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Supplementary Material

Evaluating and Enhancing the Design of Borrow Pit Wetlands for Managing Nutrients in Agricultural Runoff

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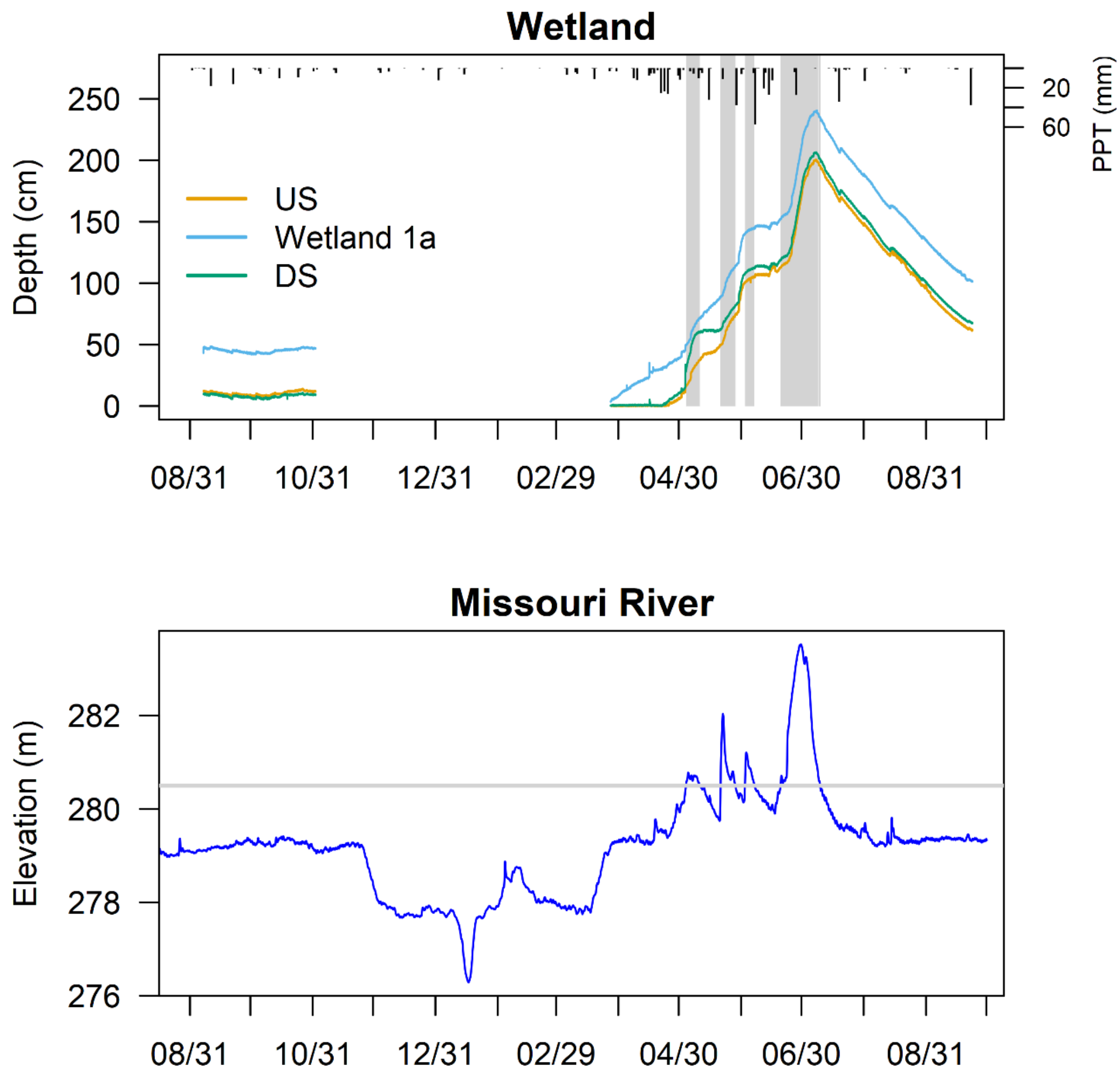

Figure S1. Observed water depths in the study wetland, along with Missouri River water elevations from USGS gage 06807000. Shaded areas show when the Missouri River was inundating the floodplain (river flow above floodplain elevation, horizontal line) and groundwater flux to the wetland was significant. US = upstream, DS = downstream, PPT = precipitation.

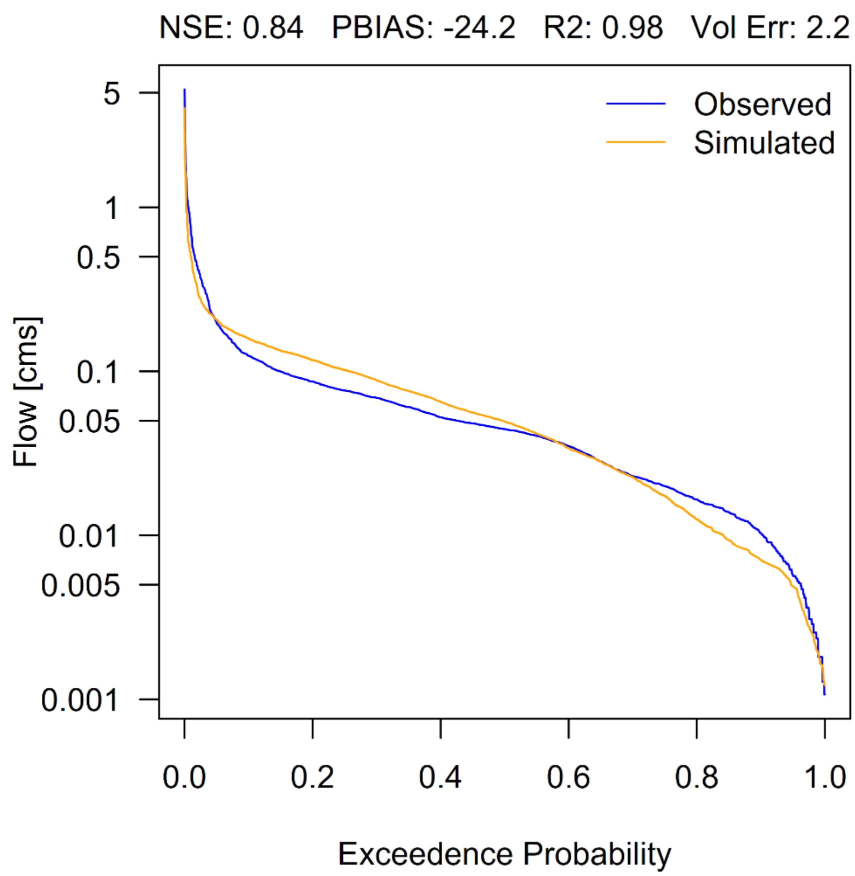

Figure S2. Modest agreement between observed and simulated (SWAT+) flow duration curves for the upstream watershed. cms = cubic meters per second. Note the log scale on the y-axis.

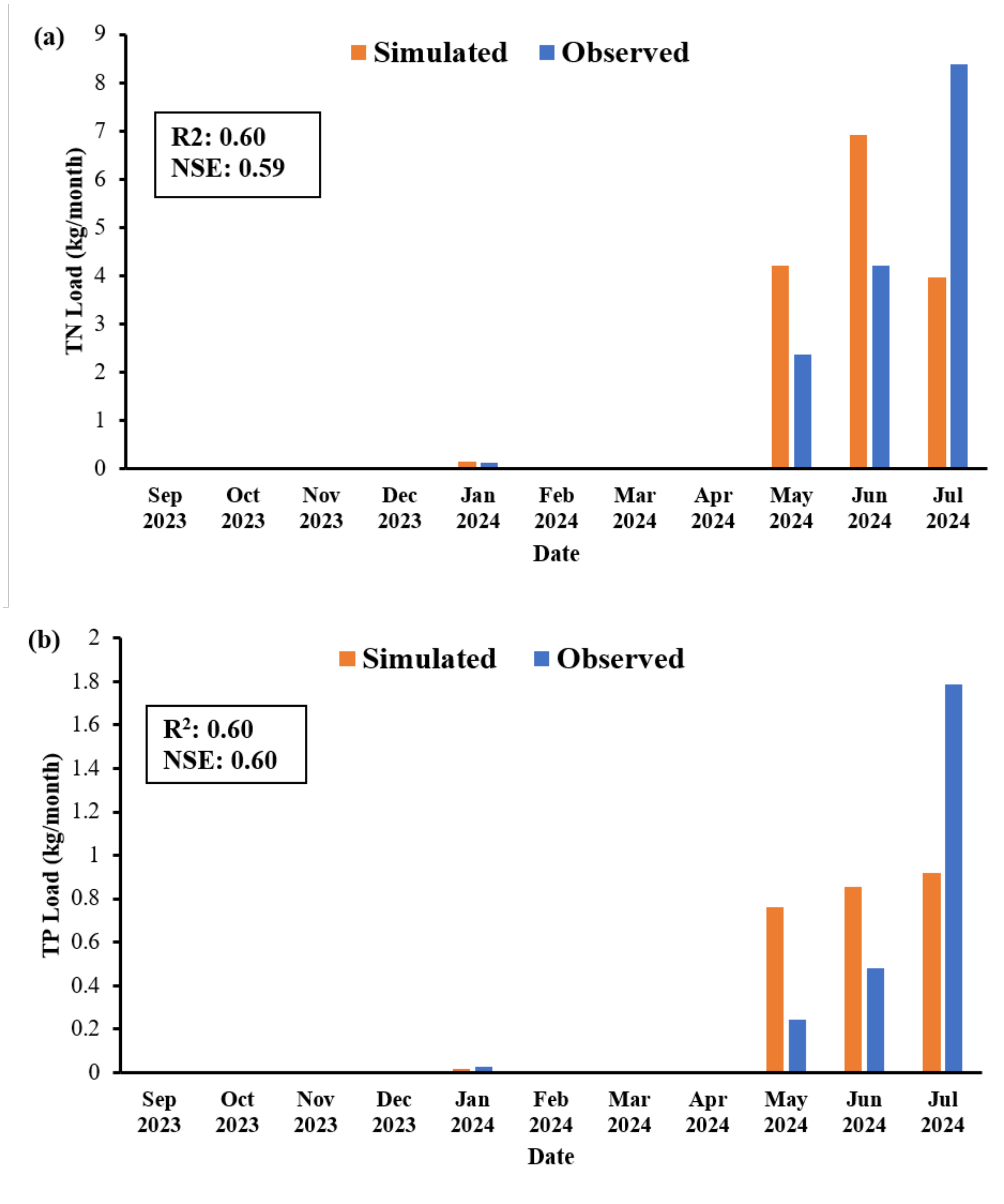

Figure S3. Modest agreement between simulated (SWAT+) and observed monthly loads of (a) TN and (b) TP into the wetland for the observation period. Observed loads were calculated based on monthly average observed concentrations and simulated monthly average flow rates. There are many months with zero or near-zero loads that are not visible on the graph.

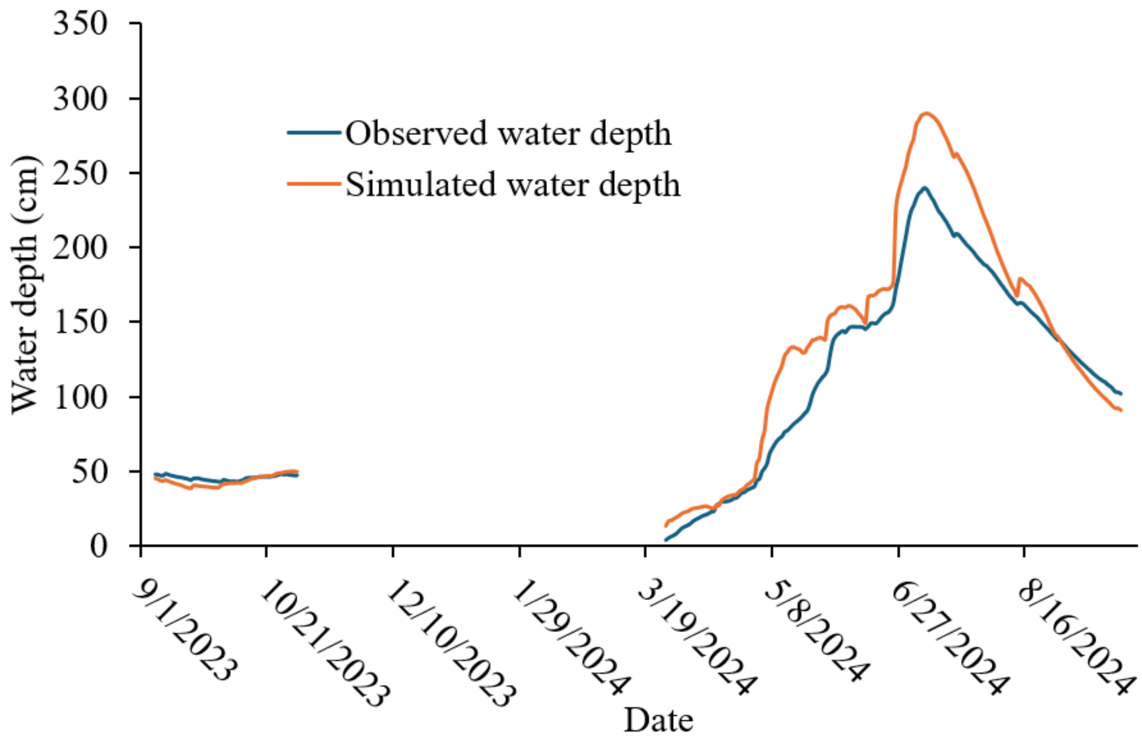

Figure S4. Modest agreement between modeled and observed wetland water depth over the calibration period. $R^2 = 0.96$, NSE = 0.86, PBIAS = 17.7%.

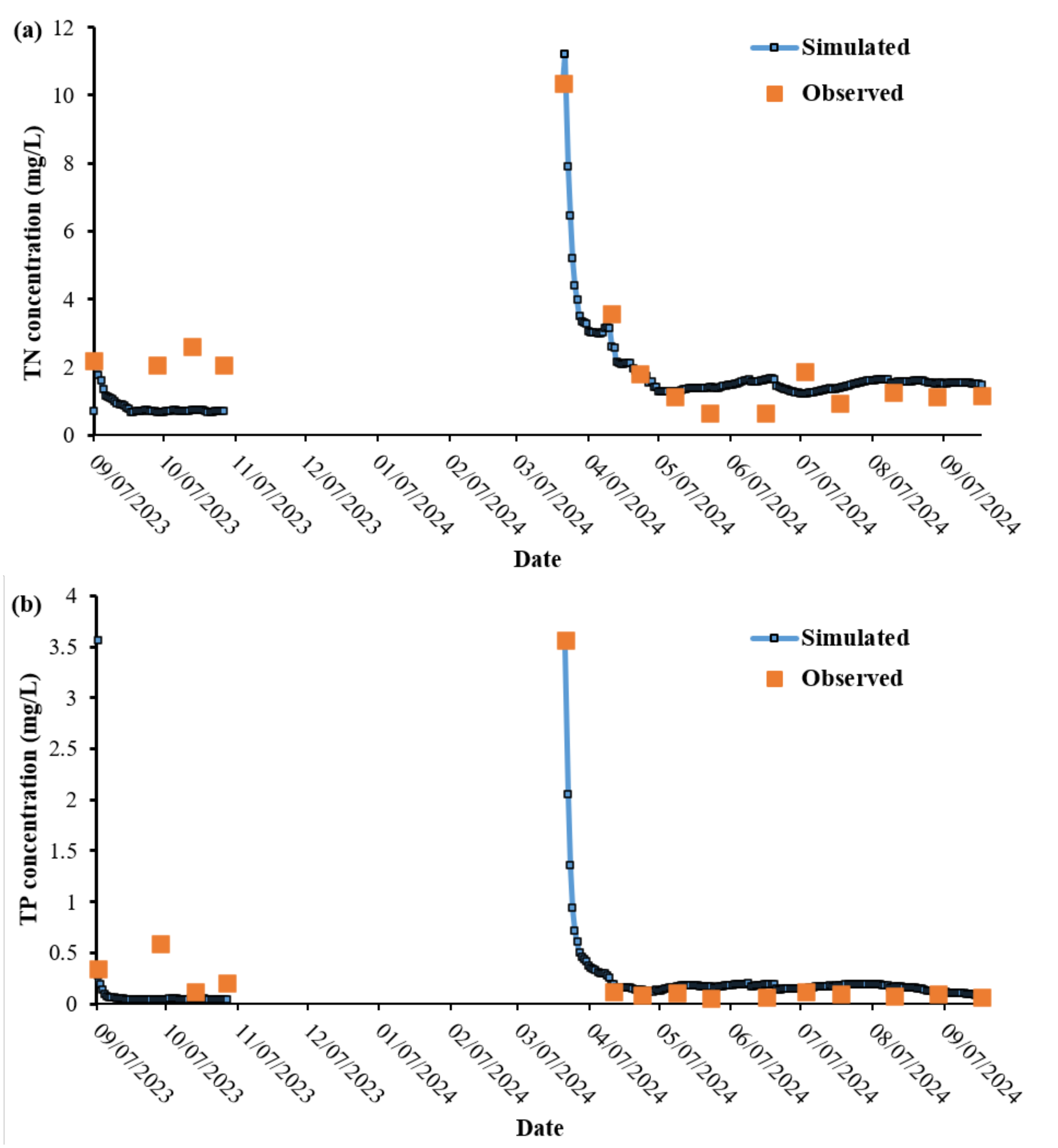

Figure S5. Comparison of observed and simulated TN (a) and TP (b) concentrations in the wetland from Sept. 2023 to Sept. 2024, showing good agreement for 2024.

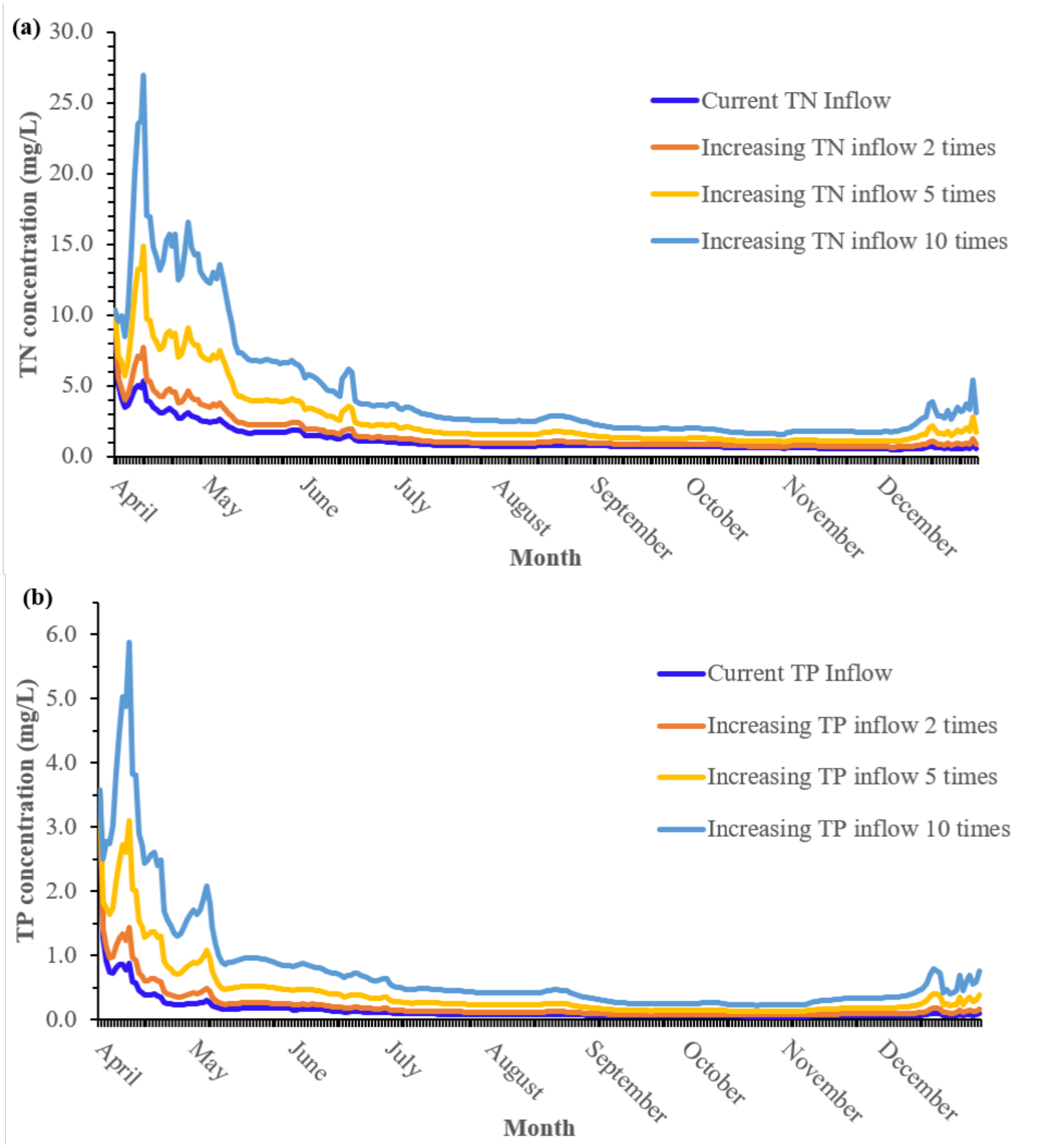

Figure S6. Average (a) TN and (b) TP concentrations in the wetland from 2013-2024 under scenarios with increased surface nutrient loading to the wetland.

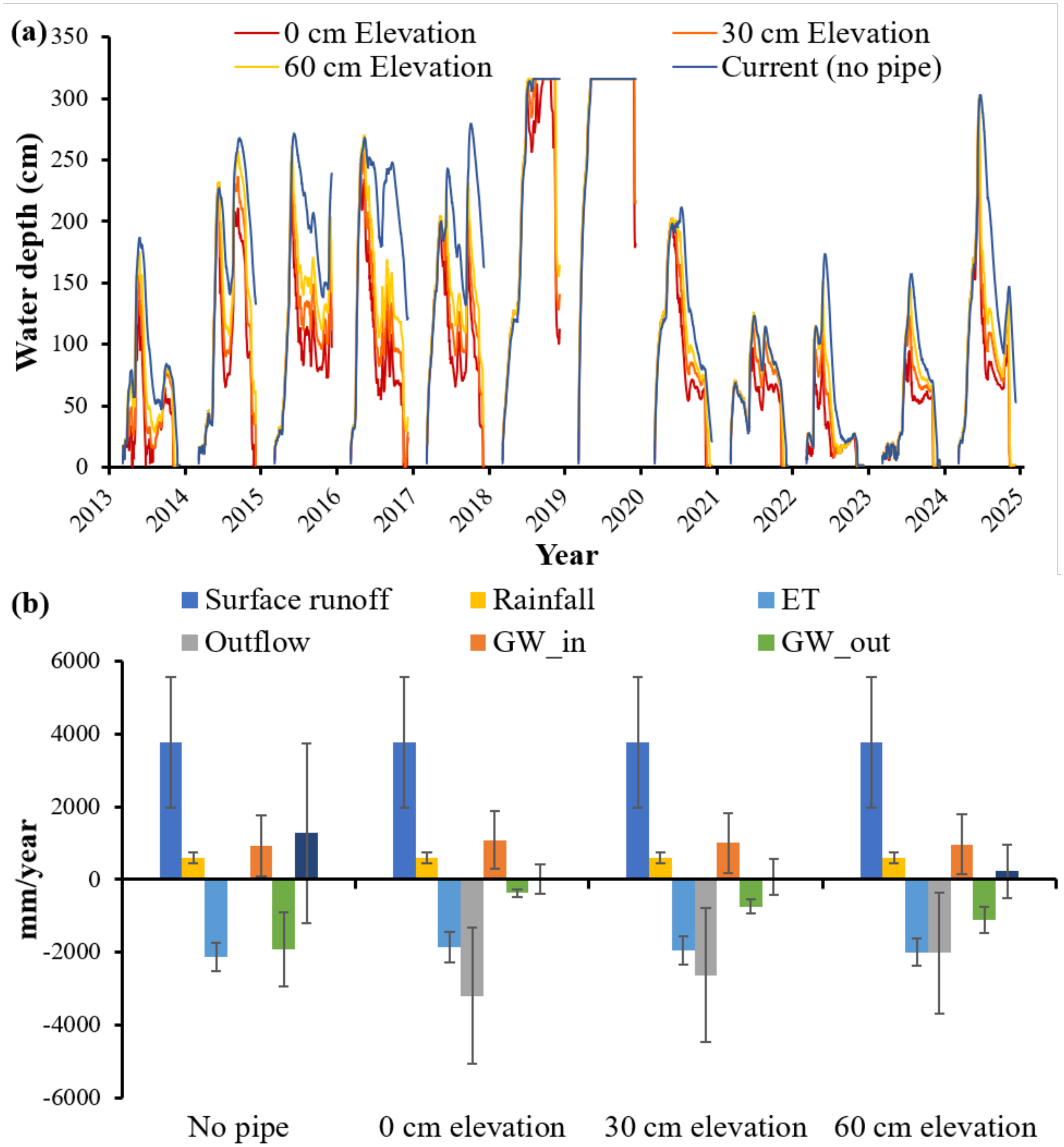

Figure S7. (a) Water depth under different scenarios of outflow, (b) Water balance components contribution in the wetland from 2013-2024 under different outlet culvert scenarios. ET = evapotranspiration, GW_in = groundwater in, GW_out = groundwater out.

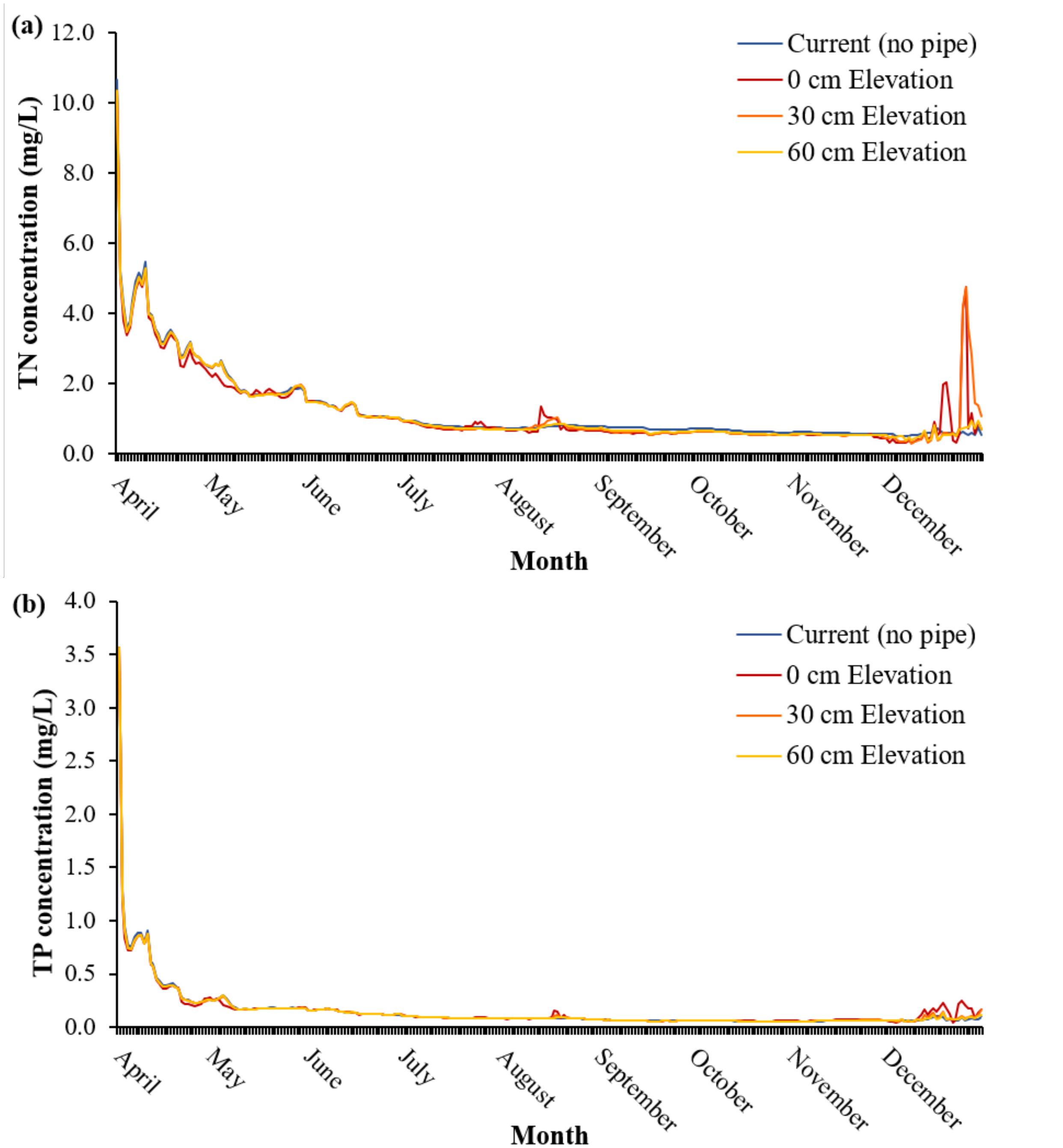

Figure S8. Outflow concentration of TN (a) and TP (b) for different outflow culvert scenarios.

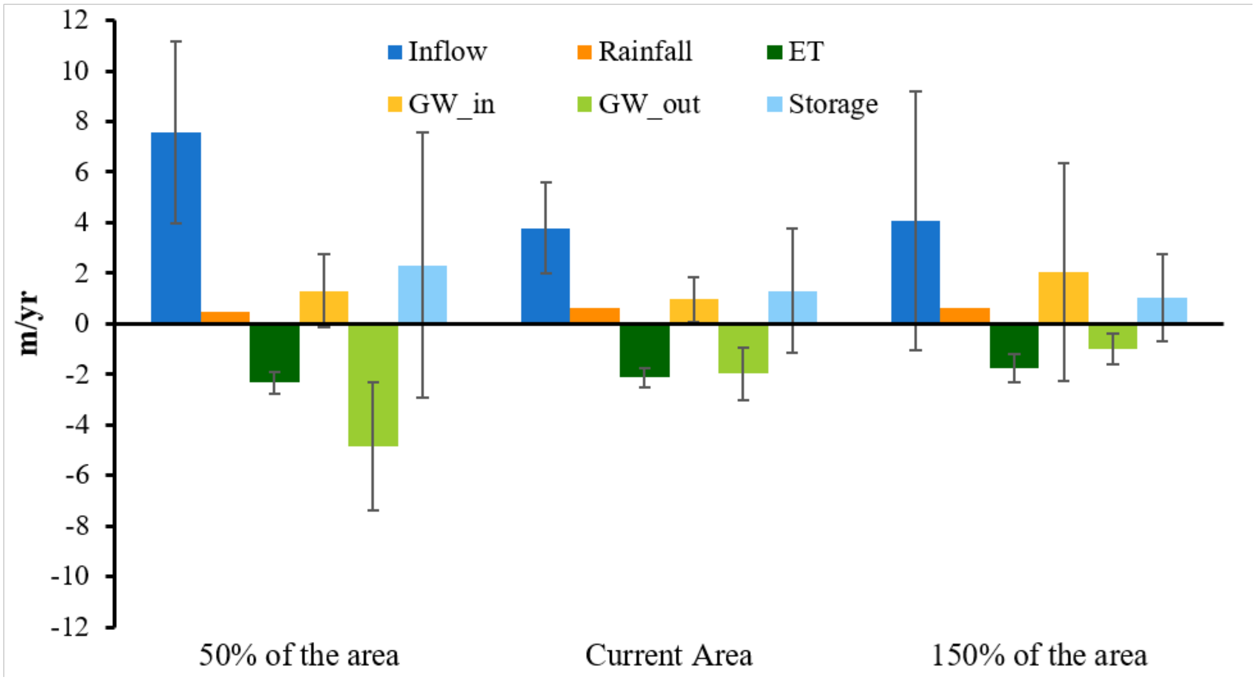

Figure S9. Water balance components in response to changing wetland size. Bars show means across all modeled years and error bars show standard deviations. ET = evapotranspiration, GW_in = groundwater in, GW_out = groundwater out.

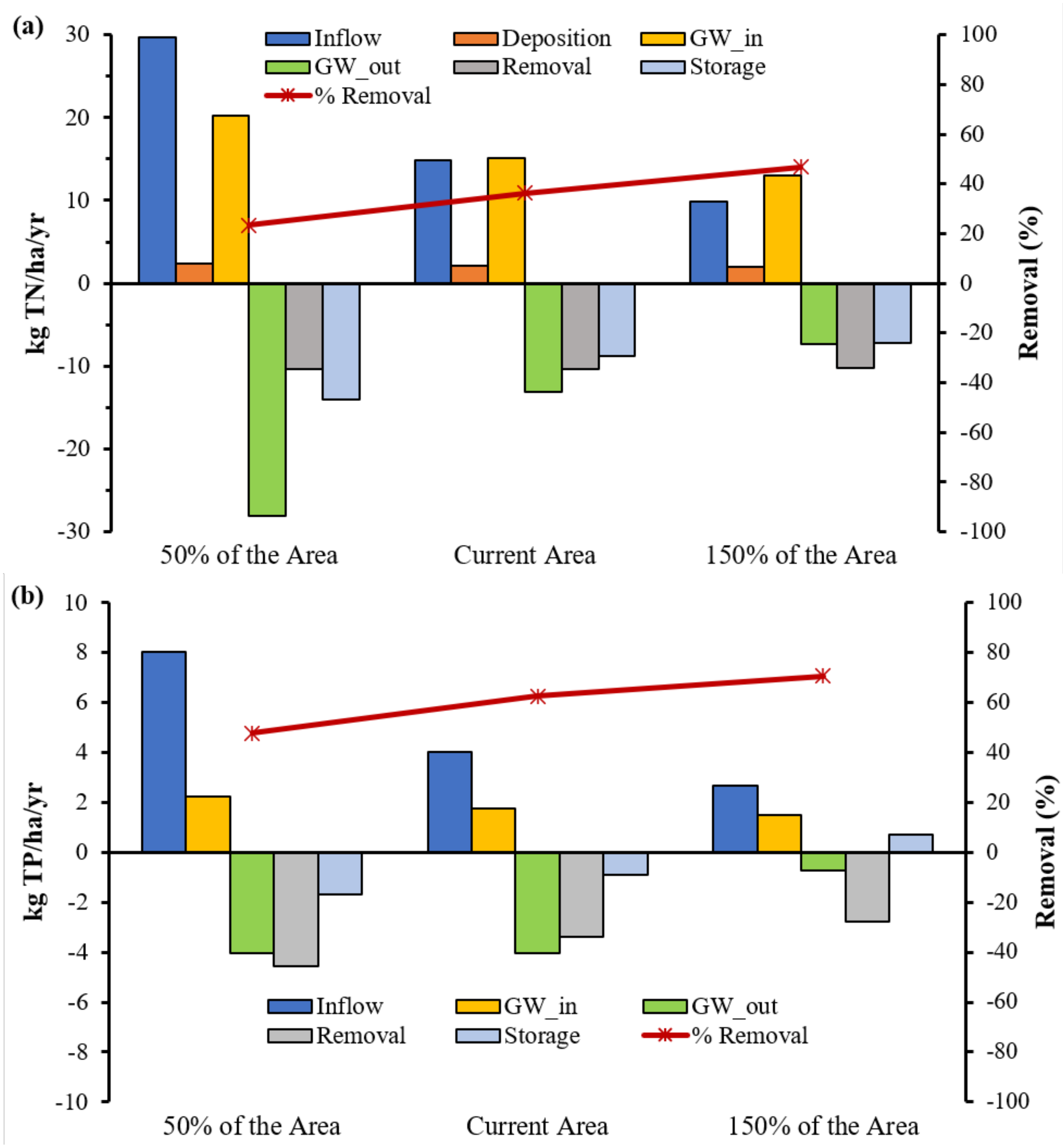

Figure S10. Comparison of simulated nutrient mass balance under different wetland areas for (a) TN and (b) TP. GW_in = groundwater in, GW_out = groundwater out.

Table S1 SWAT+ input data sources.

Data	**Source**
Terrain	Digital Elevation Model (DEM) downloaded from the Geospatial Data Gateway
Land use	National Land Cover Database (NLCD)
Soils	Soil Survey Geographic Database (SSURGO)
Climate	Data from 1955–1964 (National Centers for Environmental Information (NOAA) at the station NEBRASKA CITY 2 NW, NE US (ID: GHCND:USC00255810)). Data for 2012-2024: Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/request/daily.phtml?network=NE_ASOS)

Table S2 Calibrated SWAT+ hydrologic parameters.

Parameter	Unit	Definition	Group	Calibrated value (% change)
CN2	-	Runoff curve number	hru	3.0
Msk_x	-	Available water capacity of the soil layers	bsn	-10.18
ESCO	-	Soil evaporation compensation factor	hru	18.65
ALPHA	day^{-1}	Base flow recession constant	aqu	-21.751
SURLAG	hours	Surface runoff lag time	bsn	-38.550
EPCO	-	Plant water uptake compensation factor	hru	-40.0
Petco	-	Scaling coefficient for daily PET	hru	-0.486
Perco	-	Soil percolation coefficient	hru	39.250
Cn3-swf	-	Soil water fraction for CN3	hru	-24.894

Note: hru refers to HRUs, bsn refers to Basin, aqu refers to Aquifer.

Table S3 Calibrated SWAT+ nutrient parameters.

Parameter	Group	Calibrated value (% change)
N_updis	bsn	-100.00
P_updis	bsn	-65.735
cdn	bsn	-100.000
cmn	bsn	100.00
sdnco	bsn	-74.125
pperco	bsn	1.024
erorgn	hru	70.952
Erorgp	hru	0.52
Rs1	swq	-18.389
Rs2	swq	85.308
Disolvp	swq	100.00
Solp	res	246.998
Bc4	swq	100.00
Rs4	swq	-64.814
Organicn	swq	100.00
Organicp	swq	-10.973
Algae	swq	-95.554
N_dep_enr	rte	-100.00
N_seti	rte	6.130
N_sol_part	rte	-100.00
P_dep_enr	rte	83.638
P_seti	rte	8.532
P_sol_part	rte	-97.510
phoskd	bsn	-16.619
Psp	bsn	100.00
nperco	bsn	0.015

Note: rte refers to Routing, res refers to Reservoir, swq refers to SWQ, bsn refers to Basin.

Table S4 Physico-chemical water parameters in Wetland 1 (average of sampling locations a+b), monitoring period: 2023–2024. If a parameter was below the reporting limit, the value was set to half the reporting limit in order to calculate an average.

Date	pH	Temp. (C°)	DO (mg/L)	TN (mg/L)	NH_4^+ (mg/L)	NO_3+NO_2 (mg/L)	TKN (mg/L)	TP (mg/L)	PO_4 (mg/L)
9/6/2023	n/a	n/a	n/a	2.16	ND	ND	2.16	0.34	0.17
9/29/2023	n/a	n/a	n/a	2.04	ND	ND	2.04	0.59	0.19
10/19/2023	n/a	n/a	n/a	2.56	ND	ND	2.56	0.12	0.10
11/2/2023	n/a	n/a	n/a	2.02	ND	ND	2.02	0.20	0.04
3/27/2024	n/a	n/a	n/a	10.36	0.30	0.18	10.19	3.57	0.55
4/17/2024	n/a	n/a	n/a	3.56	ND	1.00	2.56	0.20	ND
4/29/2024	n/a	n/a	n/a	1.75	ND	ND	1.75	0.09	ND
5/14/2024	8.02	18.06	8.46	1.07	ND	ND	1.07	0.11	ND
5/29/2024	8.07	22.94	8.75	ND	ND	ND	ND	0.05	0.03
6/18/2024	7.52	25.95	4.63	ND	ND	ND	ND	0.07	ND
7/9/2024	8.10	28.39	8.18	1.81	ND	ND	1.81	0.12	0.06
7/24/2024	8.11	27.49	12.39	0.90	ND	ND	0.90	0.10	0.04
8/15/2024	8.16	25.77	7.25	1.21	ND	ND	1.21	0.08	0.06
9/4/2024	8.14	23.96	6.09	1.09	ND	ND	1.09	0.10	ND
9/24/2024	7.90	19.50	5.06	1.11	ND	ND	1.11	0.07	ND

Note: n/a refers to no data collected; ND refers to below the reporting limit; TKN = Total Kjeldahl N.

Table S5 Average water balance components for the baseline scenario (2013-2024).

Water balance components	Annual average	
	As a water depth (mm/year)	Percentage of flow components (%)
Surface runoff	3774.6	35
Groundwater in	928.2	9
Rainfall	603.0	6
Evapotranspiration	-2122.8	20
Groundwater out	-1911.5	18
Storage	1292.5	12

Table S6 Nutrient mass balance driven by different flow components to the wetland for the baseline scenario and for the increased surface nutrient loading scenarios. Mass loading rates and percent removals are given as mean ± sd for the entire modeled period.

	Baseline	2 times	5 times	10 times
TN Mass Balance (kg ha^{-1} year^{-1})				
Surface runoff	14.9±10.1	29.7±20.1	74.4±50.2	148.7±100.5
Deposition	2.2±0.9	2.2±0.9	2.2±0.9	2.2±0.9
Groundwater in	15.2±14.2	15.2±14.2	15.2±14.2	15.2±14.2
Groundwater out	13.1±7.8	17.9±10.9	31.4±21.7	53.7±39.9
Removal	10.4±6.2	17.3±9.6	38.8±21.9	75.0±43.4
Nutrients left	8.8±17.2	13.1±21.5	23.7±33.6	41.1±54.7
TN removal (%)	36.4±14.5	40.1±13.7	46.5±14.5	50.0±15.3
TP Mass Balance (kg ha^{-1} year^{-1})				
Surface runoff	4.0±1.4	8.0±2.8	20.1±6.9	40.2±13.8
Groundwater in	1.7±1.5	1.7±1.5	1.7±1.6	1.7±1.6
Groundwater out	1.5±0.8	2.3±1.3	4.7±2.7	8.8±5.2
Removal	3.4±1.1	5.9±1.5	13.4±3.4	26.0±6.7
Nutrients left	0.9±2.0	1.6±3.0	3.6±6.2	7.0±11.5
TP removal (%)	62.6±16.9	63.9±16.4	64.9±16.6	65.2±16.6

Table S7 Nutrient mass balance driven by different flow components for the baseline scenario (no pipe) and outlet culvert scenarios. Mass loading rates and percent removals are given as mean ± sd for the entire modeled period.

TN Mass Balance (kg ha^{-1} year^{-1})				
	No pipe	60 cm elevation	30 cm elevation	0 cm elevation
Surface runoff	14.9±10.1	14.9±10.1	14.9±10.1	14.9±10.1
Deposition	2.2±0.9	2.0±0.8	1.9±0.8	2.0±0.8
Outflow	--	12.9±11.6	17.5±13.9	22.3±14.6
Groundwater in	15.2±14.2	15.6±14.1	16.1±14.1	17.2±14.1
Groundwater out	13.1±7.8	7.4±3.8	4.8±2.3	2.0±1.1
Removal	10.4±6.2	9.8±5.9	9.5±5.7	9.1±5.8
Nutrients left	8.8±17.2	2.7±5.4	1.5±3.1	0.8±2.6
TN removal (%)	36.4±14.5	34.6±15.2	33.3±15.2	29.4±15.0
TP Mass Balance (kg ha^{-1} year^{-1})				
Surface runoff	4.0±1.4	4.0±1.4	4.0±1.4	4.0±1.4
Outflow	--	1.5±1.3	2.1±1.6	2.7±1.7
Groundwater in	1.7±1.5	1.8±1.5	1.9±1.5	2.0±1.5
Groundwater out	1.5±0.8	0.9±0.4	0.6±0.3	0.3±0.1
Removal	3.4±1.1	3.2±1.1	3.2±1.2	3.1±1.2
Nutrients left	0.9±2.0	0.2±0.7	0.1±0.4	0.02±0.3
TP removal (%)	62.6±16.9	59.3±17.2	57.1±17.6	53.3±17.5