

AN ABSTRACT OF THE THESIS OF

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Desiree D. Tullos

Upper Klamath Lake (UKL) and Agency Lake (AL) in southern Oregon are both hypereutrophic, in large part due to natural and anthropogenic loading of phosphorus (P), resulting in annual blooms of blue-green algae. Reduction of P loading to the lake is considered crucial to reduce the blue-green algae blooms, maintain water quality, and increase the fish populations within the lake. Restoration of fringe wetlands is one potential way to reduce external P loading to the lake. However, upon the initial period of flooding, restored wetlands have been found to also be a source of P into the lake, as a result of P resuspension due to years of soil disturbance.

We adapted a mass balance model of the biological P uptake and release to examine how P wetland dynamics change over the course of a year in restored wetlands in the Upper Klamath Basin. Our analyses focused on 1) comparing the P release and sequestration processes over each season, 2) examining whether wetlands around the lakes act as a net source or sink of P to UKL, 3) investigating wetland management strategies to determine if there is any one that is most successful at sequestering P, and 4) if release and sequestration of P in restored wetlands contribute to the P dynamics of the broader ecosystem in the UKL.

Results from this model indicate resuspension of P in the wetlands is high throughout the year, yet outflow only occurs during the first 16 days of the summer,

and macrophyte uptake and sedimentation of P are most important in sequestering P. Additionally, our findings indicate that two of the modeled management strategies are successful at preventing P from reaching the lakes, and that wetlands around the lake act as a net sink of P to UKL over time. However, the reduction or termination of external loading is not likely to reduce the algal blooms in the lakes, as the amount of P recycled from the lake sediments each year far exceeds the capabilities of the current wetlands.

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Modeling Phosphorus Sequestration and Release in an Upper Klamath Basin Wetland

by
Emily L. Mulford

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APPROVED:

Major Professor, representing Biological and Ecological Engineering

Head of the Department of Biological Ecological Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Emily L. Mulford, Author

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Modeling Phosphorus Sequestration and Release in an Upper Klamath Basin
Wetland

1.0 INTRODUCTION

Upper Klamath Lake (UKL) and Agency Lake (AL) in southern Oregon are both hypereutrophic, in large part due to natural and anthropogenic loading of phosphorus (P) (ODEQ 2002). The UKL is nitrogen (N) limited with a mass basis Redfield ratio of 3.6:1 (NRC 2004). Algae that have the ability to fix N are most successful in the system and as a result, annual blooms of *Aphanizomenon flos-aquae* occur each summer (Wood et al. 2006). During or following the blooms, degraded water quality occurs in the lakes, including depleted dissolved oxygen, high pH and high temperature (Walker 2001 and Carpenter et al. 2009). Poor water quality in the lake has been linked directly to high mortality and low growth rates of adult endangered fish species in the lake, such as the Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers (NRC 2004), and has ultimately caused several fish kills over the past two decades (Wood et al. 2006). Reduction of P loading to the lake is considered crucial to reduce the blue-green algae blooms and maintain and increase the fish populations within the lake.

Since 1899, approximately 85-90% of the original wetlands in the Upper Klamath Basin (UKB) have been drained for agriculture (Aldous et al. 2005). Inputs of P from rivers that once flowed through the adjacent wetlands now enter the lake directly which, when combined with agricultural products applied to and the decomposition of organic material in the drained wetlands, contribute to the large-scale annual algae blooms (Duff et al. 2009). Restoration of these fringe wetlands is not only important to provide marsh habitat and lake water storage (Carpenter et al. 2009), but is also one potential way to reduce external P loading to the lake (Duff et al. 2009). However, upon the initial period of flooding, restored wetlands have been found to also be a source of P into the lake, as a result of P resuspension due to years of soil disturbance (Aldous et al. 2007). Additionally, resuspension of P as a result of pH-dependent dissolution is likely to occur in summer and fall in the UKL, as microbes produce organic acids during decomposition which cause a decrease in pH (Stevens and Tullos 2011). Therefore, an understanding of seasonal dynamics of P in the restoration wetlands is important when investigating the role of fringe wetlands in P sequestration.

When wetlands are first inundated during the growing season, organic soils undergo organic matter hydrolysis, releasing P to the water column immediately from decomposed organic matter and from the wetland soil (Stevens and Tullios 2011). Resuspension of P from the soils as a result of hydrolysis is thought to occur quickly upon inundation. In one set of experiments on UKL wetlands (Aldous et al. 2007), all detectable P was resuspended from the soils during the first 60 days since flooding, with the majority released during the first 48 hours. Furthermore, the initial release of P is found to decrease over years of flooding as a result of aquatic plant communities becoming more established in the restored wetlands and accretion rates increasing (Duff et al. 2009). However, the extent of sequestration and seasonal P dynamics in restored wetlands are still not well understood.

Thus, the objective of this study was to examine questions regarding P dynamics over time in restoration wetlands in the Upper Klamath Basin. We adapted a mass balance model of P uptake and release (Mitsch and Reeder, 1991) to investigate how P wetland dynamics change over the course of a year. We applied this model to ask:

1. What processes are of greatest importance for P release and sequestration during each season?
2. Over time, do wetlands around the lakes act as a net source or sink of P to UKL?
3. How does P sequestration vary with hydrologic and vegetation management?
4. Do release and sequestration of P in restored wetlands contribute to the P dynamics of the broader ecosystem in the UKL?

2.0 WETLAND DESCRIPTION

The Upper Klamath Basin, in which the UKL and AL reside, has a semiarid climate. Most precipitation occurs between October and March, producing very noticeable seasonable fluctuations in water levels (Carpenter et al. 2009). Summer months are dry and hot and, as a result of the high elevations of the basin (greater than 1,200 m), a greater solar intensity contributes to high rates of evapotranspiration from open water and from standing vegetation (Carpenter et al. 2009).

Two adjacent wetlands that lie just to the north of AL, Agency Lake Ranch Wetland (ALRW) and Wood River Wetland (WRW), were chosen as the focus of the model, as the similar compositions and controlled management styles of these wetlands allow for application of simple modeling equations and scenarios. Both sites have the same organic soils, Histosols in the Lather series (Stevens and Tullos 2011) and similar vegetation composition, with common species including pale spikerush (*Eleocharis macrostachya*), common cattail (*Typha latifolia*) and giant bur-reed (*Sparganium eurycarpum*) (Carpenter et al. 2009). ALRW is a 29 km² wetland, restored in 2000 after decades of cattle grazing. WRW is approximately 13 km² and was drained for irrigated pasture until the area was returned to wetlands in 1995 (Carpenter et al. 2009).

Neither ALRW nor WRW are directly connected to the lakes. At ALRW, the manager (US Bureau of Reclamation) actively mimics the natural hydrology of the area as much as possible, allowing inflow to the wetland through a discrete inlet via mechanical pumping, and available water is impounded in the wetland from October to June. From July to September, water from the wetland is then mechanically pumped into AL via a separate discrete outlet. Additionally, there is a network of canals and drains which are kept full of water at all times. WRW is flooded via mechanical pumping in the winter to provide waterfowl habitat and is allowed to naturally dewater in the spring and summer to allow germination of emergent macrophytes (Stevens and Tullos 2011).

In both wetlands, release rates of TP have found to be temperature dependent, with higher summer temperatures causing a higher release of TP from the sediments (Stevens and Tullos 2011). Wetland soil pH and chemistry are important when examining release rates of soluble reactive phosphorus (SRP) from the sediment, the

form of P readily available for *Afanizomenon* uptake. As Stevens and Tullos (2011) found in their experiments, the organic soils of ALRW and WRW are acidic and were found to have low concentrations of Ca-Pi, which is where SRP would have been released. Because little SRP is released in these wetlands, readsorption by onto the Fe- and Al-Pi fractions would have also been small.

The entire 40 km² area that encompasses both WRW and ALRW (Figure 1) was modeled and then calibrated using available data from both wetlands. Outflow from ALRW only occurs from July to September, thus we used this as an assumption for our total modeled area. Additionally, Stevens and Tullos (2011) found that concentrations of TP released into the water column were significantly higher with summer temperatures in comparison to the other seasons. We first examined how P dynamics change over each season and modeled the wetland from the start of one summer throughout the year and through a second summer to compare the net change of processes at the end of both summers. After examining the seasonal changes in P dynamics throughout the year, we chose to focus on the summer growing season when simulating management strategies.

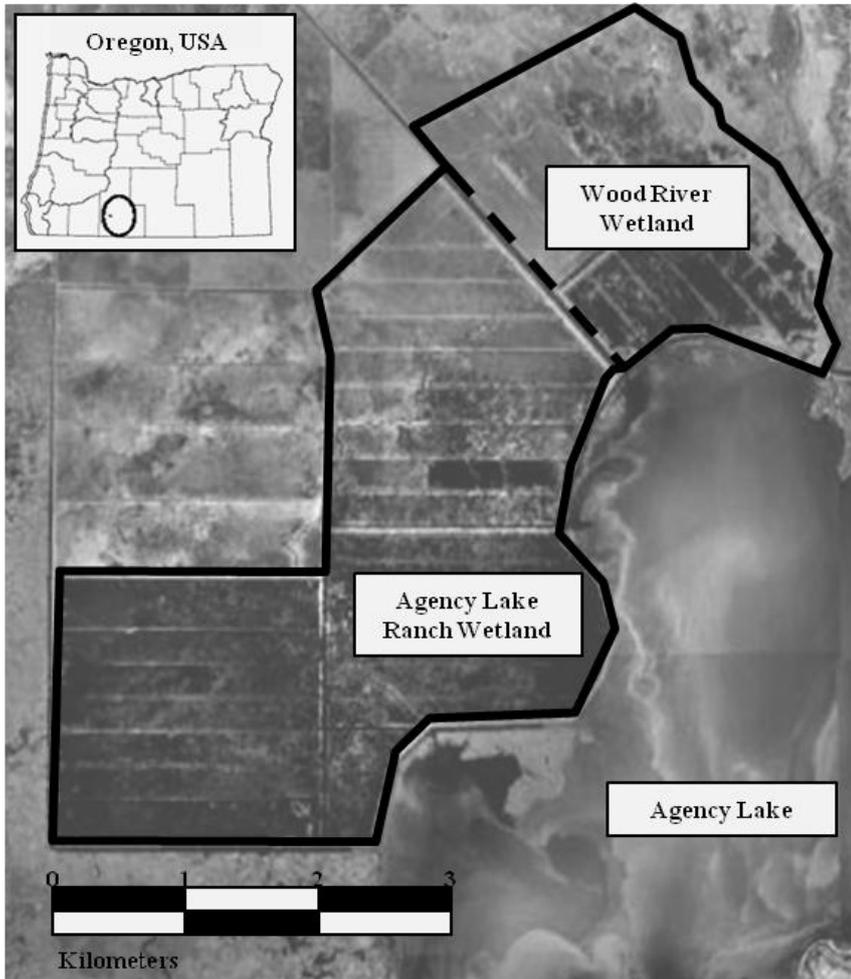


Figure 1- Location of modeled area in Upper Klamath Basin

3.0 MODEL DESCRIPTION

We chose to focus on the biologic exchange of TP in this study as the biologic processes are most modifiable from a management perspective. We used a modified version of the wetland ecosystem phosphorus model, as described by Mitsch and Reeder (1991), which represents the dynamic biologic and hydrologic exchange of TP in the water column and sediments. This model was chosen because it did not require too many parameters and most of the results obtained are reasonable and fall within published ranges. The overall model is comprised of three submodels (Hydrology, Productivity and Phosphorus) and five state variables: Water Volume in the Wetland, Energy in the Algae Biomass, Energy in the Macrophyte Biomass, P in the Water Column and P in the Wetland Sediments. The three submodels, described in detail below, were coded and simulated in Simile (v5.6p1, www.simulistics.com), an object-based software that uses logic-based declarative modeling technology to represent interactions for complex dynamic systems.

We describe the basic model mechanics in the following sections and Appendices A, B and C describe the calculation and calibration of parameters, sensitivity analysis and verification of results, respectively. We refer readers to Mitsch and Reeder (1991) for further information on this mass balance model.

3.1 Hydrologic Submodel

$$\frac{dQ}{dt} = P_r + I - ET - xQ$$

The only state variable in the hydrologic submodel is the water volume in the wetland (Q), measured in m^3 and calculated as a function of precipitation (P_r) and overland inflow (I), evapotranspiration (ET) to the atmosphere and outflow (xQ) to AL, where x is the rate of outflow. Each process is measured in cubic meters (m^3) and the individual parameters of the Hydrologic submodel are described in Table 1.

3.2 Productivity Submodel

$$\frac{dL}{dt} = L_p R - L_r L - L_s L - xL$$

$$\frac{dM}{dt} = M_pRV - M_rM - M_sM$$

In the productivity submodel, there are two state variables, Algal Energy within the Biomass (\mathbf{L}) and Macrophyte Energy within the Biomass (\mathbf{M}), which are both measured in kcal m⁻². The change in algal energy in the biomass over time is described as energy in algal respiration ($\mathbf{L}_r(\mathbf{L})$), energy in algal sedimentation ($\mathbf{L}_s(\mathbf{L})$) and the energy lost in outflow of algae from the wetland (\mathbf{xL}), all subtracted from the energy in gross algal production ($\mathbf{L}_p\mathbf{R}$). The change in energy in the macrophyte biomass over time is described as energy in macrophyte respiration ($\mathbf{M}_r(\mathbf{M})$) and energy in macrophyte sedimentation ($\mathbf{M}_s(\mathbf{M})$) subtracted from the energy in gross macrophyte production ($\mathbf{M}_p\mathbf{RV}$). Table 1 describes the individual parameters of the Productivity submodel and Appendix A details their calibration.

3.3 Phosphorus Submodel

$$\frac{dP}{dt} = CI - xP - A(L_pR - L_rL)k_p + \left(\frac{S_r}{d}\right)A$$

$$\frac{dS}{dt} = (L_sL)A - \left(\frac{S_r}{d}\right)A + k_m(M_sM)A - k_m(M_pVR - M_rM)A$$

The Phosphorus submodel has two state variables, P in the water column of the wetland (\mathbf{P}) and P in the wetland sediments (\mathbf{S}), and both are measured in grams (g). Inputs that drive changes in water column P over time include the concentration of P in the overland inflow water (\mathbf{CI}) and the resuspension of P to the water from sediments ($(\mathbf{s}_r/\mathbf{d})\mathbf{A}$). In this model, resuspension of P includes resuspension from both organic matter hydrolysis and dissolution from the sediments to the water column. The outputs from the P in the water column are the outflow of P from the wetland (\mathbf{xP}) and the P uptake by algae ($\mathbf{k}_p(\mathbf{L}_p\mathbf{R} - \mathbf{L}_r(\mathbf{L}))\mathbf{A}$). P in the wetland sediments is described as sedimentation of P as a result of macrophyte death ($\mathbf{k}_m(\mathbf{M}_s\mathbf{M})\mathbf{A}$) and settling of algae ($(\mathbf{L}_s\mathbf{L})\mathbf{A}$) minus the P resuspension into the water column ($(\mathbf{s}_r/\mathbf{d})\mathbf{A}$) and the P uptake by macrophytes ($\mathbf{k}_m(\mathbf{M}_p\mathbf{VR} - \mathbf{M}_r\mathbf{M})\mathbf{A}$). Table 1 describes the individual parameters in the Phosphorus submodel and Appendix A details their calibration.

3.4 Modeled P Dynamics in the wetland

Figure 2 describes the dynamic exchange of TP in the water column and the wetland sediments. There is an initial value of P in both the water column and the wetland sediments (Table 1). Additional P enters the wetland in the surface water inflow and is added to the water column. From the water column, P may be either taken up by algae or it may flow directly out to the UKL and AL. Phosphorus taken up by algae may either flow out to the lake in the algae, or the algae will settle and die and the P is then added to the wetland sediments.

The TP in the wetland sediments may be resuspended back into the water column as a result of either dissolution or organic matter hydrolysis, or it may be taken up by macrophytes directly from the sediments. Phosphorus taken up by macrophytes will remain in the biomass until the macrophytes die and decompose, at which point the P returns to the wetland sediments.

3.5 Model Simulations

To model the P dynamics of the wetlands over an entire year (Model Run Initial), data were examined at both ALRW and WRW to establish initial values, average rates and parameters (Table 1). Mass balance equations for each of the state variables were integrated using fourth-order Runge-Kutta equations to examine the temporal dynamics of TP release and uptake in the wetland. We used a timestep of 1 day to capture the rapid changes that may occur upon initial outflow of water from the wetland. To determine the total net sequestration of P in the wetland over time, the total P in the sediments was combined with the algal and macrophyte uptake of P, minus the outflow of P in both the water column and the algae.

Model Run “Initial” was used to investigate the P release and sequestration processes each season and whether the wetlands act as a net source or a sink of P to the UKL throughout the year. We then varied model parameters to examine how P assimilation varies with hydrologic and vegetation management scenarios (Table 2).

It has been suggested from literature that altering the timing of water outflow may be the most efficient way to prevent P outflow from the wetland (Tonderski et al. 2005, Duff et al. 2009). Therefore, two management strategies were compared to investigate the effect that outflow timing may have on P release: the “No Outflow”

and “Early Outflow” scenarios, reflecting complete outflow prevention and outflow during spring instead of summer, respectively. It is important to note that in this model, there is no limit to the amount of water that can accumulate in the wetland, and this should be taken into consideration with the “No Outflow” model run.

Established vegetation is crucial to P sequestration (Aldous et al. 2005, Duff et al. 2009), as macrophytes take up P directly from the sediments during the growing season. When the macrophytes die, the P in the decomposing organic matter either is sequestered in the sediment or is resuspended into the water column (Richardson, 1985). Therefore, we also examined the strategy of “Macrophyte Harvest,” in which we simulated harvesting macrophytes in the middle of the summer season to permanently remove sequestered P from the wetland. This was accomplished by changing the energy of the macrophyte biomass (M) to zero (Table 2).

Laboratory experiments (Aldous et al. 2005, Stevens and Tullos 2011) indicate that minimizing P release can be achieved by avoiding extended dry periods in the wetlands, which can result in the resuspension of P upon re-flooding of the wetlands. Therefore, for one modeling scenario (“Dry Wetlands”), the wetlands were assumed to be dry at $t=0$.

3.6 Applications to the UKB

A budget of the sources and sinks of P to the UKL was constructed from published sequestration and loading values (Tables 3, 4, Figure 3). Values for sources and sinks of P to UKL reported in the literature were converted to mtons per year, as necessary, and are reported in Tables 3 and 4. ODEQ (2002) reported a total yearly load to the lake of 463 mtons from both internal and external sources, and Figure 3 uses this total to display the percent contributions of the sources and sinks of P.

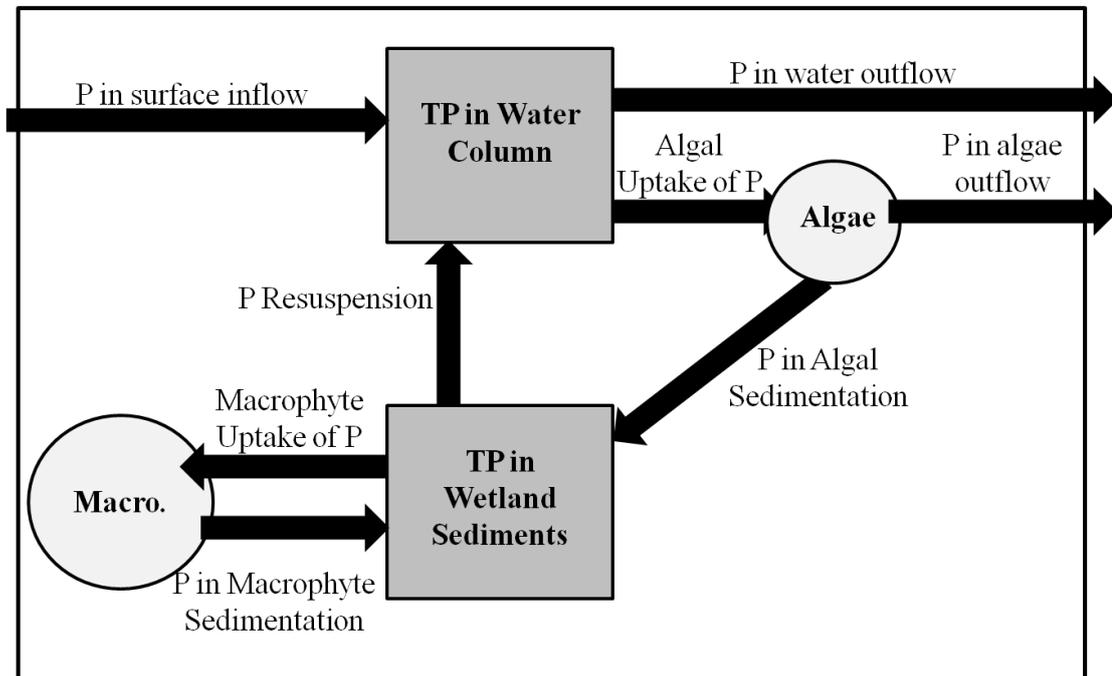


Figure 2- The dynamic exchange of TP in the water column and the wetland sediments.

Table 1- Initial values of the parameters in the wetland ecosystem phosphorus model.

Variable	Name	Value	Units	Source
<i>Hydrologic Submodel</i>				
Q	Water volume in wetland	5.5×10^7	m^3	Estimated
P _r	Average daily precipitation in wetland	3000	$m^3 \text{ day}^{-1}$	USBR (2011)
I	Avg daily surface inflow	2.45×10^5	$m^3 \text{ day}^{-1}$	Snyder and Morace (1997)
ET	Avg daily evapotranspiration	9×10^4	$m^3 \text{ day}^{-1}$	USBR (2011)
x	Outflow Coefficient	0.003	day^{-1}	Calculated
<i>Productivity Submodel</i>				
L	Energy in the algal biomass	410	kcal m^{-2}	Estimated
L _p	Avg algae solar efficiency	0.13	-	Carpenter et al. (2009)
L _r	Avg daily algae respiration coefficient	2.0	day^{-1}	Carpenter et al. (2009)
L _s	Avg daily algae sedimentation coefficient	0.03	day^{-1}	Calibration
R	Avg daily solar radiation	6230	$\text{kcal m}^{-2} \text{ day}^{-1}$	USBR (2011)
M	Energy in the macrophyte biomass	850	kcal m^{-2}	Ray et al. (2009)
M _p	Avg macrophyte solar efficiency	0.09	-	Calibration
V	Wetland area covered by macrophytes	0.75	-	Ray et al. (2009)
M _r	Avg daily macrophyte respiration coefficient	0.15	day^{-1}	Calibration
M _s	Avg daily macrophyte sedimentation coefficient	0.27	day^{-1}	Ray et al. (2009)
<i>Phosphorus</i>				
P	P in the water column	6.6×10^6	g	Calculated
C	Avg conc. of P in inflow	0.12	g m^{-3}	Carpenter et al. (2009)
k _p	Avg P to kcal ratio in algae	0.001	g P kcal^{-1}	Jorgensen and Johnson (1989)
A	Wetland Area	4×10^7	m^2	Estimated
S _r	Avg daily resuspension	0.0025	$\text{g P m}^{-2} \text{ day}^{-1}$	Mitch and Reeder (1991)
d	Avg wetland depth	variable	m	Calculated
S	P in the sediments	5.9×10^6	g	Kuwabara et al. (2010)
k _m	Avg macro P to kcal ratio	0.75	g P kcal^{-1}	Estimated

Table 2- Modeling scenarios applied during the summer season to compare management strategies

Model Run	Model Description	Model Change
Initial	Baseline, model is as described in Table 1 and Appendix A	--
No Outflow	Direct outflow to the lake is prevented and assimilation of TP back into deep sediment occurs.	x=0
Early Outflow	Outflow occurs in spring instead of summer, when macrophytes are not yet established and only starting to be productive.	M=0 at t=0
Macrophyte Harvest	Macrophytes are harvested from the wetland at the peak of their productivity and allowed to regrow until the end of the growing season.	Stop model at t=46 and change to M=0
Dry Wetland	Wetland is assumed to be dry at t=0.	Q, L, P =0 at t=0

Table 3- Sources of P to Upper Klamath Lake (in mtons)

P Sources	TP Load (in mtons)	Location(s)	References
Agricultural Pumps to UKL	20	Ag lands adjacent to UKL	ODEQ 2002, Rykbost and Charlton 2001
Restoration Wetlands	65	Fringe Wetlands	Aldous et al. 2007
Lake Sediment	282	UKL- internal sediment loading	Walker 2001, Rykbost and Charlton 2001, ODEQ 2002
Springs	44	Crystal Creek, Spring Creek, etc.	Rykbost and Charlton 2001
Atmospheric Deposition	14	Salts from human sources	Geiger 2005, ODEQ 2002, Walker 2001

Table 4- Sinks of P for Upper Klamath Lake (in mtons)

P Sinks	TP Removal (in mtons)	Location(s)	References
Original Wetlands	32	NWC, Hanks March	Aldous et al. 2005
Restoration Wetlands	32	All wetlands in UKB	Geiger 2005
Lake sediment uptake	65	Sediment of UKL	Walker 2001, Søndergard 2003
Klamath Irrigation Project (KIP)	83	Diversion to KIP at the south end of the UKL	Rykbost 2001
Outflow of UKL to Klamath River	250	South end of the UKL	ODEQ 2002

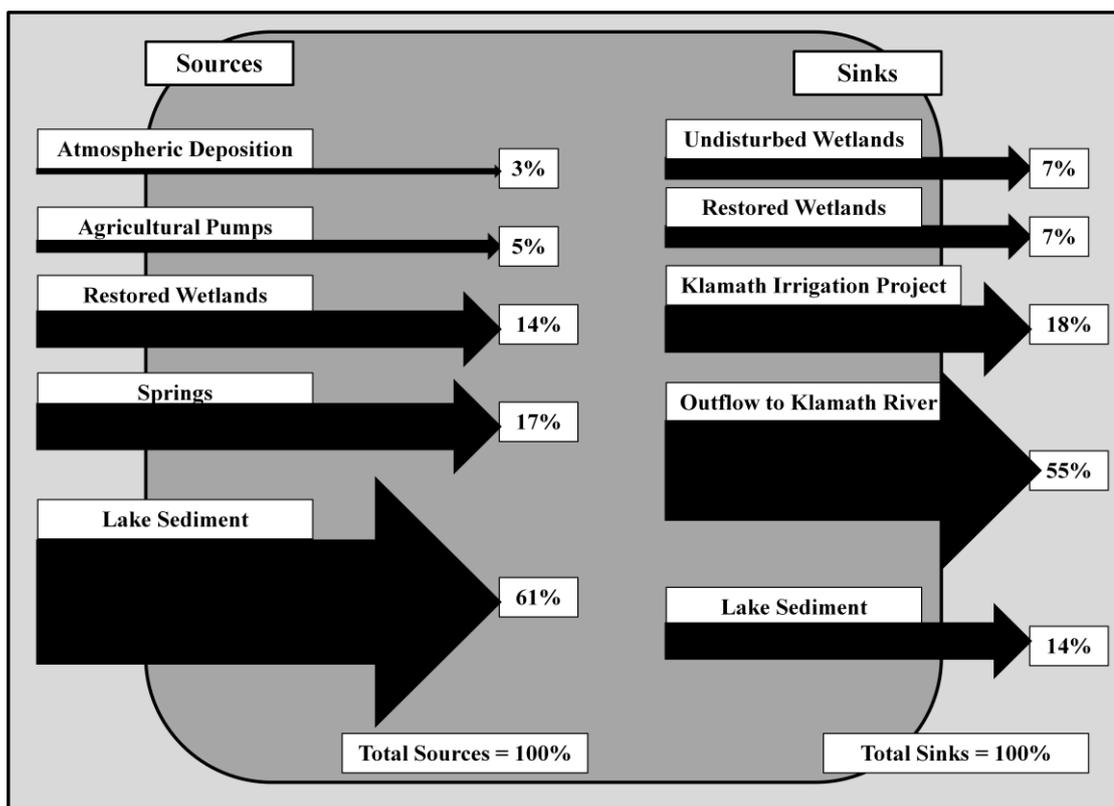


Figure 3- Percent contributions of sources of P to the UKL and percent removal of sinks of P from the UKL. Annual load of P to lake is estimated to be 463 mtons.

4.0 MODEL RESULTS

4.1 Resuspension and P Outflow Processes- The Initial Model Run

The amount of water that flows out from the wetland is dependent on the amount of water in the wetland, as it is a function of water volume times the outflow constant of 0.003 (Table 1). During the first summer, there is a net positive outflow of water from the wetland, as outflow and evapotranspiration are greater than precipitation and surface inflow. Through the second summer, less water flows out to the lake, as the wetland has a lower volume at the beginning of the season and amount of outflow is dependent on the wetland water volume.

Based on our simulations, resuspension of TP is the primary process that releases P from the sediment to the water column and it occurs through much of the year (Figure 4). Resuspension of P gradually increases to a value of $1.8 \times 10^{-3} \text{ g P m}^{-2}$ at the end of the summer (Figure 4), as the net outflow of water causes the depth of the wetland to decrease. Resuspension increases through autumn, reaching $2.2 \times 10^{-3} \text{ g P m}^{-2}$, as algae settle and macrophyte die and decompose. No resuspension of P occurs during winter, as the wetland is frozen. P resuspension resumes at a high rate at the start of spring as inflow to the wetland resumes, and then slowly decreases as more water accumulates in the wetland, reaching $1.9 \times 10^{-3} \text{ g P m}^{-2}$ at the end of spring. There is a slight net inflow of water during the second summer and as a result, resuspension remains steady at $1.9 \times 10^{-3} \text{ g P m}^{-2}$ (Figure 4), as wetland volume remains more static than in the first summer, as a result of the decreased outflow.

While resuspension of P occurred throughout the year, outflow of P to the lakes is seasonal, and most of the suspended P does not reach the lake. Outflow of P occurs either as 1) the outflow of TP in the water column from the wetland, or as 2) the outflow from the wetland of P in algae suspended in the water column. Modeled outflow of TP in the water from the wetland only occurs during the first 16 days of the first summer, with its highest value being $5.0 \times 10^{-4} \text{ g P m}^{-2}$ at $t=0$ (Figure 4), or approximately 120 μg of P per L of water flowing out from the wetland. After this point, algal uptake of P exceeds both inflow of TP and resuspension of TP from the wetland sediments to the water column. The rest of the resuspended TP remains in the wetland.

Most of the algae, and the P taken up by the algae, also remain in the wetland. Some outflow of algae and the associated P in algal biomass occurs, but only during the summer seasons, as this is the only time of year outflow of water to the lake is allowed. This reflects current operations of the ALRW. Each summer, the amount of TP in the outflow of algae is $4.0 \times 10^{-5} \text{ g P m}^{-2}$ (Figure 4), as the energy in algae outflow is a proportion of the energy in the algal biomass.

4.2 Sequestration Processes and Net Sequestration of P- The Initial Model Run

The P sequestration processes considered in the model are 1) algal uptake of P from the water column, 2) macrophyte uptake of P from the sediments, 3) P in macrophyte sedimentation, and 4) P in algal sedimentation. Based on our model results (Figure 5a), macrophyte uptake of P and macrophyte sedimentation of P sequester the greatest amount of TP throughout the year, relative to the other processes. As the macrophyte biomass continues to grow, macrophyte uptake of P increases very slowly until the end of the first summer, reaching a value of 160 g P m^{-2} (Figure 5a). There is no sequestration of P by macrophytes during the fall and winter, as macrophyte productivity is not occurring. Macrophyte uptake begins again during the spring and peaks at $t=\text{day } 277$ at 210 g P m^{-2} , while the biomass becomes re-established. The macrophyte uptake is then reduced back to 160 g P m^{-2} for the rest of the spring and does not increase at all through the second summer. Macrophyte uptake is limited during the second summer, as the net positive inflow of water volume (and increasing depth) cause the macrophytes biomass to grow more slowly than in the first summer.

As the macrophytes which sequestered P die, settle and decompose, sedimentation of P occurs. At the end of the first summer, macrophyte sedimentation of P reaches the same 160 g P m^{-2} as macrophyte uptake (Figure 5a). During the autumn, sedimentation of P from macrophytes lasts for an additional 5 days after macrophyte productivity ceases, and then goes to zero at $t=\text{day } 103$. Macrophyte sedimentation of P remains at zero for the remainder of the autumn and winter. During the spring, macrophyte sedimentation of P gradually increases to 170 g P m^{-2} before slowly decreasing and stabilizing back to 160 g P m^{-2} at the start of the second summer.

According to the model, algal uptake of P has a nearly identical pattern to that of macrophyte uptake of P, but occurs at a much smaller magnitude (Figure 5b). Algae uptake of P levels off quickly during the first summer to $1.3 \times 10^{-2} \text{ g P m}^{-2}$. No algal uptake of P occurs during fall and winter in the model. While the algal biomass increases in the spring, it resumes its uptake of P. Algal uptake of P peaks at $8.0 \times 10^{-2} \text{ g P m}^{-2}$ at $t = 275$ days, and then decreases and stabilizes at $1.1 \times 10^{-2} \text{ g P m}^{-2}$ by the end of the spring. Algal uptake increases slightly to $1.3 \times 10^{-2} \text{ g P m}^{-2}$ by the end of the second summer (Figure 5b), reaching the same levels as the first summer, while the energy in the algal biomass and productivity rates remain constant.

Sedimentation of P in the algal biomass has a similar pattern to that of macrophyte sedimentation of P. During the first summer, algal sedimentation of P reaches $1.1 \times 10^{-2} \text{ g P m}^{-2}$, nearly the same as algal uptake (Figure 5b). During the autumn, sedimentation of P from algae lasts for an additional three days after algae productivity ceases, and then goes to zero at $t = 95$ days. Algal sedimentation of P remains at 0 for the remainder of the autumn and winter, as there is no additional algae productivity during these seasons. During the spring, algae sedimentation of P gradually increases to $1.2 \times 10^{-2} \text{ g P m}^{-2}$ and remains there throughout the second summer. The energy in the algae biomass remains constant, as a result of the assumption of constant energy in the algae productivity and respiration rates.

4.3 Hydrologic and Vegetation Management Strategies

Examination of results for the outflow of TP during the summer across management strategies (Table 5) indicates that the Early Outflow and Macrophyte Harvest model runs are identical the Initial model run in regards to outflow of P from the wetland. The No Outflow and Dry Wetlands model runs do not allow any water or P to flow out to the lake for the entire summer. Instead, water accumulates in the wetlands, as evapotranspiration is the only diminishing process. Therefore, no P enters the lakes directly with these two management strategies (Table 5).

When investigating total net sequestration of TP in the wetland across management strategies, we observed that each strategy differs from the others (Table 5). For the Early Outflow model run, sequestration of P in the wetland sediments does not occur (Figure 6), as any P in the sediments or water column is instead taken up by

macrophytes and algae. The amount of P sequestration as a result of algae uptake in the Early Outflow model run is identical to that of the Initial model run during the summer season (Figure 7). Sequestration of P from macrophyte uptake begins high in the Early Outflow model run and decreases to the same values as the Initial model run by $t = \text{day } 20$ (Figure 8).

For the Dry Wetlands model run, sequestration of P in the wetland sediments is similar to the Early Outflow model run (Figure 6) and does not occur during the summer, as any excess P is once again taken up by macrophytes and algae. For sequestration of P as a result of algal uptake (Figure 7), the Dry Wetlands model run becomes identical to the other management strategies after $t = \text{day } 10$. Sequestration of P as a result of macrophyte uptake starts high and then decreases linearly over the course of the season for the Dry Wetlands model run, reaching 20 g P m^{-2} by the end of the summer (Figure 8). The highest amount of macrophyte uptake for any management strategy occurred in the Dry Wetlands model run, as energy contained in the macrophyte biomass is inversely related to water depth. Because excess P is immediately taken up by macrophytes, no P is in the water outflow to the lake at any time during the growing season.

Sequestration of TP in the sediments for the Macrophyte Harvest model run (Figure 6) is identical to the Initial model run until the point of harvest ($t = 46$ days). After harvest, the sequestration of TP in the sediments mimics that of the Early Outflow model run, because the energy in the macrophyte biomass is reset to 0, further depleting P in the wetland sediments. The Macrophyte Harvest model run is identical to that of the Initial model run in regards to the amount of P sequestered during the summer season as a result of algal uptake (Figure 7). For the Macrophyte Harvest model run (Figure 8), macrophyte uptake experiences a sharp increase directly after harvest and then returned to the pre-harvest value of 16 g P m^{-2} by $t = \text{day } 66$.

The greatest sequestration of TP in the sediments occurred for the No Outflow model run during the summer, sequestering 10 g P m^{-2} (Figure 6). However, the No Outflow model run assimilated the least P as a result of algal uptake, compared to the other management strategies (Figure 7), as a result of a slightly higher algal respiration rate than in the other management strategies. Additionally, in the No

Outflow model run, sequestration of TP as a result of macrophyte uptake decreases to 14 g P m^{-2} at the end of the summer (Figure 8). This management strategy had the highest sequestration of P, as well as no outflow of P to the lakes (Table 5).

In summary, the No Outflow and Dry Wetlands model runs were the only management strategies that prevented all P from reaching the lake (Table 5). If outflow prevention is the only goal, either of these management strategies is ideal. However, when taking net sequestration into account, the No Outflow model run has the greatest net sequestration. All management strategies have a net sequestration of at least 16 g P m^{-2} (Table 5).

Table 5- Net sequestration across management strategies at the end of summer, in g P m^{-2}

P Uptake or Release Process	Initial	No Outflow	Early Out	Mac Harv.	Dry
Sediment. of P	5	10	0	0	0
Algae and Macro Uptake of P	16	14	16	16	20
- Outflow	5.0×10^{-4}	0	5.0×10^{-4}	5.0×10^{-4}	0
Net Sequestration	21	24	16	16	20

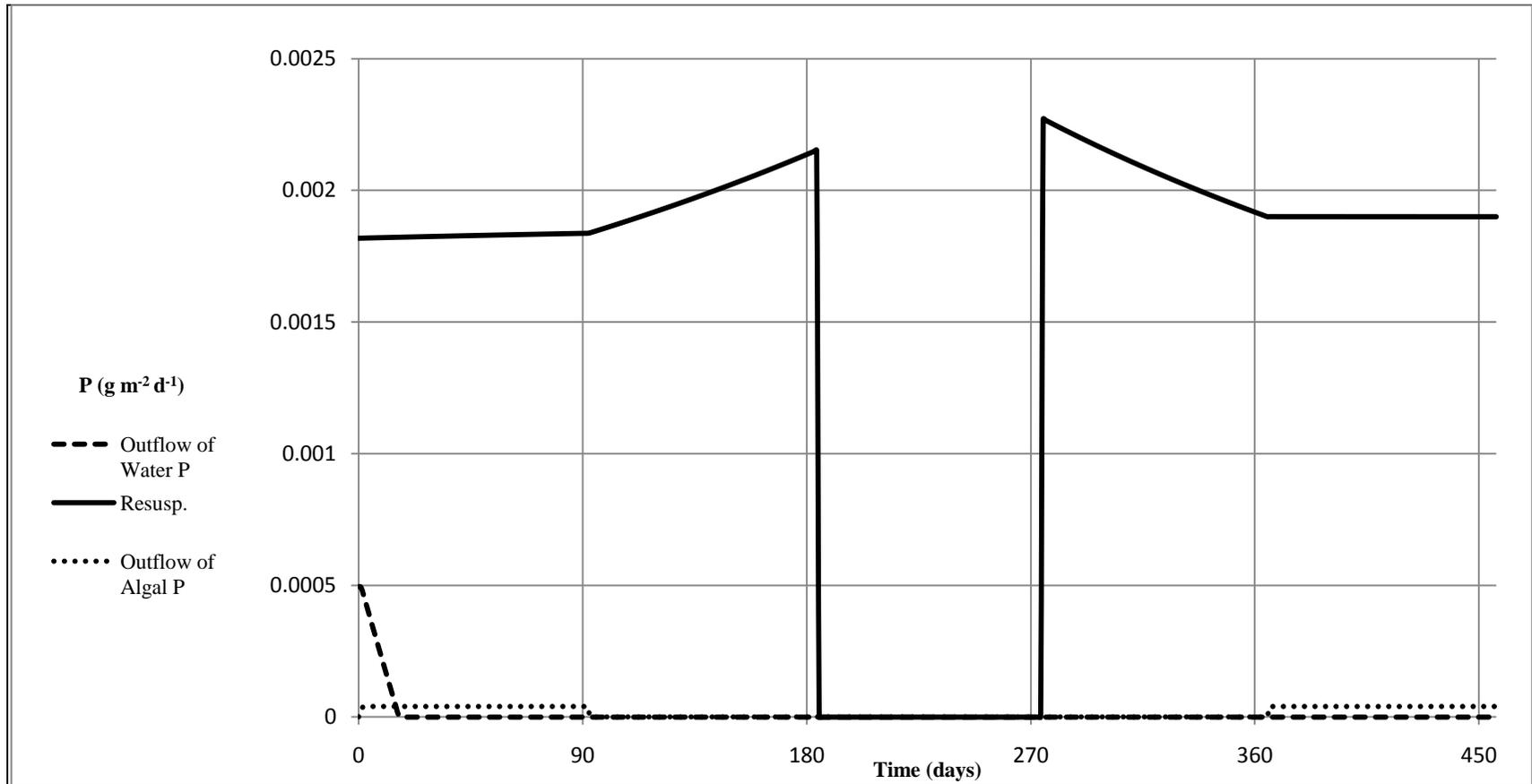


Figure 4- Rate of P resuspension and outflow from summer to summer. Phosphorus outflow in the water and algae and P resuspension from sediments to the water column in $\text{g P m}^{-2} \text{d}^{-1}$.

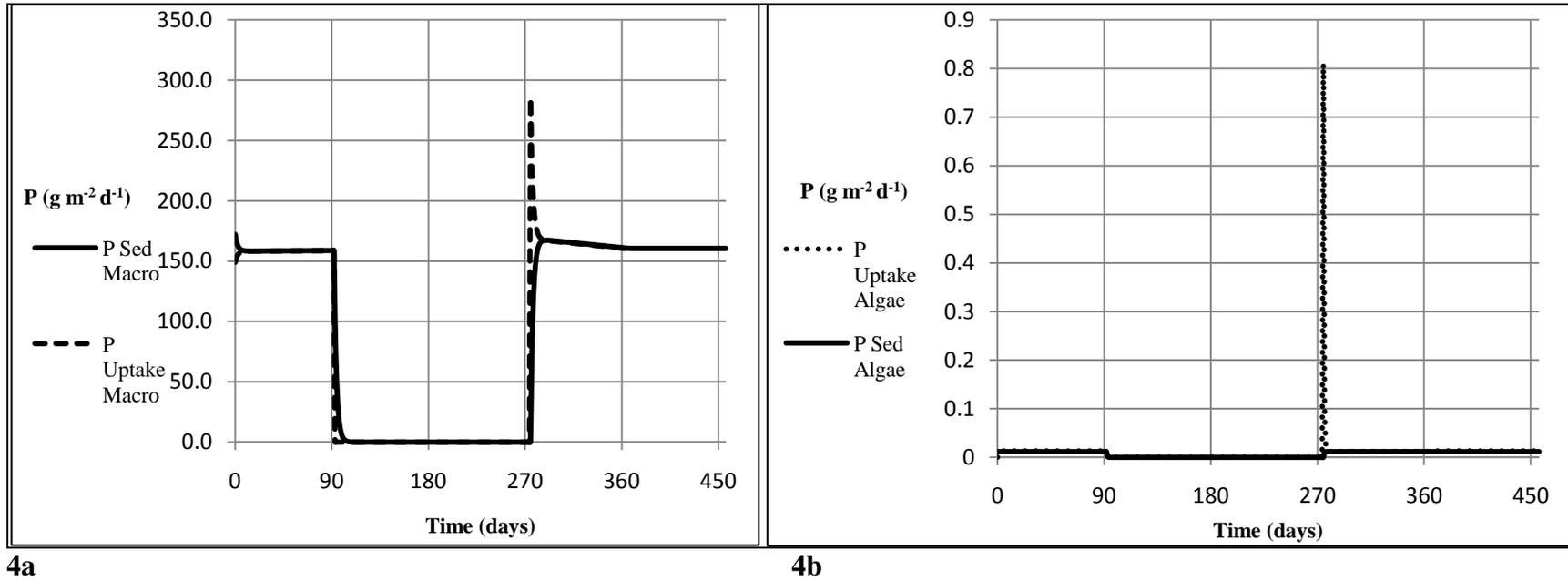


Figure 5- Processes of P sequestration processes from summer to summer: 54a- Rate of uptake and sedimentation of P by macrophytes in g m⁻² d⁻¹, 5b- Rate of uptake and sedimentation of P by algae in g m⁻² d⁻¹.

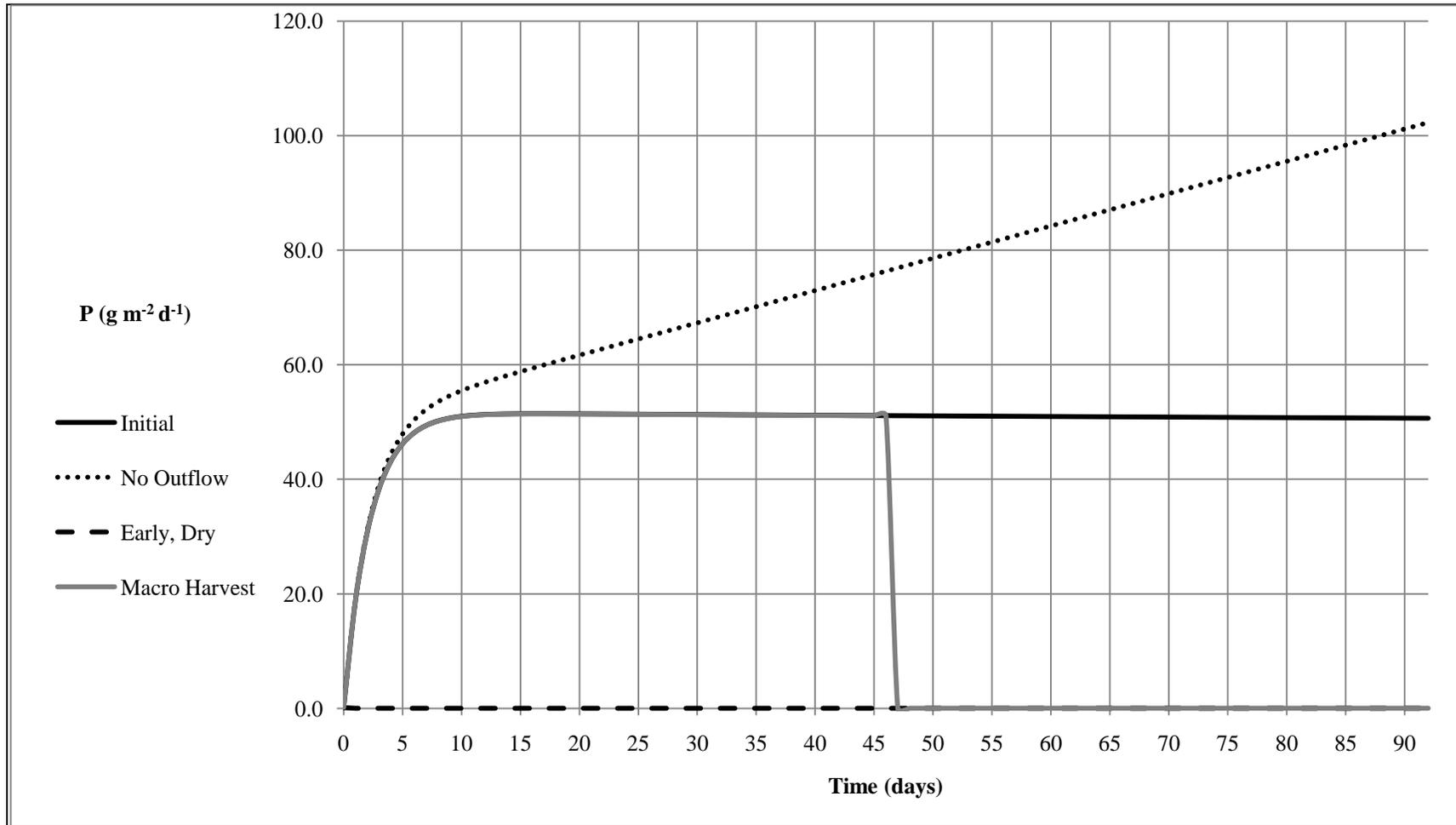


Figure 6- Rates of sequestration of P in the wetland sediments across management strategies in $\text{g m}^{-2} \text{d}^{-1}$.

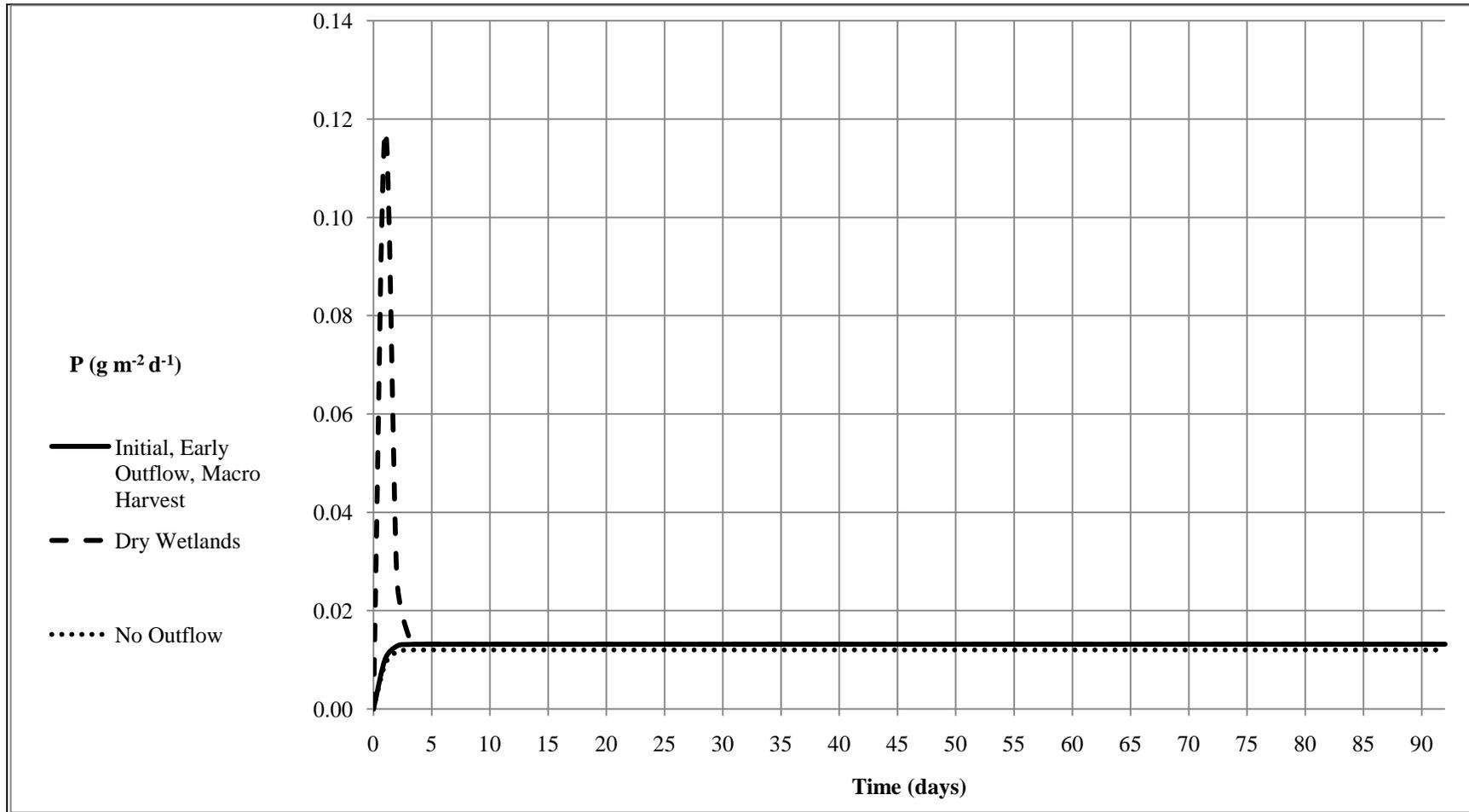


Figure 7- Rates of algal uptake of P over the summer season across management strategies in $\text{g m}^{-2} \text{d}^{-1}$.

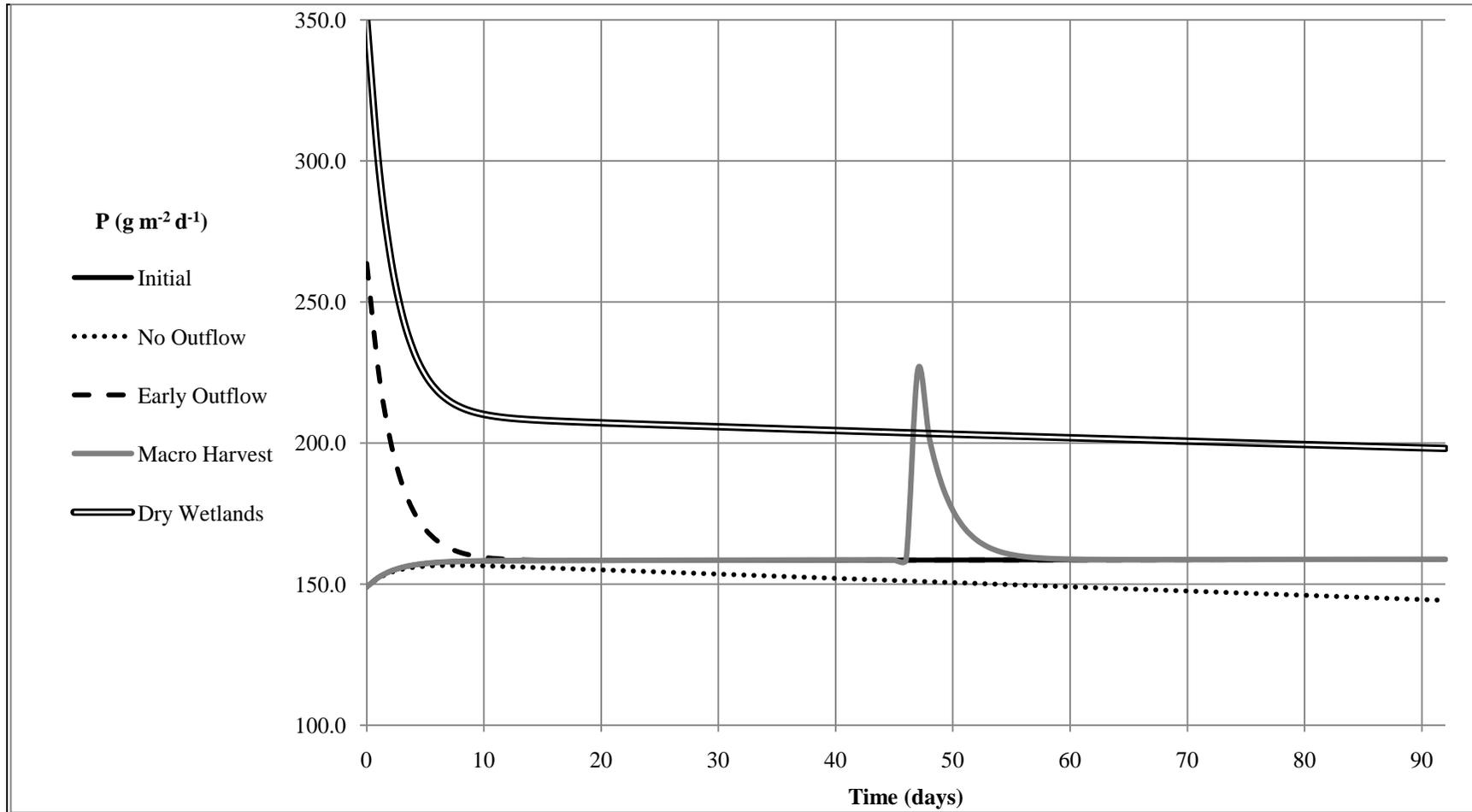


Figure 8- Rates of macrophyte uptake of P over the summer season across management strategies in $\text{g m}^{-2} \text{d}^{-1}$.

5.0 DISCUSSION

5.1 Resuspension and P Outflow Processes- The Initial Model Run

Resuspension of P is the primary way that P reaches the water column from the wetland sediments throughout the year, and the patterns of resuspension are consistent with what is reported in literature. During the first summer, resuspension of TP gradually increases, likely due to organic matter hydrolysis at the beginning of the season (Stevens and Tullos 2011) and later due to dissolution as settling aquatic plants begin to decompose (Duff et al. 2009). No resuspension of P occurs during winter, as the wetland is frozen and decomposition by microbes does not occur (Søndergard et al. 2003). Resuspension of P resumes at $2.0 \times 10^{-3} \text{ g m}^{-2}$ at the start of spring, which is the highest mass of P resuspension simulated for the modeled year. This rate of resuspension is on the higher end of the range reported by Reddy et al. (1999) of 2×10^{-5} to $3.2 \times 10^{-3} \text{ g m}^{-2}$, likely because of the high initial water velocity when inflow to the wetland resumes. When the macrophytes are established, resuspension slowly decreases and then remains steady through the end of the second summer, likely as a result of a well-established macrophyte biomass that causes a decrease in resuspension (Søndergard et al. 2003, Huang and Li, 2009, and Duff et al. 2009).

Much of the resuspended TP remains in the wetland and does not flow out to the lakes, as TP only flows out to the lakes in the water during the first 16 days of the first summer. The average TP outflow in July from the years of 2005-2008 was determined to be $445 \mu\text{g P L}^{-1}$ (USBR, unpublished). Therefore, the modeled $120 \mu\text{g P L}^{-1}$ flowing out from the wetland may be lower than the actual wetland value. After this point, much of the P that accumulates in the water column throughout the year is taken up by algae. While $4.0 \times 10^{-5} \text{ g P m}^{-2}$ flow out to the lake in the algae during each of the summer seasons, 99.6% of the energy in the algae biomass remains in the wetland, and the P it takes up ultimately accumulates in the sediments when the algae dies and decomposes.

5.2 Sequestration Processes and Net Sequestration of P- The Initial Model Run

Macrophyte uptake and sedimentation of P are most important in sequestering P across all seasons due to the extensive network of roots and rhizomes and the great potential to store P (Reddy et al. 1999). Uptake of P from soil porewater by macrophytes is the primary reason there is a large decrease of P in the sediments at the start of summer (Reddy et al. 1999). During the summer and autumn, sedimentation of P in the macrophytes also plays a large role, as P is sequestered in the sediments as the macrophytes begin to settle, die and decompose (Duff et al. 2009).

During the second summer, macrophyte uptake of P is slightly higher than it is during the first year. This is consistent with the findings of Kadlec (2005) on newly restored wetlands in the Everglades and Houghton Lake, MI; the ability of the macrophytes to sequester P increases as larger biomass and complete cover is established in the years following restoration. The increased energy in the macrophyte biomass in the second summer also led to less P sequestration in the sediments, as the biomass was able to sequester more P during the season, due to its increased size Duff et al. (2009).

Our findings illustrate how wetlands around UKL may act as a net sink of P to UKL over time. We compared net sequestration at the end of the two summer seasons, and found an annual increase in sequestration of 4.5 g P m^{-2} , primarily as a result of the increase of the energy of the macrophyte biomass. As macrophyte biomass energy stabilizes in successive years, we expect the uptake of P by macrophytes will also become stable (Aldous et al. 2007). Over the course of the entire model run, there was a net sequestration of $1.3 \times 10^9 \text{ g P}$, as a result of sequestration of P in the sediments, algal and macrophyte uptake. Therefore, our findings indicate that wetlands around the lake act as a net sink of P to UKL.

5.3 Hydrologic and Vegetation Management Strategies

Because water quality, and its impact on endangered species, can be strongly influenced by key attributes of hydrologic management (e.g., timing and duration of filling and draining) and the characteristics of individual wetlands, information about P processes must be considered in designing and managing wetland restoration projects

(Stevens and Tullos 2011). All of the management strategies that were modeled result in a reduction of P loading into Upper Klamath and Agency Lakes by the end of the summer season, and all have high uptakes of P by aquatic plant communities.

The goal of the Early Outflow management strategy was to draw down water accumulated over winter and encourage seed germination of macrophytes in the spring (Duff et al. 2009). With this management strategy, no P was sequestered in the sediments over the summer, but 16 g m^{-2} was sequestered in the aquatic plant communities (Table 5). It is important to note that this type of sequestration is thought to account for less long term P sequestration because plant P uptake is a short-term storage compartment (Reddy et al. 1999 and Aldous et al. 2007). Rapid turnover rates of macrophytes can contribute some P to the water column upon plant decomposition (Richardson, 1985 and Reddy et al. 1999). Therefore, the Early Outflow management strategy appears to be effective at sequestering P, but the sequestration may only be short term.

The Macrophyte Harvest model run is identical to the Early Outflow model run with respect to net sequestration at the end of the summer (Table 5). However, there are some important differences between these scenarios (Figures 6 and 8). The practice of harvesting macrophytes permanently removes P from the system and regenerates the P removal capacity of the macrophyte biomass (Richardson 1985 and Adler et al. 1996). However, as seen in our results, harvesting of the macrophyte biomass causes only a short-term (11 days) jump in the rate of uptake of P by macrophytes before the amount of uptake quickly returns to pre-harvest levels (Figure 8). As Adler et al. (1996) recommend, harvesting at more frequent intervals, as often as every 2 weeks, may have greater effectiveness, as the macrophyte sequestration of P will remain high.

The Dry Wetland strategy sequesters the greatest mass of P in the aquatic plant communities, at least 125% more than any other management strategy (Table 5). This is likely because, in the wetland ecosystem model, energy in the macrophyte biomass is inversely related to the water depth of the wetland (Mitsch and Reeder 1991). In this model, macrophyte biomass is allowed to grow larger in shallower (or dry) wetlands and take up more P. However, Duff et al. (2009) indicate that the complete drying of soils

(and the subsequent flooding of newly emergent plants) is not optimal to encourage macrophyte and soil development and prevent additional P resuspension. Additionally, Aldous et al. (2005) indicate that P release as result of organic matter hydrolysis is accelerated under aerobic conditions that develop when soils are allowed to dry and rewet. These factors are not reflected in the simulation of this management strategy.

The No Outflow model run is unique, as sequestration of TP in the wetland sediments increases throughout the growing season (Figure 6). This is likely because an increase in water volume leads to a decreased macrophyte biomass in the model (Mitsch and Reeder 1991). A smaller macrophyte biomass leaves more P in the sediments, which explains why the No Outflow management strategy has the highest assimilation of P in the sediments (Table 5).

As modeled, No Outflow and Dry Wetlands are the only strategies that prevent any P from entering AL and UKL (Table 3). Strictly in terms of preventing P loading to the lakes, these two strategies are ideal. However, as all of the management strategies are effective at reducing a large mass of P loads to the lake, it may be important to consider additional factors, such as temporary versus permanent storage, necessity of direct surface water inflow to the lake, and potential P release upon flooding, when determining the ideal management strategy.

5.4 Implications for water quality in UKL

Results of our model were interpreted in the context of the UKL P budget to consider whether restoration of the 4,000 hectares of modeled wetlands around UKL and AL could effectively reduce P loading to the lake. The P budget for UKL (Tables 3 and 4, Figure 3), indicates that restored wetlands could contribute up to 64 mtons of P to the lakes (Aldous et al. 2007) due to resuspension of P from flooded soils. However, when specifically examining outflow to the lake, our model indicates that of actual outflow of P from the wetland is limited to only 0.18 mtons of P in the first summer season following restoration, indicating that as the aquatic plant community becomes well established, the wetlands no longer contribute P to the lakes (Duff et al. 2009). The 0.18 mtons of P flowing out to the lake from the modeled wetland is only approximately 0.1% of the 182

mton yearly external load to the lakes (Walker, 2001) and is negligible compared to the total annual load (both internal and external) to the lakes of 463 mtons (ODEQ 2002).

Furthermore, our model indicates up to 2.2×10^9 g (2200 mtons) of P is sequestered at the end of the first year, either by the wetland sediments or by algae and macrophyte uptake. Kadlec (2005) found that 20% of the total P sequestered in wetlands is permanently sequestered, indicating complete removal from the system of 440 mtons of P in the modeled area, per year. Therefore, our findings suggest that the sequestration processes in the wetlands could play a role in reducing the mass of P externally loaded into UKL.

However, while the wetlands do appear effective at sequestering P, it is important to note the large amount (over 280 mtons, Table 3) of internal loading of P from the lake sediments within UKL and AL each year (ODEQ 2002). Loading of only 0.004 to 0.02 mtons P is considered adequate to support blue-green algae present in the lake (Rykbost and Charlton 2001). Therefore, even a complete reduction of external loading is not likely to impact the algal blooms in the UKL in the foreseeable future.

6.0 CONCLUSIONS

Based upon results of a wetland phosphorus mass balance model, restoring wetlands appears to be an effective strategy for reducing external P loading to the UKL. While some P resuspension from the soils occurs, we find that a net sequestration of P occurs via sedimentation and macrophyte and algae uptake. Over multiple years, the ability of expanding wetland vegetation to sequester P increases and further reduces loads to the lake. Furthermore, in all management strategies, wetlands do reduce external P loading to AL and UKL in the summer, both by sequestration of P in the wetland sediments and immobilization of algae and macrophytes. It is likely necessary to examine additional management factors to determine which strategy strikes a balance between TP sequestration, hydrologic connection and water level management of the lakes.

Furthermore, we find that the reduction of external loading is not likely to reduce the algal blooms in the lakes, as the amount of P recycled from the sediments each year far exceeds the capabilities of the current wetlands. Other strategies to reduce P internally, such as dredging and internal P inactivation (ENSR 2007, Søndergard et al. 2003), may be more effective in reducing the *Afanizomenon flos-aquae* blooms and restoring the water quality in the UKL. Therefore, while restoring wetlands for habitat and water storage are critically important (NRC report), restoring them with a short-term goal to reduce external P loading, even to 0, will likely not be an effective solution to decrease the algal blooms in the lakes.

7.0 BIBLIOGRAPHY

- Adler, P.R., S.T. Summerfelt, D.M. Glenn, F. Takeda. 1996. Evaluation of a wetland system designed to meet stringent phosphorus discharge requirements. *Water Environment Research* 68 (5): 836-840.
- Aldous, A.R., C.B. Craft, C.J. Stevens, M.J. Barry, and L.B. Bach. 2007. Soil phosphorus release from a restoration wetland, Upper Klamath Lake, Oregon. *Wetlands* 27(4):1025-1035.
- Aldous, A.R., P. McCormick, C. Ferguson, S. Graham and C.B. Craft. 2005. Hydrologic regime controls soil phosphorus fluxes in restoration and undisturbed wetlands. *Restoration Ecology* 13(2): 341-347.
- Boyd, C.E. 1970. Amino acid, protein, and caloric content of vascular aquatic macrophytes. *Ecology* 51 (5): 902-906.
- Carpenter, K.D., D.T. Snyder, J.H. Duff, F.J. Triska, K.K Lee, R.J. Avanzino, and S. Sobieszczyk. 2009. Hydrologic and water-quality conditions during restoration of the Wood River Wetland, Upper Klamath River Basin, Oregon, 2003-05. U.S. Geological Survey. 1-80.
- Duff, J.H., K.D. Carpenter, D.T. Snyder, K.K. Lee, R.J. Avanzino, and F.J. Triska. 2009. Phosphorus and Nitrogen Legacy in a restoration wetland, Upper Klamath Lake, Oregon. *Wetlands* 29(2): 735-746.
- ENSR Corporation. 2007. Feasibility study for the control of internal phosphorus loading in St. Albans Bay, Lake Champlain. Prepared for Vermont Agency of Natural Resources Water Quality Division: 1-66.
- Goldman C.R. and A.J. Horne. 1994. *Limnology*. 351-352.
- Huang, P. and Z. Liu. 2009. The effect of wave-reduction engineering on sediment resuspension in a large, shallow, eutrophic lake (Lake Taihu). *Ecological Engineering* 35: 1619-1623.
- Kadlec, R.H. 2005. Phosphorus removal in emergent free surface wetlands. *Journal of Environmental Science and Health* 40: 1293-1306.
- Kuwabara, J.S., B.R. Topping, J.L. Carter, F. Parchaso, J.R. Asbill, J.M. Cameron, S.V. Fend, J.H. Duff, and A.C. Engelstad. 2010. The transition of benthic nutrient sources after planned levee breaches adjacent to Upper Klamath and Agency Lakes, Oregon. U.S. Geological Survey Open-File Report 2010-162: 1-31.

Mitsch, W.J., B.C. Reeder. 1991. Modelling nutrient retention of a freshwater coastal wetland: estimating the roles of primary productivity, sedimentation, resuspension and hydrology. *Ecological Modelling* 54: 151-187.

Nairn, R.W. and W.J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. *Ecological Engineering* 14: 107-126.

National Research Council (NRC). 2004. Endangered and threatened Fishes in the Klamath River Basin: Causes of Decline and Strategies for Recovery. Committee on Endangered and Threatened Fishes in the Klamath River Basin, National Research Council.

ODEQ. 2002. Upper Klamath Lake drainage Total Maximum Daily Load (TMDL) and Water Quality Management Plan (WQMP). Prepared for Oregon Department of Environmental Quality: 25-204.

Ray, A.M., J.C. Litts, A. Lutz, M. Boyter, A.S. Hamilton. 2009. Patterns of Vegetation Development at the Wood River Wetland, Oregon. *Society of Wetland Scientists Bulletin*, 26 (1): 11-13.

Reddy, K.R., R.H. Kadlec, E. Flaig and P.M. Gale. 1999. Phosphorus retention in streams and wetlands: A review. *Critical Reviews in Environmental Science and Technology* 29(1): 83-146.

Richardson, C.J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. *Science* 228(4706): 1424-1427.

Rykbost, K.A. and B.A. Charlton. 2001. Nutrient loading of surface waters in the Upper Klamath Basin: agricultural and natural sources. Oregon State University. Special Report 1023: 4-17.

Søndergard, M., J.P. Jensen and E. Jeppesen. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*: 135-145.

Snyder, D.T. and J.L. Morace. 1997. Nitrogen and Phosphorus loading from drained wetlands adjacent to Upper Klamath and Agency Lakes, Oregon. U.S. Geological Survey Water-Resources Investigations Report 97-4059.

Stevens, C.J., 2008. Effects of timing and duration of flooding on phosphorus release in four restored wetlands around Agency and Upper Klamath Lakes, Oregon. Oregon State University: 1-65.

Tonderski, K.S., B. Arheimer, and C.B. Pers. 2005. Modeling the impact potential wetlands on phosphorus retention in a Swedish catchment. *Ambio* 34 (7): 544-551.

USBR. AgriMet Historical Archive Weather Data Access. AGKO Station- Agency Lake, OR (2003-2005) <http://www.usbr.gov/pn/agrimet/webarcread.html>.

Walker, W.W. 2001. Development of a Phosphorus TMDL for Upper Klamath Lake, Oregon. Prepared for Oregon Department of Environmental Quality. 1-80.

Wang, N. and W.J. Mitsch. 2000. A detailed ecosystem model of phosphorus dynamics in created riparian wetlands. *Ecological Modelling* 126: 101-130.

Wood, T.M., G.R. Hoilman, and M.K. Lindenberg. 2006. Water-quality conditions in Upper Klamath Lake, Oregon, 2002-04. U. S. Geological Survey Scientific Investigations Report 2006-5209. <http://pubs.usgs.gov/sir/2006/5209/>.

APPENDICES

8.0 APPENDIX A- EQUATIONS AND METHODS OF DATA COLLECTION

8.1 Hydrology Submodel

The initial water volume in the wetland, Q , was estimated to be $5.5 \times 10^7 \text{ m}^3$ at the start of the first summer, based upon the average surface inflow, precipitation and evapotranspiration rates over the 273 days per year during which outflow did not occur before the start of the model.

Precipitation (P_r) data was acquired from the AGKO AgriMet station (USBR 2011) which is operated and maintained by the USBR and is on the northwest shore of Agency Lake, within ALRW. The precipitation data used was taken from July to September and then from October to June for years 2003, 2004 and 2005. The data was converted from cumulative in to cumulative m day^{-1} . The daily average of cumulative meters was then applied to the total modeled area of the wetland to determine the precipitation in $\text{m}^3\text{day}^{-1}$ and is reported in Table 6. The precipitation data was used without adjustment, as the AGKO station lies within the area of interest.

Evapotranspiration (ET) data was also acquired from the AGKO station within ALRW (USBR 2011). The evapotranspiration data used was gathered daily using the Kimberly-Penman method. The data used in this model during the outflow period was taken from July to September and then from October to June for years 2003, 2004 and 2005, to remain consistent with P_r and many of the other initial values of the model. It was converted from inches to meters and applied over the area of the wetland and reported in Table 7.

Overland inflow (I) data was measured as discharge from the discrete inlet to ALRW (Snyder and Morace 1997). The data was estimated at the distinct inlet to the wetland, and was initially reported in acre-ft. Annual totals were determined and then converted to m^3 . Last, average daily inflow (in m^3) was determined to assume that inflow was constant throughout the year. The inflow values are reported in Table 8.

The average daily rate of outflow during the summer (xQ) was estimated to be approximately $182,000 \text{ m}^3 \text{ day}^{-1}$, based upon pumping data collected by the USBR (unpublished) in ALRW over the summer from 2004-2009. The outflow coefficient (x)

was then calculated to be 0.003 day^{-1} , from the average daily outflow rate and the initial water volume, $Q = 5.5 \times 10^7 \text{ m}^3$.

8.2 Productivity Submodel

Solar Radiation (**R**) data was acquired from the AGKO AgriMet station (USBR 2011). The solar radiation data used in this model during the outflow period was taken and averaged from July to September and then from October to June for years 2003, 2004 and 2005, to remain consistent with the time period of the precipitation data and many of the other parameters of the model. The AgriMet station measured R in Langleys and the data was converted to $\text{kcal m}^{-2}\text{day}^{-1}$. This was the final value of R used and is reported in Table 9.

For energy in the algal biomass (**L**), an initial value of 100 g m^{-2} (or 410 kcal m^{-2}) was estimated for the start of the growing season. The algal settling coefficient (**L_s**) was obtained from calibration, as no direct data was available. It was determined to be 0.03 day^{-1} of the total energy in the algal biomass.

Algal GPP (**L_pR**) and algal respiration (**L_rL**) were measured in WRW by Carpenter et al. (2009). Algal GPP was determined by measuring the change in dissolved oxygen in light and dark bottles on two dates in June and in August of 2005. Three sets of samples were taken on each date and a sample was measured for initial (I) oxygen content. The light (L) and dark (D) bottles were incubated for 4 hours and then oxygen content in each of the bottles was measured. GPP for the algae was calculated as L minus D and respiration was calculated from I minus D (Goldman and Horne 1994). DO was initially measured and reported in mg L^{-1} and the average change in dissolved oxygen was determined for $\text{mg L}^{-1} \text{ hr}^{-1}$. GPP and Respiration were then converted and reported in $\text{g L}^{-1} \text{ day}^{-1}$. Last, the values were converted from $\text{g L}^{-1} \text{ day}^{-1}$ to $\text{kcal L}^{-1} \text{ day}^{-1}$ using an energy per biomass ratio of 4.1 kcal g^{-1} as calculated by Boyd (1970) for *Typha latifolia*. These results are in Table 10.

Based upon the values in Table 10, the value for $t=0$ was calculated from taking the averages over June and August for both GPP and respiration. The values were 0.37 and $0.8 \text{ g L}^{-1} \text{ day}^{-1}$ respectively. The values were then converted to $\text{kcal m}^{-3} \text{ day}^{-1}$, giving

algal GPP a value of 370 kilocalories and respiration a value of 800 kilocalories. L_p was then determined from the Algal GPP (L_pR) and was determined to be 0.13. L_r was determined from the respiration of the total energy in the algal biomass (L_rL) to be approximately 2.0 day^{-1} .

The energy in the macrophyte biomass (M) was measured at WRW at 7 plots on July 25, 2009 and was found to be 1430g (Ray et al. 2009). The initial M (per m^2) at $t=0$ was estimated to be 205g. This was then converted to kilocalories for an initial value of 850 kcal m^{-2} . Macrophyte settling (M_sM) was also measured at the same plots (Ray et al. 2009) and was determined to be 393g when $M=1430\text{g}$. Therefore, M_s was determined to be 0.27 day^{-1} .

The wetland area covered by macrophytes (V) was measured in WRW in 2008 in September (Ray et al. 2009), when energy in the macrophyte biomass is at its maximum. The percent coverage of macrophytes was measured at 57 plots and the maximum percent coverage at these 57 plots was averaged and determined to be 0.91. The wetland area covered by macrophytes at $t=0$, was then estimated to be 0.75 and varied as a function of depth over the model run, with the equation $(1-(0.18*d))$. The macrophyte solar efficiency (M_p) and the macrophyte respiration coefficient (M_r) were both determined from calibration. They were found to be 0.09 and 0.15 day^{-1} , respectively.

8.3 Phosphorus Submodel

The area of the wetland (A) was approximated by finding the average areas of uniform characteristics from ALRW and WR from aerial photography. The modeled area of the wetland was estimated to be $4.0 \times 10^7 \text{ m}^2$.

The other measured parameters for this submodel were found from data measured in WRW by the USGS (Carpenter et al. 2009). The P concentration of the overland inflow (C) was measured several times over 2003-2005. Sampling was concentrated during the growing season with a few winter and early spring samples collected to characterize the non-growing season. Surface water was collected using a battery-operated peristaltic pump with Masterflex® tubing. Water samples were analyzed for filtered and unfiltered (total) nutrients on 15 occasions. Bulk samples were shaken and

subsampled into 125-mL bottles for TP and then filtered into 60mL sample bottles (for SRP), which were processed through 0.45- μm filtration capsules attached directly to the peristaltic tubing. SRP samples were preserved with 100 μL concentrated hydrochloric acid (HCl) per 60-mL sample. Samples were packed on ice and sent to the laboratory for analysis. The median P concentration of the overland inflow of water into the wetland was determined to be 120 $\mu\text{g L}^{-1}$ and was converted to 0.12 g m^{-3} to be used in the model.

The initial amount of P in the water column (**P**) was calculated as (CQ) at $t=0$, which equaled 6.6×10^6 g for the entire wetland. The initial amount of P in the sediments (**S**) was estimated, based upon pore-water data measurements by Kuwabara et al. (2010) during June 2008 in ALRW. SRP was measured in the pore-water of the sediments at ALRW, and averages from the first 0.03 m were determined to equal 0.139 g m^{-3} . Applying this value to the total area of the wetland gave an estimated value of 5.9×10^6 g P in the sediments for the entire wetland.

The P kilocalorie ratio in algae (**k_p**) used was 0.001 g P kcal^{-1} as determined by Jorgensen and Johnson (1989). The P kilocalorie ratio in macrophytes (**k_m**) was determined from calibration to be 0.75 g P kcal^{-1} . The average depth of water in the wetland (**d**) was taken to be the volume of water in the wetland divided by the area of the wetland. The average depth of water above the sediments in the wetland was therefore variable as the volume of water in the wetland varied. The resuspension rate of P from the wetland sediments to the water column (**S_r**) was estimated to be 0.0025 $\text{g P m}^{-2} \text{day}^{-1}$, based on the original model from Mitch and Reeder (1991).

8.4 Seasonal Changes for Model Run Initial

For the portion of the model run during the autumn, outflow of water, phosphorus and algae were assumed to not occur. Macrophyte and algae productivity were reduced to 0 and precipitation, evapotranspiration, and solar radiation were reduced to their “rest of year” values, as described in Tables 6, 7 and 9, respectively. The model was then run with these adjusted conditions and the other final values from $t=92$ for another 92 days.

At $t=185$, the model was adjusted for the winter. Outflow was again not allowed. Surface inflow was assumed to not occur (as the surface water was frozen). Energy in the

Algae and Macrophyte biomass pools were set to 0 and all other final values from t=184 were used for an additional 90 days to simulate January to March.

For the spring season, surface inflow, macrophyte productivity and algae productivity resume. Outflow is not allowed and the final values from t=275 were used for an additional 90 days. At t=366, outflow was allowed and rates determined for the first summer were used, along with final values from t=365 to simulate the second summer.

Table 6- Precipitation data for 2003-2005 at ALRW

Daily Avg. Precip.	2003	2004	2005	Overall (in)	Overall (m)	Overall (m³)
Summer	0.016	0.003	0.004	0.008	0.0002	3,000
Rest of Year	0.05	0.05	0.04	0.047	0.0012	18,000

Table 7- ET data for 2003-2005 at ALRW

Daily Avg. ET	2003	2004	2005	Overall (in)	Overall (m)	Overall (m³)
Summer	0.24	0.23	0.26	0.26	0.006	90,000
Rest of Year	0.11	0.09	0.10	0.10	0.003	45,000

Table 8- Inflow data at ALRW

Inflow (f³ s⁻¹)	Inflow (m³ s⁻¹)	Daily Avg. Inflow (m³ day⁻¹)
100	2.83	245,000

Table 9- Solar Radiation for 2003-2005 at ALRW

Daily Avg. (R)	2003	2004	2005	3-yr (Langleys)	3 yr (kcal m⁻²day⁻¹)
Summer	612	619	637	623	6230
Rest of Year	353	366	336	352	3520

Table 10- GPP and Resuspension of algae for 2005

Date	GPP g L⁻¹ day⁻¹	GPP kcal L⁻¹ day⁻¹	Resp. g L⁻¹ day⁻¹	Resp. kcal L⁻¹ day⁻¹
06-05	0.0024	0.010	0.093	0.38
06-05	0.0022	0.0090	0.21	0.86
08-05	0.18	0.74	0.24	0.98

9.0 APPENDIX B- SENSITIVITY ANALYSIS

A sensitivity analysis, similar to that of Wang and Mitsch (2000), was carried out to assist in the initial model calibration. Parameters and initial values were changed, one at a time, to values 0.5p, 2p, 5p and 10p, where **p** is the selected parameter or initial value. Model Run Initial was run over the summer season and changes to both the **P** (p in the water column) and **S** (p in the sediments) were recorded and compared. The sensitivity (**S(p)**) of each parameter was then determined using the following equation (Wang and Mitsch 2000):

$$S(p) = \left(\frac{\Delta x}{x}\right) / \left(\frac{\Delta p}{p}\right)$$

where **x** is the selected state variable. Changes to parameters or initial values that caused a change of greater than 10% on either the water or sediment phosphorus state variables are reported, as a percent change, in Table 11. These were the parameters of the greatest focus when calibrating the model.

As Table 11 illustrates, phosphorus in the water column is most greatly affected by three parameters: the amount of water volume in the wetland (**Q**), the area of the wetland (**A**) and the resuspension rate of P from the sediments into the water (**S_r**). This indicates that the pool of phosphorus in the water of the wetland is heavily driven by the flow and movement of water.

The phosphorus in the sediment is most greatly affected by the initial value of the energy macrophyte biomass pool (**M**), the phosphorus to kcal ratio in macrophytes (**k_m**), and area of the wetland (**A**) (Table 11). This indicates that the pool of phosphorus in the sediments of the wetland is driven primarily by the size of macrophyte biomass and its ability to use phosphorus.

Table 11- Parameters that cause 10% change or greater in the phosphorus state variables in a sensitivity analysis

State Variable	Greatest % Sensitivity Least					
	P	Q	A	S _r		L
1700		1100	104		11	10
S	M	k _m	A	V	M _p	R
	143	100	92	42	20	20

10.0 APPENDIX C- MODEL VERIFICATION

To verify our model, we compared the results of Model Run Initial to existing literature on P processes in wetlands to investigate if they were reasonable. The average resuspension of P is $1.5 \times 10^{-3} \text{ g P m}^{-2} \text{ day}^{-1}$. This is consistent with the findings of Reddy et al. (1999) who found that resuspension from soil to the overlying water column is variable, with values in the range of 2.0×10^{-5} to $3.2 \times 10^{-3} \text{ g P m}^{-2} \text{ day}^{-1}$.

Net macrophyte uptake of P over the entire year was found to be $8.2 \text{ g P m}^{-2} \text{ yr}^{-1}$. This is consistent with the findings of Kadlec (2005), who determined that uptake of P by macrophytes may range from 0.5 to $20 \text{ g P m}^{-2} \text{ yr}^{-1}$. Macrophyte sedimentation of P was found to be $8.0 \text{ g P m}^{-2} \text{ yr}^{-1}$, which is consistent with Reddy et al. (1999) who noted that a large amount of the P taken up during macrophyte growth is subsequently released during decomposition (included in macrophyte P sedimentation in our model).

Algae uptake of P is $8.8 \times 10^{-3} \text{ g P m}^{-2} \text{ yr}^{-1}$ or $0.09 \text{ kg P ha}^{-1} \text{ yr}^{-1}$. This value may be low, as seen when comparing it to the results of Nairn and Mitsch (2000) which found that algae contained approximated $2.6 \text{ kg P ha}^{-1} \text{ yr}^{-1}$, when assuming maximum algal coverage of the wetlands. Algal sedimentation of P was less than that of uptake, reaching only $6.0 \times 10^{-3} \text{ g P m}^{-2} \text{ yr}^{-1}$. This is due to the outflow of some algae to the lakes and that algae dying and decomposing outside the modeled area.

Net P accumulation in the sediment was found to be $6 \text{ g P m}^{-2} \text{ yr}^{-1}$. This falls well within the wide range that Kadlec (2005) reports, which states that P load removal in wetlands can range from less than 0.1 to well over $100 \text{ g P m}^{-2} \text{ yr}^{-1}$, depending on the inflow concentrations. The net P accumulation is much higher than that reported by Richardson (1985) who determined that in temperate wetlands, there was an annual accumulation of p of only 0.005 to $0.24 \text{ g P m}^{-2} \text{ yr}^{-1}$, but lower than that of that of Braskerud (2002) who saw an average retention of p of 26-71 $\text{g P m}^{-2} \text{ yr}^{-1}$.

Because many of these results fell within a range of variability, and the outflow of P from the wetland was low compared to measured values, it would be advantageous to further measure and examine actual rates of P uptake, resuspension and accumulation in

the Upper Klamath Basin wetlands. Similar data would be needed to use this model to other wetlands with varying climates and management strategies.

