SOUTH FLORIDA WATER MANAGEMENT DISTRICT

LAKE OKEECHOBEE WATERSHED RESTORATION PROJECT PHOSPHORUS LOADING SPREADSHEET MODEL - PLSM

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EXECUTIVE SUMMARY

The major goals of the Lake Okeechobee Watershed Restoration Project—part of the Comprehensive Everglades Restoration Plan—are to improve the quantity, timing, and distribution of water entering Lake Okeechobee. The Lake Okeechobee Watershed Restoration Project will improve management of lake water levels, reduce excessive releases of water to the St. Lucie and Caloosahatchee estuaries, and increase operational flexibility. These goals will be achieved through storage of water in surface reservoirs and underground in aquifer storage and recovery wells. Additional wetland areas also will be restored to enhance habitat utilization in the subwatersheds that are the focus of this project.

An expected ancillary benefit of this project is a phosphorus load reduction to Lake Okeechobee. To evaluate this ancillary benefit, a simple phosphorus loading spreadsheet model was created to estimate the phosphorus loads to Lake Okeechobee from the proposed project features. The spreadsheet model uses daily simulated values from alternative scenarios generated by the Regional Simulation Model Basins model to evaluate subwatershed and feature (reservoirs and ASR wells) flows to the lake. The model was reviewed through the United States Army Corps of Engineers validation process for engineering software, as part of the Central Everglades Planning Project. The Regional Simulation Model was classified as "allowed for use" for South Florida applications in August 2012. The phosphorus loading spreadsheet model used the daily Regional Simulation Model Basin flow estimates to estimate phosphorus loads for each scenario. These load scenarios were compared to the Future Without Project scenario estimated loads to evaluate the phosphorus load reduction benefit for each alternative. The PLSM uses conservative estimates to account for uncertainty in reservoir and watershed conditions and to maximize the probability that the predicted benefit is achieved.

To estimate phosphorus loads, a constant concentration value for each simulation is needed. Because a single value has not been determined for the Future Without Project condition, a range of values was used in a sensitivity analysis that encompasses the likely flow-weighted concentration that will occur. These values range from 40 micrograms phosphorus per liter, which is based on the Lake Okeechobee Total Maximum Daily Load of 105 metric tons per year divided by the average annual flows to Lake Okeechobee from water years 1974 to 2016 (2.1 million acre-feet or 2.6 billion cubic meters) to 100 micrograms phosphorus per liter, which is the current upper Kissimmee Subwatershed flow-weighted mean concentration.

Each alternative spreadsheet model includes independent ASR net loads, reservoir net loads (including reservoir-assisted ASR wells, if applicable), and subwatershed loads (exclusive of reservoirs and ASR loads). Loads are summed by year and then averaged over the Reservoir Sizing and Operations Screening simulation period (41 years: 1965–2005) to obtain an average annual phosphorus load for each alternative.

The average annual phosphorus load for each alternative was compared to the Future Without Project estimate. All alternatives showed a load reduction to Lake Okeechobee (within the range of 5 to 16%). These results indicate that the Lake Okeechobee Watershed Restoration Project will provide a phosphorus load reduction benefit to the future conditions to the lake.

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INTRODUCTION

The Lake Okeechobee Watershed Restoration Project (LOWRP) is part of the Comprehensive Everglades Restoration Plan (CERP). The goals of LOWRP are to improve the quantity, timing, and distribution of water entering Lake Okeechobee. The project will assist the management of Lake Okeechobee water levels, reduce excessive releases of water to the St. Lucie and Caloosahatchee estuaries, and increase operational flexibility. LOWRP alternatives have been developed that will achieve these goals though storage of water in surface reservoirs and underground in aquifer storage and recovery (ASR) wells (**Figures 1** and **2**). Wetland areas also will be restored to enhance habitat utilization in the subwatersheds that are the focus of this project.

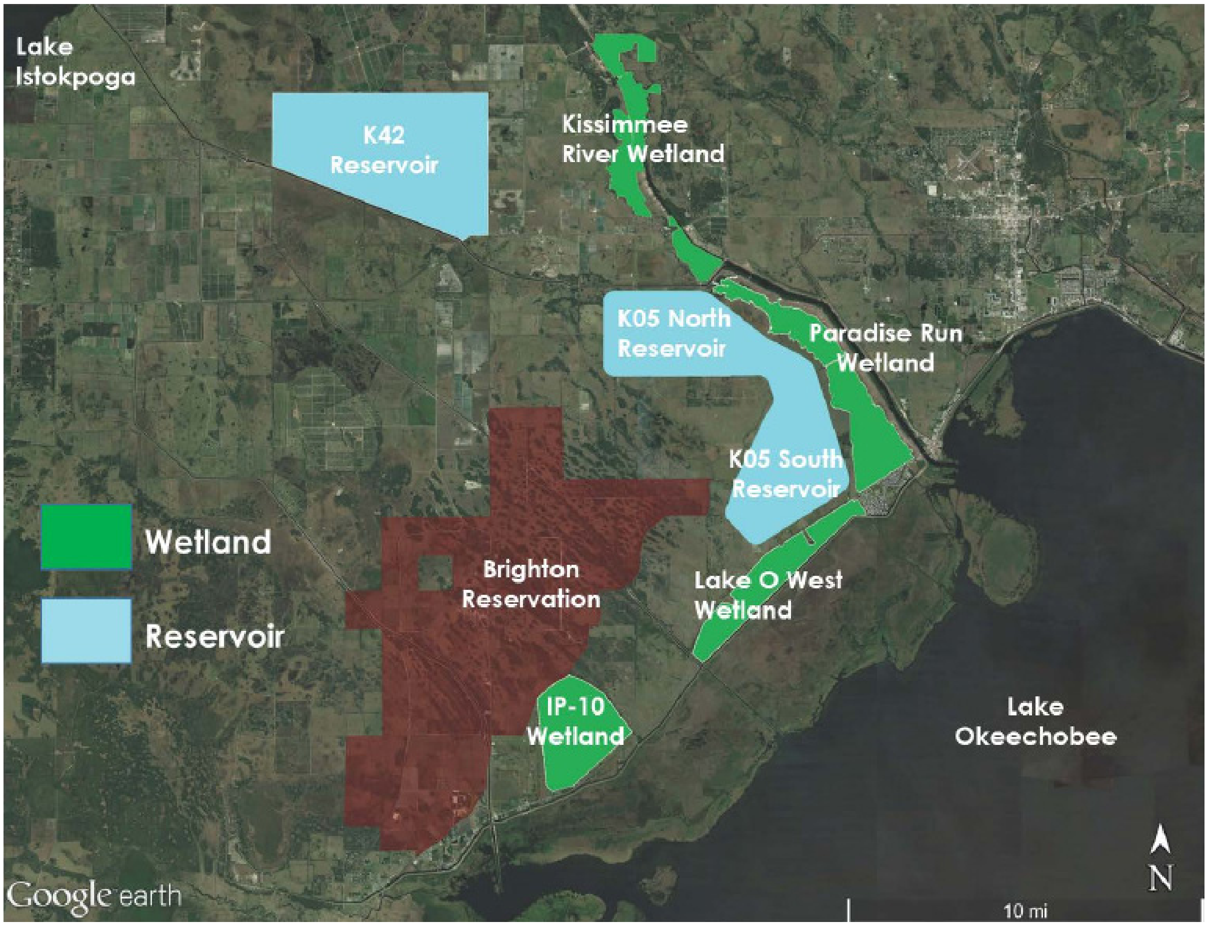

Figure 1. Project map showing all alternative wetland and reservoir features.

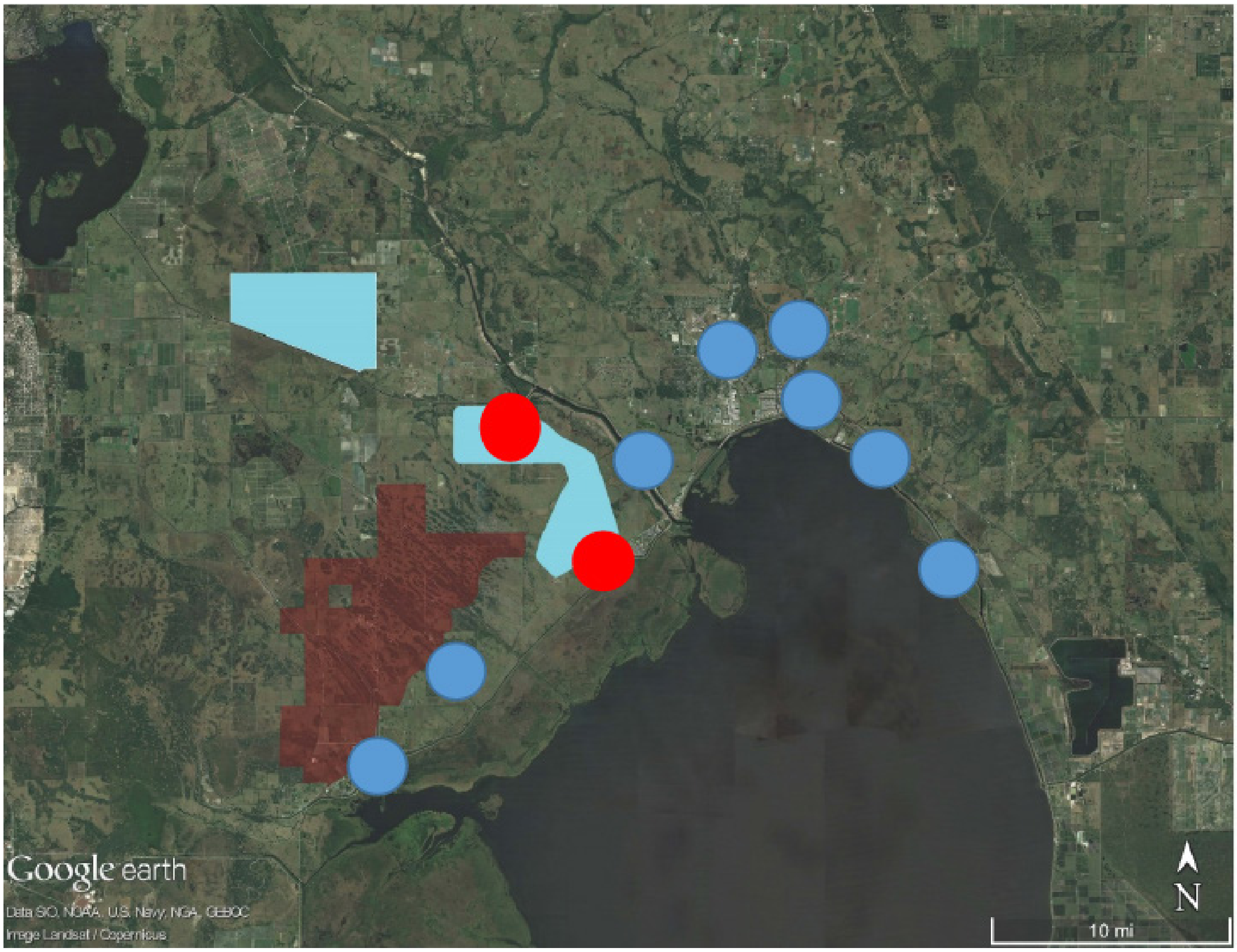

Figure 2. Project map showing Alternative 2A ASR well locations.
Each blue dot represents 10 independent wells. Each red dot represents 15 reservoir-assisted wells.

Four alternatives were included in the second round of modeling (**Table 1**). To evaluate the effect of these LOWRP alternatives on phosphorus (P) loads to Lake Okeechobee, a simple P loading spreadsheet model (PLSM) was developed to quickly estimate the potential P loads from features simulated by the Regional Simulation Model Basins model (RSMBN; SFWMD 2005a, b). The objective of the PLSM is to develop P load estimates on a daily time step for the reservoirs, ASR wells, and watersheds included in the LOWRP, sum the P loads by year, and compare the average annual P loads against the estimated future without project (FWO) condition. The percent differences of the LOWRP alternatives as compared to FWO condition will be estimated.

The spreadsheet model uses daily simulated values from alternative scenarios generated by the RSMBN; SFWMD to evaluate subwatershed and feature (reservoirs and ASR wells) flows to the lake. The RSMBN (SFWMD 2011) was reviewed through the United States Army Corps of Engineers validation process for engineering software, as part of the Central Everglades Planning Project. The Regional Simulation Model was classified as “allowed for use” for South Florida applications in August 2012. The PLSM model used the daily RSMBN flow estimates to estimate P loads for each scenario. These load scenarios were compared to the FWO condition estimated loads to evaluate the P load reduction benefit for each alternative. The PLSM uses conservative estimates to account for uncertainty in reservoir and watershed conditions and to maximize the probability that the predicted benefit is achieved.

Table 1. Alternatives retained for the third round of modeling.

Alternative	Reservoir Component		ASR Component		Rationale
	Reservoir(s)	Storage Capacity (acre-feet)	Number of ASR Wells	Storage Capacity (acre-feet per year)	
2A	Revised K-05 North and revised K-05 South, and K-42	361,000	110	616,000	Maximum storage
2B	Revised K05 North and K-42	276,000	70	392,000	Seminole Tribe of Florida's 'least objectionable alternative,' RESOPS-informed ASR
1Br	Revised K05 North and revised K-05 South	199,500	80	480,000	Maximize public lands, RESOPS-informed ASR
2Cr	K-42	199,500	65	364,000	Least-cost, minimum storage, watershed only ASR (no reservoir-assisted ASR)

METHODS

Daily flow estimates from the RESOPS model were used to estimate P loads for three major categories: subwatersheds, ASR recovery, and reservoir discharge. The first two categories are based on constants while the third is based on a simple reservoir model. The constant for the subwatersheds and ASR recovery is based on a baseline P concentration used for all inflows to features and discharges from subwatersheds to determine P loads. Included in the simple model are recharge P loads to reservoir-assisted ASR wells (if applicable). The FWO scenario P loads are based on the baseline constant for direct comparisons to the alternatives to estimate the difference that can be attributed to each alternative's features. The simple model developed here uses daily values for daily volume flow (Q), P concentration (C), daily P load (L), reservoir volume (V), and reservoir P mass (M). All equations use a time step of 1 day, which is implied.

SUBWATERSHED FEATURE AND FWO SCENARIO P CONCENTRATIONS

To estimate P loads, a constant P concentration value for each simulation is needed. Because a single value has not been determined for the FWO condition, a range of values was used in a sensitivity analysis that encompasses the likely flow-weighted P concentration that will occur. These values range from 40 micrograms phosphorus per liter ($\mu g\ P\ L^{-1}$), which is based on the Lake Okeechobee Total Maximum Daily Load (TMDL) of 105 metric tons per year (FDEP 2001) divided by the average annual flows to Lake Okeechobee from water years 1974 to 2016 (2.1 million acre-feet or 2.6 billion cubic meters; Figure 8B-18 in Sharfstein and Zhang 2017) to 100 $\mu g\ P\ L^{-1}$, which is the current upper Kissimmee Subwatershed flow-weighted mean concentration (Sharfstein and Zhang 2017). Two intermediate values of 60 and 80 $\mu g\ P\ L^{-1}$ were also included.

INDEPENDENT ASR WELL PHOSPHORUS LOADS

P recharge loads to the independent ASR wells were calculated as the recharge flow multiplied by the baseline P concentration (**Equation 1**). The recovered P load was calculated from the recovery volume multiplied by a constant recovery concentration value determined from total phosphorus (TP) measurements of recovery water at the Hillsboro ASR Pilot Project (page 9-196 in USACE and SFWMD

2013). The mean recovery P concentration over four cycles was 10.8 ± 11.6 µg P L^{-1} (sample size [n] = 44). A value of 34 µg P L^{-1} was selected (mean + 2 standard deviations) as the recovery concentration. This value was greater than 95% of the samples to assure that future ASR recovery loads will be at or below the estimated P load (e.g. a conservative estimate). The daily P loadings of the independent ASR wells are based on a simple equation (**Equation 1**):

$$L_{ASR,net,t} = Q_{recovery,t} * C_{recovery} - Q_{recharge,t} * C_{baseline} \quad \textbf{(1)}$$

Where $Q_{recovery}$ and $Q_{recharge}$ are the recovery and recharge volumes for the ASR wells on day t, $C_{recovery}$ is 34 µg P L^{-1} as described above and $C_{baseline}$ is the estimated subwatershed flow concentration as described above.

RESERVOIR MODEL

The reservoir model is based on daily time step equations to track changes in volume (**Equation 2**) and changes in mass (**Equation 3**):

$$Vol_{res,t} = Vol_{res,t-1} + Q_{in,t} + Q_{rain,t} + Q_{recovery,t} - Q_{recharge,t} - Q_{evap,t} - Q_{out,t} \quad \textbf{(2)}$$

$$M_{res,t} = M_{res,t-1} + L_{in,t} + L_{atm,t} - v_{set,t} + L_{recovery,t} - L_{recharge,t} - L_{out,t} \quad \textbf{(3)}$$

Where t represents the current time (day), t-1 is the previous day, and Vol_{res} is the volume of the reservoir at the end of the current time. Q_{in}, Q_{rain}, $Q_{recovery}$, $Q_{recharge}$, Q_{evap}, and Q_{out} are inflow, rainfall, reservoir-assisted ASR recovery from and recharge to the reservoir (if applicable), evaporation, and discharge, respectively. M_{res} is the mass of P in the reservoir at the end of the current time. L_{in} is the inflow P load to the reservoir and is based on the inflow ($Q_{in,t}$) multiplied by a constant P concentration (C_{in} **Equation 4**):

$$L_{in,t} = C_{in} * Q_{in,t} \quad \textbf{(4)}$$

Where L_{atm}, v_{set}, $L_{recharge}$, $L_{recovery}$, and L_{out} are the atmospheric deposition, net settling of P, the reservoir-assisted ASR recovery to and recharge from the reservoir (if applicable), and the discharge P load out of the reservoir, respectively (described below).

Because of the coarse time step (1 day) and the potential for the average reservoir volumes to be small at times, a lower boundary was set to prevent the TP mass from becoming negative. If the daily estimated P mass was at or below this boundary, the daily mass was set to the lower mass boundary (**Equation 5**):

$$if \begin{cases} M_{res,t} > M_{min,t} \rightarrow M_{res,t} = M_{res,t} \\ M_{res,t} \leq M_{min,t} \rightarrow M_{res,t} = M_{min,t} \end{cases} \quad \textbf{(5)}$$

Where

$$M_{min,t} = Vol_{res,t} * C_{min} \quad \textbf{(6)}$$

Where C_{min} is this lower P concentration boundary and was based on equilibrium phosphorus concentrations (EPC) measured for several lakes in the upper Kissimmee River Basin (**Table 2**; Belmont et al. 2009). These EPCs were measured from sediment cores overlain with water containing various concentrations of P. The concentration at which P did not change over time was considered the EPC. Using the 75th percentile of all measured values the lower concentration bound was set at 16 μg P L^{-1}. The daily average P concentration in the reservoir did not fall below this minimum boundary.

Table 2. EPC in milligrams per liter (mg L^{-1}) measured from sediment samples of several lakes in the Kissimmee River Basin. (Source: Belmont et al. 2009.)

Lake	Station	EPC_0 (mg L^{-1})
Cypress	C13	0.006
	C15	0.011
	C16	0.004
	C18	0.006
	C19	0.008
Hatchineha	H101	0.002
	H103	0.005
	H105	0.001
	H107	0.015
	H109	0.002
Istokpoga	I10001	0.055
	I10004	0.016
	I10005	0.034
	I10007	N/D
	I10009	0.001
Kissimmee	K1001	0.001
	K1003	0.001
	K1004	0.000 [a]
	K1009	0.006
	K1012	0.006
Tohopekaliga	T1	0.063
	T2	0.001
	T3	0.005
	T5	0.016
	T8	0.019
	T10	0.11
Median		**0.006**
75th percentile		**0.016**

a. Not included in the calculation because it is below the detection limit.

PHOSPHORUS CONCENTRATION AND RESERVOIR DEPTH

Reservoir volume and mass were used to determine P concentrations C_{res} at the end of the current time (**Equation 7**):

$$C_{res,t} = \frac{M_{res,t}}{Vol_{res,t}} \tag{7}$$

C_{res} is used to calculate ASR net P loads (e.g. recharge P loads) and reservoir discharge P loads (see below).

The average reservoir depth D_{res} was also determined on a daily basis (**Equation 8**):

$$D_{res,t} = \frac{Vol_{res,t}}{A_{res}} \tag{8}$$

Where A_{res} is the area of the reservoir. The depth is used to determine the net removal of P by settling (see below).

Atmospheric P Deposition

Two forms of atmospheric P deposition are considered: wet and dry. Wet deposition was estimated from rainfall volume (included in the RESOPS daily estimate for the reservoirs) multiplied by 10 μg P L^{-1} (**Equation 9 and Table 3**; estimate from Ahn and James 2001). Dry deposition was estimated as a proportion of the 18 milligrams P per square meter per year estimate of atmospheric deposition used to develop the Lake Okeechobee TMDL (FDEP 2001). This proportion was set at 0.75 based on estimates from Ahn and James (2001; see **Table 3**). Total atmospheric P load is the sum of wet and dry loads (**Equation 9**):

$$L_{atm,t} = Q_{rain,t} * C_{rain} + L_{dry\ deposition} * A_{res} \tag{9}$$

Where C_{rain} = 10 μg P L^{-1}, $L_{dry\ deposition}$= 0.0370 milligrams per square meter per day, and $A_{reservoir}$= area of the reservoir.

Table 3. TP concentrations in wet bucket and proportion of dry deposition in estimated total P loads at selected locations. (Source: Ahn and James 2001).

Station	Number of Samples (April 1992–December 1996)	TP Rainfall Concentration (μg P L^{-1})	Proportion of Dry Deposition in Estimated TP Load
Okeechobee Field Station	240	6.8	0.76
S131	166	13.1	0.74
S65A	240	10.8	0.74
Mean		**10**	**0.74**

Net P Settling

A first order net P settling rate was applied to the reservoir P mass on a daily time step using the methods of Smith and Hornung (2005). The settling rate (W) was set to 1 meter per year (0.27 centimeter per day). If $M_{res,t-1}$—the reservoir mass at time t-1—is greater than $M_{min,t}$—the minimum mass at time t—the mass settling rate ($V_{set,t}$) was set to zero (**Equation 10**):

$$if \begin{cases} M_{res,t-1} > M_{min,t} \rightarrow v_{set,t} = \dfrac{(M_{res,t-1} - M_{min,t}) * W}{D_{res,t-1}} \\ M_{res,t-1} \leq M_{min,t} \rightarrow v_{set,t} = 0 \end{cases} \quad \textbf{(10)}$$

Where $D_{res,t-1}$ is the average depth of the reservoir at time t-1.

Reservoir-assisted ASR P Loads

Recharge P loads to the reservoir-assisted ASR wells were estimated as the recharge flow times the reservoir P concentration, estimated from the daily estimated reservoir P mass and volume (**Equation 11**). Recovery P load from the ASR wells to the reservoir was the recovery flow times the 34 µg P L^{-1} value described previously (**Equation 12**).

$$L_{recharge,t} = Q_{recharge,t} * C_{res,t} \quad \textbf{(11)}$$

$$L_{recovery,t} = Q_{recovery,t} * C_{recovery} \quad \textbf{(12)}$$

Where $Q_{recovery,t}$ and $Q_{recharge,t}$ are the recovery and recharge flows on day t and $C_{recovery}$ is the P concentration as determined for the independent ASR wells (34 µg P L^{-1}; see *Independent ASR Well Phosphorus Loads* section above).

Reservoir Discharge P Load

Reservoir discharge P load ($L_{out,t}$) is simply based on the discharge flow ($Q_{out,t}$) multiplied by reservoir P concentration ($C_{out,t}$ **Equation 13**):

$$L_{out,t} = Q_{out,t} * C_{out,t} \quad \textbf{(13)}$$

ANNUAL AVERAGE P LOADS

Daily P loads summed by year and the average of the 41 years of P load for each alternative were determined and compared. The individual component P loads were averaged for the 41-year period of record and compared to the FWO condition P load estimate averaged for the same 41-year period. Flow-weighted mean P concentration of each alternative also was calculated as a check for calculation errors and comparison against the FWO scenario estimates.

RESULTS

The estimated FWO condition average annual flow and P load were 1,625.1 thousand acre-feet per year and 80.2 metric tons (t) per year, respectively (**Tables 4** and **5**). Assuming a concentration of 40 μg P L^{-1}, the P loads from the Indian Prairie/Istokpoga, Upper and Lower Kissimmee, and Taylor Creek Nubbin Slough subwatersheds are approximately 76% of the P TMDL (105 t excluding atmospheric deposition) and 77% of the baseline surface flow to Lake Okeechobee (Calendar Years 1991–2005) average of 2.56 million acre-feet per year (SFWMD et al. 2008). The total watershed flow and P load is much greater than the net flows from the ASR wells and reservoirs.

Table 4. Average 41-year volume estimates for elements of the various alternatives.

Alternative	Volume Estimates (1,000 acre-feet)				
	Watershed Independent of Project [a]	Net ASR Wells	Net K05 Reservoir	Net K42 Reservoir	Total Flow to Lake
Future Without Project	1,625.1				1,625.1
2A	1,615.2	-127.8	-46.8	-10.1	1,430.4
2B	1,619.5	-85.1	-18.6	-11.4	1,504.5
1Br	1,614.6	-77.9	-52.9		1,483.9
2Cr	1,625.0	-42.9		-10.9	1,571.2

a. Includes Indian Prairie/Istokpoga, Kissimmee River, and Taylor Creek/Nubbin Slough subwatersheds.

Table 5. Average 41-year P load estimates for elements of the various alternatives. (Note: Assumes a baseline concentration of 40 μg P L^{-1}.)

Alternative	P Load Estimates (metric tons)				
	Watershed Independent of Project [a]	Net ASR Wells	Net K05 Reservoir	Net K42 Reservoir	Total Load to Lake
Future Without Project	80.2				80.2
2A	79.7	-6.9	-2.1	-0.5	70.2
2B	79.9	-4.7	-1.0	-0.5	73.7
1Br	79.7	-4.3	-2.4		73.0
2Cr	80.2	-2.5		-0.5	77.1

a. Includes Indian Prairie/Istokpoga, Kissimmee River, and Taylor Creek/Nubbin Slough subwatersheds.

Independent ASR wells, which vary from 65 to 110 wells in the alternatives, are not 100% efficient and thus remove more surface water through recharge than is returned in recovery (**Figure 3**). The net removal of water is between 45 and 62% (**Table 4**). Given a baseline concentration of 40 μg P L^{-1} and an assumed recovery flow P concentration of 34 μg P L^{-1}, the net removal of volume is the largest contributor of P load reductions, between 53 to 68%, and results in an overall net negative load of P to the lake from the ASR wells (**Figure 4** and **Table 5**).

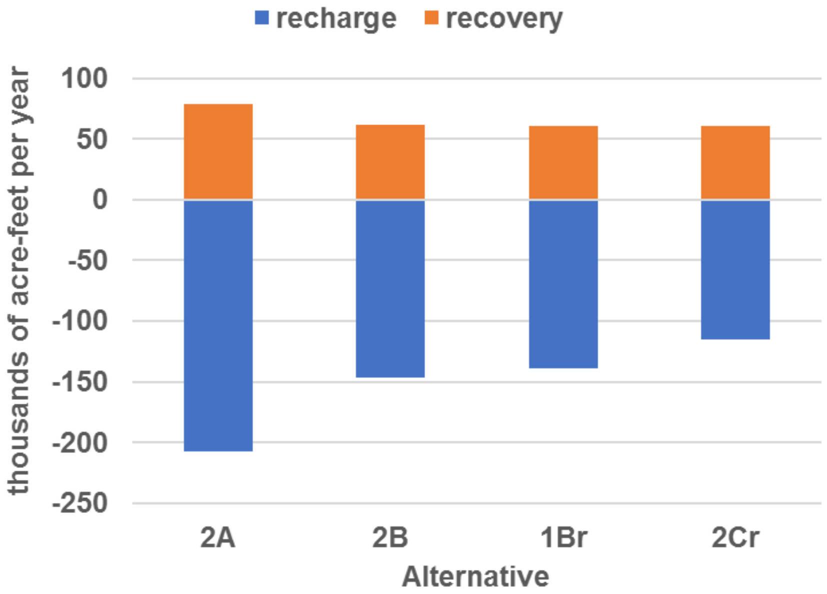

Figure 3. Average annual recharge and recovery volume estimated for independent ASR wells in the four alternatives.

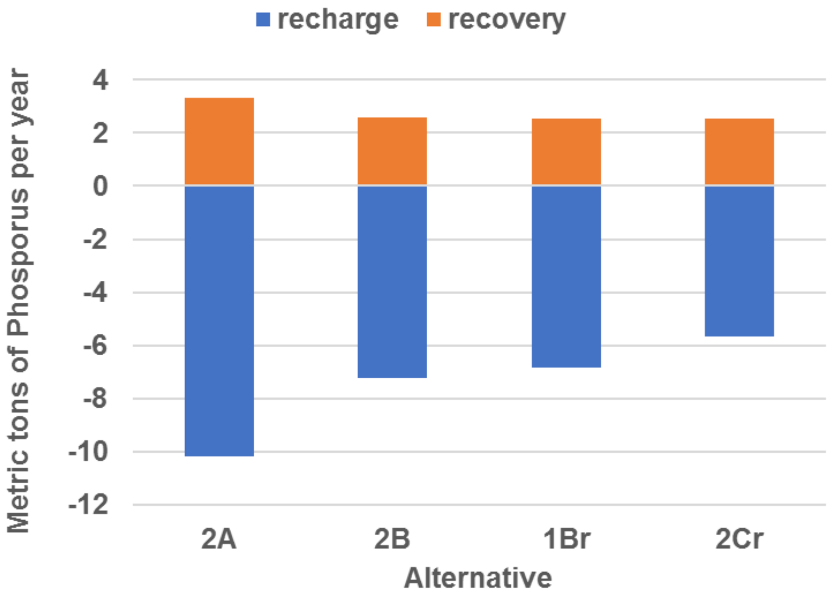

Figure 4. Average annual recharge and recovery P load estimated for independent ASR wells in the four alternatives using a baseline P concentration of 40 μg P L^{-1}.

Surface inflows to the reservoirs exceed discharge to Lake Okeechobee. For the K42 Reservoir this difference is attributed solely to evaporation which exceeds rainfall by 26 to 28% (**Figure 5**). For the K05 Reservoirs, evaporation exceeds rainfall by 23 to 26%. In addition, the recovery volume from the ASR wells associated with the K05 Reservoirs is between 42 to 53%, which also reduces the volume available for discharge. For the K42 Reservoir, the resulting discharge volume to the lake is between 15 and 26% less than the surface inflow to the reservoir. For the K05 Reservoirs the resulting discharge volume to the lake is between 47 and 58% less than the surface inflow to the reservoir.

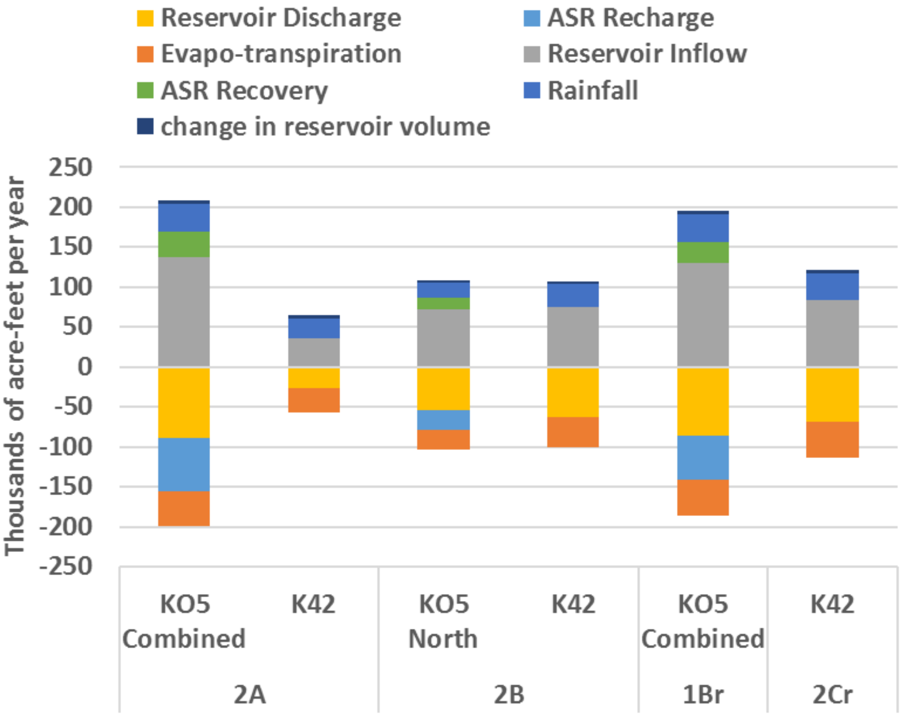

Figure 5. Estimated average annual water budgets for reservoirs in each alternative.

The atmospheric deposition of P is between 17 and 27% of the load to the K05 Reservoirs and 27 to 51% of the load to the K42 Reservoir (**Figure 6**). This is closely balanced by removal of P through net settling: between 16 and 34% for the K05 Reservoirs and 27 to 51% for the K42 Reservoir. The difference in the percentages between the reservoirs and among the scenarios is due to differences in reservoir area, the water depth, and the hydraulic turnover time. Because atmospheric P loads and net P settling are closely matched, the P load reduction for these reservoirs can primarily be attributed to the difference between the inflow and discharge volumes of water. For the K05 Reservoir these reductions were between 28 and 31% and for the K42 Reservoir between 15 and 26%. These reductions result in net negative P loads from all reservoirs. Despite the similarity of inflows to the reservoirs and recharge to independent ASR wells in the various alternatives, the ASR wells remove more P than the reservoirs (given a baseline concentration of 40 µg P L^{-1}**)** due primarily to the lower recovery from the wells as compared to the discharges from the reservoirs. Increasing the baseline P concentration results in greater net P removal with a majority of this attributed to the P concentration assumption in the ASR recovery volume.

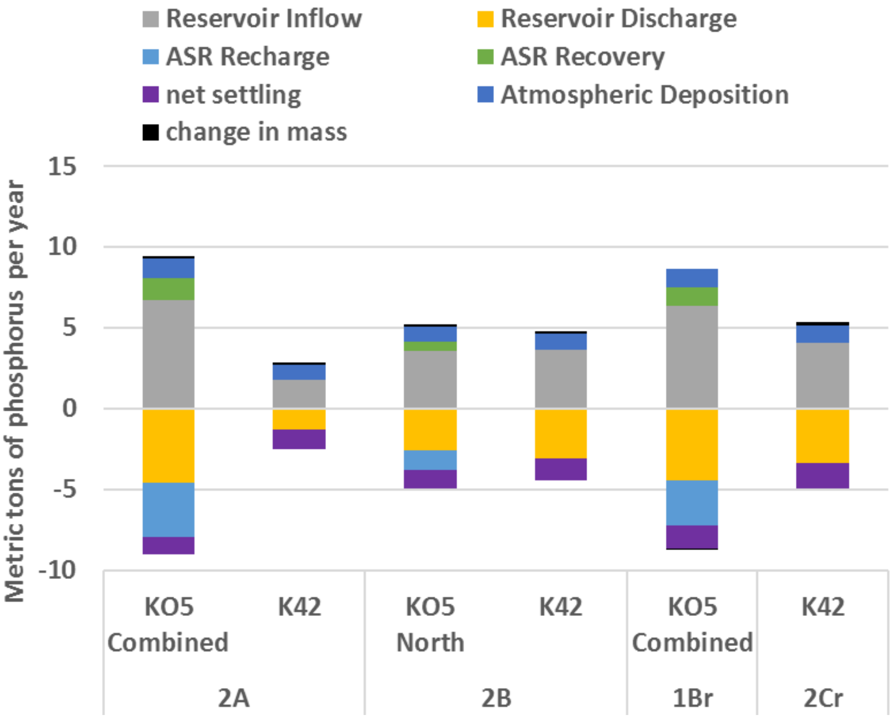

Figure 6. Estimated average annual phosphorus budgets for reservoirs in each alternative using a baseline concentration of 40 µg P L^{-1}.

Using the four baseline P concentrations demonstrates the increased P loadings for each alternative with larger concentrations (**Figure 7**). Comparison of all alternatives against the FWO condition P loads demonstrates that all alternatives provide some P load reduction benefit. Depending on the alternative and the baseline P concentrations, these benefits can range between 4 and 16% (**Figure 8**).

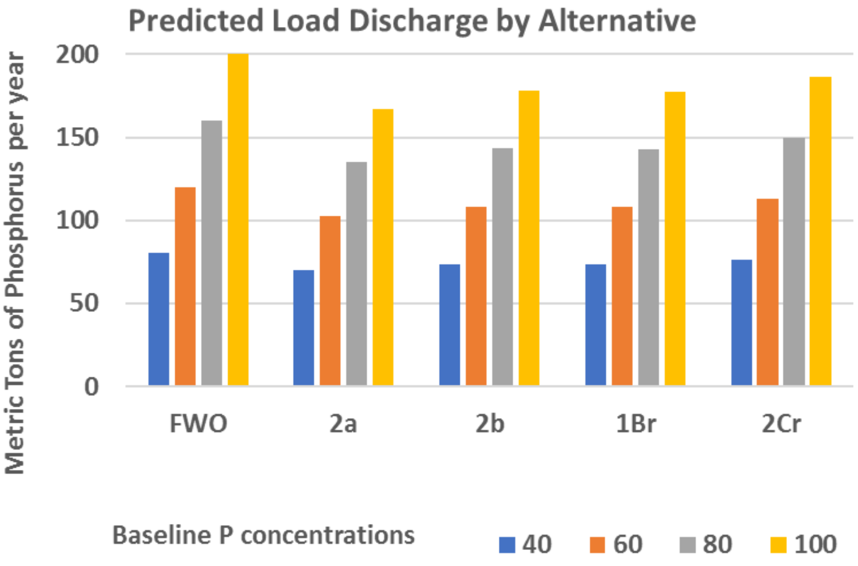

Figure 7. Estimated P loads resulting from LOWRP alternatives. (Note: Includes Indian Prairie/Istokpoga, Kissimmee River, and Taylor Creek/Nubbin Slough subwatersheds.)

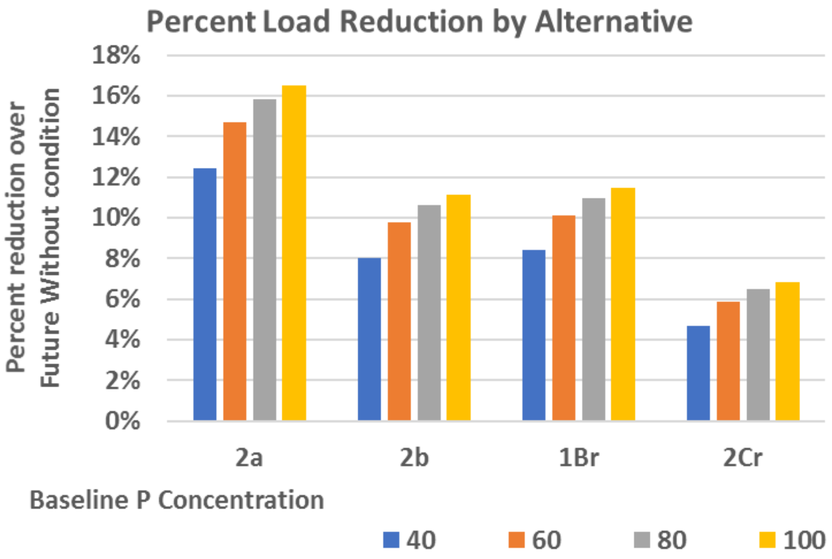

Figure 8. Estimated percent P load reduction resulting from LOWRP alternatives compared to the FWO condition.
(Note: Includes Indian Prairie/Istokpoga, Kissimmee River, and Taylor Creek/Nubbin Slough subwatersheds).

DISCUSSION

Given the conservative assumptions of the PLSM, all alternatives considered are predicted to result in P load reduction as compared to the FWO conditions. Most of these reductions are small and can be attributed to the reduced water volume that is discharged to Lake Okeechobee. The major contributor to this reduced volume is the recovery volume from ASR wells, which is assumed to be approximately 50% of the recharged volume. Because the assumed recovery water concentration is 34 μg P L^{-1}, when the recharge water concentration is at a baseline value of 40 μg P L^{-1} there is a small reduction due to removal of P. Given higher baseline concentrations (60 to 100 μg P L^{-1}), the net P reduction from the ASR wells increases (data not shown).

The flow and storage of water in the reservoirs is also substantial. However, the net P load reduction is smaller than the ASR well reductions. This is due to the higher percent of inflow water that is discharged from the reservoirs (71% or more) and low removal of P in the reservoir due to net P settling that is offset by atmospheric deposition and rainfall.

CONCLUSIONS

Based on results from this PLSM, the LOWRP alternatives provide some benefit of P load reduction. Using conservative estimates, the P load reduction is primarily attributed to reduction in volume due to assumed 50% recovery from ASR wells and to a small extent due to net P settling in reservoirs.

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