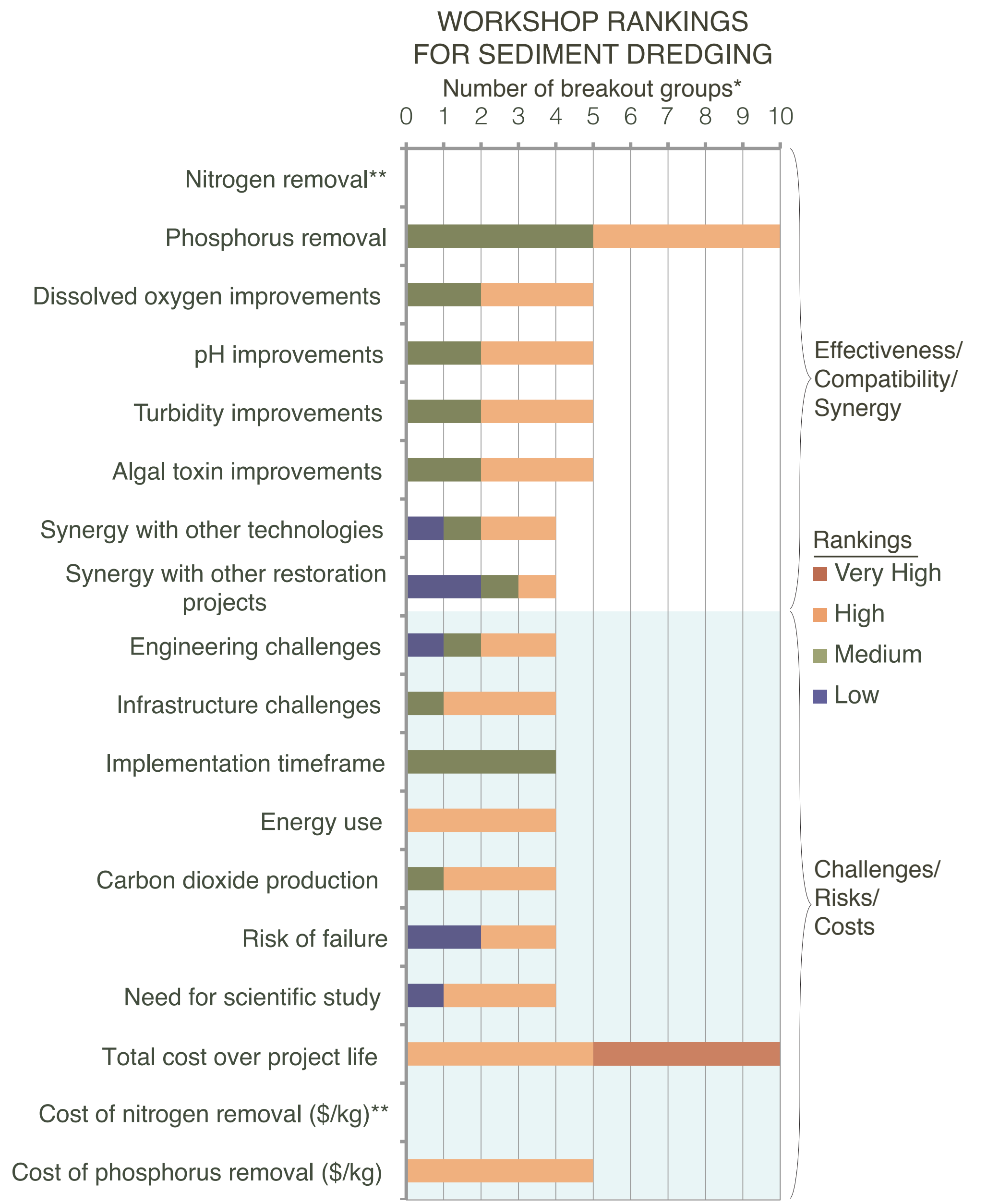
Once the area to be dredged has been identified, the appropriate dredging methodology, the fate of the dredged material (i.e., re-use or disposal), and transportation requirements must be considered. Sediment composition, contaminant levels, and possible presence of debris that could interfere with dredge 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.



*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).

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).

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

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]

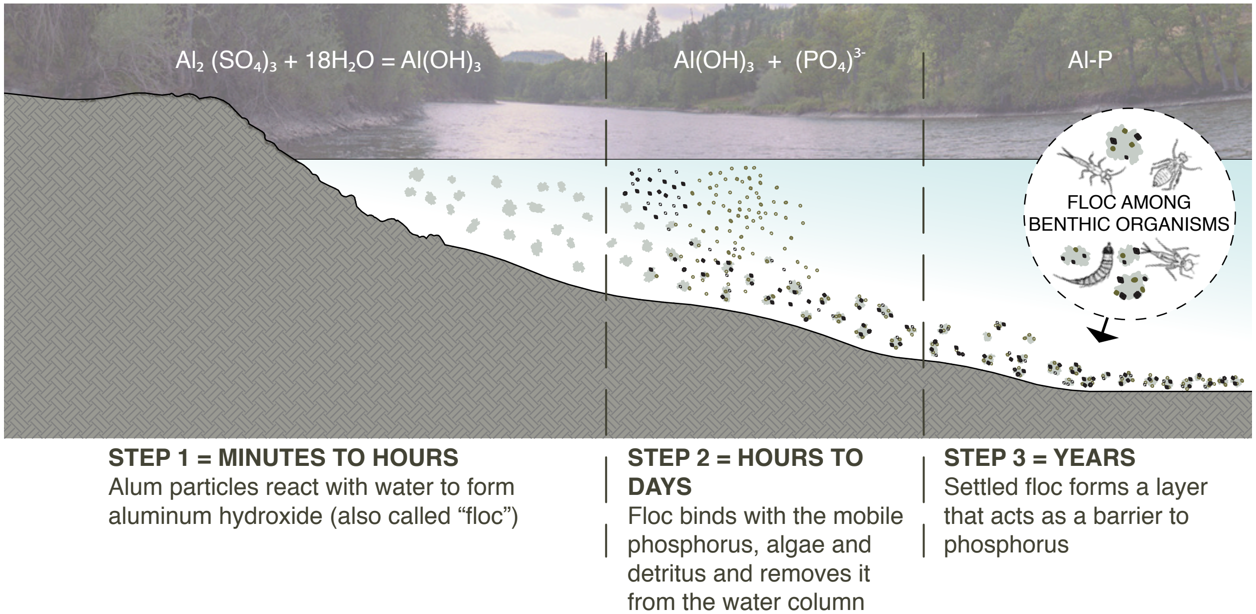


Fig. 2.23 Process of sediment phosphorus sequestration (inactivation) using alum.

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

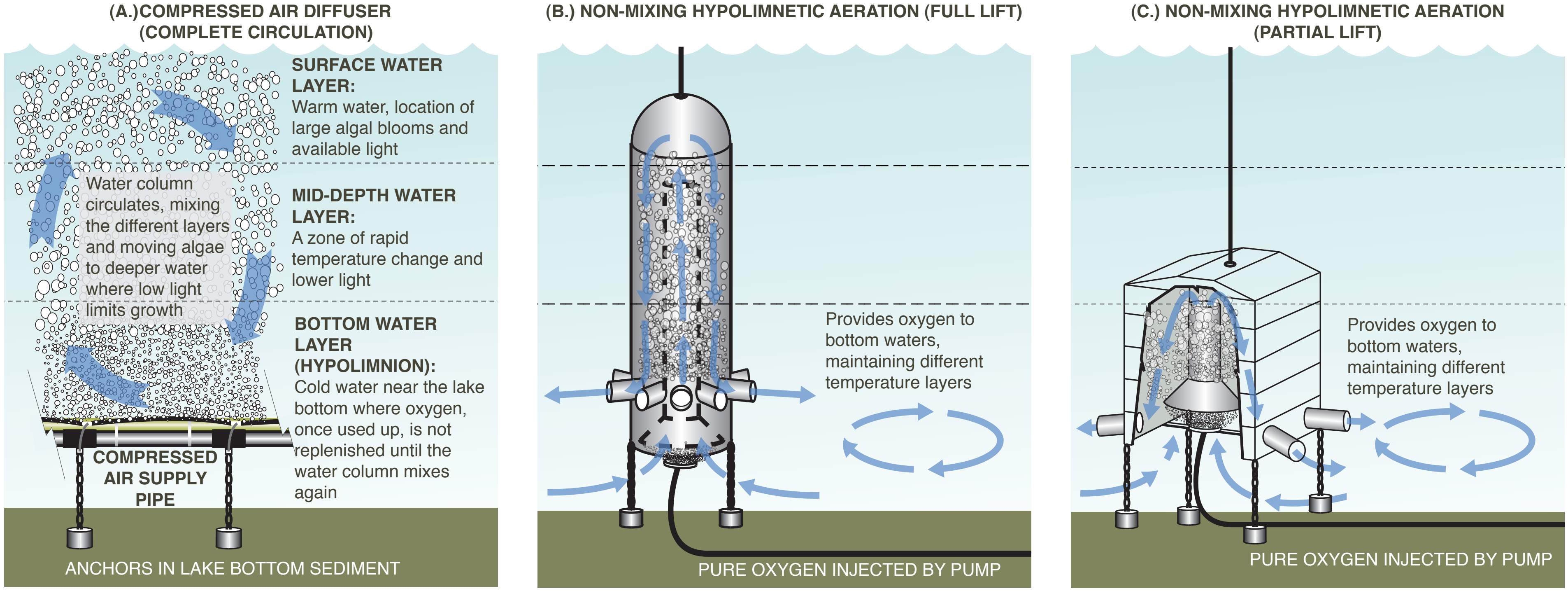


Fig. 2.25 Aeration schematics for complete circulation (A) and non-mixing hypolimnetic aeration (B and C).

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:

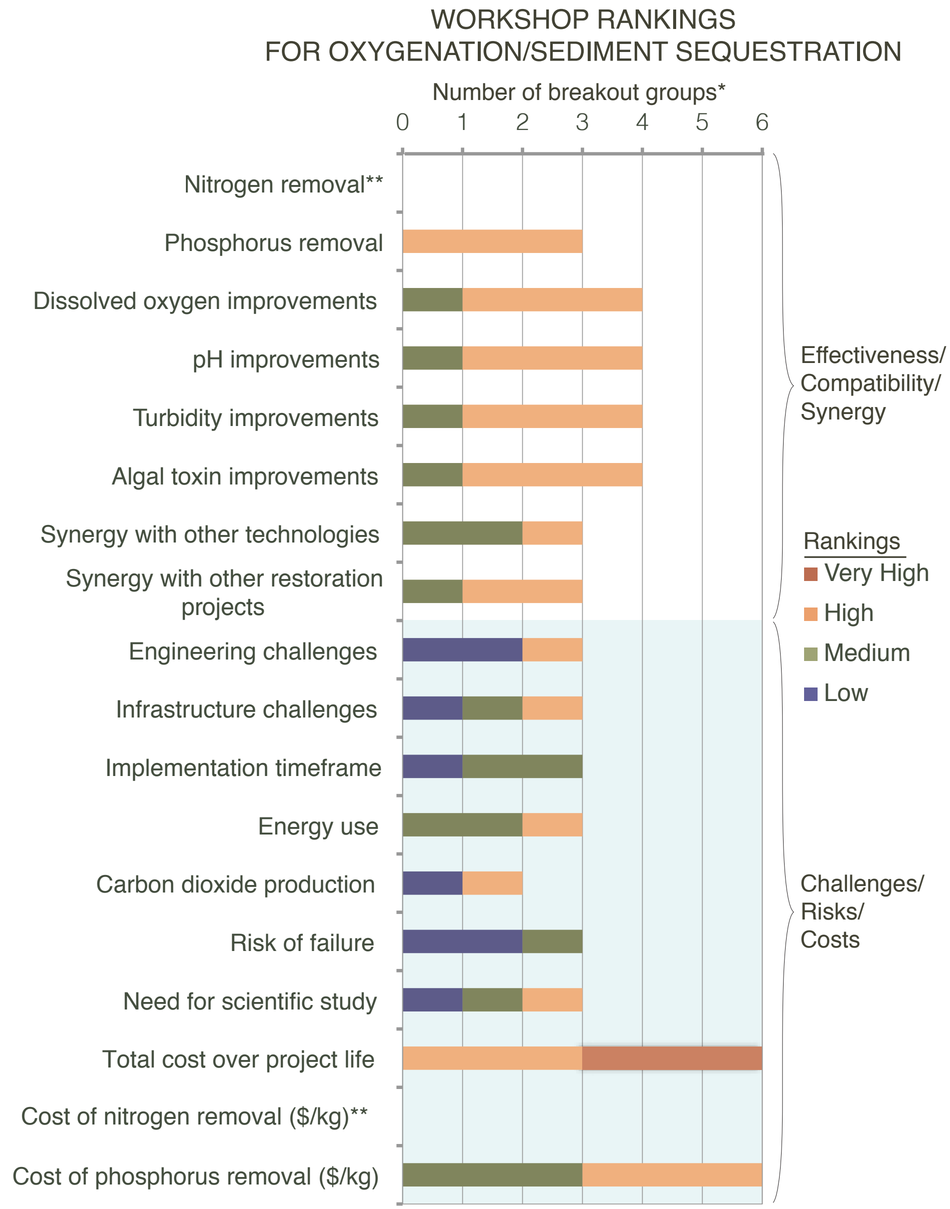
19 Cooke et al. 2005

- 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

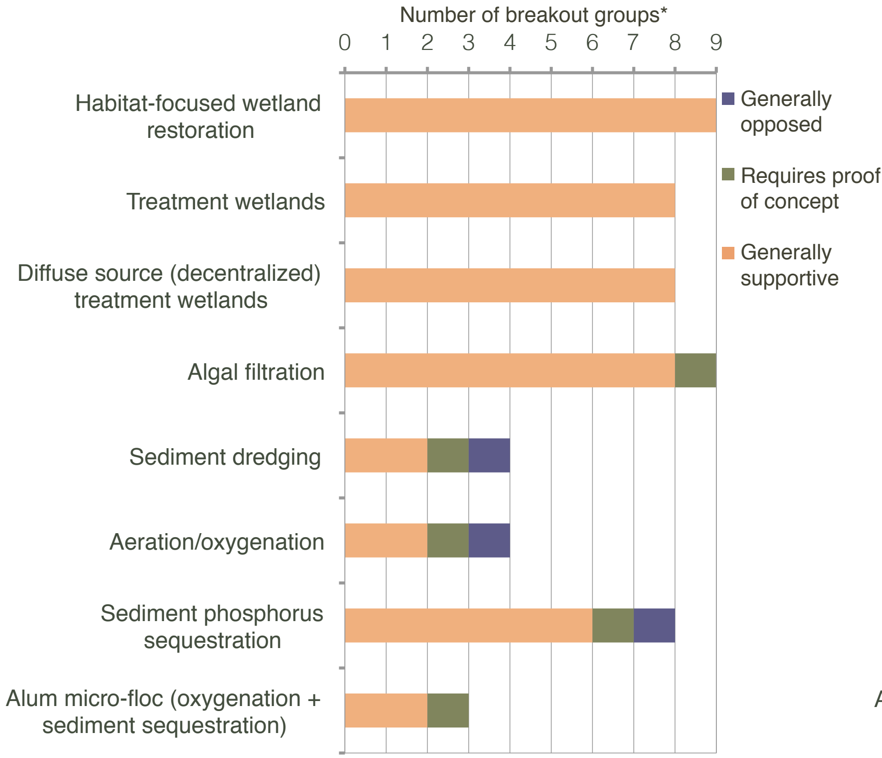
Workshop participants were generally supportive of algal filtration and wetland rehabilitation, the latter including habitat-focused wetlands, treatment wetlands, and diffuse source (decentralized) treatment wetlands (Figure 2.27). Participants recognized that these water quality improvement strategies 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).

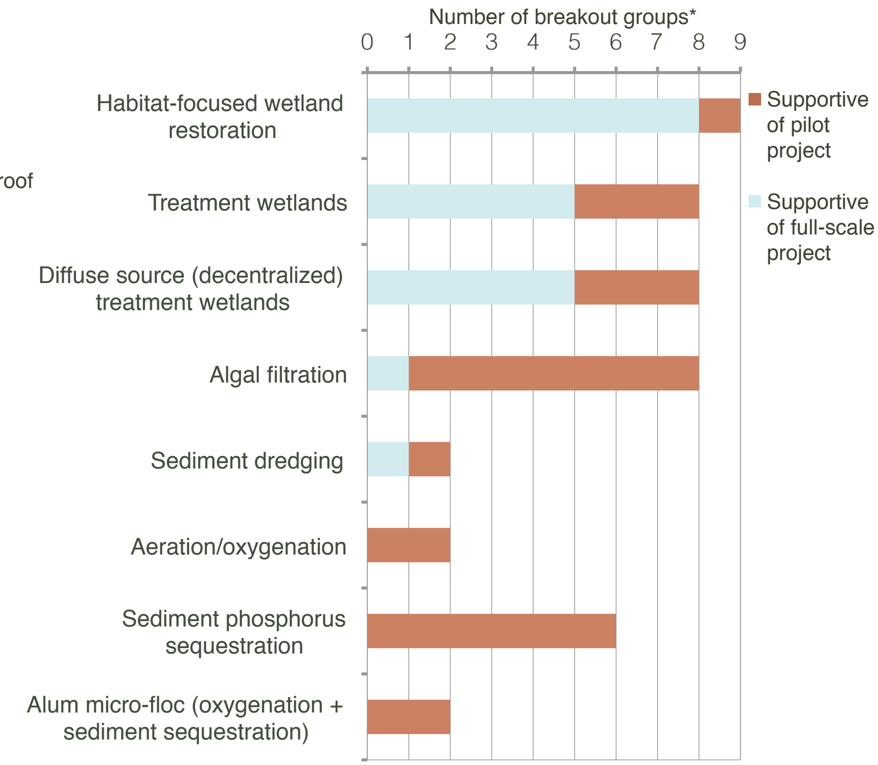
Workshop participants were also intrigued by algal filtration because of the spatial and temporal responsiveness and the economic potential as a potential by-product of this technique. While algal filtration only treats the *symptoms* of water quality problems, this strategy provides the opportunity 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

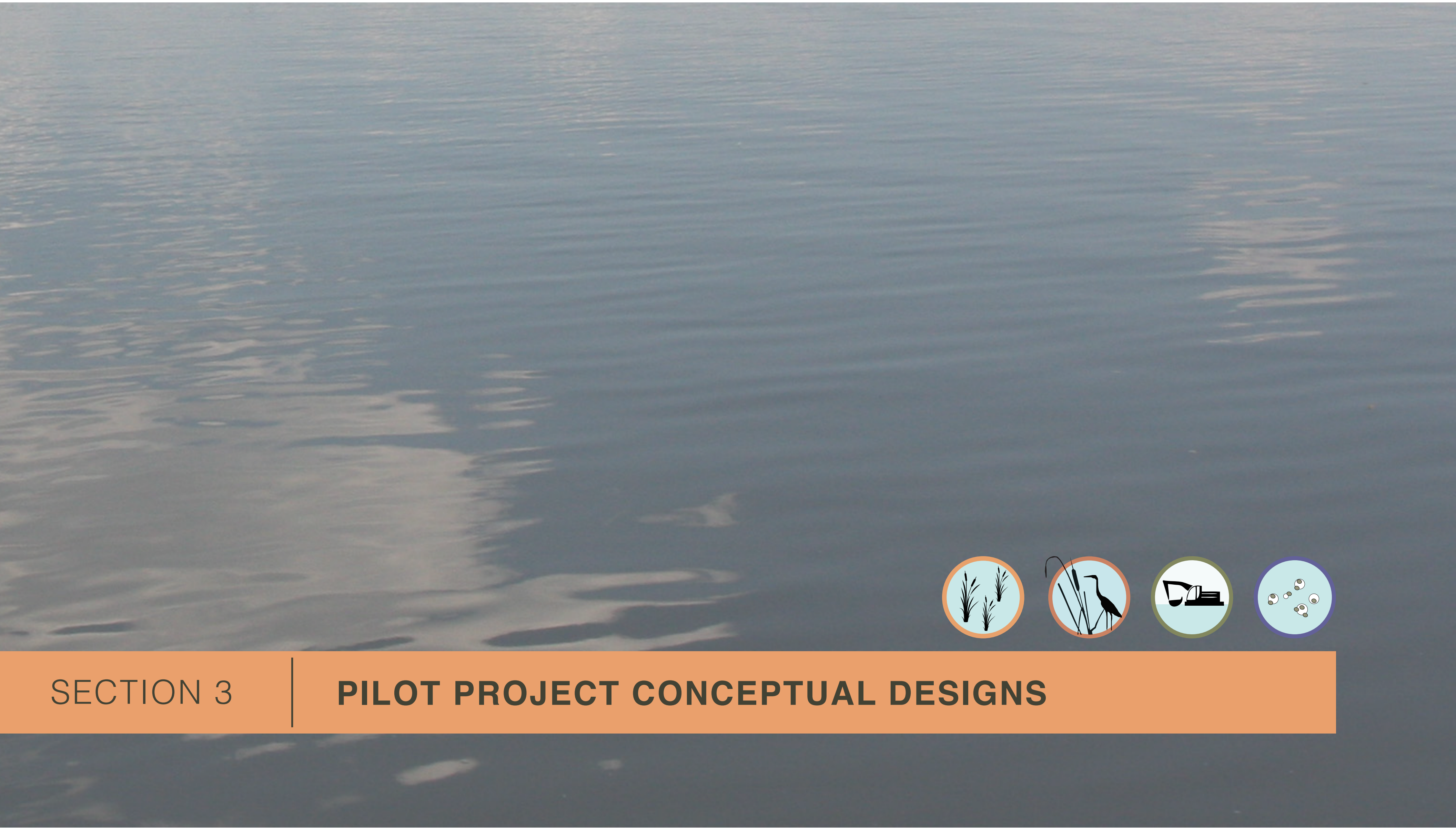
PROJECT TYPE		PROS	CONS	UNCERTAINTIES
TREAT SYMPTOMS				
ALGAL BIOMASS FILTRATION	Nutrient Removal & Water Quality Improvements	Directly removes oxygen demand from decaying algae, reducing nutrients (e.g., nitrogen, phosphorus) in the water column	External sources of nutrients are not addressed necessitating 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



SECTION 3 | PILOT PROJECT CONCEPTUAL DESIGNS

Fig. 3.1 (Above) Numerous low-lying areas and former wetlands in the Wood River Valley are connected through agricultural canals and drainage ditches. Photo: C. Anderson.

Fig. 3.2 (Below) West Canal in the Wood River Valley. Photo: Graham Matthews & Associates.

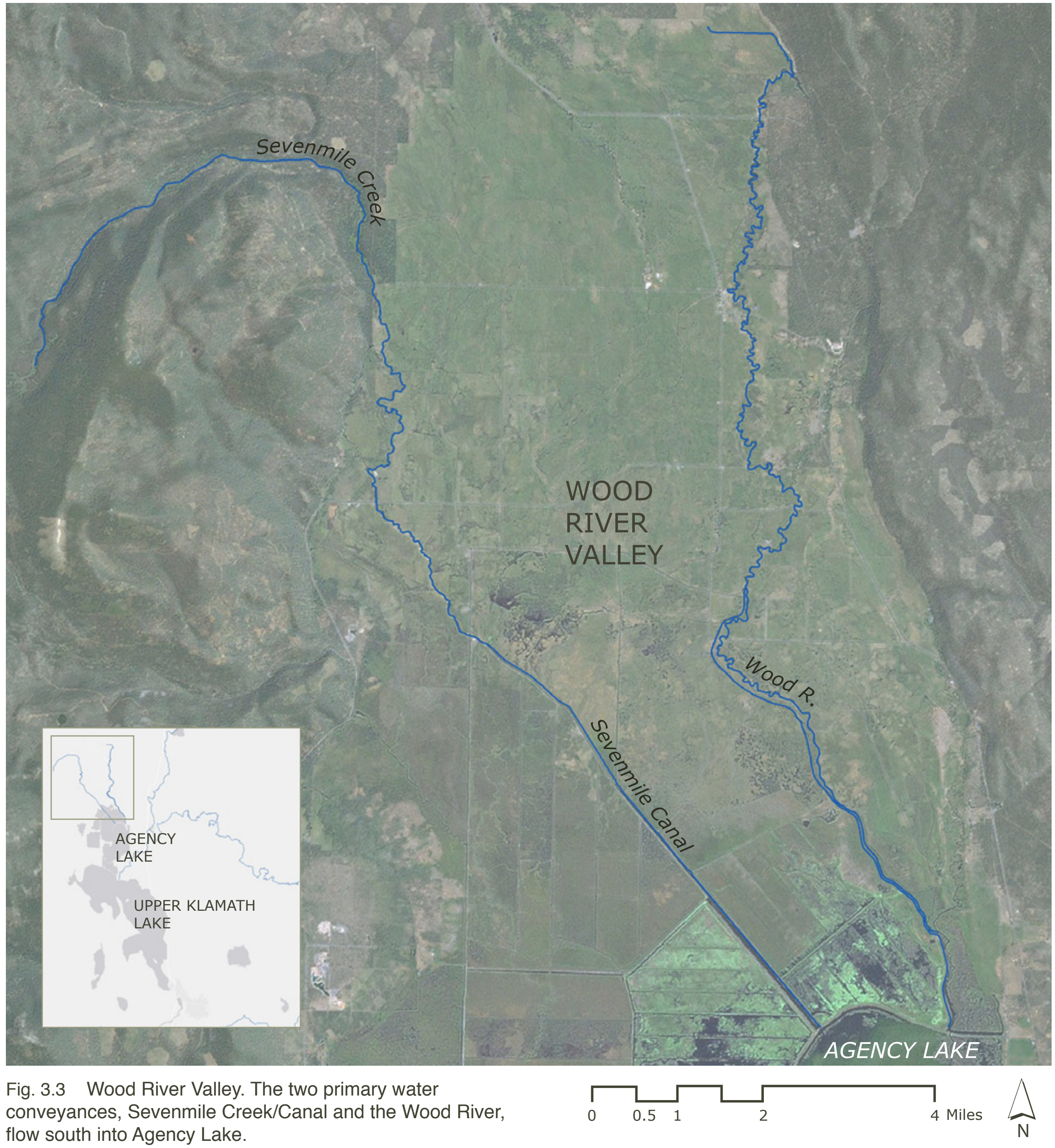


Fig. 3.3 Wood River Valley. The two primary water conveyances, Sevenmile Creek/Canal and the Wood River, flow south into Agency Lake.

WETLAND REHABILITATION

Conceptual designs for wetland rehabilitation in the Upper Klamath Basin are presented as two overarching types with the following general characteristics:

Diffuse source (decentralized) treatment wetlands (DSTWs)

- 1 to 10s of acres
- Wood and Sprague river valleys
- Water quality improvements
- Minimal earthwork, pumping, and infrastructure

Large wetlands

- 10s to 1,000s of acres
- Surrounding Upper Klamath and Agency lakes and along Keno Impoundment
- Water quality improvements
- Sucker habitat

DIFFUSE SOURCE (DECENTRALIZED) TREATMENT WETLANDS

Workshop recommendations related to DSTWs generally prioritized the Wood and Sprague river valleys (Section 2, pages 19-20), which contribute 21% and 23% respectively of the external total phosphorus load to Upper Klamath and Agency lakes.[1] This section presents a conceptual design for large-scale implementation of DSTWs in these watersheds that relies upon a generalized GIS analysis to identify potentially available land area and maximize treatment capacity. No individual parcels were identified for this conceptual-level analysis. This section also provides a conceptual design for two different types of pilot systems for these two watersheds.

OBJECTIVE - To evaluate the potential for large-scale removal of nutrients in the Upper Klamath Lake watershed, in order to decrease external loading of phosphorus and nitrogen to Upper Klamath and Agency lakes and decrease resulting nuisance algal blooms in these waterbodies.

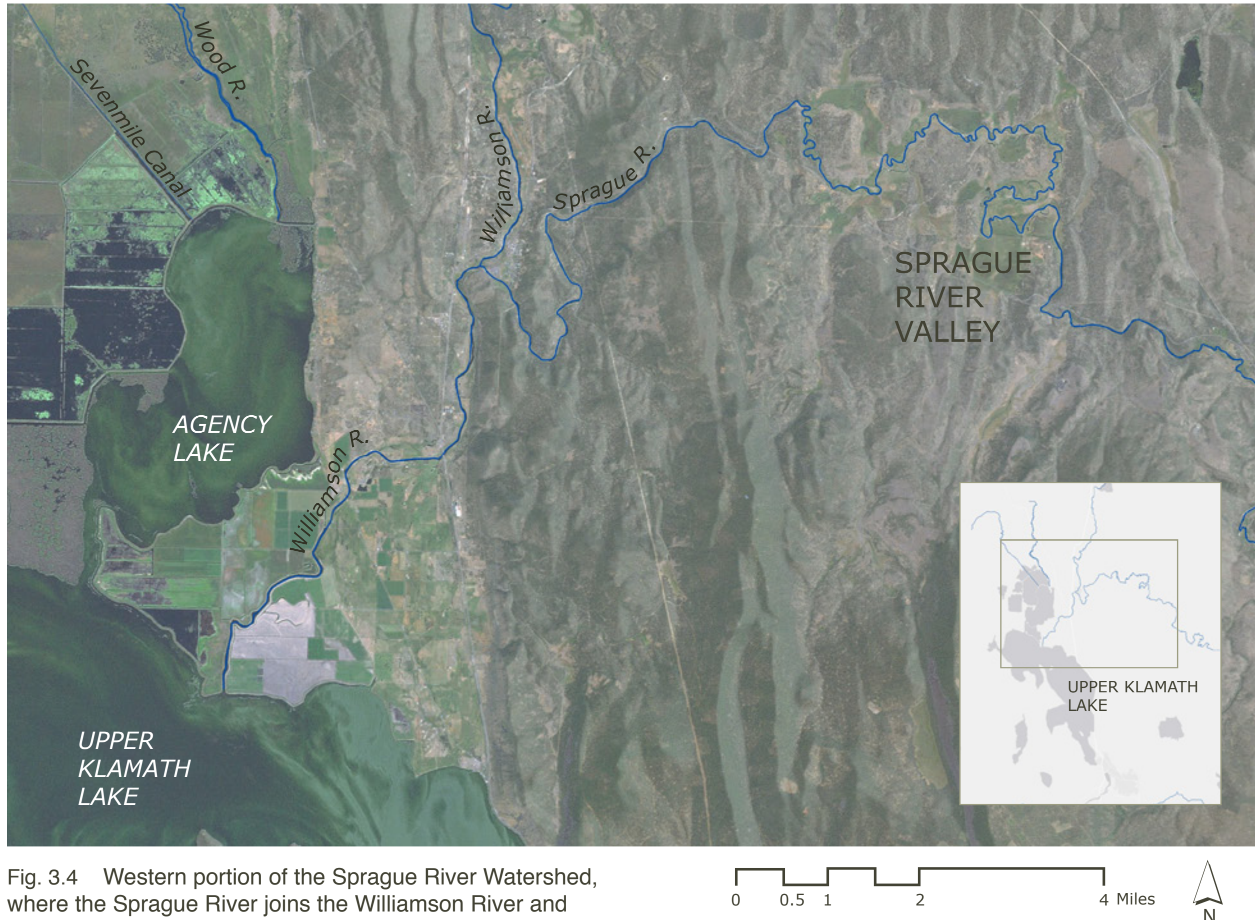


Fig. 3.4 Western portion of the Sprague River Watershed, where the Sprague River joins the Williamson River and empties into Upper Klamath Lake.

1 Walker et al. 2012

Watershed Characteristics

Wood River

The Wood River Valley is located on the northern end of Upper Klamath and Agency lakes, with a relatively small area of approximately 32,260 acres. Ranging in size from less than one to 7,100 acres, parcels in the Wood River Valley are primarily located in low-lying areas and former wetlands and are connected through numerous agricultural canals and drainage

DSTWs AND SPRAGUE RIVER RESTORATION

Numerous stream restoration projects have been conducted in the Sprague River Basin since the early- to mid-1990s, including fencing, wetland creation, floodplain reconnection, levee breaching, meander bend cutoff plugging, riparian planting, channel realignment, fish screens, spring reconnection, and wetland connection. A recent effort was undertaken to evaluate the performance of completed stream restoration projects in the basin, identify key lessons learned, and guide future project prioritization, planning, and design.[2] Based on this evaluation, several project types have the potential to contribute to basin wide restoration goals for the Sprague River. Of these, riparian expansion, floodplain reconnection, and floodplain modification project types hold the most promise for accommodation of DSTWs located along creeks and rivers because they involve actions such as levee removal/notching and wetland excavation that could support typical DSTW design features (see Figures 3.7 and 3.8).

In the Sprague River Basin, floodplain reconnection and modification projects are desirable because they possess a high magnitude and certainty of benefits and a low level of effort and/or number implemented in the basin,[2] consistent with characteristic features of DSTWs.

It is critical that DSTW design and implementation occur within existing Sprague River riparian and floodplain conceptual models, such that these systems do not interfere with the anticipated benefits of a properly functioning riparian corridor. For example, existing riparian conceptual models in the basin are based on seasonal inundation of wetlands during high flows, which, for DSTWs, would focus water treatment from December to May and would be a primary hydrologic design component.

DSTWs located outside of the riparian corridor and floodplain would not necessarily be subject to the same design considerations as those located within the riparian corridor. These DSTWs could potentially treat water during the low-flow period (June to October) when nutrient inputs can also be high.

Regardless, design and implementation of DSTWs in the Sprague River Basin would benefit from recommendations common to all of the stream restoration project types considered, including the use of basin-specific conceptual models, the development of tailored monitoring metrics and assessment approaches, and adaptive management.[2] Additionally, a targeted study to quantify the water quality benefits of a properly functioning riparian corridor in the Sprague River Basin would help identify to what degree additional treatment by DSTWs is needed to meet water quality goals.

2 NewFields River Basin Services and Kondolf 2012

ditches (Figures 3.1 and 3.2). These characteristics make the Wood River Valley an ideal location for DSTWs. The Wood River and the Sevenmile Creek[3] are the two primary water conveyances in the Wood River Valley (Figure 3.3). Preliminary GIS analysis indicates that roughly 16,000 acres of parcels in the Wood River Valley are bounded or crossed by one or both of these conveyances and approximately 42 miles of land is directly adjacent to the conveyances.

3 The creek becomes the Sevenmile Canal as it moves toward Agency Lake.

Fig. 3.5 A recent wetland restoration, Anderson Ranch, Sprague River Valley. Photo: River Design Group.

Sprague River

The larger Sprague River Valley is approximately 52,000 acres located on the north eastern side of Upper Klamath Lake (Figure 3.4). The Sprague River flows through constrained reaches and small river valleys on its path to the lake. In the small valleys, the river is sinuous, containing multiple bends and oxbows.[4] Here, given the “flashy” seasonal hydrology of the Sprague River, the river has opportunities to overflow its banks and sustain seasonal wetlands and wet meadows, sequestering natural phosphorus transported downstream with sediments during snow melt periods. Parcel sizes in the Sprague River Valley range in size from less than one acre to 20,000 acres. There are fewer canals and agricultural ditches bounding or crossing parcels in the Sprague River Valley as compared to the Wood River Valley. However, the total acreage of river-front, valley land along the Sprague River is still relatively large, at roughly 15,100 acres.[5]

4 Rasmussen 2012
5 This value is estimated using a 1,000 foot buffer on either side of the river.

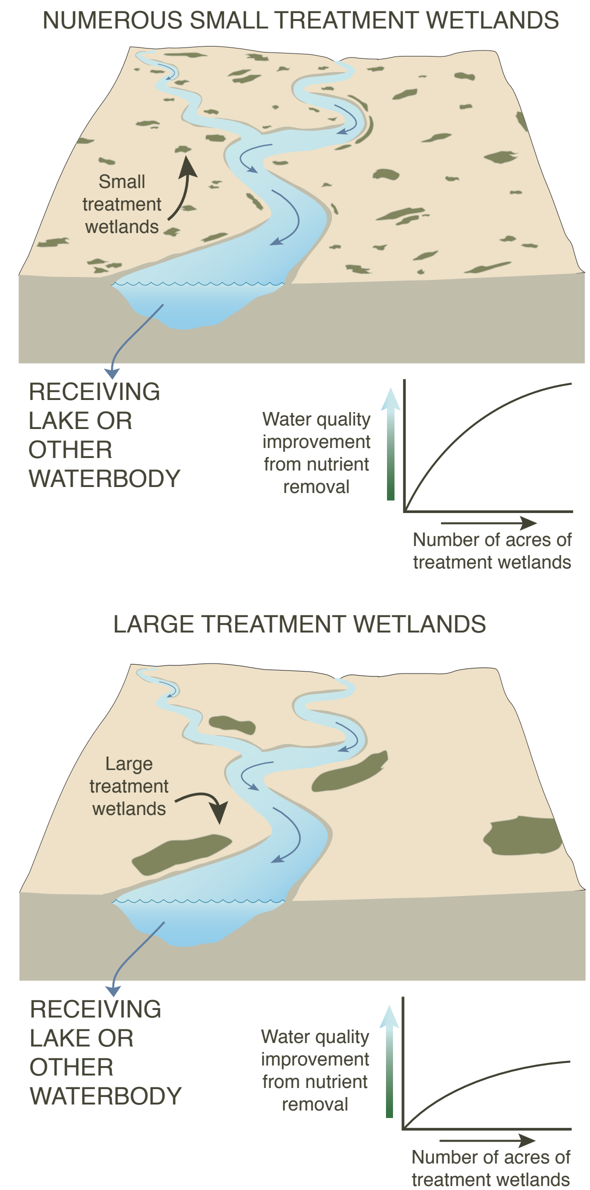


Fig. 3.6 Numerous small, distributed wetlands can have greater treatment potential than a few larger wetlands in the same watershed. Although generalized for illustration purposes in this figure, rates of removal for nitrogen and phosphorus would be different based on the specific removal mechanisms for each.

In the Sprague River Valley, recent projects have restored wetlands on private agricultural lands by removing levees to allow winter/spring time flooding of lands adjacent to the river banks (see text box on page 42).[6]

Pilot Project Conceptual Design

DSTWs are a network of relatively small pockets of wetlands distributed throughout the watershed (Section 2, page 18). In order to accomplish large-scale water quality improvement goals at the scale of the watershed, a sufficient cumulative acreage is required. For nitrogen removal, this is typically 1-2% of the total watershed area, but varies depending on treatment needs and local conditions.[7] Phosphorus removal can require relatively more area.[8] Theoretical consideration of typical wetland hydraulics and treatment potential suggests that for the same total area of wetlands, many smaller wetlands scattered throughout a watershed may be more efficient than a few larger wetlands in the same watershed (Figure 3.6).

Through the TMDL process, ODEQ has established an external loading target for total phosphorus in Upper Klamath and Agency lakes that would require a 40% reduction from current levels (Section 1, page 10). Available GIS information for the Upper Klamath Basin was used to consider the type, general location, and size of DSTWs in the Wood and Sprague river valleys that would contribute to a meaningful reduction in external phosphorus loading to the lake. No individual parcels were identified for this conceptual-level analysis.

6 K. Gorman (Oregon Division of Water Rights), personal communication, 2013.
7 Mitsch and Day 2006, Mitsch et al. 2011
8 Richardson et al. 2011

Types of Diffuse Source (Decentralized) Treatment Wetlands

Two different types of DSTWs were considered for implementation in the Wood and Sprague River valleys; *flow-through wetlands* and *terminal wetlands*. These are described in general terms below.

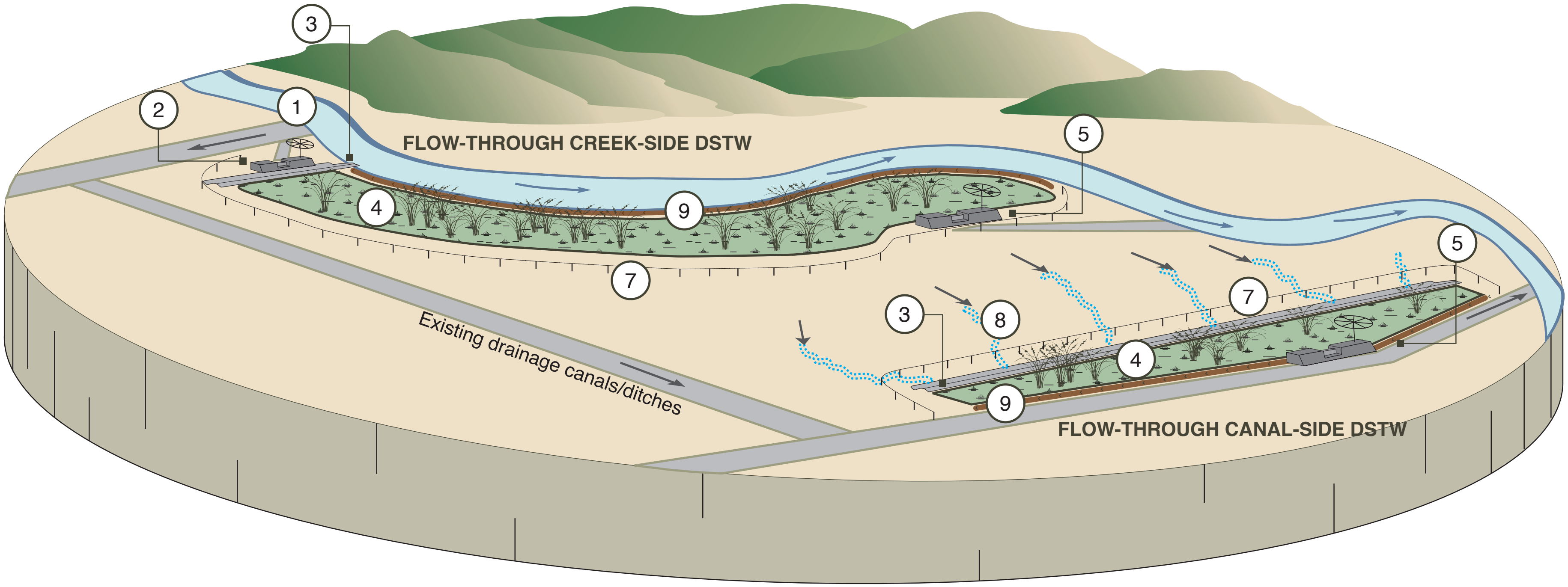
Flow-through DSTWs

Flow-through DSTWs rely on continuous flow for water treatment. By installing overflow weirs in appropriate locations, flow from rivers, creeks, canals, and fields can be diverted into adjacent low-lying areas, treated, and returned to a waterway. As with larger treatment wetlands, the required wetland area is linked to the amount of time water spends in the wetland. This is called *hydraulic residence time* (HRT) and is typically on the order of 2–5 days for these wetlands in order to reduce water losses (evapotranspiration) while still maintaining treatment and wildlife habitat values. The required area for individual flow-through DSTWs is determined using the relationship between wetland area, inlet flow, hydraulic residence time, and average water depth.

Flow-through DSTWs have a designated outflow and can be located along waterways and in naturally low-lying depressions in pastures and agricultural fields.

Nutrient reduction potential in flow-through wetlands is typically estimated using performance models reported in the scientific literature, where the potential to reduce sediment-associated pollutants such as total suspended solids, total phosphorus, and pathogens is based on particle settling time, and reduction for biochemical oxidation and nitrogen reduction processes is based on reaction time. One such model is called the "P-k-C* model" and is a model of

Fig. 3.7 Concept designs for flow-through creek-side and flow-through canal-side DSTWs.



1. **EXISTING POINT OF DIVERSION** - Water is diverted from the creek by way of existing drainage canals/ditches adjacent to or near the proposed site.
2. **OVERFLOW WEIR AND DIVERSION BOX** - Water flows over the weir and into the diversion box to control inflow. The diversion box can be shut off completely if necessary.
3. **DISTRIBUTION TRENCH** - Constructed at the head of the wetland, the distribution trench ensures the water is 4 feet deep and at right angles to the direction of flow.
4. **VEGETATION** - DSTW is planted with primary species such as cattail (*Typha spp.*), bulrush (*Scirpus spp.*), bur-reed (*Sparganium eurycarpum)*, and spike rush (*Eleocharis spp.*) for water treatment; secondary species such as pond lilies (*Nuphar lutea* ssp. *polysepala*) for food and habitat.
5. **ADJUSTABLE DISCHARGE WEIR** - Maintains water levels in the vegetated area at 2 feet or less for a system with a designated discharge.
6. **LEVEL CONTROL STRUCTURE** - Maintains water levels in the vegetated area at 2 feet or less for a terminal system.
7. **EXCLUSION FENCING** - Keeps grazing animals out of the wetlands.
8. **VEGETATED SWALE** - Diverts run-off from higher elevations on the parcel.
9. **EARTHEN BERMS** - Generally to be avoided, since the site is likely to be wet and difficult to work with using typical earth moving equipment. If required, berms should have two feet of freeboard and should be higher at the discharge end of the wetlands.

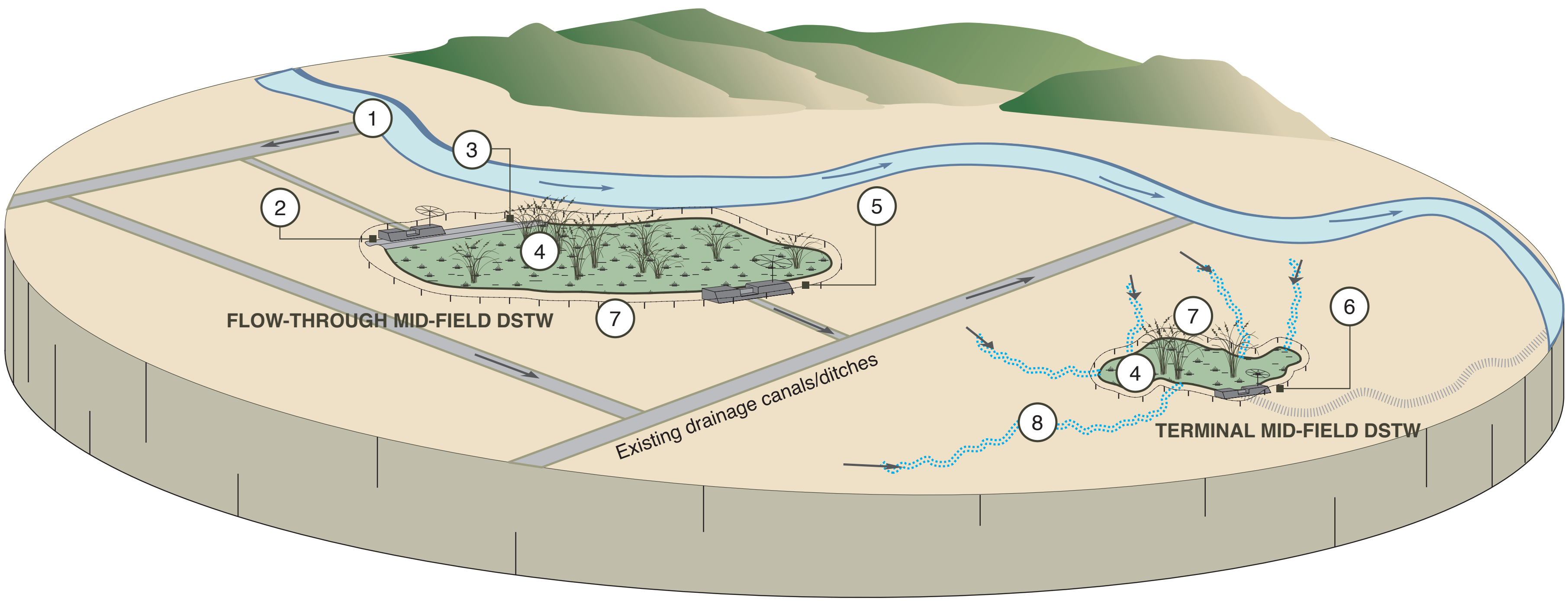


Fig. 3.8 Concept designs for flow-through mid-field and terminal mid-field DSTWs.

central tendency for nitrogen and phosphorus outlet concentrations for treatment wetlands.[9] Estimates of wetland evapotranspiration and groundwater seepage for typical flow-through wetlands are also available in the scientific literature.

Terminal DSTWs

Terminal DSTWs are located in naturally low-lying depressions in pastures and agricultural fields and do not have a designated outflow. These wetlands are designed to mimic the natural variability in water depth and areal extent of wetlands dependent on runoff. For this type of application, DSTWs can be conceived of as vegetated detention basins, designed on the basis of estimated runoff. The required wetland area is determined using annual rainfall, parcel area, a runoff coefficient, and annual evapotranspiration. The resulting wetland area tends to be on the order of 1 to 2% of the parcel area.[10]

Nutrient reduction potential in terminal wetlands is typically estimated using performance models developed for a "batch" system, or a system lacking a designated outflow.[11]

9 Kadlec and Wallace 2009

10 Michael Ogden (NSI/Biosystems), personal communication, 2013.

11 Kadlec and Wallace 2009

General Location of Diffuse Source (Decentralized) Treatment Wetlands

In the Wood River and Sprague River valleys, flow-through DSTWs would be located in the following two general locations:

Creek/Canal-side Sites

DSTWs located along the primary water conveyances would be flow-through systems sized to maximize waterway frontage and elevation difference between system inlet and outlet. Where possible, the wetland cells would be relatively long and narrow, supporting gravity flow through the wetlands and minimizing the need for pumping. Direct diversion from the creek or canal into this type of DSTW may not be feasible

TABLE 3.1 - CONCEPTUAL DESIGN ELEMENTS FOR DSTWS

DESIGN ELEMENT	FLOW-THROUGH CREEK/ CANAL-SIDE AND MID-FIELD	TERMINAL MID-FIELD
Water treatment period	Diversion season	Year round
Habitat period	Year round	
DSTW inflow and outflow rates	0.5-2 cfs	0.01-0.5 cfs (no designated outflow)
Hydraulic residence time	2 - 5 days	> 5 days
Width	Variable	
Length	As needed to meet minimum 10:1 length:width aspect ratio	Variable
Water depth	2 - 2.5 feet	
Consumptive use due to evapotranspiration[12]	2-3 feet per acre per year (April-October)	
Nitrogen removal rate[13]	35 m/yr (April-October) 15 m/yr (November-March)	
Phosphorus removal rate[13]	20 m/yr (April-October) 10 m/yr (November-March)	

12 Typical wetland evapotranspiration losses in the Upper Klamath Basin: 1.7 feet per acre for May - October (Bidlake 2002); 2.6 to 2.9 feet per acre annually (emergent vegetation and seasonal wetland) (Risley and Gannett 2006); 2.2 to 2.3 feet per acre for May-September (Stannard et al. 2013).

13 Rates are generalized from Kadlec and Wallace (2009). Wetland performance models are sensitive to k values and site-specific rates should be developed during pilot studies.

due to water availability challenges. Instead, irrigation water could be collected on-site through existing small agricultural drains and treated prior to tailwater/ effluent discharge from the DSTWs. Common design elements, including target width, length, and water depth for wetland cells are presented in Figure 3.7 and Table 3.1; however, wetland cell orientation along the creek/canal would be dependent on local topography and the pre-existing point of diversion for a given site.

Mid-field Sites

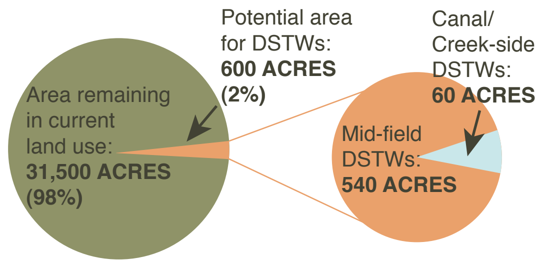
DSTWs located in natural low-lying areas in existing pastures or fields that support the hydrology, vegetation, and soils characteristic of wetlands would be either flow-through or terminal systems, depending on site characteristics (see Figure 3.8). The dimensions of each DSTW would be variable and based on local conditions to minimize the need for earthmoving, pumping, and exclusion fencing. The mid-field, flow-through DSTWs would be designed for a target hydraulic residence time, so cell dimensions would, where possible, achieve the target width, length and depth values presented in Table 3.1.

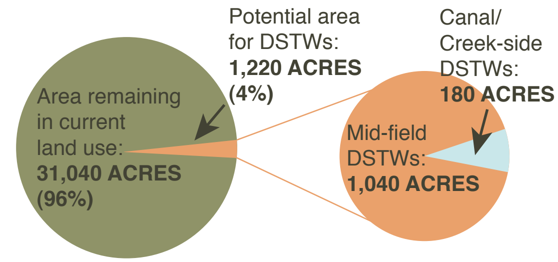
Potential Area and Treatment Capacity for DSTWs

A generalized GIS analysis of the Wood River Valley indicates that DSTWs sized at 10 acres or less using design elements presented in Figures 3.7 and 3.8, could theoretically represent a maximum potential cumulative area of 600 acres (Figure 3.9). This analysis assumes that for any given parcel, a theoretical maximum of 5% of the existing land use would be converted to a DSTW, regardless of the parcel size. While not an established regulatory threshold, the 5% assumption represents a “small amount", which, in the case of an actual project would minimize the requirement to transfer an existing water right for irrigation or agricultural use to a wetland use (see text box on page 48). For the creek/canal-side DSTWs, approximately 60 acres in the Wood River Valley are theoretically available for this purpose, not including lands that recently have been or may soon be enrolled in programs such as the NRCS Wetland Reserve Program (WRP). The majority of DSTW acreage (540 acres) would be mid-field systems scattered throughout the valley (Figure 3.9). Typical DSTW size would be 5-6 acres. For the valley as a whole, 31,500 acres or 98% of the existing land use would remain the same.

To project annual nutrient removal for an individual DSTW, the removal rates for April-October and November- March (Table 3.1) can be used. Summing the estimates across 600 acres suggests that a roughly 5-20% cumulative annual reduction of phosphorus and a roughly 5-15% cumulative annual reduction of nitrogen would be possible for the valley, depending on the relative amounts of flow-through and terminal DSTWs (Figure 3.11). The corresponding cumulative flow reduction from the adjacent waterways would be just over 3%, based on estimated evapotranspiration losses (calculations are shown in Appendix B).

Including wetlands greater than 10 acres in size, but still maintaining a theoretical land use conversion for individual parcels of no more than 5%, would expand treatment potential and wildlife habitat by increasing the potential cumulative wetlands area to 1,220 acres or 4% of the Wood River total valley area. This would support approximately 180 acres of creek/canal-side DSTWs, where the average wetland would be just over 10 acres in size. The majority of DSTW acreage (1,040 acres) would be mid-field





For any given parcel, a theoretical maximum of 5% of the existing land use would be converted to DSTWs, regardless of the parcel size. No individual parcels were identified for this conceptual design.

Fig. 3.9 (Above left) Potential area in the Wood River Valley for DSTWs assuming all wetlands are less than or equal to 10 acres in size.

Fig. 3.10 (Above right) Potential area in the Wood River Valley for DSTWs assuming wetlands of any size.

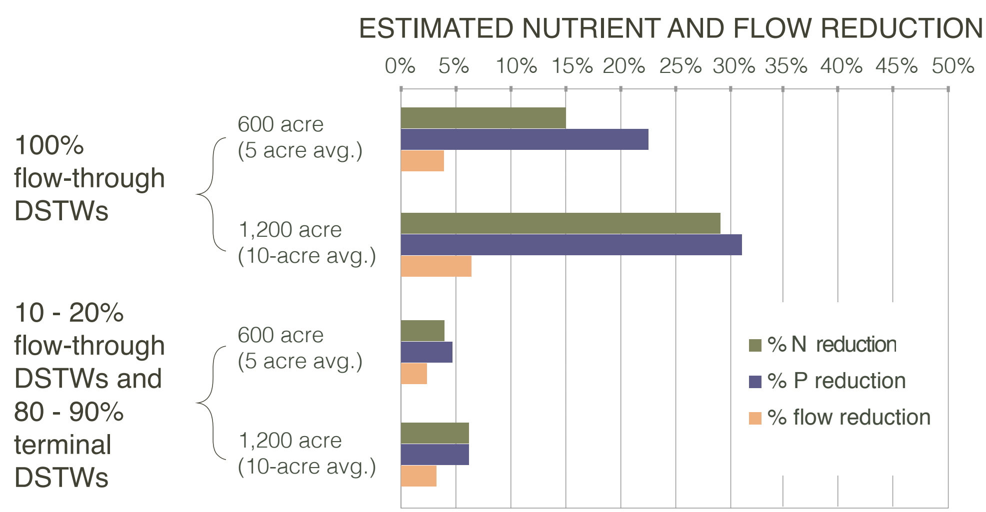


Fig. 3.11 Estimated annual reduction in nutrients and creek/canal flow for DSTWs in the Wood River Valley (see Appendix B for detailed calculations).

WATER RIGHTS

Anticipated water right requirements for creation of creek/canal-side and mid-field DSTWs in the Upper Klamath Basin are presented in Table 3.2. It is assumed that DSTWs would treat water primarily during the irrigation season (May – September) when water quality conditions in the basin are most in need of improvement. However, treatment outside of the irrigation season may be possible if existing parcel water rights support year-round water use. This would allow treatment of the first flush storm event, which would be particularly important for phosphorus removal.

Measured wetland evapotranspiration rates range 0.6 to 1.1 times those of pasture and cropland,[14] meaning that conversion from an irrigation water use to a wetland water use could either slightly decrease or increase overall consumptive water use for a given parcel. However, if land conversion to DSTWs remains at or less than 5% of the total parcel area, any net change in consumptive water use would be correspondingly small and would not likely require a change in the existing water right. For DSTW conversions greater than a small percentage of the total parcel area, additional land may need to be removed from irrigation such that no net increase in consumptive use occurs for a particular parcel and its associated water right. A partial or full water right transfer may be necessary for this situation, depending on the amount of area to be converted to DSTW.

14 Cuenca et al. 1992, Bidlake 2002, Risley and Gannett 2006, Stannard et al. 2013

TABLE 3.2 - ANTICIPATED WATER RIGHTS REQUIREMENTS FOR DSTWs

DSTW TYPE	REQUIREMENT
Creek/Canal-Side	
Flow-through	No water right transfer if wetland is a small fraction of total parcel area
Mid-field	
Flow-through	No water right transfer if wetland is a small fraction of total parcel area
	Partial to full water right transfer depending on how much area is used as a wetland. No net increase in consumptive use.
Terminal	No water right transfer if wetland is a small fraction of total parcel area
	Partial to full water right transfer depending on how much area is used as a wetland. No net increase in consumptive use.

systems and the valley as a whole would support 31,040 acres or 96% of existing land uses (Figure 3.10).

Increasing the area of flow-through wetlands by including wetlands greater than 10 acres in size would increase cumulative annual phosphorus and nitrogen reduction to roughly 5-30% in the Wood River Valley. However, this scenario may also increase flow reduction in the creeks/canals to values on the order of 3-7% (Figure 3.11) (calculations are shown in Appendix B).

Pilot Project Sites

The pilot project would establish proof-of-concept test sites for both DSTW types—flow-through and terminal (Table 3.3). Test sites would be identified and implemented in the Wood River Valley over a period of five years, to allow for site selection, permitting, construction and operation (Figure 3.14). The pilot sties would be used to test the efficacy of design elements, nutrient removal performance, and the potential for unintended consequences such as invasive species and mosquitos.

TABLE 3.3 - PROOF OF CONCEPT TEST SITES FOR DSTWs

DSTW TYPE	NUMBER OF TEST SITES FOR PILOT PROJECT
Creek/canal-side flow-through	2
Mid-field flow-through	2
Mid-field terminal	2

Prior to development of final site designs, the capacity of the soil to bind or adsorb phosphorus would be determined at each DSTW pilot site using an

LOW INTENSITY CHEMICAL DOSING (LICD)

LICD systems can be used in existing stormwater basins and wetlands to make them more effective at removing phosphorus from waters. LICD involves the addition of small amounts of coagulants to waters in wetlands or stormwater treatment systems. Coagulants are important for a variety of human uses and can be applied in a safe way. LICD coagulants are typically aluminum-based, iron-based, or a type of organic chemical called a polymer that contains almost exclusively carbon and hydrogen. The coagulants cause dispersed particles in a liquid to come together and form a larger particle called a "floc" (see also Figure 2.23). The floc, a soft, semi-solid, or solid mass, settles out of the water column and becomes a part of the wetland sediments. For LICD, small doses of coagulants are used to minimize costs and to avoid the potential for toxicity to aquatic species.

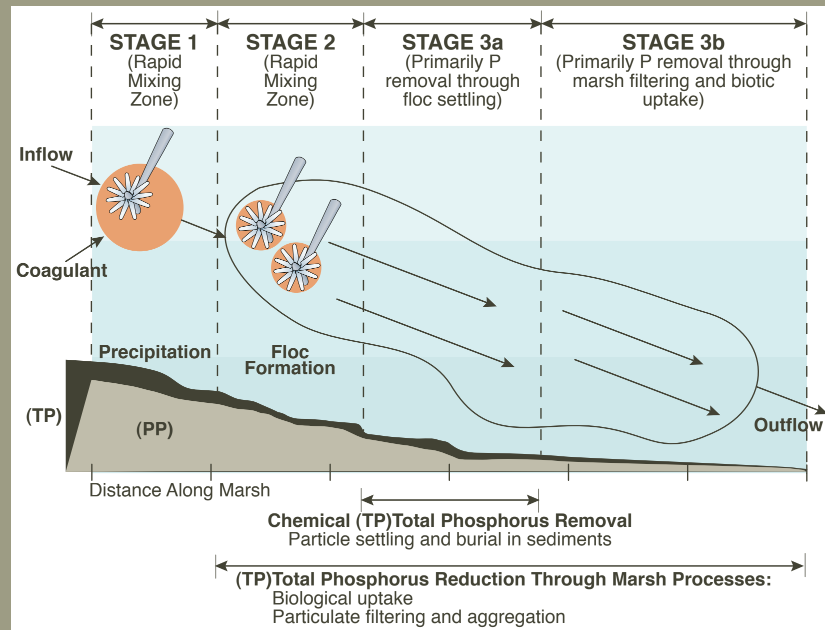


Fig. 3.12 (Left) Phosphorus removal stages for a storm water basin or wetland in the Lake Tahoe basin, California, using LICD. STA = storm water treatment area. Source: Bachand et al. 2006.

Fig. 3.13 (Below) LICD wetland system for enhanced removal of dissolved organic carbon and mercury in the Sacramento-San Joaquin River Delta, California. Photo: Philip Bachand.

LICD can enhance the removal of phosphorus in wetlands where incoming phosphorus is either dissolved in the water or attached to tiny sediment particles that are suspended in water. LICD systems have recently been tested for removal of phosphorus and fine sediments in stormwater in the Lake Tahoe basin, California. Studies found that existing stormwater basins and wetlands, could be more effective when used with LICD.[15] Initial tests of potential toxicity due to coagulant dosing showed no effect on algae or fish test species compared to Lake Tahoe basin stormwater.[16] Coagulant dosing increased chronic toxicity to zooplankton, which may have been due to specific test conditions or the kind of coagulant used (polyaluminum chloride). LICD systems are also being tested in the Sacramento-San Joaquin River Delta for enhanced removal of dissolved organic carbon and mercury in wetlands (Figure 3.13).

15 Bachand et al. 2010

16 Lopus et al. 2009

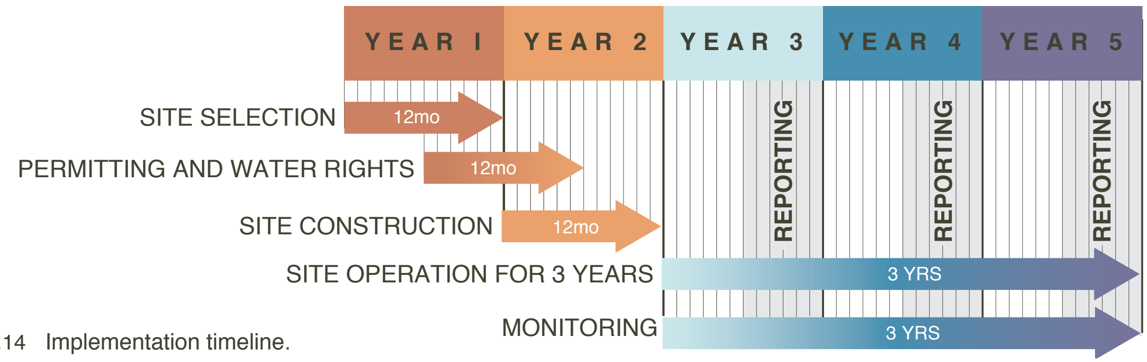


Fig. 3.14 Implementation timeline.

established testing procedure called a Langmuir isotherm test.[17] Based on testing results, the need for soil amendments such as limestone, gypsum, or zeolite minerals, or low intensity chemical dosing (LICD) using aluminum- or iron-based coagulants to increase the efficiency of phosphorus removal (see text box on page 49), would be determined for each DSTW. If an increase in phosphorus removal efficiency is warranted, then the pilot study would be adjusted to include design features such as an equalization basin and/or a coagulant dosing area prior to the DSTW inflow (Bachand et al. 2006).[18] The cost of the enhanced DSTW design would be balanced against the cost per mass phosphorus removed.

At each test site, the following parameters would be monitored on a monthly basis:

- Inflow/outflow quantity (for flow-through systems)
- Water depth
- Water temperature, conductivity, dissolved oxygen, pH, oxidation-reduction potential
- Total suspended solids (TSS), bacteria (fecal coliform, *E. coli*)
- Nitrogen (total, nitrate, and ammonium for flow-through systems)
- Phosphorus (total and ortho-phosphorus for flow-through systems)
- Vegetation cover by species
- Mosquito presence/absence

Wetland nutrient removal performance would be calculated using inflow and outflow quantity and nutrient concentrations. If soil amendments or LICD are incorporated into the pilot DSTW design, concentrations of the coagulant of choice would also be measured at the inlet and outlet of the wetland along with the other water quality parameters.

Environmental, Regulatory and Permitting Requirements

The following permits would be required for the pilot project:

- Water rights transfer through Oregon Division of Water Rights, as needed
- Water Quality Certification from Oregon Department of Environmental Quality (ODEQ)
- Oregon Department of State Lands Standard Exemption for certain voluntary habitat restoration projects (if DSTW creation would involve less than 50 cubic yards of removal-fill volume) or a General Authorization (if DSTW would involve more than 50 cubic yards)[19]

Implementation Timeline and Estimated Costs

The anticipated timeline for implementing the conceptual design for a DSTW pilot project spans approximately 3 years (Figure 3.14). Estimated costs for a pilot project are presented in Table 3.4.

TABLE 3.4 - ESTIMATED COSTS FOR PILOT STUDY INCLUDING SIX APPROXIMATELY 1-ACRE DSTW PILOT SITES

Final site selection[20]	$10 - 15K
Permitting and water rights[21]	$20 - 30K
Sites construction[22]	$60 - 75K
Sites operation for 5 years[23]	$9 - 10K
Monitoring[24]	$120 - 130K
Total	**$230 - 270K**

17 Bachand and Heyvaert 2005
18 Bachand et al. 2006

19 A permit from the U.S. Army Corps of Engineers (USACE) would only be necessary if a DSTW project is connected to a navigable water, which is not anticipated.
20 Includes landowner coordination, 1-2 site visits per site, and $10-12K for soil sampling and analytical determination of soil capacity to bind or adsorb phosphorus.
21 Assumes only partial or no water rights transfers needed and standard exemptions for state lands permits apply for all sites.
22 Cost estimate includes site survey, diversion box, level control, minimal earthwork, planting, and exclusion fencing for each site.
23 Assumes $300/acre/year for operation and maintenance at each site.
24 Includes field data collection and laboratory analysis cost estimates across all sites. No reporting costs included.

LARGE WETLANDS

Workshop recommendations related to rehabilitation of large wetlands surrounding Upper Klamath Lake and along the Keno Impoundment were generally supportive, since wetlands would provide water treatment as well as fish and wildlife habitat, with a relatively low degree of infrastructure challenges and energy use. In addition, workshop participants ranked wetland rehabilitation as having a high degree of synergy with other restoration projects and technologies being considered in the Klamath Basin, with a particular emphasis on rehabilitation of habitat for the endangered shortnose and Lost River suckers (Section 2, pages 19-20). This section describes conceptual pilot studies for large wetland rehabilitation projects at three locations in the Upper Klamath Basin: on the margins of Upper Klamath and Agency lakes, along the Keno Impoundment, and along the Klamath Straits Drain. The level of detail presented for each conceptual design is a reflection of the amount of readily available information for the three considered locations.

OBJECTIVE - To evaluate the potential for large-scale removal of nutrients and habitat rehabilitation using large (10s to 1,000s of acres) wetlands in the Upper Klamath Basin in order to decrease external loading of phosphorus and nitrogen to downstream water bodies, decrease nuisance algal blooms, increase general water quality (i.e., dissolved oxygen), and provide habitat for the endangered shortnose and Lost River suckers.

EXISTING WETLANDS

Existing large wetland rehabilitation projects along the Upper Klamath Lake and Agency Lake shorelines, such as the Wood River Wetland (Figure 3.15) and the Williamson River Delta (Figure 3.16) are generally managed for water storage, subsidence reversal and/or wildlife habitat (Table 2.1 and Figure 2.6). Water quality improvement is a secondary, albeit important, management goal, with recent data indicating that nutrient retention is occurring at the Wood River Wetland,[25] the Williamson River Delta,[26] and the Upper Klamath Lake National Wildlife Refuge. The Fourmile Canal property, just under 1,900 acres in size, is located along the northern edge of Agency Lake and was recently acquired by The Nature Conservancy for the purposes of wetland restoration. Design planning for this site is currently underway. While these existing wetland systems already meet the majority (if not all) of the physical siting requirements for treatment wetlands and would not require additional land acquisition or water rights allocations, major changes to physical conditions (e.g., changes in the ratio of open water to vegetated stands, use of supplemental techniques to enhance nutrient removal) or management approaches (e.g., flood frequency, water depth) to accommodate increased water treatment efficiency may not be compatible with current habitat goals. For this reason, existing large wetland rehabilitation projects, including the Wood River Wetland, Williamson River Delta, Fourmile Canal, Upper Klamath National Wildlife Refuge, Miller Island National Wildlife Refuge, and the Lower Klamath National Wildlife Refuge, are excluded from this conceptual design until their dual habitat and water treatment values are more fully determined.

Fig. 3.15 The Wood River Wetland, post-restoration in 2011. Photo: Andy Hamilton, BLM.

Fig. 3.16 The Williamson River Delta following flooding as a restoration measure in 2012. Photo: Chauncey Anderson, USGS.

25 Hamilton 2011
26 Wong et al. 2011, Hayden and Hendrixson 2013

SUCKER HABITAT REQUIREMENTS

Shortnose and Lost River suckers utilize a variety of aquatic habitats in Upper Klamath Lake and its tributaries during different times of the year, and their habitat needs vary by life stage. Sub-adult and adult suckers seek deeper water than younger fish, generally occupying water depths of 3 feet or deeper (Figure 3.17). They are generally limited to lake habitats when not spawning, although small river-resident populations have been documented. During the months of February through May, adult suckers migrate from the deep, quiescent waters of Upper Klamath Lake into the faster flowing waters of Upper Klamath Lake tributaries to spawn. Areas with gravel bottoms are preferred spawning habitat.[27] A significant number of Lost River suckers also spawn over gravel substrates at shoreline springs along the margins of Upper Klamath Lake. [28]

From roughly April to July, larval suckers are dispersed by currents from their hatching areas to shallow (0.5-1.5 feet deep) waters along the shoreline of Upper Klamath Lake (Figure 3.18). They seek habitat in or near emergent wetland vegetation, which provides cover from predators, protection from currents and turbulence, and abundant food for the growing fish.[29] Juvenile suckers also utilize a wide variety of near-shore habitat, including emergent wetlands and non-vegetated areas as they grow and slowly migrate off-shore (Figure 3.17).

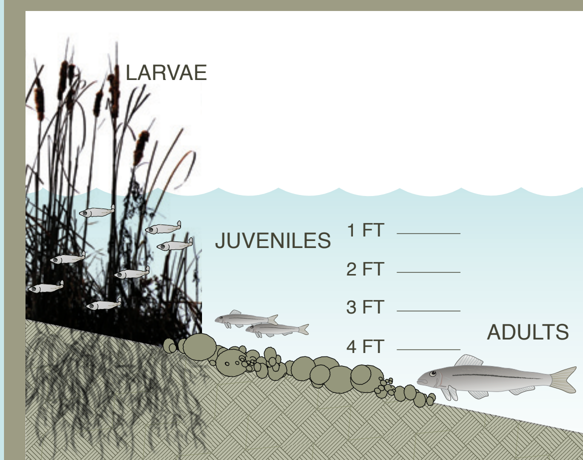


Fig. 3.17 Simplified schematic of habitat use by different sucker life stages. Source: USFWS 2008.

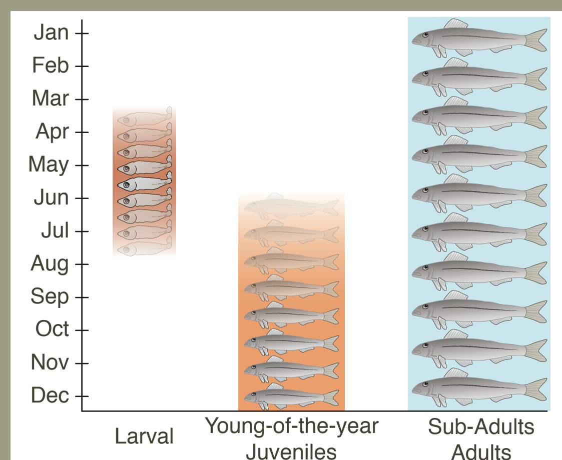


Fig. 3.18 Presence of sucker critical lifestages in Upper Klamath Lake by month. Larval and first year young-of-the-year juveniles are only present during certain months. Source: USFWS 2008.

27 USFWS 2008
28 USFWS 2011
29 USFWS 2008

Wetlands on the Margin of Upper Klamath and Agency Lakes

Site Characteristics

The target area for large wetlands in the Upper Klamath Basin is located along the shores of Upper Klamath and Agency lakes. The target area was chosen for the following reasons:

- Several large parcels of land in the target area are previously drained wetlands[30] that possess hydrology and soils characteristics of these ecosystems. In the long term, the reconnection of these wetlands to the lake would provide rehabilitated habitat for larval and juvenile suckers,[31] as well as peat accumulation and nutrient accumulation.[32]
- Several parcels in the target area currently possess surface water diversions for irrigation use and given landowner willingness, these sites may be eligible for water rights transfer to wetland use during the irrigation season.

The proposed pilot site is located along the west shoreline of Agency Lake near the mouth of Sevenmile Canal and the Wood River (additional site description is provided on page 66).

The location of the Agency Lake Ranch and Barnes Ranch parcels near the mouth of the Wood River and along the Agency Lake shoreline offers the potential for rehabilitation of larval and juvenile sucker rearing habitat during spring and summer months (see text

30 Wood et al. 2009
31 USFWS 2008
32 Lindenberg and Wood 2009

box on page 52), as well as refuge habitat for adult and subadult suckers to avoid extreme poor water quality in Upper Klamath Lake during July through September.[33] Agency Lake Ranch and Barnes Ranch are also included in the conceptual design for targeted dredging of Upper Klamath Lake sediments (Section 3, pages 65-71), whereby the parcels would receive dredged lake sediments to increase the elevation of subsided areas for habitat improvement and for levee maintenance.

Pilot Project Conceptual Design

Pre-project Surveys

Prior to wetland construction, review of existing bathymetric and LiDAR data, existing inlet and outlet structures, agricultural canals/ditches, and associated berms/levees for the Agency Lake Ranch and Barnes Ranch parcels would be conducted to ensure that conceptual habitat and water treatment design elements can be supported.

Additionally, as described for the DSTWs, site-specific soil testing would be conducted to determine the potential need for soil amendments or LICD (see text box on page 49) to increase the efficiency of phosphorus removal. If an increase in phosphorus removal efficiency is warranted, then the conceptual design would be adjusted to include design features such as an equalization basin and/or a coagulant dosing area prior to the treatment cell inflow. The cost of the enhanced phosphorus removal design would be balanced against the cost per mass of phosphorus removed. Additionally, testing would be included to determine the potential for soil expansion upon re-wetting and, if warranted, account for an adjusted soil volume in the final design of wetland terraces/slopes.

TABLE 3.5 - WETLAND ZONES FOR A TERRACED/SLOPED WETLAND REHABILITATION CONCEPTUAL DESIGN ON THE MARGINS OF UPPER KLAMATH AND AGENCY LAKES

TERRACED/ SLOPED WETLAND ZONE	SUCKER LIFESTAGE SUPPORTED	WATER TREATMENT POTENTIAL	AVERAGE WATER DEPTH (FT)	PERCENT OF TOTAL WETLAND AREA	VEGETATION TYPE/ SUBSTRATE
Zone 1	Larvae	High	0.5	10%	Emergent aquatic (e.g., bulrush, cattail), fine sediment
Zone 2	Larvae, juveniles		1.5	10%	Emergent aquatic (e.g., bulrush, cattail), fine sediment to small gravel
Zone 3	Juveniles		2.5	20%	Emergent aquatic (e.g., bulrush, cattail), small gravel
Zone 4	Subadults, adults	Moderate	3.5	30%	None, small gravel to fine sediment
Zone 5	Subadults, adults	Low	>3.5	30%	

Design Elements

Terraced or gradually sloped wetlands can be an efficient way to meet the dual objectives of water treatment and habitat improvement for shortnose and Lost River suckers, given that different life stages require particular water depths and vegetation cover (Figure 3.17). Maximum water treatment efficiency in wetlands typically occurs at 2-2.5 ft water depth, which supports dense growth of emergent aquatic vegetation such as cattail and bulrush and overlaps with known habitat needs for juvenile suckers.

In order to maximize habitat availability and treatment efficiency in the rehabilitated wetland, re-contouring of the sediment surface would be undertaken to create terraced or gradually sloped zones, each with a different design water depth (Table 3.5). It is anticipated that some degree of sediment augmentation would be required to support differing water depths, which is primarily due to the amount of subsidence that has occurred at many parcels surrounding Upper Klamath and Agency lakes, including at the pilot site. The conceptual design assumes an average subsidance depth of 3-4 feet across the entire pilot site, which would need to be confirmed through review of existing bathymetric and LiDAR data. Currently, lake levels vary by 3-5 feet annually, with the highest levels in April/May and the lowest levels in October/November.[34] Larval suckers tend to move into shoreline rearing habitat from April through July (see text box on page

33 USFWS 2011

34 USFWS 2008

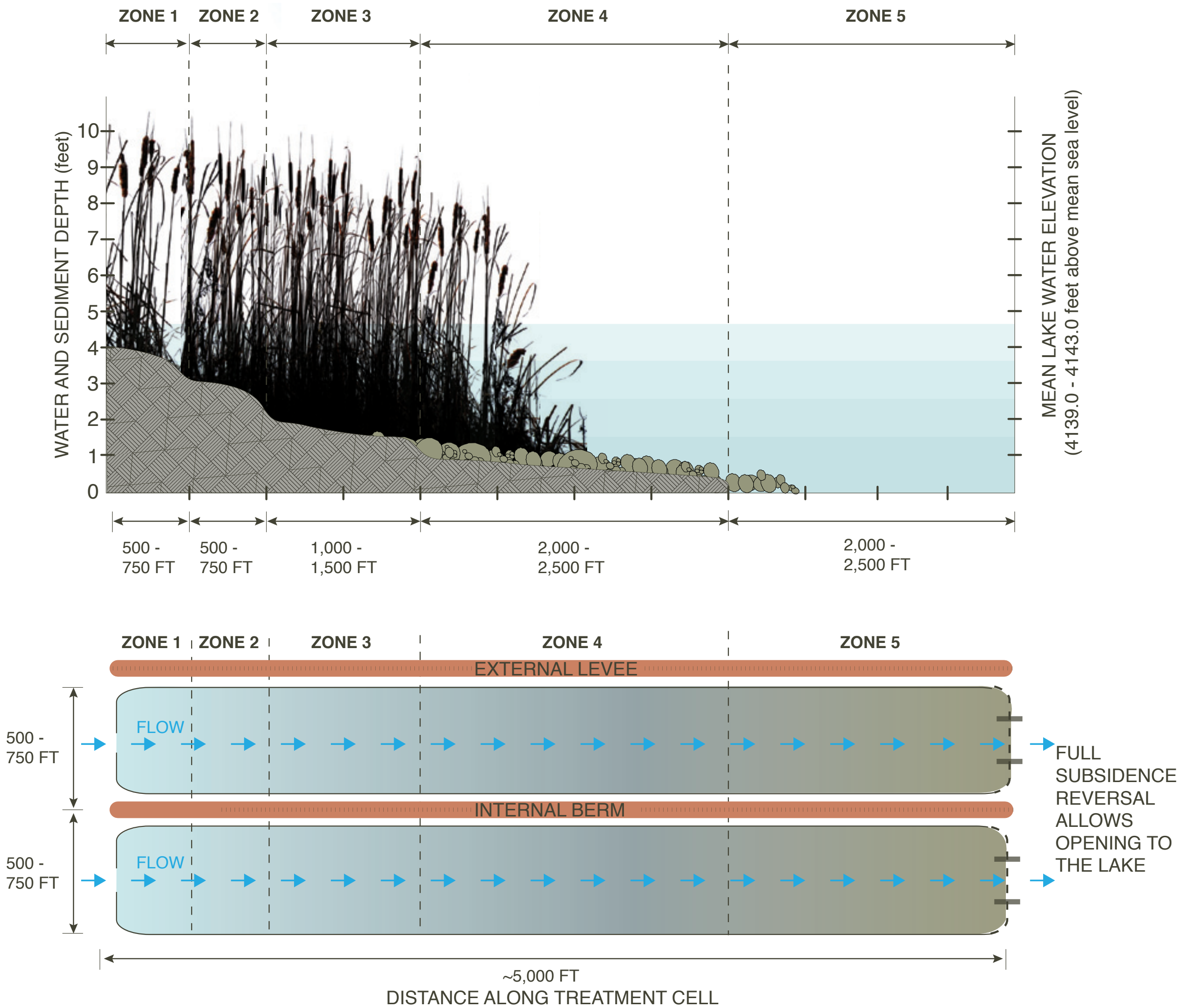


Fig. 3.19 Phase I conceptual design for terraced/sloped wetland rehabilitation along the perimeter of Upper Klamath Lake.

52), coinciding with the period when lake levels are relatively high. Thus, final maximum water depths for the wetland would be tied to mean lake water surface elevations during April through July (4,141 to 4,143 feet)[35] (Figure 3.19). The final design would also need to consider the effects of above normal, below normal, dry, and critically dry water year types on habitat and treatment capacity.

Sediment augmentation for terraced or sloped surfaces would utilize dredged sediments from Upper Klamath Lake (see Section 3, pages 65-71) or another suitable source. Sediment augmentation could be undertaken to fully reverse subsidence such that the augmented sediment depth for wetland Zone 1 would be 4-5 ft, and for Zones 2 through 4 it would be 1 to 2.5 ft (Figure 3.19). Under this scenario, the external levees for the parcels could be breached early in the project, to allow the rehabilitated wetland area to be reconnected with Upper Klamath/Agency Lake almost immediately.

However, due to the relatively high cost of sediment dredging and/or sediment placement, particularly for a site as large as Agency Lake Ranch/Barnes Ranch (~10,000 acres), partial subsidence reversal, which minimizes sediment requirements for building terraces or slopes, may be a more likely scenario. Partial subsidence reversal would involve a lower level of initial sediment augmentation followed by several decades of natural peat accumulation. The conceptual design assumes a rate of peat accumulation of 0.2 inches per year in the vegetated treatment cells. This rate represents an average of several measurements from undrained wetlands around Upper Klamath

35 USFWS 2011

TABLE 3.6 - CONCEPTUAL ESTIMATES OF NUTRIENT REMOVAL POTENTIAL FOR A 1,000-1,200-ACRE TERRACED/SLOPED PILOT TREATMENT AND HABITAT WETLAND ON THE MARGINS OF UPPER KLAMATH AND AGENCY LAKES

ESTIMATED NUTRIENT CONCENTRATIONS AND REMOVAL POTENTIAL	TREAT ALL OF SEVENMILE CREEK FLOW (115 CFS)[36]	TREAT ROUGHLY 40% OF SEVENMILE CREEK FLOW (45 CFS)
Concentration nitrate entering wetland (mg/L)[37]	0.6	0.6
Concentration nitrate leaving wetland (mg/L)[38]	0.2	0.06
Estimated nitrate removal	50 - 55%	80 - 85%[39]
Concentration total phosphorus entering wetland (mg/L)[37]	0.2	0.2
Concentration total phosphorus leaving wetland (mg/L)[40]	0.15	0.06
Estimated phosphorus removal	40 - 45%	65 - 70%[39]

36 Annual mean flow at “7 Mile” Dike Station for water years 2002-2010 (from Figure D5 in Walker et al. 2012).
37 Assumes annual mean concentration at “7 Mile” Dike Station for water years 2002-2010 (from Figure D5 in Walker et al. 2012). Mean concentrations at upstream locations along Sevenmile Creek/Canal can be an order of magnitude lower (Walker et al. 2012; Rick Carlson, personal communication, 2013), resulting in lower annual mean percent removal estimates (35-65%) if water from upstream locations were diverted directly into a wetland.
38 See Appendix B for detailed calculations and assumptions.
39 Removal efficiency increases in the wetland due to increased hydraulic residence time at a lower flow.
40 See Appendix B for detailed calculations and assumptions.

Lake.[41] In order to support design water depths, partial subsidence reversal would require that existing external levees remain in place until peat accumulation in the wetland has sufficiently raised the land surface. Access points for suckers along the external levees, particularly those nearest to spawning habitats, would be required for the partial subsidence reversal scenario.

As an additional cost consideration, the relative amount of wetland area in treatment cells requiring sediment augmentation would be balanced against the higher treatment potential and habitat value of these zones. Thus, the conceptual design assigns 70% of the wetland area in Zones 1-4, which support high to moderate water treatment potential, and 30% of wetland area in Zone 5, which is primarily habitat for subadult/adult suckers due to deeper waters and lack of emergent vegetation (Table 3.5).

Several possibilities for wetland cell configuration at sites along the margins of Upper Klamath and Agency lakes would support the dual water treatment and sucker habitat goals. Costs of the different cell configurations would vary, depending on the level of sediment augmentation and internal berm construction needed to support consistent flow paths and desired treatment levels. Surface information gathered during the pre-project data review would be used to select the most appropriate cell configuration for the project. Estimated nitrogen (nitrate) and phosphorus (total phosphorus) removal in the terraced/sloped wetlands would range from 50-85% and 40-70%, respectively, depending on inflowing nutrient concentrations and how much of the Sevenmile Creek flow is diverted into the wetlands (Table 3.6).

41 Graham et al. 2005, Aldous 2013

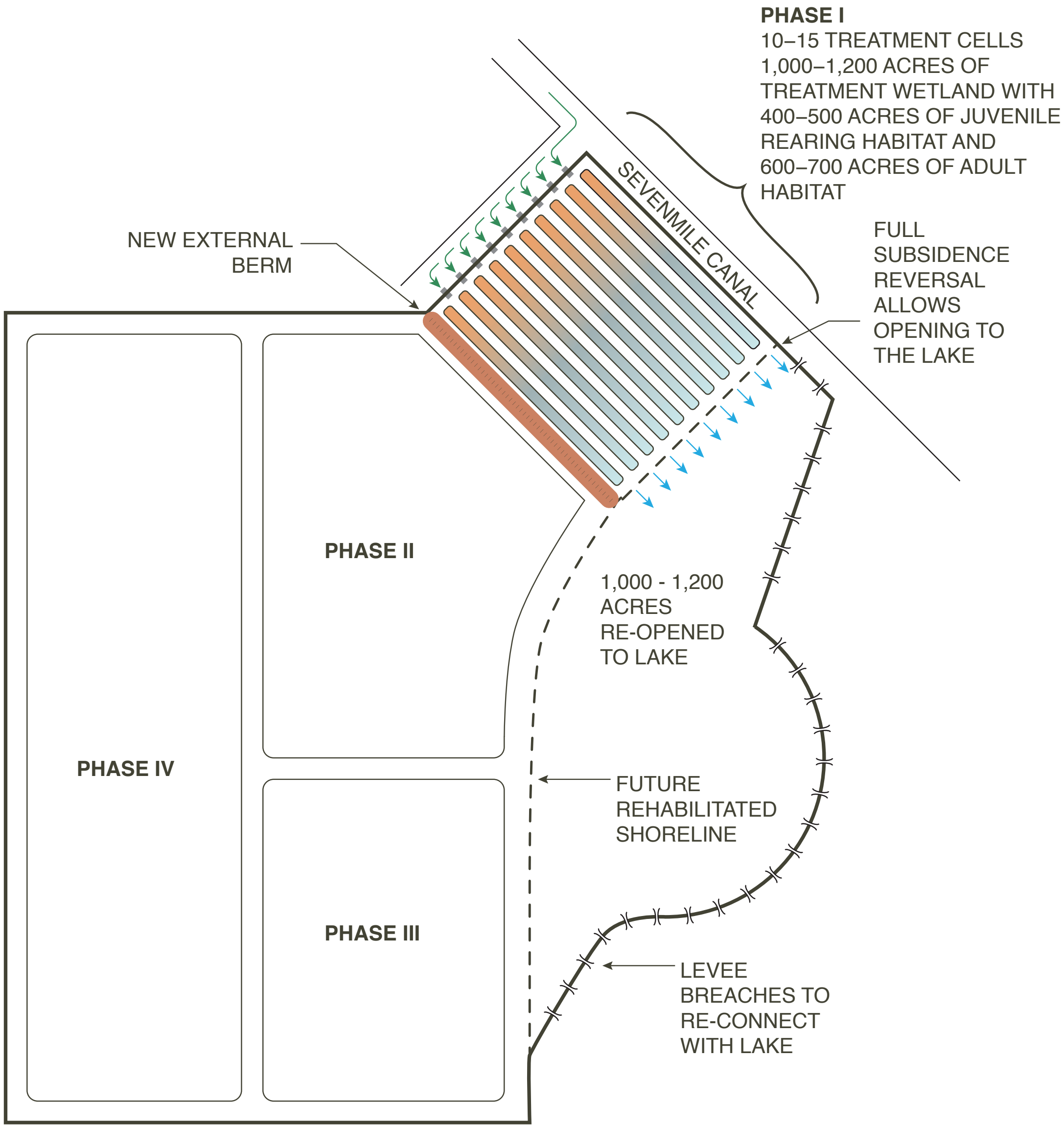


Fig. 3.20 Conceptual design for phased wetland rehabilitation along the perimeter of Upper Klamath/Agency Lake. Drawing not to scale. Phase I cell configuration is one possibility for supporting water treatment and habitat goals.

Phased Implementation

The pilot project conceptual design makes use of a phased approach to constructing dual water treatment and habitat cells throughout the large area (9,830 acres) of the Agency Lake/Barnes Ranch parcels. During Phase I, 1,000 to 1,200 acres of subsided land nearest the mouth of the Sevenmile Canal would serve as a pilot site for wetland rehabilitation. Phase I would also involve levee breaches to re-connect an approximately equal area to Agency Lake and construction of a new external levee along a future re-oriented shoreline (Figures 3.19 and 3.20). Lastly, Phase I would include an investigation of the most effective interim uses of the remaining 7,400-7,800 acres at the Agency Lake/Barnes Ranch parcels that would not be immediately rehabilitated as wetland cells or areas re-connected to Agency Lake (see text box on page 57). During Phases II to IV, additional acreage adjacent to the pilot site would be rehabilitated, starting with roughly 1,800 acres of subsided lands directly west of the pilot site (Figure 3.20). The amount of acreage ultimately rehabilitated to dual water treatment and sucker habitat cells would be dependent on the success of interim land uses and adaptive management.

Wetlands Along Lake Ewauna, the Keno Impoundment and the Klamath Straits Drain

Site Characteristics

Smaller Upstream Wetlands

Wetlands located at the upstream end of the Keno Impoundment would be relatively small (10s of acres) due to limited land and water rights availability

ASSESSMENT OF INTERIM LAND USES

As part of Phase I, the following potential interim land uses would be considered and developed as proof-of-concept projects at the Agency Lake/Barnes Ranch parcels. Depending on the project results, one or more of the interim land uses would be selected for implementation during Phases II through IV.

Nutrient Harvest and Export – Growing crops can remove nutrients from agricultural soils because nutrients incorporated into plant material during growth are exported from the field when the crop is harvested and transported off-site. Nutrient uptake and export rates vary and are specific to crop type, as well as local soil and climate conditions and degree of fertilization. In general, forage crops such as alfalfa, clover, and vetch exhibit relatively high phosphorus and nitrogen export rates, followed by field crops such as cotton, corn, and peanuts. Vegetable crops, such as potatoes and tomatoes, tend to exhibit the lowest rates of nutrient export (IPNI). Of the agricultural crops typically grown in the Upper Klamath Basin (i.e., hay, wheat, alfalfa, potatoes), alfalfa may have the greatest potential for nutrient export given its published values (12 lbs phosphorus per ton on a dry weight basis).[42]

Phase I would involve the development of a study plan for using small (1-2 acre) experimental plots to test the phosphorus export capacity of 2-3 kinds of locally grown crops in the Upper Klamath Basin, as well as one or more new crop types that could be readily grown for increased phosphorus export. The study would evaluate the amount of water that would need to be pumped off the fields to facilitate growing crops, because such pumping could also export phosphorus to Upper Klamath Lake and negate the benefit of crop uptake.

Flooding and Wetland Rehabilitation – Wetland rehabilitation via direct reconnection to Upper Klamath Lake hydrology (i.e., flooding) has recently been undertaken at the Williamson River Delta (see also Figure 3.28). Phase I would involve an investigation of the potential for long-term rehabilitation of lake hydrology and wetland function in a portion of the Agency Lake/Barnes Ranch parcels not slated for immediate transfer to treatment wetland/sucker habitat cells.

Flooding as a means for wetland rehabilitation would require monitoring of phosphorus release from flooded soils following reconnection with Upper Klamath Lake.

Fig. 3.21 The "Walking Wetland" cycle. (Below, from left) First year after flooding; second year after flooding; third year after flooding; first year following wetland cycle. Photo: USFWS.

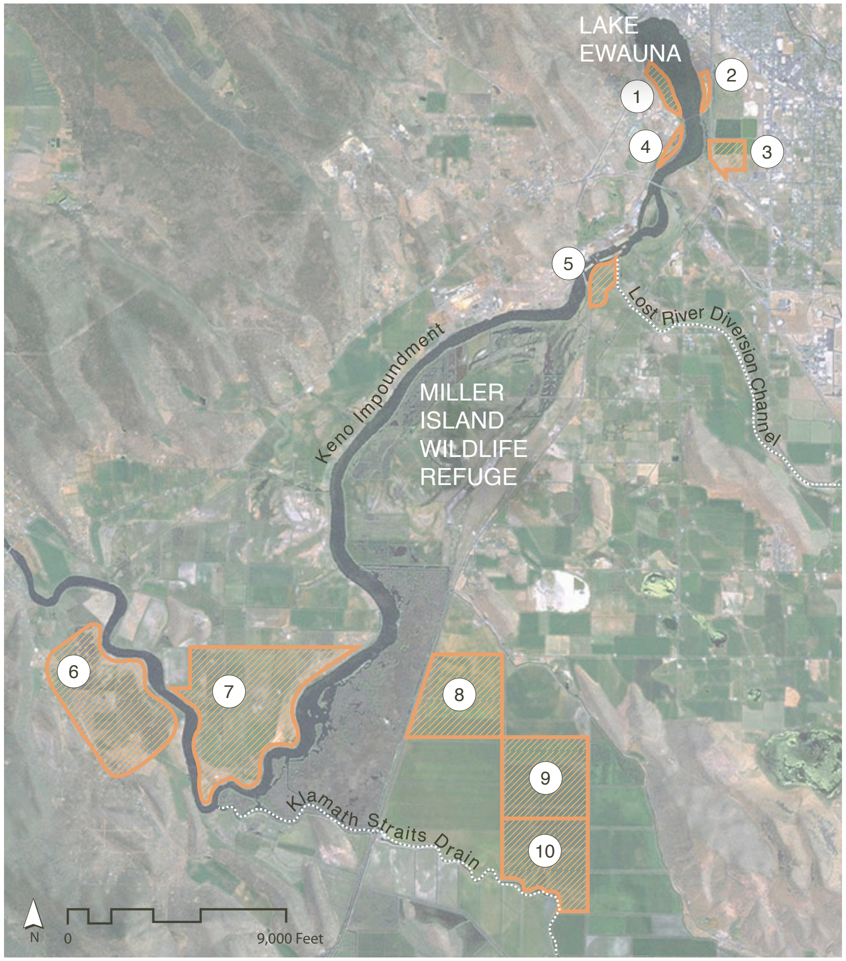
42 International Plant Nutritional Institute (http://www.ipni.net/)

Recent data collected at the Williamson River Delta indicate that the initial pulse of phosphorus from flooded soils was far less than anticipated (2.5 tons released versus the 64 tons predicted) and seasonally averaged total phosphorus concentrations became progressively more stable and lower over the five year monitoring period.[43] As with DSTWs, site-specific soil testing would be conducted to determine the potential need for soil amendments or LICD (see text box on page 49) to increase the efficiency of phosphorus removal under a flooding scenario.

Walking Wetlands – The USFWS' Walking Wetlands program is currently in use in the Lower Klamath National Wildlife Refuge and involves rotating areas of agricultural production with areas of marsh or treatment wetlands on refuge lands. Program proponents indicate that higher crop yields are maintained in farmed areas with lower inputs of fertilizers and pesticides and at the same time, high-quality wetlands are available for wildlife. While the two land uses (i.e., agricultural and wildlife habitat) are traded, such that the net habitat area remains the same at any given point, the decrease in use of fertilizers and pesticides in the watershed is likely an overall benefit to water quality. The use of Walking Wetlands would combine habitat benefits from partial flooding and wetland rehabilitation approach with phosphorus export benefits from nutrient harvest and export approach.

Phase I would involve an investigation of the potential for the use of Walking Wetlands in a portion of the Agency Lake/Barnes Ranch parcels not slated for immediate transfer to treatment wetland/sucker habitat cells or re-connection to Agency Lake.

43 Wong et al. 2010, Hayden and Hendrixson 2013



SITE 1 (Mahugh et al. 2009)
- 63 acres
- Some water conveyance structures (no pumps)
- Road access
- Configured favorably for linear treatment cells
- Supports wetland soils and plants
- Water rights unknown

SITE 2 (Mahugh et al. 2009)
- 30 acres
- Some water conveyance structures (no pumps)
- Road access
- Supports wetland soils and plants
- Existing slough habitat

SITE 3 (Mahugh et al. 2009)
- 100 acres
- Ownership and water rights unknown

SITE 4 (Mahugh et al. 2009)
- 32.5 acres
- Road access
- Supports wetland soils and plants
- Water rights unknown

SITE 5 (Mahugh et al. 2009)
- 54 acres
- No water control structures or pumps
- Existing surface water right for irrigation
- Adjacent to Lost River Diversion Channel

SITE 6 (Lyon et al. 2009)
- 600 acres
- Water conveyance structures
- Wetland soils
- Existing primary surface water right for irrigation use

SITE 7 (Mahugh et al. 2009)
- 1,300 acres
- 11 individual parcels
- Water conveyance structures
- Road access
- Supports wetland soils and plants
- Portions of the site possess existing surface water diversion for irrigation use from March through October, while other portions are pending adjudication

SITES 8 - 10 (Mahugh et al. 2009)
- Total ~1,800 acres
- Close proximity to the Keno Impoundment
- Existing primary surface water rights for irrigation use
- If used for treating Klamath Straits Drain, possible augmentation of winter and/or spring flows to avoid seasonal periods of drying and soil oxidation

Fig. 3.22 Ten potential wetland locations along Lake Ewauna and the Keno Impoundment.

in the vicinity of Link River Dam and Lake Ewauna.[44] Placement of wetlands near Lake Ewauna and the upstream end of the Keno Impoundment is desirable because the number of suckers tends to be relatively greater than elsewhere in the reach.[45] Additionally, placement of wetlands upstream in the reach could improve water quality downstream and provide increased habitat for suckers.

Target sites include five parcels identified in a prior study of potential treatment wetland locations along Lake Ewauna and the Keno Impoundment (sites 1-5 in Figure 3.22). For the pilot project, one of the five parcels would be selected to test conceptual design elements for the smaller upstream wetland systems.

Larger Downstream Wetlands

Potential treatment wetland sites on larger parcels (100s to 1,000s of acres) in the middle and towards the downstream end of the Keno Impoundment and the downstream end of the Klamath Straits Drain were

44 The floodplain area between Link River Dam and Miller Island is relatively narrow, parcels are relatively small (<100 acres), and there are few existing individual water rights for surface diversion.

45 Terwilliger et al. 2004, Kyger and Wilkens 2011

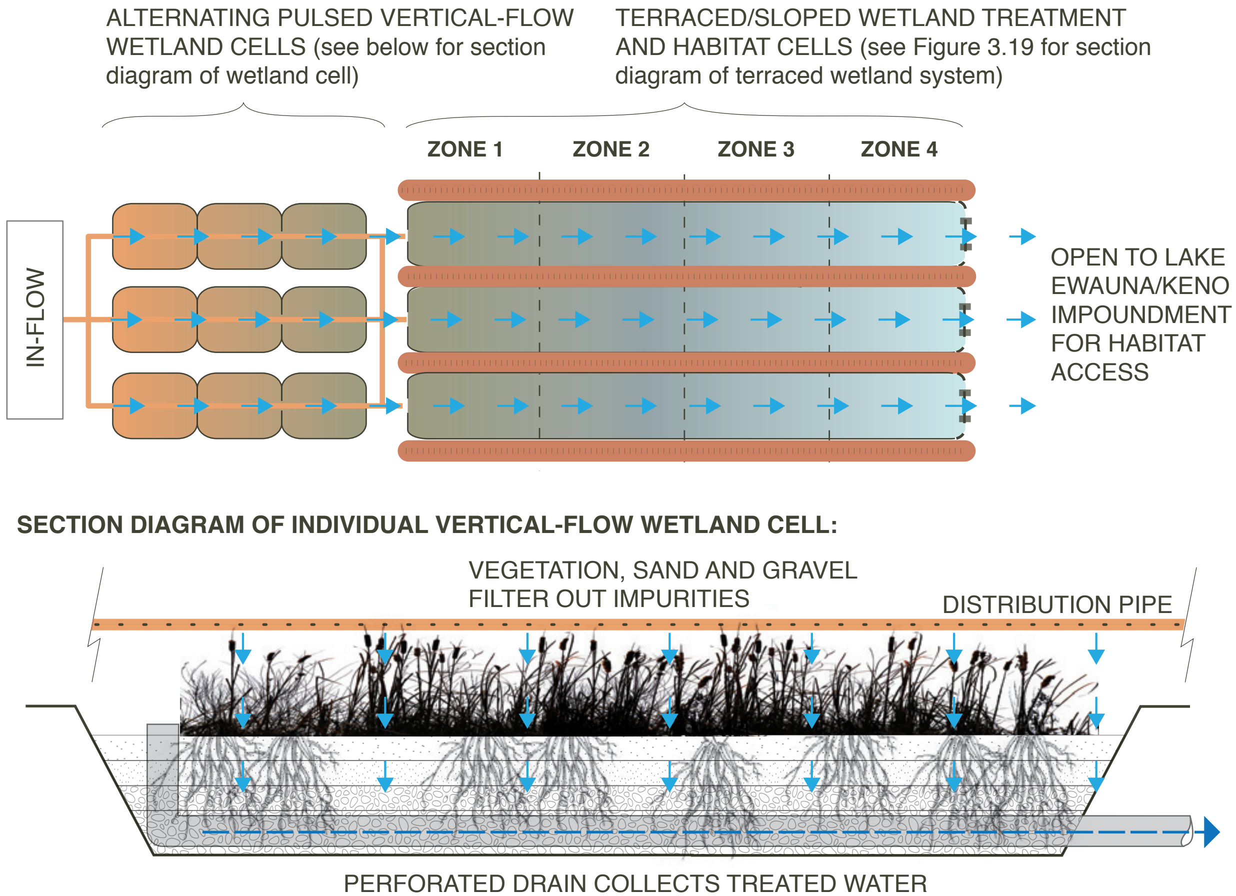


Fig. 3.23 Conceptual design for small hybrid treatment wetlands along Lake Ewauna.

identified in prior studies.[46] Recent modeling shows that routing Klamath River flow through large (1,400 to 2,950-acre) treatment wetlands located between Miller Island and the Klamath Straits Drain would improve summertime water quality. The wetlands would filter and remove biochemical oxygen demand (BOD) and algal particulate organic matter originating primarily from Upper Klamath Lake and would increase dissolved oxygen and decrease ammonia and orthophosphorus in Keno Impoundment downstream of the wetlands. Whether the water-quality standard can be met (and thereby support fish habitat) using this approach is still a matter for more research; preliminary model results indicate that treatment wetlands may need to remove 50 to 90% of BOD and algal particulate organic matter. Treatment of Klamath Straits Drain flows prior to discharge into the Keno Impoundment would also improve water quality in the reservoir itself.

46 Mahugh et al. 2009, Lyon et al. 2009

Target sites include five parcels identified in a prior study of potential treatment wetland locations along Lake Ewauna and the Keno Impoundment, and the downstream end of the Klamath Straits Drain (sites 6-10 in Figure 3.22). For the pilot project, one of the five parcels would be selected to test conceptual design elements for the larger downstream wetland systems.

Pilot Project Conceptual Design

Pre-project Surveys

Prior to wetland construction, review of existing bathymetric and LiDAR data, existing inlet and outlet structures, agricultural canals/ditches, and associated berms/levees would be conducted to ensure that conceptual habitat and water treatment design elements can be supported.

Design Elements

Smaller Upstream Wetlands - Given the very high organic loads in Lake Ewauna and the upstream end of the Keno Impoundment during the summer and early fall (see Figure 1.11), wetlands located along Lake Ewauna and the upstream end of the Keno Impoundment would be designed to filter high concentrations of suspended solids and allow rapid oxidation of the filtered biomass. The inlet portion of each wetland would be designed as a high-efficiency vertical flow cell, where water would be distributed across the surface of a gravel bed planted with native vegetation and percolate through the plant root zone.[47] A similar

47 Kadlec and Wallace 2009

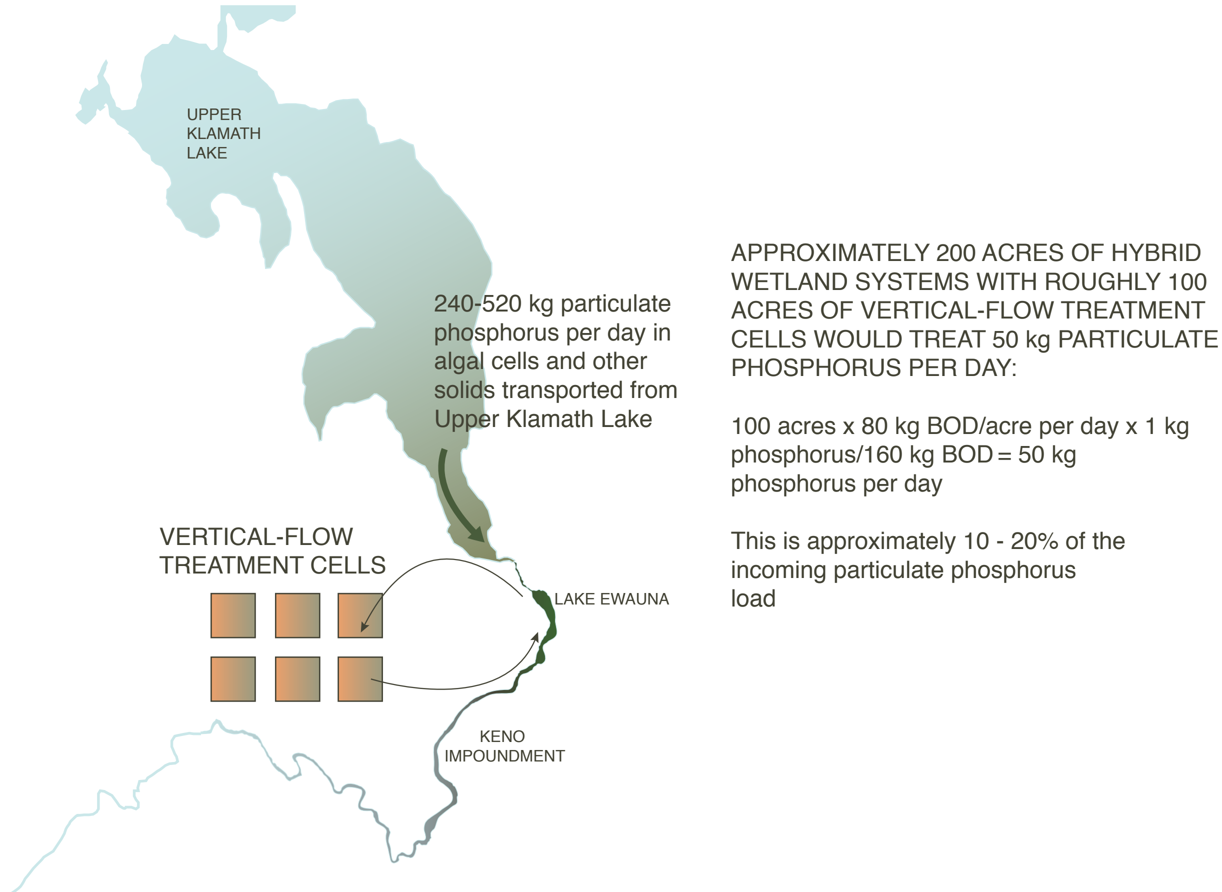


Fig. 3.24 Multiple hybrid vertical flow and terraced/sloped wetland treatment and habitat systems would be required to treat particulate phosphorus loading from Upper Klamath Lake.

type of system, called an infiltration-based vegetated swale system, was presented as a conceptual project type for areas adjacent to Copco and Iron Gate reservoirs in the Hydroelectric Reach, in order to remove algae from accumulations at reservoir cove sites.[48] To avoid clogging of the gravel matrix with biomass and to promote oxygenated pore spaces to support rapid decomposition of algal cells, the vertical flow cells alongside Lake Ewauna and the Keno Impoundment would operate as pulse-flow systems, with intermittent wetting and drying cycles (Figure 3.23). The number of daily pulse cycles would be seasonally dependent and would be optimized as part of the pilot study.

While vertical flow wetland cells are efficient at treating ammonia and total nitrogen, they do not treat

48 Lyon et al. 2009

TABLE 3.7 - ESTIMATED AREA OF VERTICAL-FLOW WETLAND TREATMENT CELLS, LAKE EWAUNA AND THE UPPER KENO IMPOUNDMENT

	JUNE - OCTOBER[49]
Average oxygen demand in outflow from Upper Klamath Lake (mg/L)[50]	15
Daily average flow at the Link River USGS gage WY1991-2010 (cfs)[51]	790-1,400
Area of vertical flow wetland treatment cells required to treat all of the Link River flow (acres)[52]	360-630
Area available for small wetlands around Lake Ewauna and the Upper Keno Impoundment (acres)[53]	200
Ratio of area in vertical flow wetland treatment cells to area in surface flow wetland cells	50/50
Area available for vertical flow wetland cells (acres)	100
% of daily oxygen demand treated by vertical flow wetland cells	15-30%

49 As conceptual design estimates, the values below are reported to 1-2 significant figures.

50 Includes biochemical oxygen demand (BOD5) + nitrogeneous BOD (NBOD5). Summertime Link River estimates from Table 4 in Sullivan et al. (2011). Samples collected in August to early Sept (2006), late June to early Sept (2007), July to August (2008).

51 Data from USGS gage no. 11507500 for water years 1991-2010. Flows do not include contributions from Westside Canal.

52 Assumes a rate of 20 grams of biochemical oxygen demand (BOD) per m^2 per day based on the range of 10–40 $g/m^2/d$ reported in Crites and Tchobanoglous (1998), as cited by Kadlec and Wallace (2009), page 734. Most vertical flow wetland designs use a rate less than 25 $g/m^2/d$.

53 Assumes 30% of the available land area would be used for berms, roads, and other infrastructure.

nitrate, nor do they provide aquatic habitat. Thus, the vertical wetland cells would discharge to free-water surface wetland cells that would function much as Zones 1-3 in the conceptual design for the Agency Lake Ranch and Barnes Ranch parcels (Figure 3.23). The free-surface water cells would provide nitrate removal and habitat for juvenile suckers.

Based on the relatively high efficiency of hybrid wetland systems, it is anticipated that the approximately 200 acres of land potentially suitable for creation of wetlands along Lake Ewauna and the upper portion of the Keno Impoundment (Figure 3.24) would be capable of removing 10-20% of the oxygen demand created by algal blooms transported from Upper Klamath Lake (Table 3.7).

The pilot study would test important removal assumptions about the amount of algal material and particulate phosphorus that can be applied to the vertical flow wetland treatment cells, gravel size, pulsing rates, and whether recirculation of water is needed for optimal treatment.

Larger Downstream Wetlands - Further downstream in the Keno Impoundment, generally larger parcels allow for increased hydraulic residence time for wetlands and may negate the need for high efficiency filtration and oxidation of suspended solids in the smaller parcels surrounding Lake Ewauna. However, organic matter and phosphorus loads can still be relatively high during the summer and early fall in downstream reaches of the Keno Impoundment (see Figure 1.11). Wetlands located along the middle and lower reaches of the Keno Impoundment are also likely to benefit from design features that enhance water treatment under these conditions, such as hybrid systems with pre-filtration vertical flow wetland cells.

Relative to water in the Keno Impoundment, water leaving the Klamath Straits Drain (KSD) has lower total suspended solids, higher total and dissolved phosphorus, and higher dissolved organic carbon.[54] Based on this mixture of water quality constituents, it is anticipated that treatment in the KSD would likely benefit from a LICD system to improve the efficiency of phosphorus and dissolved organic carbon (DOC) removal in the wetland. Since potentially available parcels near the downstream end of the drain are also located along the Keno Impoundment (Figure 3.22), a wetland system that is designed to treat flows from both the Klamath Straits Drain and the Keno Impoundment may be the best opportunity to provide flexible water treatment in this location. The US Bureau of Reclamation is currently working on potential KSD recirculation projects that could change the amount and timing of flow and nutrients leaving the drain.[55] Further development of a pilot treatment wetland project in this location would require coordination with the US Bureau of Reclamation regarding future management of flows in the KSD.

Environmental, Regulatory and Permitting Requirements

The following permits would be required for a pilot "large wetland" project:

- Water rights transfer through Oregon Division of Water Rights, as needed

- Water Quality Certification from Oregon Department of Environmental Quality (ODEQ)

- General Authorization or Individual Permit from the Oregon Department of State Lands

- Permit from the U.S. Army Corps of Engineers (USACE) if the wetland project is connected to a navigable waterway. USACE consults with the National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS) on endangered species concerns.

Monitoring

Since monitoring programs for small and large wetland rehabilitation projects are dependent on specific design criteria, including total area, design flows, and treatment cell configuration, the conceptual-level monitoring program (Table 3.8) would necessarily be adjusted based on the final design for wetlands located along the margins of Upper Klamath and Agency lakes, Lake Ewauna, the Keno Impoundment and/or the Klamath Straits Drain. Specific monitoring associated with sediment augmentation in wetland rehabilitation projects along Upper Klamath and Agency lakes is presented in Section 3 Sediment Removal (Dredging) (pages 65-71).

Wetland nutrient removal performance would be calculated using inflow and outflow quantity and nutrient concentrations. If LICD is incorporated into the pilot project wetland designs, concentrations of the coagulant of choice would also be measured at the inlet and outlet of the wetland along with the other water quality parameters.

54 Appendix C, Figure C-35, in Stillwater Sciences et al. 2012

55 Rick Carlson, personal communication, 2013.

TABLE 3.8 - ANTICIPATED MONITORING ELEMENTS FOR A WETLAND REHABILITATION CONCEPTUAL DESIGN ALONG THE MARGINS OF UPPER KLAMATH AND AGENCY LAKES, LAKE EWAUNA, THE KENO IMPOUNDMENT, AND THE KLAMATH STRAITS DRAIN

PARAMETER	SAMPLING STRATEGY	SAMPLING FREQUENCY
Inflow/outflow	In each treatment cell	• Continuously during April through October • Monthly November through March
Evapotranspiration	Representative number of treatment cells and zones	Monthly
• **Water temperature** • **Conductivity** • **Dissolved oxygen** • **pH** • **Oxidation-reduction potential**	In each treatment cell	• Bi-weekly during April through October, with 2-3 continuous 48-hr monitoring events • Monthly November through March
• **Total suspended solids** • **Nitrogen (total, nitrate, and ammonium)** • **Phosphorus (total and ortho-phosphorus)**	In each treatment cell	• Bi-weekly during April through October[56] • Monthly November through March
Vegetation cover and species distribution	Representative number of treatment cells and zones	Quarterly
Abundance/ distribution of sucker life stages[57]	Representative number of treatment cells and zones	May, September, December

56 Some periods, such as first flush, may require more frequent monitoring.
57 Assumes 30% of the available land area would be used for berms, roads, and other infrastructure.

Implementation Timeline and Estimated Costs

The anticipated timeline for implementing one or more of the large wetland conceptual designs spans approximately 5-7 years depending on the duration of site operation for each pilot study (Figure 3.25).

Anticipated costs for the conceptual design of rehabilitated wetlands along Upper Klamath and Agency lakes include some degree of subsidence reversal in order to support both nutrient removal and sucker habitat in the short-term and a phased implementation with investigation of interim land uses (Table 3.9). Further downstream, anticipated costs for a smaller (5-10 acre) pilot project for a hybrid wetland system include testing of design elements to support vertical flow treatment cells and terraced/ sloped wetland cells supporting sucker habitat (Table 3.9).

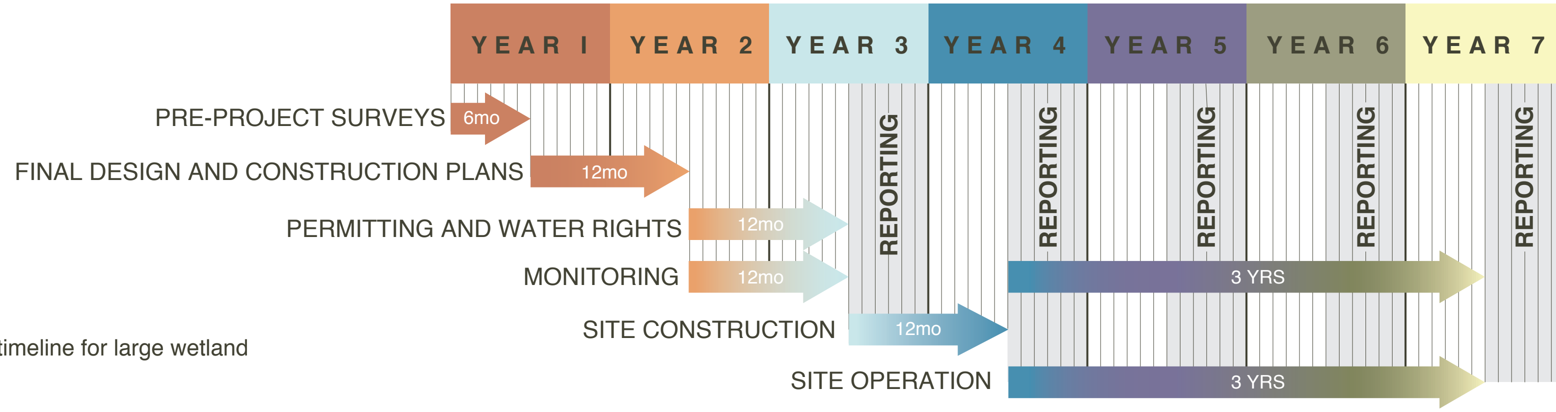


Fig. 3.25 (Right) Implementation timeline for large wetland conceptual design.

TABLE 3.9 - COST ESTIMATES FOR PILOT WETLAND REHABILITATION DESIGNS

	A TERRACED/SLOPED WETLAND REHABILITATION CONCEPTUAL DESIGN AT AGENCY LAKE RANCH/ BARNES RANCH	PILOT HYBRID WETLAND SYSTEMS FOR A 5-10 ACRE PILOT SITE ALONG LAKE EWAUNA, THE KENO IMPOUNDMENT, AND THE KLAMATH STRAITS DRAIN
Pre-project survey[58]	$5-10K	$5-7K
Final design and construction plans[59]	$50-100K	$25-50K
Permitting and water rights[60]	$20-30K	$20-30K
Site construction (sediment augmentation, earthmoving, planting)[61]	$5-20M	$50-100K
Site operation for 3 years[62]	$800-950K	$4-8K
Monitoring for 3 years[63]	$130-200K	$50-80K
Total	**$6-21M**	**$150-275K**

58 Includes review of existing data and minimal to no new surveys.
59 Assumes some degree of subsidence reversal included in design of terraced/sloped cells for Agency Lake/Barnes Ranch, plus pumping or water diversion from Sevenmile Canal.
60 Assumes partial to full water rights transfers needed for each parcel, general authorization for state lands permits applies, and the majority of potential impacts from any sediment placement to combat subsidence reversal are analyzed outside of this budget (i.e., as part of any associated dredging project).
61 Assumes $5-20K per acre, depending on the degree of sediment augmentation and number of treatment cells.
62 Assumes operation and maintenance is $260/acre/year (average value from SFWMD [2004]).
63 Includes field data collection and laboratory analysis costs based on monitoring elements presented in Table 3.8. No reporting costs included.

Fig. 3.26 Williamson River Delta Preserve. Photo: David Garden.

SEDIMENT REMOVAL (DREDGING)

Workshop recommendations related to sediment removal in Upper Klamath Lake and the Keno Impoundment were that whole-lake or whole-reservoir dredging are infeasible from a cost and sediment disposal perspective (Section 2, pages 25-26). Instead, targeted dredging of phosphorus "hotspots" in Upper Klamath Lake sediments with in-basin reuse of sediments offers the potential for water quality improvement and simultaneous reversal of subsidence in agricultural lands and wetlands adjacent to Upper Klamath Lake. Lake sediments could also be used as an agricultural soil amendment, since the sediments have elevated levels of phosphorus (Section 1, pages 8-9).

This section describes a conceptual pilot project to dredge a portion of Upper Klamath Lake just south of Goose Bay and re-deposit the sediments in adjacent areas targeted for wetland rehabilitation, as well as local agricultural areas that would benefit from subsidence reversal and soil amendment (Figure 3.28). The pilot project includes testing to determine applicable sediment properties for each of these potential uses.

OBJECTIVE - To evaluate the potential for large-scale removal of sediments in Upper Klamath Lake containing relatively high concentrations of phosphorus, thereby decreasing the potential for internal loading of phosphorus to the lake and subsequent nuisance algal blooms.

Fig. 3.27 Williamson River Delta Preserve. Photo: Rick McEwan.

SITE CHARACTERISTICS

Proposed Dredge Site

The proposed dredge site is located within a target area immediately adjacent to Goose Bay, which, along with Tulana Bay on the northwest side of the Williamson River Delta, has recently been restored to its historical status as wetlands as part of The Nature Conservancy's Williamson River Delta Restoration Project. The target area for dredging was chosen for the following reasons:

1. It is immediately downstream of the Sprague and Williamson rivers, which together contribute 44% of the external total phosphorus load to Upper Klamath Lake.[64]

2. It is characterized by relatively high phosphorus per unit area of wet sediment.[65] Under typical

64 Walker et al. 2012
65 Simon and Ingle 2011

spring and summer conditions, water from the Williamson River flows into the lake and moves clockwise along the shoreline.[66] As water velocity slows in the lake, sediments containing elevated phosphorus can be deposited in the lake bed. Recent sediment sampling results suggest that phosphorus concentrations in the dredging target area are among the highest in Upper Klamath Lake (Figure 3.28).[67,68]

3. It is located near subsided agricultural lands and wetlands currently managed for water storage, so dredged sediments could be deposited with minimal transport costs and energy use.

Proposed Deposition Sites and Uses

Reuse sites and beneficial uses of dredged sediments for the pilot project are described below.

- ***Agency Lake Ranch and Barnes Ranch parcels*** These two parcels are located on the west side of Agency Lake and total 9,830 acres. The parcels were historically wetlands and were converted to agricultural croplands and pasture. Following their acquisition by USBR (1998 for Agency Lake Ranch; 2006 for Barnes Ranch) the parcels were converted to pumped water storage facilities for the Klamath Project. The parcels have been turned over to the USFWS for management as part of the Upper Klamath NWR. USFWS is currently developing

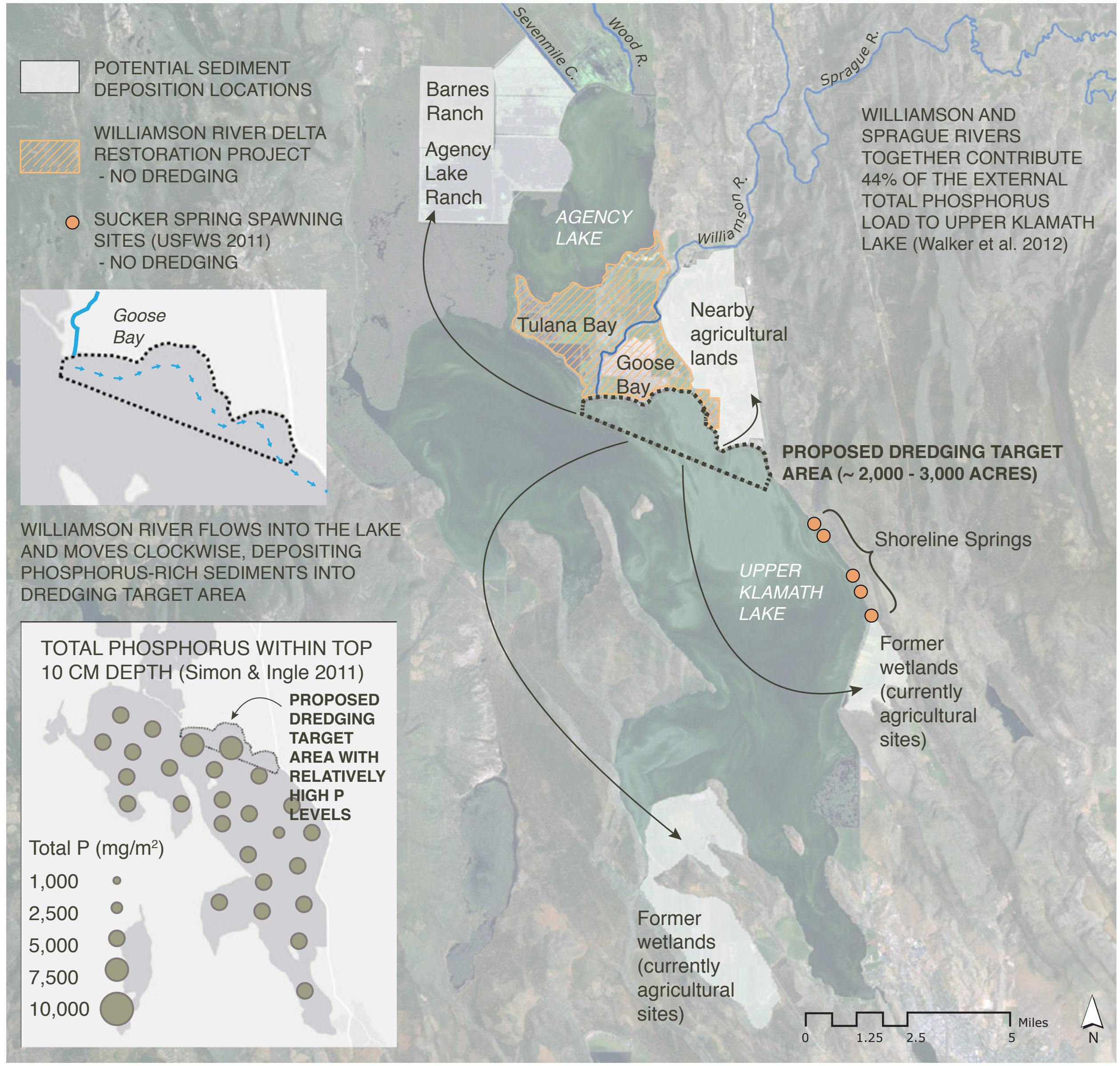


Fig. 3.28 Proposed dredging area and sediment deposition locations adjacent to Upper Klamath Lake.

66 Wood 2012
67 Simon and Ingle 2011
68 Another possible location for the target area is near the inflow from Agency Lake. USGS is currently analyzing sediment cores to determine if a relatively high fraction of bioavailable phosphorus is associated with sediments in this general area (Simon and Ingle 2011).

DREDGED SEDIMENT REUSE EXAMPLES

Dredged sediments have often been used to construct and repair levees in the San Francisco Bay and Sacramento-San Joaquin Delta. There are also several examples of successful application of dredged sediments for habitat creation/restoration,[69] including the Sonoma Baylands in San Francisco Bay, where mud from dredging the Port of Oakland was applied to subsided tidal wetlands (Figures 3.29 and 3.30).

The majority of agricultural lands in the Upper Klamath Lake area are irrigated pasture for cattle grazing; crops grown in the basin include hay, wheat, alfalfa and potatoes. Multiple studies have shown positive impacts of dredged sediments on crop yields. Lake-dredged sediments applied to pasturelands in south Florida led to significantly higher forage yields of bahiagrass.[70] Sediments dredged from the Potomac River and applied to a reclaimed sand and gravel mine (Shirley Plantation) resulted in reasonable wheat yields and outstanding corn yields.[71] Other studies produced similar results when sediment was mixed with soil, compost, biosolids, and/or sand, for crops including corn,[72] snapbeans and barley,[73] lettuce[74] and other field and forage crops, including alfalfa.[75] As a regional example, implementation of the Salt River Ecosystem Restoration Project in nearby Humboldt County, California, involves the re-use of excavated Salt River sediments in upland agricultural pasturelands in the surrounding area. For the Salt River restoration project, the sediment is viewed as a beneficial resource that various farmers and ranchers are interested in receiving for agronomic re-use (California Coastal Commission 2011).

Fig. 3.29 (Left top) Restored wetlands in Sonoma Baylands, San Francisco Bay. Photo: Gahagan & Bryant Associates.

Fig. 3.30 (Left bottom) Wetland created from dredged materials in Sonoma Baylands. Photo: Gahagan & Bryant Associates.

Fig. 3.31 (Right top) Wheat harvest. Photo: GoldDustFarms.com.

Fig. 3.32 (Right bottom) Alfalfa grown in the Klamath Basin. Photo: OPB.org.

69 Craig Vogt, Inc. 2010
70 Sigua 2009
71 Daniels et al. 2007
72 Lembke et al. 1983
73 Diaz and Darmody 2004
74 Canet et al. 2003
75 Woodard 1999

a management plan that includes both parcels. Potential beneficial reuses for the lake sediment at these sites are to maintain the dikes around the parcels and to increase the elevation of subsided areas for wetland restoration.

- *Agricultural lands surrounding Upper Klamath Lake* Of closest proximity to the proposed dredge site are former wetlands, currently in agricultural production, in the Williamson River floodplain, west of Highway 97 and north of Goose Bay. There are also agricultural lands along the southeast and southwest shores of the lake that may be good locations to receive dredged lake sediments as a soil amendment or fill for subsided areas (Figure 3.28).

PILOT PROJECT CONCEPTUAL DESIGN

Pre-dredging Surveys and Testing

Prior to dredging, review of existing bathymetric and LiDAR data for the site would be conducted in order to determine whether the site can accommodate a loaded barge and tug unit. Physical and chemical analyses of the sediments would also be undertaken to:

- Characterize sediment quality for permitting
- Ensure phosphorus and/or contaminants do not leach from sediments
- Inform selection of the most appropriate dredge
- Refine sediment area and volume of the proposed dredge site
- Confirm that potential beneficial reuses would be supported (outside of the research questions presented below)

Precision dredging using small hydraulic dredges would be among the techniques considered since it is optimal for removing thin layers of sediment (especially fine sediment) and for dredging along shorelines without removing existing rooted aquatic vegetation.

Dredging Operations

Based on aerial images and available bathymetry data, the target area for sediment dredging in Upper Klamath Lake spans 2,000-3,000 acres. Within this target area, the dredge site would be approximately 15 acres in size, and sediment would be removed from the top 1 ft (30 cm) of the lake bed (Figures 3.28 and 3.33). Recent studies of Upper Klamath Lake indicate P concentrations are highest in the upper 10 cm of sediment[76] (Figure 3.33) and drop off considerably below 20 cm.[77]

The dredging site would be delineated using steel pipes and pilings to cordon off the area and guide dredging operations. Based on refinements to the proposed dredging area identified during the pre-dredging surveys, phased dredging may be employed to maximize efficiency and minimize impacts. Dredging would be done on consecutive days until the desired quantity of dredged sediments is obtained. Methods to control turbidity, such as silt screens and other turbidity barriers, would be utilized such that turbidity would not exceed relevant Oregon standards. In addition, dredging operations would be timed to avoid periods of rough water and high winds that increase turbidity levels.

Dredging operations would avoid sucker impacts by conducting dredging outside of critical life history periods for this species. In the spring months, adult suckers congregate in the northern end of the lake near Goose Bay and Modoc Point prior to moving into tributaries or shoreline areas for spawning.[78] Spawning occurs February through May and juveniles move away from the spawning grounds from April through July. Therefore, dredging operations may need to occur from August through January. Other

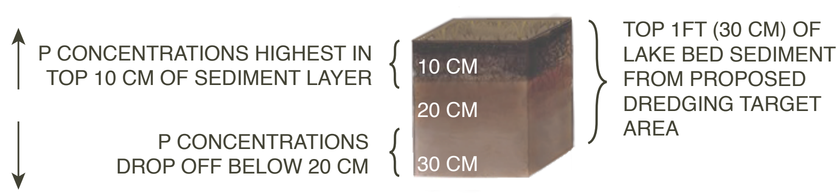


Fig. 3.33 Thirty centimeters of sediment, where the phosphorus concentration is deepest, would be removed from the proposed dredging area.

76 Simon et al. 2009, Simon and Ingle 2011
77 Eilers et al. 2004
78 Hendrixson et al. 2004

factors would be taken into consideration for the final timing of dredging operations, including the life history stages of other special status aquatic species and seasonal lake levels. Lake depth in the target dredging area is estimated to range from 3 to 7.5 feet during October, which is sufficient for operating a hydraulic dredge.

Deposition and Beneficial Reuse

The pilot project would generate approximately 15 acre-ft (approximately 24,000 cubic yards) of sediments for reuse. The potential for beneficial reuse of the sediment would be determined based in part on sediment quality characterization conducted during the pre-dredging surveys.[79] Additionally, the pilot project would simultaneously test the effectiveness of the dredged sediments for multiple beneficial uses to determine the preferred use (Figures 3.34).

A temporary confined disposal facility (CDF) or re-handling facility is necessary to store the sediments after dredging and before placement (Figure 2.18). The CDF would be designed to accommodate the quantity of sediment to be removed plus sufficient freeboard (estimated at 2-15 acres of land dependent upon the water volume content of dredged materials). Ideally the CDF would be constructed on land that is adjacent to the shoreline in the vicinity of the dredging area, making transport much easier and less expensive. Once in the CDF, the dredged material is allowed to dewater, which can take several weeks to months depending on the water content and the beneficial reuse option. The water fraction of the total weight of the sediment ranged from 0.84 to 0.94 in the samples closest to Goose Bay in a study

79 Harding Lawson Associates 2000, San Francisco Bay Regional Water Quality Control Board 2000

PILOT TESTING FOR DETERMINING LOCAL SEDIMENT REUSE OPPORTUNITIES

In addition to the standard sediment quality characterization and leaching nutrient and contaminant leaching test conducted as part of the pre-dredging surveys (see page 68), the pilot project would include the following research questions to address key uncertainties in the opportunities for local beneficial reuse of dredged lake sediments:

General - *Is phosphorus in the sediments to be dredged in Upper Klamath Lake mainly present as a bioavailable or non-bioavailable form of phosphorus?*

Are the high concentrations of silica in the dredged sediments recoverable through simple drying and separation techniques such that they might be used as a marketable source of this mineral?

Site(s) for Wetland Rehabilitation Through Subsidence Reversal - *Do elevated phosphorus content and percent fines in dredged lake sediments affect the growth of native wetland vegetation (e.g., bulrush, cattail) in wetland rehabilitation projects?*

Does the application of dredged lake sediments for increasing land surface elevation in wetland rehabilitation projects affect water quality, including nutrient levels (i.e., phosphorus, nitrogen) and toxins (e.g., mercury, arsenic, pesticides), in wetland surface water and site outflow?

Are there toxins (e.g., mercury, arsenic, pesticides) present at low levels in lake sediments that would be biomagnified in the wetland food web to levels of concern?

Site(s) for Maintenance of Existing Levees and Berms Using a Local Source of Sediments - *Do dredged and dried lake sediments possess physical properties that support their use as a local source of levee strengthening and/or building material?*

Site(s) for Agricultural Soil Amendments and Subsidence Reversal - *Do elevated phosphorus content and percent fines in dredged lake sediments affect the growth rate and yield of primary crops grown in the Upper Klamath Basin (hay, wheat, alfalfa, potatoes)?*

Does the application of dredged lake sediments as an agricultural soil amendment affect water quality, including nutrient levels (i.e., phosphorus, nitrogen) and toxins (e.g., mercury, arsenic, pesticides), in agricultural runoff?

Does application of dredged lake sediments as a soil amendment affect local soil hydrologic conductivity and site hydrology?

Are there toxins (e.g., mercury, arsenic, pesticides) present at low levels in lake sediments that would be biomagnified in crops to levels of concern?

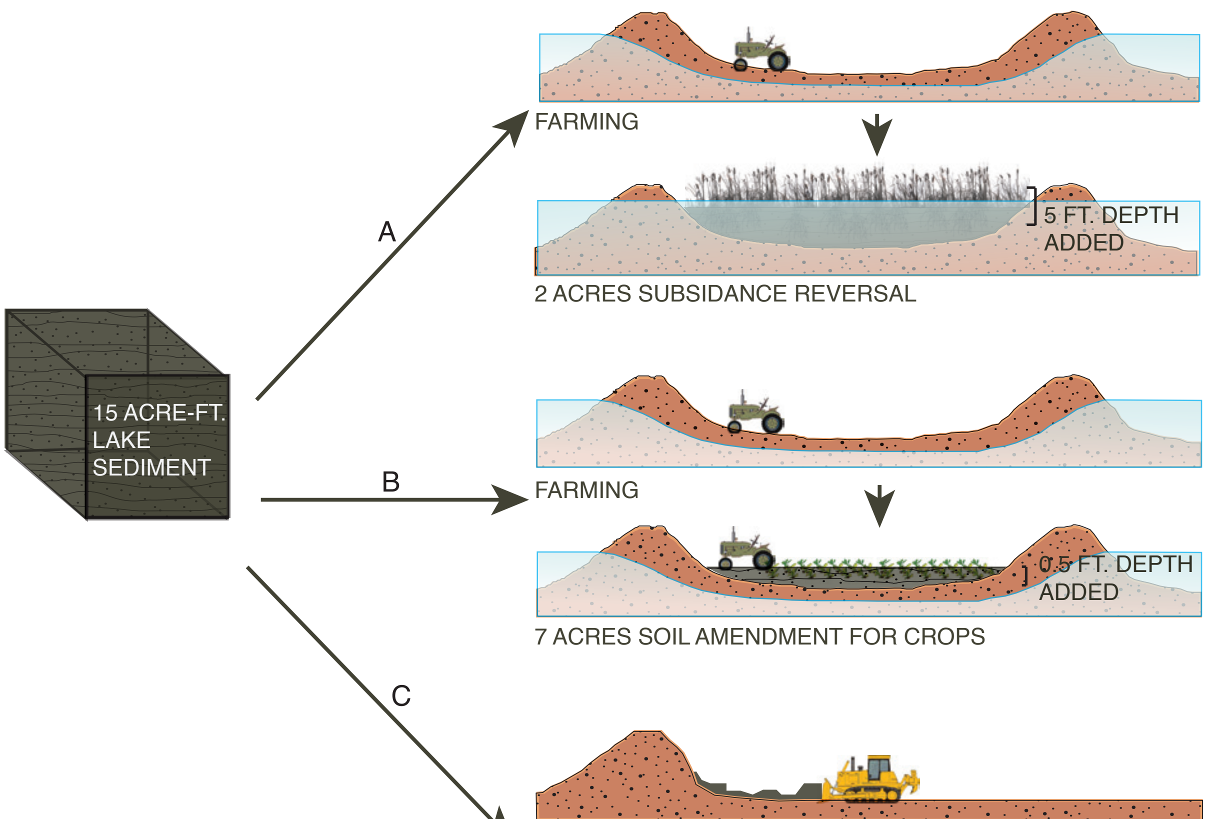


Fig. 3.34 Pilot project experimental applications for sediment re-use.

by Simon and Ingle (2011). Other techniques exist for rapid dewatering (e.g., geotextile tubes); however, they are more expensive.

For agricultural and levee application, the dredged sediments would be dried prior to use. Wetland application does not require as much dewatering; however, perimeter levees and interior dikes would need to be constructed at the deposition site to temporarily contain the dredged material, as well as water control systems to reduce sedimentation.

Assuming that the pre-dredging surveys and tests support multiple uses of the dredged sediments,[80] the total dredged volume would be applied to the following:

- 1-2 wetland rehabilitation sites in Agency Lake Ranch and Barnes Ranch parcels (or other similar parcels) totaling 2 acres (see Figure 3.34A)
- 1-3 agricultural soil amendment sites totaling 7 acres (see Figure 3.34B)
- 250-500 linear feet of levee/dike sites (see Figure 3.34C)

MONITORING

Prior to dredging, and as part of pilot project permitting, sediment quality characterization would include testing for levels of common sediment contaminants of concern, including pesticides, herbicides, metals, and PCBs, as well as algal toxins. Routine water quality monitoring would be

80 The final design should include a plan to manage dredged sediments if the results of the pre-dredging surveys and tests do not support multiple re-use options.

conducted in the vicinity of the dredge site before, during, and after dredging operations to ensure the dredging operation meets permit requirements (see below). Routine water quality monitoring would focus on turbidity and quantification of re-suspended phosphorus.

In addition to routine monitoring, the pilot project would also include targeted monitoring at multiple test sites to answer questions regarding the potential for beneficial reuse of dredged sediments (see text box on page 69).

Lastly, the net effect of dredging on phosphorus concentrations and recycling rates in the target area would be assessed by monitoring total phosphorus in multiple locations. Replicated sediment cores would be collected from the target area prior to, immediately following, and 1 to 2 years following dredging activities. Core sediments would be sampled for total phosphorus and phosphorus associated with different geochemical phases at multiple depths between 0 and 60 cm within each core. It is anticipated that 10-15 sediment cores would be collected to allow for the normal level of variability between core sites. The number of cores would be determined as part of the pilot study final design.

In order to provide information on the external phosphorus load coming into the target area before, during, and after dredging activities, total phosphorus concentrations and river flow would be measured every two weeks at the mouth of the Williamson River. Total phosphorus concentrations would also be measured in the water column within the target area. This study component would be coordinated with ongoing efforts to model phosphorus dynamics in Upper Klamath Lake and may also include determination of silica concentrations and bioturbation rates in the sediment cores (see Figure 1.18).

LAND AND WATER RIGHTS REQUIREMENTS

The following land and water rights requirements would be required for the pilot project:

- Approval from landowner(s) for application of dredged sediments
- Approval from landowner(s) for temporary use for CDF construction and operation (if rented)
- Waterside access for barge/dredge entry to lake

ENVIRONMENTAL, REGULATORY AND PERMITTING REQUIREMENTS

The following permits are anticipated necessary for the pilot project:

- Permits from Oregon Division of State Lands (DSL) and U.S. Army Corps of Engineers (USACE) for dredge and fill activities in U.S. waters, using a joint permit application. USACE consults with the National Marine Fisheries Service (NMFS) and U.S. Fish and Wildlife Service (USFWS) on endangered species concerns.
- Water Quality Certification from Oregon Department of Environmental Quality (ODEQ)
- Certification from local city or county planning department that proposed project is consistent with local comprehensive plan and applicable zoning.

IMPLEMENTATION TIMELINE AND ESTIMATED COSTS

The anticipated timeline for implementing the conceptual design for a sediment dredging pilot project spans approximately 7 years (Figure 3.35).

The production rate of a hydraulic dredge ranges from 500 to 1,000 cubic yards per day to pump the dredged material to the CDF. Assuming a production rate of 500 cubic yards per day with the dredge operating 24 hours per day, it would take 48 days to dredge the estimated 24,000 cubic yards of material.

The time required for sediment deposition depends on its beneficial reuse and the extent to which it has to be dewatered. As noted earlier, dewatering may take several weeks to months depending on the water content and the beneficial reuse option. Given high water fractions in the sediment samples closest to Goose Bay (Simon and Ingle 2001), dewatering times could be at the high end of the range.

Estimated costs for a pilot project are presented in Table 3.10.

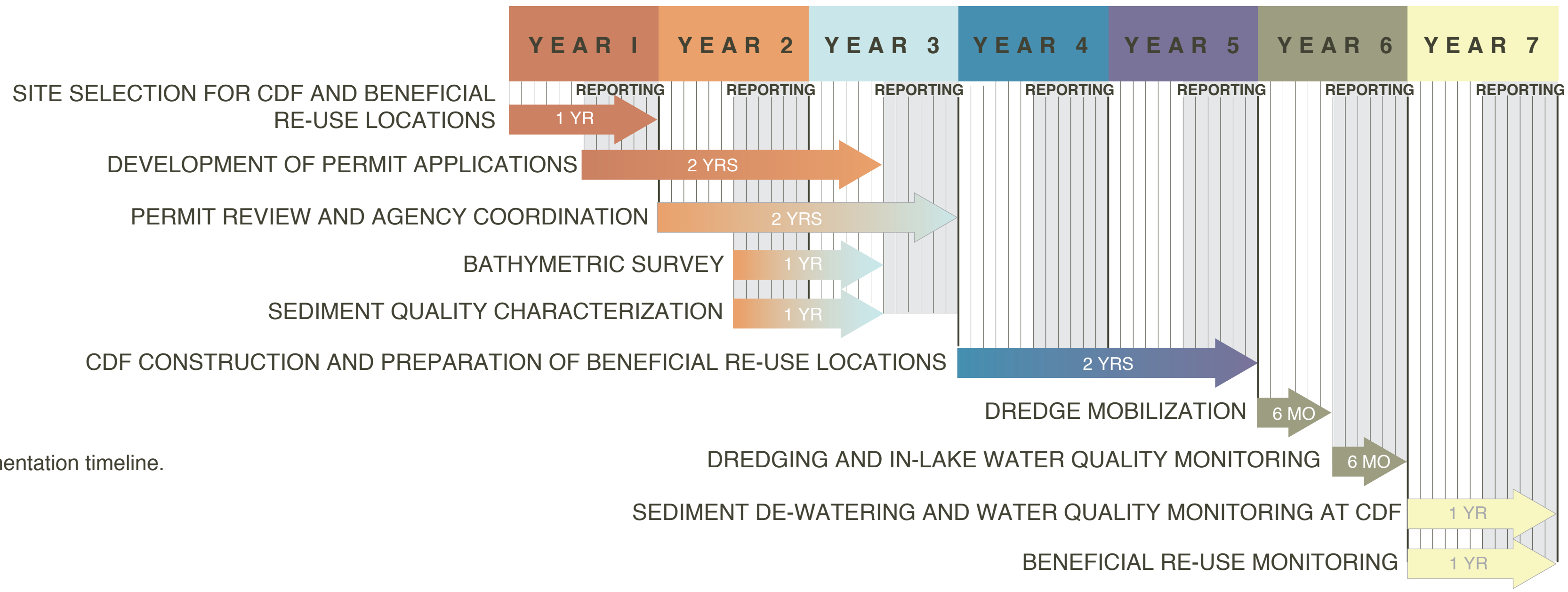


Fig. 3.35 (Right) Implementation timeline.

TABLE 3.10 - ESTIMATED COSTS FOR SEDIMENT REMOVAL (DREDGING) PILOT PROJECT

Site selection for CDF (Confined Disposal Facility) and beneficial re-use locations[81]	$10 - 15K
Final design[82]	$4-5K
Permitting[83]	$50-100K
Sediment quality characterization[84]	$25 - 35K
Hydraulic dredging[85], construction of open-pit CDF,[86] transport dredged material to beneficial re-use site	$360-400K
Dredge mobilization and demobilization[87]	$250 - 500K
O&M (Operation and Maintenance) of CDF and water quality monitoring[88]	$40 - 50K
Water quality and sediment monitoring at beneficial re-use locations[89]	$190 - 290K
Total	**$940K - 1.4M**

81 Includes review of existing data, landowner coordination, and 1-2 site visits. Minimal to no new surveys needed.
82 Assumes relatively simple CDF.
83 Assumes permitting needed for CDF and in-lake dredging activities.
84 Assumes collection and analysis of 25 sediment samples at approximately $1K each for combined analyses.
85 Assumes a dredging area of 15 acres, a depth of 30 cm (1 foot) and a hydraulic dredging cost of $15 per cubic yard (24,000 cubic yards of dredged material).
86 Factors that may influence the cost of the CDF include: land availability (purchase or rental cost), proximity of the land to the lakeshore and dredging area (transportation costs) and local topography of the site (number of sides needed).
87 Includes transport of dredge equipment to and from the upper basin.
88 Assumes three months of operation, weekly site visits and water quality monitoring at $1K per sample for combined constituents.
89 Assumes monthly water quality monitoring for one year at one wetland site, 1-2 agricultural sites, and one berm site at $400-600 per sample for combined constituents.

SEDIMENT SEQUESTRATION OF PHOSPHORUS AND AERATION/ OXYGENATION

CONCEPTUAL DESIGN AND PILOT STUDY

Injection of an alum micro-floc, along with aeration/ oxygenation, was considered for use in Lake Ewauna/ the Keno Impoundment by a relatively small number of workshop breakout groups (Figure 2.26). This technique was recognized for its potential to provide substantial short-term water quality benefits by adding dissolved oxygen to, and stripping phosphorus from, the water column and keeping phosphorus from being released by reservoir sediments. However, workshop attendees generally expressed a need for further scientific studies of alum dosing due to basin-specific water chemistry and toxicity concerns. Therefore, this section describes a conceptual pilot study to 1) determine the efficacy of buffered alum dosing in the low alkalinity and seasonally high pH waters of Lake Ewauna and the Keno Impoundment using bench-scale testing; 2) determine the potential for impacts to aquatic organisms in the project vicinity using toxicity tests; and 3) based on results of the bench-scale tests, to inject alum micro-floc and oxygen into a 40-acre pilot site in Lake Ewauna.

OBJECTIVE - To evaluate the potential for a large-scale effort to significantly reduce oxygen demand in Lake Ewauna and the Keno Impoundment and to sequester or inactivate phosphorus in the sediments and water column using alum micro-floc with aeration/oxygenation.

Fig. 3.36 (Right, above and below) Target area in Lake Ewauna and the upper end of the Keno Impoundment for alum micro-floc aeration/oxygenation pilot study. The alum/ air injection system would be placed in the 40-acre pilot site (green shaded area). White squares indicate water quality monitoring locations.

SITE CHARACTERISTICS

The target area for the alum micro-floc with aeration/ oxygenation pilot project is located downstream of the Link River Dam in Lake Ewauna. The area of Lake Ewauna is approximately 410 acres. The target area was chosen for the following reasons:

1. It receives large seasonal loads of algae from Upper Klamath Lake, which carry high concentrations of phosphorus and cause acutely low dissolved oxygen water column concentrations during the summer and fall (see Figure 1.11).

2. It is characterized by very high water column and sediment oxygen demand rates measured in Lake Ewauna/the Keno Impoundment.[90]

3. It experiences internal loading of phosphorus from sediments during periods of seasonal anoxia.

4. It is a relatively small, confined area with local power and road access.

5. It is situated at the upstream end of the 8-mile long Keno Impoundment, which provides

90 Doyle and Lynch 2005, Sullivan et al. 2011

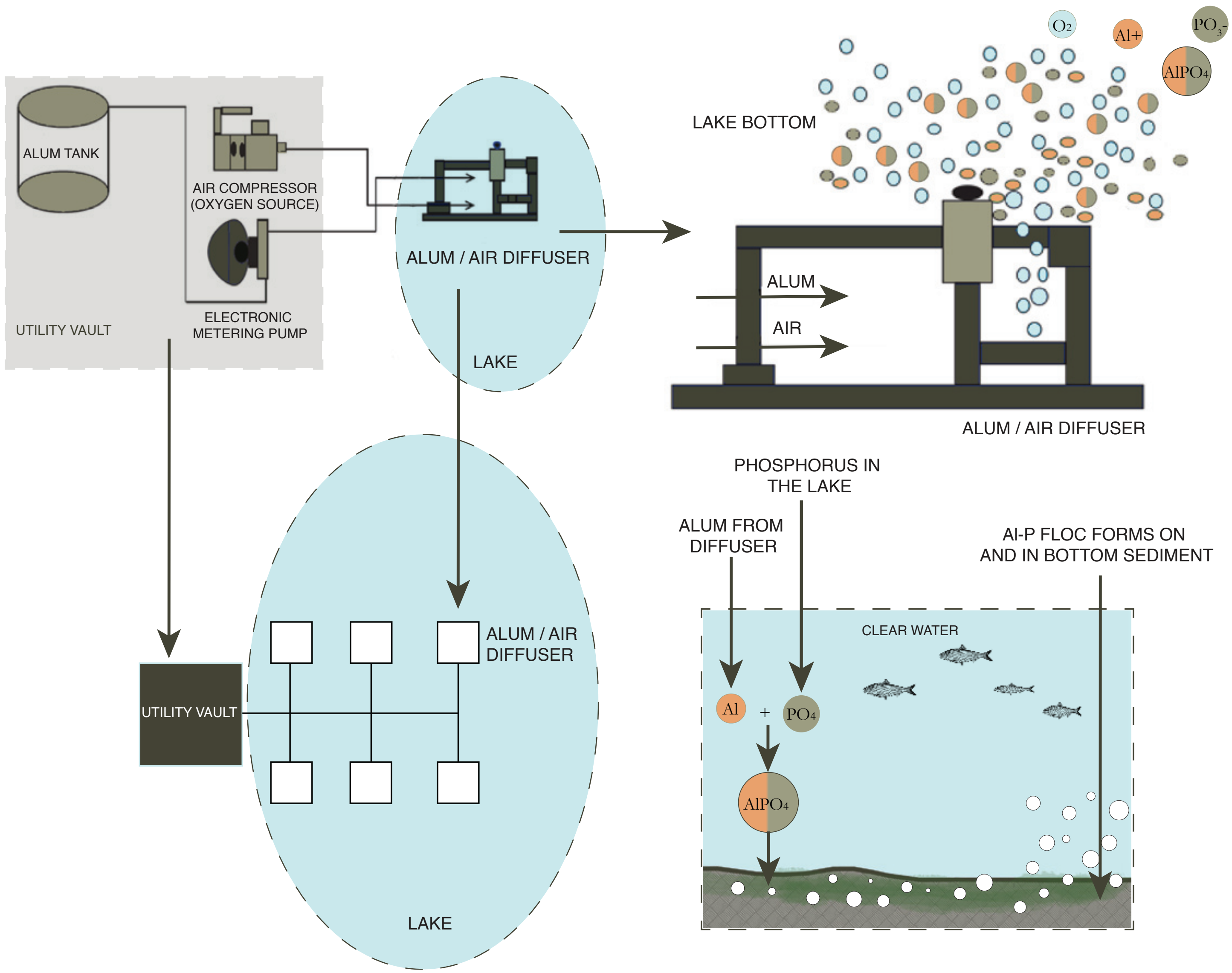


Fig. 3.37 Alum micro-floc aeration/oxygenation injection system.

a sufficient settling distance for the stable and chemically inert alum micro-floc prior to discharge at Keno Dam.

The pilot project would treat 10% of the target area, or approximately 40 acres.

BENCH-SCALE TESTING

As part of the pilot study, alum dosing tests would be conducted to ascertain how buffered alum responds to the low alkalinity, high pH, high dissolved organic matter (DOM), and high suspended solids (due to algae) concentrations present in the target area water column in summer and early fall months. The laboratory "bench-scale" dosing tests would examine alum efficacy and would determine if any dissolved aluminum, which can be toxic to aquatic organisms at high concentrations and pH less than 6, is present in the treated cells (Figure 3.38). Concentrations measured in the dosing tests would be compared against known aluminum toxicity thresholds

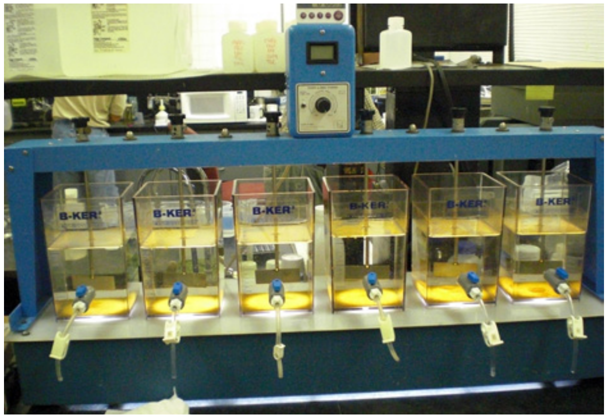


Fig. 3.38 Bench-scale dosing tests can be used to test the efficacy of alum treatment under water chemistry conditions specific to the Upper Klamath Basin. Photo: T. Kirk.

ALUM INJECTION SYSTEMS

Liquid alum[91] and sodium aluminate buffer are stored in a tank housed within a utility vault on the edge of the lake. Alum and buffer are pumped from the tank through a line and metering pump to an air compressor that adds oxygen to the liquid alum. The alum-buffer-oxygen mixture is then pumped at a specified rate through lines to alum diffusers placed strategically along the lake bottom. The buffered alum-oxygen mixture forms a floc that binds with particulate matter and the aluminum in the alum binds with soluble phosphate molecules in the water column as it is dispersed, creating an aluminum phosphate ($AlPO_4$) precipitate that settles to the bottom of the lake and incorporates into the sediments. The aluminum inactivates the phosphate in the water and sediments, clearing the water column of particulates as it settles to the bottom and reducing phosphorus recycling from the sediments. By removing the excess phosphorus from the water column, alum treatment allows greater light penetration in the water column and other species of aquatic plants may grow along the lake bottom. These plants are healthy for a balanced lake ecosystem and provide food and habitat for fish and other organisms.

Alum micro-floc injectors similar to the one described here have been designed by Tetra Tech for a pond in Tukwila, WA and have been implemented in Lake Oswego, Oregon. Micro-floc injection has also been used in several other Midwestern and Eastern States.

91 Alum is typically added as a salt of aluminum sulfate. Non-sulfate alternatives are available.

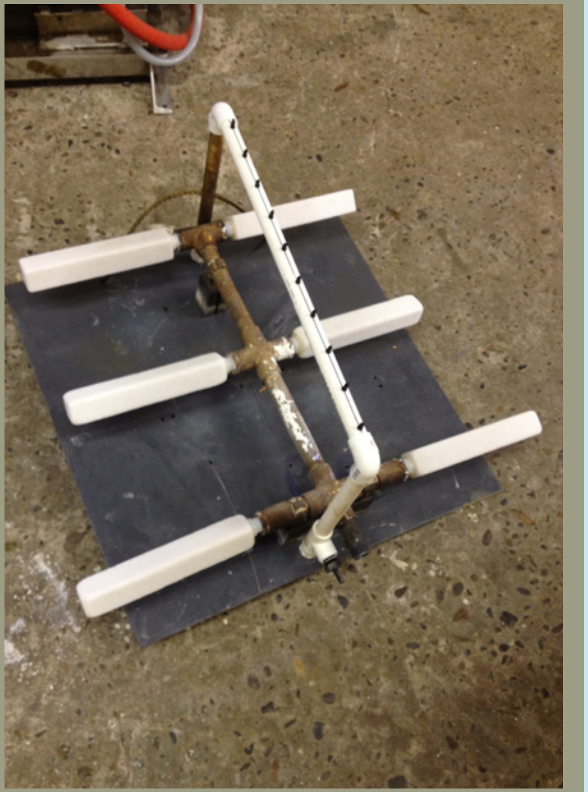


Fig. 3.39 Alum micro-floc injector unit for Lake Oswego, Oregon. Photo: M. Rosenkranz.

TABLE 3.11 - ESTIMATED DAILY TOTAL PHOSPHORUS LOAD TO LAKE EWAUNA AND THE KENO IMPOUNDMENT FROM UPPER KLAMATH LAKE

	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
Average total phosphorus concentration in outflow from Upper Klamath Lake (ug/L)[92]	106	244	211	216	144
Daily average flow at Link River (cfs)[93]	1,385	1,030	944	791	815
Estimated daily total phosphorus load (kg/day)	358	615	488	418	286

92 Value represents the average for water years 1991-2010. Data collected by the Klamath Tribes at PM (Pelican Marina) and FB (Freemont Bridge) sites.
93 Data from USGS gage no. 11507500 for water years 1991-2010. Flows do not include contributions from Westside Canal.

for freshwater fish in the pH range of 6 to 9 and alkalinity less than 100 mg/L, which are conditions typical for the target area during summer and fall (see Section 2, pages 3-5). Note that with full-scale treatment in Lake Ewauna, alum additions would be expected to reduce photosynthetically induced high pH values so that these conditions would not exist. Although the potential for alum toxicity to aquatic species is very small (Section 2, page 28), the dosing tests would also include acute water column testing using a common laboratory toxicity test organisms such as the zooplankton *Daphnia spp.* and rainbow trout to ensure a clear understanding of the likely *in-situ* effects of alum use in the Upper Klamath Basin prior to injection at the target site. In addition, alum bench-scale dosing tests would identify the potential for increased sulfate concentrations in the target area due to alum additions,[94] which may be an important consideration related to sulfur and mercury cycling in the Upper Klamath Basin.

94 Alum is typically added as a salt of aluminum sulfate, but non-sulfate alternatives are available.

PILOT PROJECT CONCEPTUAL DESIGN

Pre-Project Surveys

Prior to alum/aeration unit installation, review of existing bathymetric and LiDAR data, as well as consideration of seasonal circulation patterns[95] for the target area, would be conducted to ensure that conceptual design elements can be supported. The pre-project surveys would also identify an available shoreline site for placement of the air compressor, alum tanks, and other required alum dosing and oxygen supply equipment. It is anticipated that approximately 300 ft^2 would be required for the aerator and 4000 ft^2 would be required for the liquid alum tanks and pumps. If necessary, the equipment could also be stored in underground vaults.

95 Sullivan et al. 2011

TABLE 3.12 - ESTIMATED ALUM DOSE FOR CONCEPTUAL PILOT STUDY IN LAKE EWAUNA

	JUNE	JULY
Whole-lake treatment		
Alum dose (kg/day)[96]	4,000	7,000
Alum dose (gal/day)[96]	18,000	31,000
Pilot study - Treat 10% of incoming total phosphorus load		
10% of daily total phosphorus load (kg/day)	35.8	61.5
Alum dose (kg/day)	400	700
Alum dose (gal/day)	1,800	3,100

96 For June and July daily average flows, this would result in an buffered alum concentration of 1-2.5 mg/L (whole-lake), and 0.1-0.25 mg/L (pilot study), in Lake Ewauna, or less than the range of 5-26 mg/L found to be safe for aquatic species in previous studies (see text box on page 28).

Additionally, replicated sediment samples would be collected from the target area and downstream locations in the Keno Impoundment prior to alum aeration unit installation in order to characterize the community of sediment-dwelling organisms under low oxygen or anoxic conditions (June – October) as well as during well-oxygenated conditions (November – May) prior to any alum dosing (see additional detail under *Monitoring*).

Alum/Aeration Unit Operation

Up to six alum/aeration injection units would be located at roughly uniform distances apart within the 40-acre pilot site (Figure 3.36). Exact placement of the units would be based on results of the pre-project surveys. Liquid alum and buffer would be pumped from onsite storage through a hose to each dispersal unit on the bottom of the lake, and then into the overlying water column (Figure 3.37). Simultaneously, air (or near pure oxygen) would be transported from the on-shore compressor to each dispersal unit and into the water column. The force of the injected air would convert the released liquid alum into a micro-floc that is mixed with overlying water and transported upward and out of each unit. Multiple injection units promote optimum dispersal and coverage of the alum micro-floc and dissolved oxygen.

Alum Dose

For this conceptual design, the required dose of alum micro-floc for the pilot study is based on the estimated daily total phosphorus load entering Lake Ewauna and the Keno Impoundment from Upper Klamath Lake during the months of June through October (Table 3.11). This is in contrast to whole-lake alum systems, which are often designed

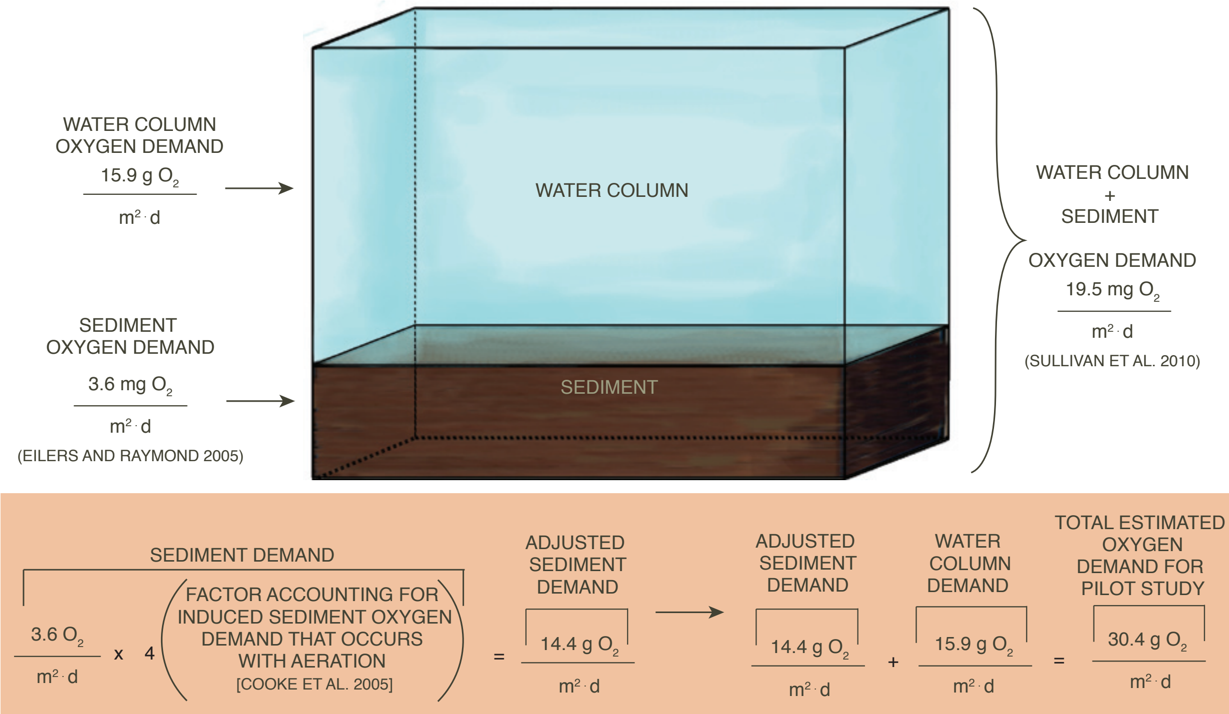


Fig. 3.40 (Above) Combined sediment and water column oxygen demand for estimating required oxygen dose for pilot study.

TABLE 3.13 - ESTIMATED OXYGEN DOSE REQUIRED FOR PILOT STUDY

COMBINED SEDIMENT AND WATER COLUMN OXYGEN DEMAND ($g\ O_2/m^2$ per day)	PILOT SITE AREA (ACRES)	REQUIRED OXYGEN DOSE (kg/d)	EFFICIENCY-ADJUSTED OXYGEN DOSE FOR AIR INJECTION (kg/d)[97]	EFFICIENCY-ADJUSTED OXYGEN DOSE FOR PURE O_2 INJECTION (kg/d)[97]
30.4	40	4,921	61,514	24,606

97 Assumes the efficiency of fine bubble delivery is 8% for air and 20% for pure oxygen.

TABLE 3.14 - ANTICIPATED MONITORING ELEMENTS FOR ALUM MICRO-FLOC AERATION/OXYGENATION PILOT STUDY

MONITORING PARAMETER	SAMPLING STRATEGY	SAMPLING FREQUENCY
• **Water temperature** • **Conductivity** • **Dissolved oxygen** • **pH**	Vertical profiles every 0.5-m	Daily during June through September
• **Total suspended solids** • **Turbidity** • **Total and ortho-phosphorus**	Surface, mid-depth (~3.0 m) and 0.5-m from the bottom sediments	Daily during June through September
• **Alum and phosphorus profiles in sediments** • **Number (abundance) and type (species) of sediment-dwelling organisms**	Replicated sediment samples from the target area and downstream locations in the Keno Impoundment	• Before and after alum dosing and aeration/oxygenation • Summer/early fall (low oxygen conditions) • Winter/spring (well-oxygenated conditions)
Number (abundance) and location (distribution) of sucker life stages	Representative number of treatment areas	1 survey during each of May, September, December

on the basis of the mass of phosphorus in the sediments.[98] It is anticipated that dosing in proportion to the incoming phosphorus load at Link River Dam would also provide adequate residual floc binding sites to inactivate a large fraction of mobile sediment phosphorus over time.

While basic chemical stoichiometry indicates that one unit of aluminum can bind with one unit of phosphate, other compounds, such as DOC and other forms of less bioavailable phosphorus found in natural waters, can compete with phosphate and reduce the efficiency of the micro-floc. A study of six lakes in Washington indicated that an average ratio of 11:1 represents the ultimate binding capacity of alum after several years of treatment.[99] As a conservative estimate, applying the ratio of 11:1 to the estimated daily total phosphorus load to Lake Ewauna and the Keno Impoundment equates to whole-lake required alum doses of roughly 4,000 to 7,000 kg/day during June and July (pilot testing period) (Table 3.12). At 0.22 kg/gallon alum, the whole-lake liquid alum dose would be roughly 18,000 to 31,000 gallon/day.

To dose the 40-acre pilot site, which is approximately 10 percent of the target area, the alum dose would be 1,800 to 3,000 gallon/day (Table 3.12). To ensure water quality stability, a sodium aluminate buffer would be added with the alum, resulting in 800 to 1,200 gallons of alum and 400 to 700 gallons of sodium aluminate per day.

Oxygen Supply

The quantity of dissolved oxygen required to offset the very high water column and sediment demand measured in Lake Ewauna and the Keno Impoundment during summer and early fall is based on a sediment-plus-water-column oxygen demand rate of 19.5 g O_2/m^2 per day (Figure 3.40). A factor of four is applied to the sediment oxygen demand rate due to additional induced sediment demand that typically occurs with aeration.[100] Oxygen supply to meet water column oxygen demand is usually doubled to account for the induced demand, but for the Lake Ewauna/the Keno Impoundment pilot study, where existing oxygen demand is extremely high, the maximum factor would be used. The efficiency-adjusted oxygen doses for an air injection option and a pure oxygen injection option for the pilot study are presented in Table 3.13.

MONITORING

During the pilot study, water samples would be collected at 8-11 monitoring sites located between Link River Dam and the upper end of the Keno Impoundment (Figure 3.36). Water samples collected at the Link River Dam would be used to determine the inflow load of total phosphorus during and after the pilot study (Table 3.14). Daily water samples collected from sites spaced along the length of Lake Ewauna and the upper end of the Keno Impoundment

98 Cooke et al. 2005

99 Rydin et al. 2000

100 Cooke et al. 2005

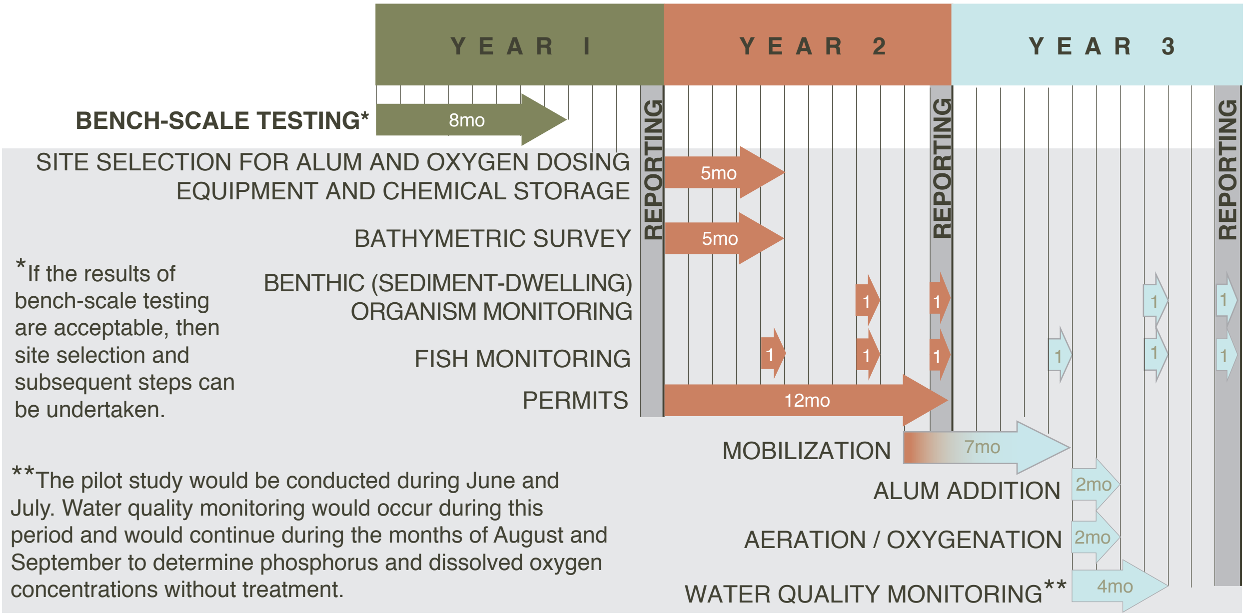


Fig. 3.41 Implementation timeline.

would be used to determine treatment effectiveness. The monitoring program includes a component to determine the potential effects of alum micro-floc and aeration/oxygenation on the community of organisms that currently inhabit the sediments (called "benthic" organisms) and on suckers that live in Lake Ewauna and the Keno Impoundment (Table 3.14).

LAND AND WATER RIGHTS REQUIREMENTS

A small shoreline staging area would be required for dosing equipment, including the air compressor (approximately 300 ft^2) and alum storage tanks and pumps (approximately 4,000 ft^2). The staging area would also need to provide easy access for supply trucks. It is anticipated that the pilot study storage capacity requirements for alum would be small compared to most lake treatments; however, if necessary, the equipment can be stored in underground vaults. There would be no diversion of water for the pilot project and no water right would be required.

ENVIRONMENTAL, REGULATORY, AND PERMITTING CONSTRAINTS

A water quality permit from Oregon Department of Environmental Quality would likely be required to add alum and air to Lake Ewauna and the Keno Impoundment.

IMPLEMENTATION TIMELINE AND ESTIMATED COSTS

The anticipated timeline for implementing the conceptual design for a phosphorus sediment sequestration and aeration/oxygenation pilot project in the Keno Impoundment spans approximately 3 years (Figure 3.41). Estimated costs for a pilot project are presented in Table 3.15.

TABLE 3.15 - ESTIMATED COSTS FOR SEDIMENT PHOSPHORUS SEQUESTRATION AND AERATION/ OXYGENATION PILOT PROJECT

Bench-scale testing dosing tests[101]	$60-75K
Site selection for alum and oxygen dosing equipment and chemical storage[102]	$6-8K
Permitting	$20-30K
Alum addition[103]	$290-350K
Aeration/oxygenation[104]	$365-437K
Water quality monitoring[105]	$94-124K
Benthic (sediment-dwelling) organism monitoring[106]	$26-38K
Fish monitoring[107]	$12-18K
Total	**$880-1.1M**

101 Includes operation and analytical costs for replicated bench-scale tests using flow-through treatment cells and toxicity testing with standardized benthic and fish test species.
102 Includes review of existing information, landowner coordination, and 1-2 site visits. Minimal to no new surveys needed.
103 Includes alum pump line, six injection units, chemical storage tanks, alum, sodium aluminate buffer, mobilization, electrical, and O&M.
104 Includes air compressor (50 HP), airline, equipment housing, electrical controls, mobilization, electrical, and O&M.
105 Assumes in situ water quality measurements plus 3 grab samples per site per day for 120 days at 8-11 sites.
106 Assumes 3-4 surveys to identify benthic macroinvertebrates at approximately 10 sites within and downstream of the target area.
107 Assumes 3 surveys to identify benthic macroinvertebrates at approximately 10 sites within and downstream of the target area.

SECTION 4 | LINKED TECHNIQUES

Fig. 4.1 (Above left) Spawning Lost River suckers. Photo: USGS.

Fig. 4.2 (Above right) Algae bloom on Upper Klamath Lake. Photo: Brett Cole.

LINKED TECHNIQUES

Poor water quality in the Upper Klamath Basin is the result of multiple factors, including decades of NPS pollution that has exacerbated naturally elevated phosphorus levels in basin water bodies. Both external and internal sources of phosphorus to Upper Klamath and Agency lakes are important contributors to summertime poor water quality, resulting in excessive seasonal blooms of blue-green algae, low dissolved oxygen, high pH, high ammonia, and problematic levels of algal toxins, primarily microcystin. Water quality conditions have been identified as a significant threat to the long-term survival of endangered Lost River and shortnose suckers in Upper Klamath Lake (see Section 1, pages 3-5).

Given the large scale of the problem, no single technique or approach will be sufficient to improve water quality to the degree that it can support all designated beneficial uses in the Upper Klamath Basin. A recent effort to set theoretical boundaries on expected nutrient removal performance for wetlands in the vicinity of Link River indicated that tens of thousands of acres of treatment wetlands would be needed to reduce phosphorus and nitrogen concentrations by 50% and 15%, respectively.[1] This assumes that all water quality treatment for the basin would occur by diverting water into wetlands at the Link River Dam. While this is not a realistic assumption, the result underscores the importance of treating water at locations further upstream in the Upper Klamath Lake watershed and its tributaries. Another recent modeling effort indicates that water quality improvements in and around Upper Klamath Lake would have a far greater effect on water quality in the Keno Impoundment than treating water in the reservoir or treating water that is discharged to the reservoir by point sources and irrigation drains.[2]

Accordingly, no one technique or treatment approach was singled out by workshop participants or the technical team as a "silver bullet" solution to current water quality problems (Section 2). Rather, implementation of multiple techniques, linked both in time and in space, is key for treating both the symptoms and the causes of Upper Klamath Basin water quality problems.

TREATING THE SYMPTOMS

Short- term projects that treat the symptoms of excessive nutrient loading are focused on addressing acutely low dissolved oxygen concentrations during summer and early fall months and inactivating sediment hot spots for phosphorus recycling. Conceptual designs developed by the project technical team include two types of projects that treat poor water quality symptoms (Figure 4.6):

- Sediment phosphorus sequestration with aeration/oxygenation in the Keno Impoundment
- Targeted dredging in Upper Klamath and Agency lakes with local sediment reuse opportunities for wetland rehabilitation, subsidence reversal, and agricultural soil amendment

1 CH2MHill 2012

2 Sullivan et al. 2013

Fig. 4.3 (Top right) Grazed pasture in the Wood River watershed. Photo: Damion Ciotti.

Fig. 4.4 (Center right) Tailwater from grazed pasture in the Wood River watershed. Photo: Damion Ciotti.

Fig. 4.5 (Bottom right)The Keno Impoundment and wetlands near the mouth of the Klamath Straits Drain. Source: Chauncey Anderson.

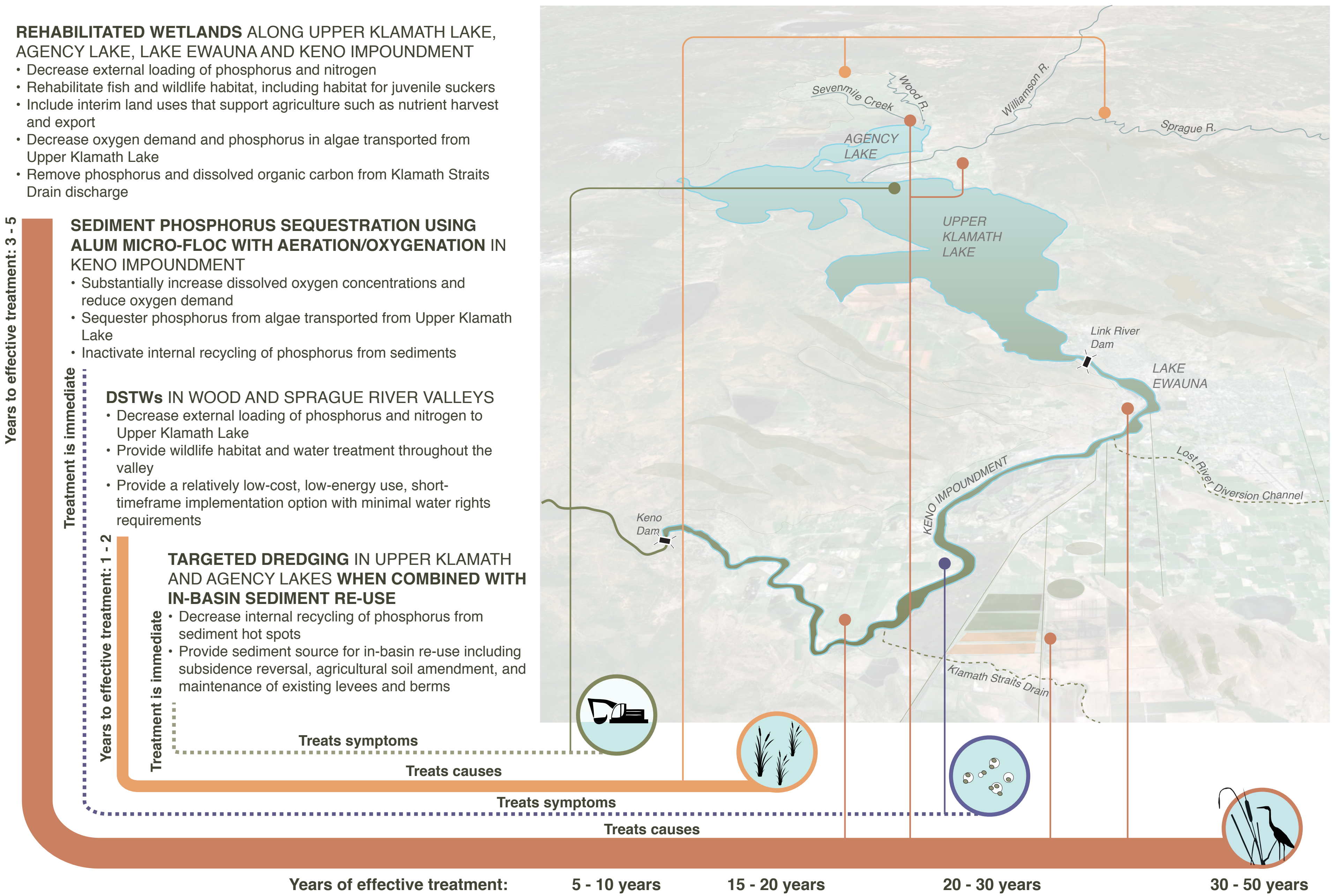


Fig. 4.6 Linked techniques for treating the symptoms and causes of poor water quality in the Upper Klamath Basin over a 50-year timeline.

Algal filtration, another project type that treats the symptoms of poor water quality, was not developed as a conceptual design in this report due to a lack of information on how well this technology can be scaled up to remove large quantities of biomass and improve water quality. However, there is currently momentum for implementing an algal filtration pilot project in the basin, which could shed light on basic questions about harvest efficiency, effects on water quality, and re-use opportunities for harvested material (see Section 2, page 23).

In general, projects that treat poor water quality symptoms have a relatively short implementation timeframe. As soon as they are implemented, water quality and/or sediment conditions improve. However, the longevity of the timeframe for effective treatment tends to be shorter (Figure 4.6). Once treatment stops, poor water and/or sediment quality conditions may return within a relatively short time period (1-3 years). Further, these projects are targeted at specific geographic areas (i.e., the Keno Impoundment, Upper Klamath and Agency lakes) rather than the basin as a whole and they are energy intensive. It is likely that fossil fuels would power the dredge equipment and transfer of sediment to re-use locations and it would run the pumps for dispensing alum and oxygen into the Keno Impoundment. Given climate change, future energy costs may be considerably greater than they are today, increasing the costs of these projects with time.

Therefore, projects that treat the symptoms of poor water quality must be linked with projects that treat the causes. As the sources of water quality problems in the Upper Klamath Basin diminish over time, these projects could be phased out.

TREATING THE CAUSES

Medium- to long-term projects that treat the causes of excessive nutrient loading are focused on external inputs of nutrients to Upper Klamath and Agency lakes. These projects include the following (Figure 4.6):

- DSTWs in Wood River and Sprague River valleys
- Rehabilitated dual treatment and habitat wetlands along margins of Upper Klamath and Agency lakes, Lake Ewauna, and the Keno Impoundment, including the downstream end of the Klamath Straits Drain

Projects that treat the causes of poor water quality have a longer implementation timeframe. From the time that they are implemented, measurable water quality improvements take 1-2 years to occur for DSTWs and 3-5 years for larger wetlands. However, the timeframe for effective treatment tends to be longer (greater than 15 years, see Figure 4.6). These projects have a broader geographic range. DSTWs in particular could be scattered through the Wood and Sprague river valleys, and the larger treatment wetlands could be located at multiple locations along lake or reservoir shorelines. Projects treating the causes are less energy intensive and would therefore be more resilient in the face of climate change and increasing energy costs. These projects would also provide wildlife habitat along with improving water quality (Section 3, pages 41-63).

It is anticipated that linking project types in space and time to treat both the symptoms and causes of poor water quality would result in substantial basin-wide improvements over an approximately 50-year

Fig. 4.7 (Above) Seasonal wet meadows and agricultural areas characteristic of the Sprague River Valley. Photo: Google Earth.

Fig. 4.8 (Below) Farm scene along Sprague River. Photo: Jan Tik.

timeframe (Figure 4.6). Successful implementation of pilot projects presented in Section 3 would help to refine performance estimates for the different conceptual designs.

OTHER POSSIBLE PROJECTS SUPPORTING WATER QUALITY IMPROVEMENT IN THE UPPER KLAMATH BASIN

In addition to the projects discussed above, several other creative ideas were discussed by workshop participants as possible contributors to improved water quality in the Upper Klamath Basin. These include the following:

- Education, outreach and landowner incentive programs to support restoration/rehabilitation goals
- An Upper Klamath Basin Watershed Plan to explicitly state restoration/rehabilitation goals and nutrient targets
- Water diversion into Lower Klamath National Wildlife Refuge from the Klamath Straits Drain and/or the Klamath River via Ady Canal
- Use of wetlands to produce humate[3]
- Harvest algal biomass from the outlet of Upper Klamath Lake (Section 2, page 23)
- Use Biochar or other type of soil amendment to reducenutrient runoff or as a filter media to removenutrients from agricultural drains

In the Sprague River Valley

- Change the point of diversion for agricultural uses and reconnect the groundwater spring system to allow cold groundwater recharge of the river
- Riparian restoration
- Control juniper encroachment at springs and seeps

Further development of these ideas is outside the scope of this report. However, the first two bullets in particular represent critically important steps in the successful implementation of large-scale water quality improvement projects in the basin. Social and cultural factors such as social context, awareness, attitudes, capacities, constraints, and behaviors in a watershed must be considered along with environmental goals.

Research Needs

The remaining bullets could be considered as additional information becomes available. During the development of final pilot project designs, these concepts could be included, as applicable. In particular, a final design for implementation of DSTWs throughout the Sprague River Valley would need to consider how these systems would interact with ongoing efforts for riparian restoration reconnection of groundwater springs (see text box on page 42).

Lastly, there are several ongoing research needs related to nutrient cycling and ecosystem processes in the Upper Klamath Basin. Research needs include continuing data collection and a combination of empirical (based on direct observation) and mechanistic (simulations based on mathematical representations of the processes) models to better describe the following:

- Phosphorus dynamics in Upper Klamath Lake and the Keno Impoundment
- Effects of water flow, temperature, nutrients, and wind circulation on algal blooms in Upper Klamath Lake
- Sucker survival and recruitment in Upper Klamath Lake

These modeling efforts could progress in a coordinated fashion with the recommended pilot projects (Section 3). Information collected during the pilot studies may serve as useful calibration data for the models, or it may help modelers to develop algorithms more appropriate for Upper Klamath Lake conditions.

3 An organic substance that naturally produced in wetlands and is high in humic acids. Humate has been shown to decrease algal bloom density in other locations, although results are mixed for the Klamath Basin for control of *Aphanizomenon flos aquae* blooms in Upper Klamath Lake (Milligan et al. 2009).

Fig. 4.9 West-facing view from a hillside, Upper Klamath Lake. Photo: David Garden.

Fig. 4.10 Shoreline, Upper Klamath Lake. Photo: David Garden.

CONCLUSION

The purpose of the September 2012 Klamath River Water Quality Workshop was to evaluate approaches for improving water quality in the Upper Klamath Basin and to inform decision making on nutrient reduction approaches. The workshop focused on upper basin projects to foster a new, healthier equilibrium condition for basin headwaters, to treat the symptoms as well as the causes of elevated phosphorus and nitrogen levels, and, ultimately, to support water quality improvements in downstream reaches of the Klamath River. Six pollutant reduction technologies or approaches were pre-selected by the project Steering Committee for consideration at the workshop. The pre-selected technologies have demonstrated success in other systems challenged by nutrient pollution, and include the following:

- Wetland restoration (habitat focus)
- Treatment wetlands (water quality focus)
- Diffuse source (decentralized) treatment wetlands
- Algal filtration
- Sediment dredging
- Sediment sequestration of phosphorus and aeration/oxygenation

Feedback from workshop participants was used by the project technical team to develop pilot project conceptual designs for three overarching project types; wetland rehabilitation, sediment removal (dredging), and sediment sequestration of phosphorus with oxygenation/aeration. No single approach to addressing water quality improvements was selected because the current scale of the problems is too large. Instead, the team developed conceptual designs for multiple pilot projects at several locations in the Upper Klamath Basin with an eye toward treating both the symptoms and the causes of water quality problems. Linking both types of projects, in space and time, represents an exciting opportunity to improve water quality and thereby support multiple beneficial uses. Lastly, continuing education, outreach, and incentives for landowners and managers is an important component of the successful implementation of pilot, and ultimately full-scale, water quality improvement projects in the Upper Klamath Basin.

REFERENCES

Ackerman N. K., B. Pyper, I. Courter, S. Cramer. 2006. Estimation of returns on naturally produced coho to the Klamath River—review draft. Klamath coho integrated modeling framework technical memorandum #1 of 8. Prepared by Cramer Fish Sciences, Gresham, Oregon for U.S. Bureau of Reclamation, Klamath Basin Area Office, Klamath Falls, Oregon.

Aldous, A. 2013. Subsidence reversal potential for Upper Klamath Lake fringe wetlands. The Nature Conservancy.

Asarian, E., and J. Kann. 2011. Phytoplankton and nutrient dynamics in Iron Gate and Copco Reservoirs 2005–2010. Prepared by Kier Associates and Aquatic Ecosystem Sciences for Klamath Basin Tribal Water Quality Work Group, Klamath, California.

Bachand, P. A. M., C. J. Richardson, and P. Vaithiyanathan. 2000. Phase II Low Intensity Chemical Dosing (LICD): development of management practices. Final report. Prepared for Florida Department of Environmental Protection in fulfillment of Contract No. WM720.

Bachand, P. A. M, A. C. Heyvaert, S. E. Prentice, and T. Delaney . 2010. Feasibility study and conceptual design for using coagulants to treat runoff in the Tahoe Basin. ASCE Journal of Environmental Engineering 136: 1,218–1,231.

Barbiero, R. P., and J. Kann. 1994. The importance of benthic recruitment to the population development of *Aphanizomenon flos-aquae* and internal loading in a shallow lake. Journal of Plankton Research 16: 1,581–1,588.

Barr, B. R., M. E. Koopman, C. D. Williams, S. J. Vynne, R. Hamilton, and B. Doppelt. 2010. Preparing for climate change in the Klamath basin. National Center for Conservation Science and Policy and The Climate Leadership Initiative.

Bidlake, W. R. 2002. Evapotranspiration from selected fallowed agricultural fields on the Tule Lake National Wildlife Refuge, California, during May to October 2000. Water-Resources Investigations Report 02-4055. Prepared by U.S. Geological Survey and U.S. Fish and Wildlife Service, Tacoma, Washington.

Bradbury, J. P., S. M. Colman, and R. L. Reynolds. 2004. The history of recent limnological changes and human impact on Upper Klamath Lake, Oregon. Journal of Paleolimnology 31: 151–161.

Busby. P. J., T. C. Wainwright, and R. S. Waples. 1994. Status review for Klamath Mountains Province steelhead. NOAA Technical Memorandum NOAA Fisheries Service-NWFSC-19. National Marine Fisheries Service, Seattle, Washington.

Canet, R., C. Chaves, F. Pomares, and R. Albiach. 2003. Agricultural use of sediments from the Albufera Lake (eastern Spain). Agriculture, Ecosystems and Environment 95: 29–36.

CH2M Hill. 2009a. Analysis of microcystin in resident fish and mussel tissues in the vicinity of the Klamath Hydroelectric Project in 2008. Prepared by CH2M Hill, Redding, California for PacifiCorp, Portland, Oregon.

CH2M Hill. 2009b. Occurrence of microcystin in Chinook salmon and steelhead in the Klamath River in 2007. Prepared by CH2M Hill, Redding, California for PacifiCorp, Portland, Oregon.

CH2M Hill. 2012. Approaches to water quality treatment by wetlands in the Upper Klamath Basin. Prepared by CH2M HILL, Portland, Oregon for PacifiCorp Energy, Portland, Oregon.

Colman, S. M., J. P. Bradbury, and J. G. Rosenbaum. 2004. Paleolimnology and paleoclimate studies in Upper Klamath Lake, Oregon. Journal of Paleolimnology 31: 129–138.

Cooke, G. D., E. B. Welch, S. A. Peterson, and S. A. Nichols, 2005. Restoration and management of lakes and reservoirs, third edition. CRC Press, Boca Raton, Florida.

Craig Vogt, Inc. 2010. Beneficially using dredged materials to create/restore habitat and restore brownfields, and team collaborative efforts that have achieved success: examples/case studies. Prepared for the Great Lakes Commission.

Cuenca, R. H., J. L. Nuss, A. Martinez-Cob, and G. G. Katul. 1992. Oregon crop water use and irrigation requirements. Prepared by Oregon State University, Water Resources Engineering Team, Department of Bioresource Engineering, Agricultural Experiment Station, and OSU Extension Service, Corvallis.

Daniels, W. L., G. R. Whittecar, and C.H. Carter III. 2007. Conversion of Potomac River dredge sediments to productive agricultural soils. Paper presented at the 2007 National Meeting of the American Society of Mining and Reclamation, Gillette, Wyoming.

Diaz, D. R. and R. Darmody. 2004. Illinois River dredged sediment and biosolids used as greenhouse soil mixtures. University of Illinois at Urbana-Champaign Waste Management and Research Center Report TR-038.

Doyle, M. C., and D. D. Lynch. 2005. Sediment oxygen demand in Lake Ewauna and the Klamath River, Oregon, June 2003. U.S. Geological Survey Scientific Investigations Report 2005–5228.

Eilers, J. M., J. Kann, J. Cornett, K. Moser, and A. St. Amand. 2004. Paleolimnological evidence of a change in a shallow, hypereutrophic lake: Upper Klamath Lake, Oregon. Hydrobiologia 520: 7–18.

Eldridge, S. L. C., T. M. Wood, and K. R. Echols. 2012. Spatial and temporal dynamics of cyanotoxins and their relation to other water quality variables in Upper Klamath Lake, Oregon, 2007–09. Scientific Investigations Report 2012–5069. U.S. Geological Survey.

Fetcho, K. 2006. Klamath River blue-green algae bloom report: Water Year 2005. Prepared for Yurok Tribe Environmental Program, Klamath, California.

Fetcho, K. 2008. 2007 Klamath River blue-green algae summary report. Yurok Tribe Environmental Program. Klamath, California.

Fetcho, K. 2011. 2009 Klamath River blue-green algae summary report. Yurok Tribe Environmental Program, Klamath, California.

Graham, S. A., C. B. Craft, P. V. McCormick and A. Aldous. 2005. Forms and accumulation of soil P in natural and recently restored peatlands - Upper Klamath Lake, Oregon, USA. Wetlands 25: 594-606.

Hamilton, A. 2011. Wood River wetlands subsidence reversal studies presentation.

Harding Lawson Associates. 2000. The beneficial reuse of dredged material for upland disposal. Prepared for Port of Long Beach, California.

Hayden, N.J. and H.A. Hendrixson. 2013. Water quality conditions on the Williamson River Delta, Oregon: Five years post-restoration. 2012 annual report. The Nature Conservancy, Portland, OR.

Hendrixson, H. A., E. C. Janney, and R. S. Shively. 2004. Monitoring of Lost River and shortnose suckers at Upper Klamath Lake non-spawning locations. In Monitoring of adult Lost River suckers and shortnose suckers in Upper Klamath Lake and its tributaries, Oregon: Annual Report 2003. U.S. Geological Survey, Western Fisheries Research Center, Klamath Falls Field Station, California.

Hewitt, D. A., B. S. Hayes, E. C. Janney, A. C. Harris, J. P. Koller, and M. A. Johnson. 2011. Demographics and run timing of adult Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers in Upper Klamath Lake, Oregon, 2009. U.S. Geological Survey Open-File Report 2011-1088.

Jacoby, J. M., and J. Kann. 2007. The occurrence and response to toxic cyanobacteria in the Pacific Northwest, North America. Lake and Reservoir Management 23: 123–143.

Janney, E. C., B. S. Hayes, D. A. Hewitt, P. M. Barry, A. Scott, J. Koller, M. Johnson, and G. Blackwood. 2009. Demographics and 2008 run timing of adult Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers in Upper Klamath Lake, Oregon, 2008. U.S. Geological Survey Open-File Report 2009-1183.

Kadlec, R. H. and S. D. Wallace. 2009. Treatment wetlands. Second edition. CRC Press. Boca Raton, Florida.

Kann, J., and W. W. Walker. 1999. Nutrient and hydrologic loading to Upper Klamath Lake, Oregon, 1991–1998. Draft report submitted to Klamath Tribes, Chiloquin, Oregon and U. S. Bureau of Reclamation, Klamath Falls, Oregon.

Kann, J., and E. Asarian. 2006. Longitudinal analysis of Klamath River phytoplankton data 2001–2004. Technical Memorandum. Prepared by Kier Associates and Aquatic Ecosystem Sciences for Yurok Tribe Environmental Program, Klamath, California.

Kann, J., and E. Asarian. 2007. Nutrient budgets and phytoplankton trends in Iron Gate and Copco reservoirs, California, May 2005–May 2006. Final Technical Report. Prepare for State Water Resources Control Board, Sacramento, California.

Kann, J. 2008. Microcystin bioaccumulation in Klamath River fish and freshwater mussel tissue: preliminary 2007 results. Technical Memorandum. Prepared for Karuk Tribe Department of Natural Resources, Orleans, California.

Kann, J., and S. Corum. 2009. Toxigenic *Microcystis aeruginosa* bloom dynamics and cell density/chlorophyll a relationships with microcystin toxin in the Klamath River, 2005–2008. Technical Memorandum. Prepared for Karuk Tribe, Orleans, California.

Kann J., S. Corum, and K. Fetcho. 2010. Microcystin bioaccumulation in Klamath River freshwater mussel tissue: 2009 results. Prepared by Aquatic Ecosystem Sciences for Karuk Tribe Natural Resources Department, Orleans, California and Yurok Tribe Environmental Program, Klamath, California.

Kann J, L. Bowater, G. Johnson, and S. Corum. 2011. Preliminary 2010 microcystin bioaccumulation results for Klamath River salmonids. Technical Memorandum. Prepared by Aquatic Ecosystem Sciences, Ashland, Oregon and Karuk Tribe Department of Natural Resources, Orleans, California.

Kann, J., and C. Bowman. 2011. Middle Klamath River toxic cyanobacteria trends, 2010. Technical Memorandum. Prepared for Karuk Tribe Department of Natural Resources, Orleans, California.

Kuwabara, J. S., D. D. Lynch, B. R. Topping, F. Murphy, J. L. Carter, N.S. Simon, F. Parchaso, T. M. Wood, M. K. Lindenberg, K. Wiese, and R. J. Avanzino. 2007. Quantifying the benthic source of nutrients to the water column of Upper Klamath Lake, Oregon. Open File Report 2007– 1276. U.S. Geological Survey, Reston, Virginia.

Kuwabara, J. S., B.R. Topping, D. D. Lynch, J. L. Carter, and H. I. Essais. 2009. Benthic nutrient sources to hypereutrophic Upper Klamath Lake, Oregon, USA. Environmental Toxicology and Chemistry 28: 516–524.

Kuwabara, J. S., B. R. Topping, J. L. Carter, T. M. Wood, F. Parchaso, J. M. Cameron, J. R. Asbill, R. A. Carlson, and S. V. Fend. 2012. Time scales of change in chemical and biological parameters after engineered levee breaches adjacent to Upper Klamath and Agency Lakes, Oregon. Open-File Report 2012-1057. U. S. Geological Survey.

Kyger, C., and A. Wilkens. 2011. Endangered Lost River and shortnose sucker distribution and relative abundance in Lake Ewauna, and use of the Link River Dam fish ladder, Oregon. Annual Report 2010. Prepared by U.S. Bureau of Reclamation, Klamath Basin Area, Office, Klamath Falls, Oregon.

Laenen, A., and A. P. LeTourneau. 1996. Upper Klamath Basin nutrient-loading study—estimate of wind-induced resuspension of bed sediment during periods of low lake elevation. Open-File Report 95-414. U.S. Geological Survey, Portland, Oregon.

Leidy R. A., G. R .Leidy. 1984. Life stage periodicities of anadromous salmonids in the Klamath River basin, northwestern California. U.S. Fish and Wildlife Service, Sacramento, California.

Lembke, W. D., Mitchell, J. K., Fehrenbacher, J. B. and M. J. Barcelona. 1983. Dredged sediment for agriculture: Lake Paradise, Mattoon, Illinois. University of Illinois at Urbana-Champaign. Research Report No. 175.

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

Lindenberg, M. K., and T. M. Wood. 2009. Water quality of a drained wetland, Caledonia Marsh on Upper Klamath Lake, Oregon, after flooding in 2006. Scientific Investigations Report 2009–5025. U.S. Geological Survey.

Lopus, S. E., P. A. M. Bachand, A. Heyvaert, I. Werner, S. J. Teh, and J. Reuter. 2009. Potential toxicity concerns from chemical coagulation treatment of stormwater in the Tahoe Basin, California, USA. Journal of Ecotoxicology and Environmental Safety 72: 1,933–1,941.

Lyon, S., A. Horne, J. Jordahl, H. Emond, and K. Carlson. 2009. Preliminary feasibility assessment of constructed treatment wetlands in the vicinity of the Klamath Hydroelectric Project. Draft report. Prepared by CH2MHill for PacifiCorp Energy, Portland, Oregon.

Mahugh, S., M. L. Deas, R. A. Gearheart, J. Vaughn, R. Piaskowski, and A. Rabe. 2009. w Feasibility Study, Phase II—identification and assessment of potential treatment wetland sites in the upper Klamath River. Prepared by Rabe Consulting, Klamath Falls, Oregon; GeoEngineers, Inc., Portland, Oregon; and Watercourse Engineering, Inc., Davis, California for U.S. Bureau of Reclamation, Klamath Basin Area Office, Klamath Falls, Oregon.

Mekebri A, G. J. Blondina, and D. B. Crane. 2009. Method validation of microcystins in water and tissue by enhanced liquid chromatography tandem mass spectrometry. Journal of Chromatography A 1216: 3,147–3,155.

Merrill, A., S. Siegel, B. Morris, A. Ferguson, G. Young, C. Ingram, P. Bachand, H. Shepley, M. Singer, and N. Hume. 2010. Greenhouse Gas Reduction andEnvironmental Benefits in the Sacramento-San Joaquin Delta: Advancing Carbon Capture Wetland Farms and Exploring Potential for Low Carbon Agriculture. Prepared for The Nature Conservancy, Sacramento, California. Available at: (http://www.stillwatersci.com/).

Miller M.A., R.M. Kudela, A. Mekebri, D. Crane, and S.C. Oates. 2010. Evidence for a novel marine harmful algal bloom: cyanotoxin (microcystin) transfer from land to sea otters. PLoS ONE 5: e12576. doi:10.1371/journal.pone.0012576.

Milligan A., P. Hayes, S. Geiger, K. Haggard, and M. Kavanaugh. 2009. Use of aquatic and terrestrial plant decomposition products for the control of *Aphanizomenon flos-aquae* at Upper Klamath Lake, Oregon. Prepared for U. S. Fish and Wildlife Service, Klamath Basin Ecosystem Restoration Office by Wetland Research Consortium. Oregon State University, Corvallis.

Mitsch, W. J., and J. G. Gosselink. 2007. Wetlands. Fourth edition. John Wiley & Sons, Hoboken, New Jersey.

Mitsch W.J., J.W. Day, J. W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. BioScience 51(5):373-388.

Mitsch W.J., and J.W. Day. 2006. Restoration of wetlands in the Mississippi-Ohio-Missouri (MOM) River Basin: Experience and needed research. Ecological Engineering 26:55-69.

Moyle P. B., R. M. Yoshiyama, J. E. Williams, E. D. Wikramanayake. 1995. Fish species of special concern in California. Prepared by Department of Wildlife and Fisheries Biology, University of California, Davis for California Department of Fish and Game, Inland Fisheries Division, Rancho Cordova.

Moyle P. B. 2002. Inland fishes of California. Second edition. University of California Press, Berkeley.

NCRWQCB (North Coast Regional Water Quality Control Board). 2010. Klamath River total maximum daily loads (TMDLs) addressing temperature, dissolved oxygen, nutrient, and microcystin impairments in California, the proposed site specific dissolved oxygen objectives for the Klamath River in California, and the Klamath River and Lost River implementation plans. Final Staff Report. North Coast Regional Water Quality Control Board, Santa Rosa, California.

NMFS and USFWS (National Marine Fisheries Service and U.S. Fish and Wildlife Service). 2013. Biological Opinions on the Effects of Proposed Klamath Project Operations from May 31, 2013, through March 31, 2023, on Five Federally Listed Threatened and Endangered Species. Prepared by NMFS, Southwest Region, Northern California Office, and USFWS Pacific Southwest Region, Klamath Falls Fish and Wildlife Office. May 2013. NMFS file number: SWR-2012-9372. USFWS file number: 08EKLA00-2013-F-0014.

ODEQ (Oregon Department of Environmental Quality). 2002. Upper Klamath Lake drainage total maximum daily load (TMDL) and water quality management plan (WQMP). Oregon Department of Environmental Quality, Portland.

ODEQ. 2010. Upper Klamath and Lost River subbasins total maximum daily load (TMDL) and water quality management plan (WQMP). Oregon Department of Environmental Quality, Bend, Oregon.

Osgood, D., H. Gibbons, P. Eberhardt, A. Shortelle. 2011. Alum for phosphorus inactivation and interception. North American Lake Management Society Workshop Manual. Spokane, Washington.

Pilgrim, K. M. and P. L. Brezonik. 2005. Evaluation of the potential adverse impacts of lake inflow treatment with alum. Lake and Reservoir Management. 21: 78–88.

Prendergast, L., and K., Foster. 2010. Analysis of microcystin in fish in Copco and Iron Gate reservoirs in 2009. Technical Memorandum. PacifiCorp, Portland, Oregon.

Rasmussen, C. G. 2012. Geomorphology, hydrology and biology of floodplain vegetation in the Sprague basin. Doctoral dissertation. University of Oregon, Department of Geography, Eugene.

Raymond, R. 2010a. Water quality conditions during 2009 in the vicinity of the Klamath Hydroelectric Project. Prepared by E&S Environmental Chemistry, Inc., Corvallis, Oregon for PacifiCorp, Portland, Oregon.

Raymond R. 2010b. Phytoplankton species and abundance observed during 2009 in the vicinity of the Klamath Hydroelectric Project. Prepared by E&S Environmental Chemistry, Corvallis, for PacifiCorp, Portland, Oregon.

Richardson, C.J., N.E. Flanagan, M. Ho, and J.W. Pahl. 2011. Integrated stream and wetland restoration: A watershed approach to improved water quality on the landscape. Ecological Engineering, 37 (1): 25–39.

Risley J. C., and M. W. Gannett. 2006. An evaluation and review of water-use estimates and flow data for the Lower Klamath and Tule Lake National Wildlife Refuges, Oregon and California.

Rydin, E. B.J. Huser, and E.B. Welch. 2000. Amount of phosphorus inactivated by alum treatments in Washington lakes. Limnology and Oceanography 45: 226–230.

San Francisco Regional Water Quality Control Board. 2000. Draft staff report: beneficial reuse of dredged materials: sediment screening and testing guidelines. San Francisco Regional Water Quality Control Board, California.

Sigua, G. C. 2009. Recycling biosolids and lake-dredged materials to pasture-based animal agriculture: alternative nutrient sources for forage productivity and sustainability: A review. Agronomy for Sustainable Development 29: 143–160.

Simon, N. S., D. Lynch, and T. N. Gallaher. 2009. Phosphorus fractionation in sediment cores collected in 2005 before and after onset of an *Aphanizomenon flos-aquae* bloom in Upper Klamath Lake, Oregon. Water Air Soil Pollution 204: 139–153.

Simon, N. S., and S. N. Ingle. 2011. Physical and chemical characteristics including total and geochemical forms of phosphorus in sediment from the top 30 centimeters of cores collected in October 2006 at 26 sites in Upper Klamath Lake, Oregon. Open File Report 2011-1168. U. S. Geological Survey.

Stannard, D. I., M. W. Gannett, D. J. Polette, J. M. Cameron, M. S. Waibel, and J. M. Spears. 2013. Evapotranspiration from wetland and open-water site at Upper Klamath Lake, Oregon, 2008–2010. Scientific Investigations Report 2013-5014. Prepared by U.S. Geological Survey in cooperation with the Bureau of Reclamation.

Stillwater Sciences, Riverbend Sciences, Aquatic Ecosystem Sciences, Atkins, Tetra Tech, NSI/Biohabitats, and Jones & Trimiew Design. 2012. Klamath River pollutant reduction workshop—information packet. Revised. Prepared for California State Coastal Conservancy, Oakland, California.

Sullivan, A. B., M. L. Deas, J. Asbill, J. D. Kirshtein, K. Butler, and J. Vaughn. 2009. Klamath River water quality data from Link River Dam to Keno Dam, Oregon, 2008. U. S. Geological Survey Open File Report 2009-1105. U. S. Geological Survey.

Sullivan, A. B., S. A. Rounds, M. L. Deas, J. R. Asbill, R. E. Wellman, M. A. Stewart, M. W. Johnston, and I. E. Sogutlugil. 2011. Modeling hydrodynamics, water temperature, and water quality in the Klamath River upstream of Keno Dam, Oregon, 2006–09: U.S. Geological Survey Scientific Investigations Report 2011-5105.

Sullivan, A.B., I.E. Sogutlugil, S.A. Rounds, and M.L. Deas. 2013. Modeling the water-quality effects of changes to the Klamath River upstream of Keno Dam, Oregon: U.S. Geological Survey Scientific Investigations Report 2013–5135.

Terwilliger, M., D. Simon, and D. Markle. 2004. Larval and juvenile ecology of Upper Klamath Lake suckers: 1998–2003. Oregon State University Final Report for contract hq-97-ru-01584-09 provided to U.S. Bureau of Reclamation, Klamath Falls, Oregon.

USDOI and NMFS (U.S. Department of the Interior and National Marine Fisheries Service). 2012. Klamath Dam Removal Overview Report for the Secretary of the Interior: An Assessment of Science and Technical Information. October 2012. http://klamathrestoration.gov/sites/klamathrestoration.gov/files/2013Updates/FinalSDOR/0.FinalAccessibleSDOR11.8.2012.pdf

USEPA (U.S. Environmental Protection Agency). 1988. Ambient water quality criteria for aluminum. EPA 440/5-86-008. U.S. Environmental Protection Agency, Office of Water Regulations and Standards Criteria, Washington, D.C.

USEPA (U. S. Environmental Protection Agency). 2005. Protecting water quality from agricultural runoff. Prepared by USEPA, Washington, D.C.

USFWS (U.S. Fish and Wildlife Service). 2008. Biological/Conference Opinion regarding the effects of the U.S. Bureau of Reclamation's proposed 10-Year Operation Plan (April 1, 2008–March 31, 2018) for the Klamath Project and its effects on the endangered Lost River and shortnose suckers. Klamath Falls Fish and Wildlife Office, Klamath Falls, Oregon and Yreka Fish and Wildlife Office, Yreka, California.

USFWS (U. S. Fish and Wildlife Service). 2011. Draft revised Recovery Plan for the Lost River sucker (*Deltistes luxatus*) and shortnose sucker (*Chasmistes brevirostris*). Prepared by USFWS, Pacific Southwest Region, Sacramento, California.

VanderKooi S. P., S. M. Burdick, K. R. Echols, C. A. Ottinger, B. H. Rosen, and T. M. Wood. 2010. Algal toxins in Upper Klamath Lake, Oregon: Linking water quality to juvenile sucker health. Fact Sheet 2009-3111. US Geological Survey, Western Fisheries Research Center, Seattle, Washington.

Walker, W., J. Walker, and J. Kann. 2012. Evaluation of water and nutrient balances for the upper Klamath Lake basin in water years 1992–2010. Prepared for Klamath Tribes Natural Resources Department, Chiloquin, Oregon by Environmental Engineers, Concord, Massachusetts and Aquatic Ecosystem Sciences, Ashland, Oregon.

WEF (Water Education Foundation) 2011. Layperson's Guide to the Klamath River. Prepared by the Water Education Foundation, Sacramento, California.

Welch, E. B., and H. Gibbons. 2005. World-wide use of alum in lake restoration. Presented at the North American Lake Management Conference, Madison, Wisconsin, November.

Welch, G., and H. Gibbons. 2009. Aeration of lakes and reservoirs. Lake Line 29: 8–10.

WHO (World Health Organization). 1999. Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management. E & FN Spon, London, England.

Wood, T. M. 2012. Dependence of flow and transport through the Williamson River Delta, Upper Klamath Lake, Oregon, on wind, river inflow, and lake elevation. Scientific Investigations Report 2012–5004. Prepared by U.S. Geological Survey in cooperation with the Bureau of Reclamation.

Wood, T., C. Anderson, and S. Rounds. 2012. Scientific framework for implementing treatment options: Upper Klamath Lake, wetlands, Klamath River. Presentation at Klamath River Water Quality Workshop, 11 September 2012.

Wong, S.W., M.J. Barry, A.R. Aldous, N.R. Rudd, H.A. Hen-drixson, and C.M.Doehring. 2011. Nutrient release from a recently flooded delta wetland: comparison of field measurements to laboratory results. Wetlands. 31:433-443.

Woodard, H. J. 1999. Plant growth on soils mixed with dredged lake sediment. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering 34(6). Abstract available from: http://www.tandfonline.com/doi/abs/10.1080/10934529909376893.

WQST (Water Quality Sub Team). 2011. Assessment of Long Term Water Quality Changes for the Klamath River Basin Resulting from KHSA, KBRA, and TMDL and NPS Reduction Programs: Klamath Secretarial Determination Regarding Potential Removal of the Lower Four Dams on the Klamath River, 21 p. + Appendices. Available online at http://KlamathRestoration.gov/