Restored Wetlands in California's Central Valley Provide Nutrient Management and Waterfowl Habitat

Conservation Effects Assessment Project (CEAP) Conservation Insight

High levels of nutrients, including nitrogen and phosphorus, contribute to water quality concerns in California's Central Valley (CCV) and locations worldwide. While wetland restorations are often aimed at establishing waterfowl habitat, water management practices also influence nutrient capture and storage. The U.S. Department of Agriculture's Conservation Effects Assessment Project (CEAP) collaborated with California Polytechnic University, Humboldt and the San Joaquin River National Wildlife Refuge to monitor 21 restored wetland sites in the CCV. This was the first study in the region examining nutrient dynamics in a broad range of restored managed wetlands during drought and flooding periods. Findings highlight the potential for managing wetlands in the region to improve nutrient retention, as well as the complex nature of hydrological and nutrient dynamics in managed wetlands in the CCV.

Key Takeaways

- Wetland losses in California's Central Valley have led to reductions in multiple ecosystem services.
- Wetland restorations are often aimed at re-establishing waterfowl habitat. Seasonal flooding and water management practices that benefit wildlife can provide additional wetland ecosystem services, including nutrient removal.
- Hydrology and nutrient dynamics across wetlands varied, mainly due to differences in management practices and climatic conditions that affected access to limited water resources.
- The duration and timing of the presence of water affected nutrient concentrations at inflows and discharges in restored wetlands over the six-year monitoring period that included a range of climatic conditions, including exceptional drought, above-average flooding, and relatively stable water levels.
- Privately-managed wetlands retained water for longer periods, but at shallower depths than seasonal wetlands in National Wildlife Refuges managed by the U.S. Fish and Wildlife Service.
- Multivariate analysis indicated that, in addition to climate, location influenced nutrient concentrations largely due to water inflows from the Sacramento River versus agricultural water from the Colusa Basin Drain.
- Nutrient concentrations tended to increase in downstream serially connected wetland units in National Wildlife Refuges, likely a consequence of evapotranspiration as water moved through each upstream wetland.
- Restored wetlands tended to be a source of phosphorus but demonstrated consistent retention of ammonium and nitrate across all management types, locations, and time periods.
- In order to improve nutrient mitigation performance, vegetation management should include establishment of fast-growing emergent vegetation and when managed to create open water, biomass should be removed prior to flooding.

Wetland Losses Exacerbate Water Quality Issues

High levels of nitrogen (N) and phosphorus (P) contribute to water quality concerns in natural waterways and groundwater in California's Central Valley (CCV), as well as worldwide. Increased nutrient concentrations have been linked to toxic algal blooms and fish kills in the Sacramento-San Joaquin Delta and other water bodies (California Natural Resources Agency 2010). Despite increased use of advanced

Wetlands like this one located within the Sacramento National Wildlife Refuge provide habitat for ducks, geese, and other waterfowl. They also provide a suite of ecosystem services.
Photos by U.S. Fish and Wildlife Service

nutrient application technologies, a recent report from USDA's Conservation Effects Assessment Project shows that declines in subsurface incorporation of nutrients on cultivated cropland have resulted in N and P losses that continue to exceed thresholds (USDA 2022).

Loss of wetlands in the CCV has contributed to declines in multiple ecosystem services, including nutrient capture and storage, making wetland restoration a priority. Restoration is offered through NRCS's Agricultural Conservation Easement Program (ACEP), formerly the Wetland Reserve Program (WRP). While elevated nutrients in agricultural runoff continue to be a major issue, few studies have examined the contributions of restored wetlands to nutrient management in the region.

Freshwater wetlands once covered about 1.6 million hectares in the CCV but have been reduced to less than 8% of their original extent (Fredrickson and Taylor 1982; Garone 2011). Wetlands restored under federal programs such as the U.S. Fish and Wildlife Service's National Wildlife Refuge (NWR) System and the former USDA WRP, now ACEP, as well as through state, non-profit, and private landowners, have re-established many key functions. However, these wetlands are often managed for a few specific objectives rather than a broad suite. Adaptive management, including strategically sited restorations, can leverage multiple ecosystem benefits (Fisher and Acreman 2004), but it is unclear how current management regimes affect water quality outcomes. While wetlands receiving water from irrigated cropland can potentially contribute to improved water quality by retaining sediments and transforming nutrients, many of those restored in the CCV are managed with the primary goal of providing food and cover for wintering waterfowl (Harter et al. 2012; Goslee et al. 1997).

Hydrologic regime is a strong determinant of nutrient dynamics through its effects on sediment oxygen levels, redox potential (Jassby 2005; Johannesson 2008; Kadlec and Knight 1996), and vegetation communities (Kahara et al. 2012; Knobeloch et al. 2000). The nutrient retention characteristics of the moist soil regime implemented for wildlife habitat, however, is not currently well understood. Previous studies suggest an inverse relationship between moist soil management and nutrient reduction due to vegetation removal, substrate exposure during drawdowns, and inputs from waterfowl manure (Goslee et al. 1997; Kim et al. 2020).

This study sought to better understand nutrient retention potential by monitoring duration and timing of inundation, along with associated nutrient loads, in 21 wetlands in the CCV under various hydrological regimes and climate conditions. The objectives of this study (Kahara et al. 2022) were to:

- describe the principal drivers of hydrology in restored managed wetlands of the CCV; and
- quantify nutrient concentrations and loads received and discharged to determine whether current management practices provide water quality benefits.

Study Design

Monitoring of water depth and inputs and outputs of nutrient and sediment loads was conducted from 2015 to 2018 in 21 restored wetland sites in CCV, including four on private land, and 13 at the Colusa National Wildlife Refuge (CNWR) (Figure 1). The same four private wetlands and four additional wetlands in the San Joaquin River National Wildlife Refuge (SJRNWR) (Figure 1) were monitored from May 2019 to October 2020. The CCV experienced exceptional drought prior to and in the first year of the study (2011–2015), as well as extreme flooding in 2016 and 2017 followed by a period of relatively normal water conditions thereafter.

Wetlands in the SJRNWR and CNWR included serially connected units in which wetlands received water one after another sequentially. The hydrology of privately managed wetlands aligned best with seasonal irrigated wetlands of NWRs, including fall and winter flooding followed by spring drawdown and possible summer irrigation at two sites. Regimes at the four private wetlands and four SJRNWR wetlands included reverse cycle, permanent, and seasonal hydrologic management.

We collected empirical data from restored wetlands during the two time periods in order to explore relationships between wetland water quality and local climate. Since wetland inflows and outflows are manually controlled, we communicated closely with wetland managers to ensure surveys coincided with active flows.

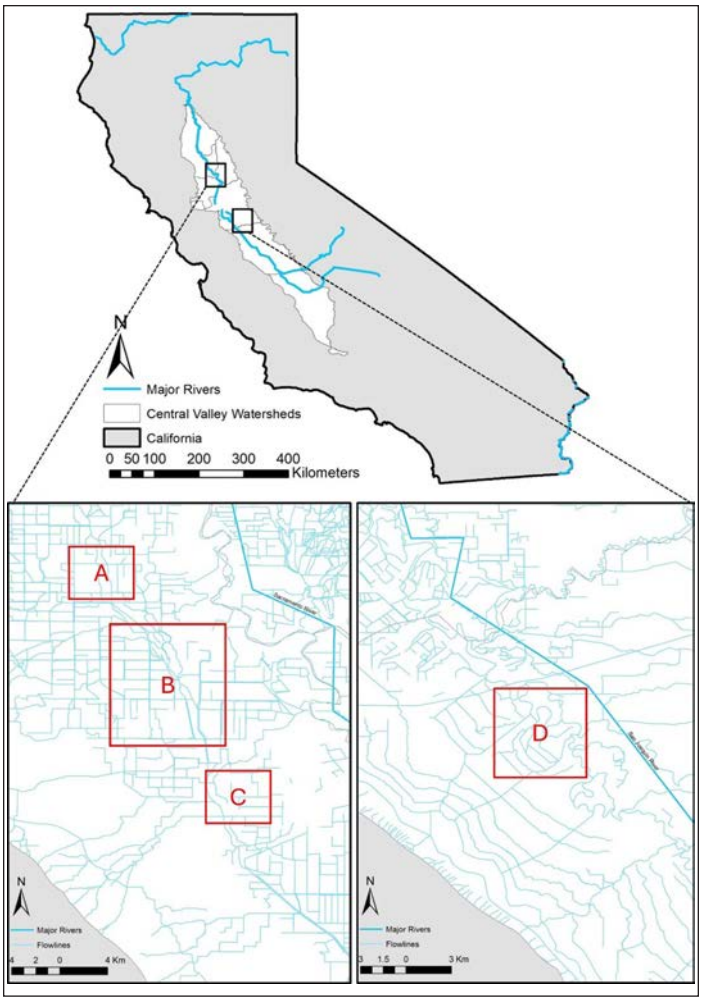

Figure 1. Locations of major rivers, water channels, and surveyed restored managed wetland sites in California's Central Valley. Lower left is the location of the Colusa NWR (B) and private sites (A,C). Lower right is the location of the San Joaquin River NWR (D) sites surveyed between 2015 and 2020.

CCV Wetland Hydrology: Historic versus Current

Prior to the 1800s, the majority of wetlands in the CCV were in riparian floodplains and received overland flows driven by spring snowmelt. Today, the majority of wetlands are artificially flooded and drained, with water coming from irrigation and drainage canals that service croplands. The quantity of water received by each wetland is dictated by the management objective and a complex combination of state legislation governing water rights. Water rights are legal entitlements that authorize landowners to divert water onto their property for beneficial uses, with permits stipulating the timing and volume of water that may vary with changes in water availability. Senior (pre-1914) water rights holders have more immediate access to water than junior (post-1914) water rights holders, particularly during drought. Wetlands that fall within a parcel with riparian water rights may appropriate those waters under certain conditions (California State Water Resources Control Board 2022). State-legislated water curtailments are more likely during drought. For example, in 2014, following four years of below average precipitation, California saw reduced water allocations for agriculture and wetland management. Further reductions in wetland irrigation were implemented over summer 2015 when NWRs received only 75% of their typical water allocations, with private land managers receiving as little as 50 or even 0%.

Management goals also play an important role in determining flood frequency, depth, and duration. Studies have found that wetlands managed intensively for wintering waterfowl are more frequently flooded and for longer periods of time than unmanaged wetlands (Goslee et al. 1997). Long-term records obtained from NWRs indicate five categories of inundation frequency: (1) permanent, (2) semi-permanent, (3) irrigated seasonal, (4) unirrigated seasonal, and (5) reverse cycle. Reverse cycle wetlands are flooded over the summer months and drawn down in the fall and winter. These only occurred in the San Joaquin Basin. Permanent wetlands are inundated year-round, and semi-permanent wetlands are inundated from fall through summer, with a short drawdown period from August through September to facilitate vegetation management. Seasonal wetlands are flooded in the fall and drawn down in the spring to germinate seed-producing wetland plants. Although some may be unirrigated for a variety of reasons, irrigated seasonal wetlands receive a brief pulse of shallow water in the mid-summer months to bring seed-producing plants to maturity.

Restored Wetland Hydrology and Management

Data collected, including flow volumes and water quality, allowed for exploration of relationships among wetland water management, water quality, and local climate. Previous studies found high variability in flood management among privately managed wetlands, with some wetlands left unflooded in drier years (Goslee et al. 1997). With the exception of the fall/winter flooding period, temporal trends at privately-managed wetlands exhibited greater variability in water depth, duration, and timing than those at CNWR (Figure 2 A–D). Average depths on privately managed wetlands were similar to seasonal wetlands on both CNWR and SJRWR (Table 1), but they were drawn down less frequently than the seasonal wetlands on CNWR, where sediments were often exposed in the spring and early summer (Figure 2).

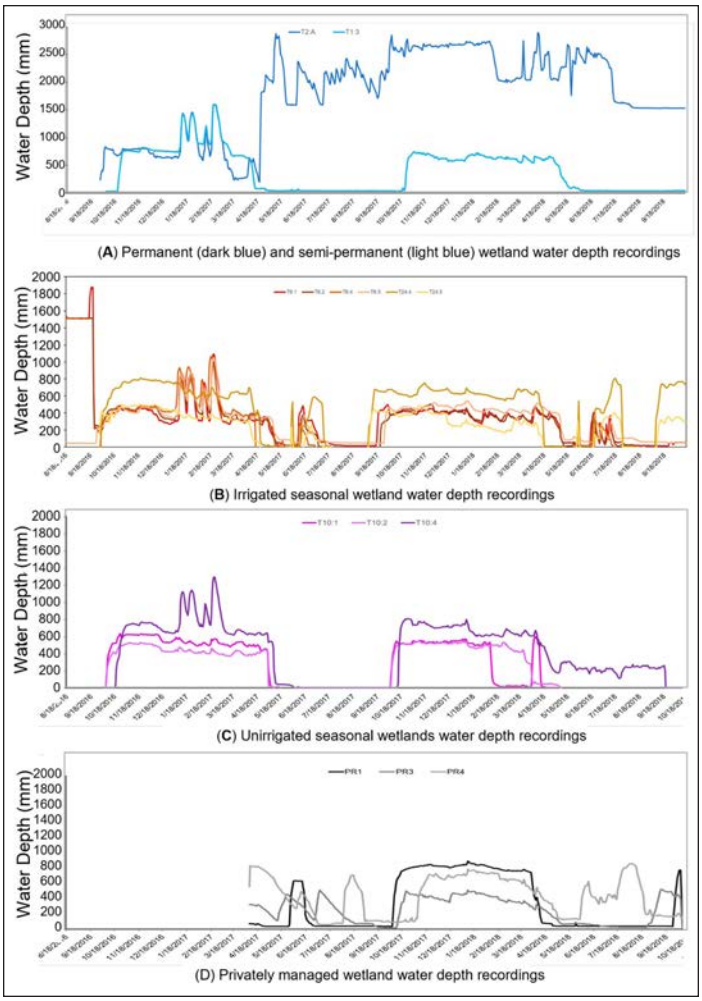

Figure 2. Managed wetland hydrographs representing two principal hydrological management categories—(A) permanent, semi-permanent; (B) irrigated seasonal; (C) unirrigated seasonal; and (D) privately managed wetlands. Wetlands that were monitored for less than one year are not shown.

Vegetation composition differed among wetland types, with permanent and semi-permanent wetlands exhibiting larger proportions of tall emergent perennial plants such as hardstem bulrush (*Scheonoplectus acutus*) and cattails (*Typha spp.*), while irrigated and unirrigated seasonal wetlands were dominated by a mix of shorter annuals such as watergrass (*Echinochloa crusgalli*), smartweeds (*Polygonum spp.*), and grasses (*Crypsis spp.*), along with perennials such as alkali bulrush (*Bolboschoenus maritimus*) and joint grass (*Paspalum distichum*). Vegetation control treatments such as mowing, disking, herbicide application, or burning are often applied annually in irrigated and unirrigated seasonal wetlands and are applied periodically in semi-permanent and permanent wetlands. Management of vegetation may have consequences for evapotranspiration, nutrient uptake, and soil characteristics such as organic matter content, water holding capacity, and porosity.

Water Quality Improvement and Wildlife Habitat

Unlike constructed wetlands that are designed to receive a consistent flow of nutrient rich water, restored wetlands in the CCV experience hydrological interruptions that are both intentional

and unintentional. This study supports previous conclusions regarding the potential for restored wetlands to improve water quality, but nutrient removal performance in the region varied due to seasonal factors (California Department of Water Resources 2015) including loading rates, substrate exposure to oxygen in the spring, or vegetation mowing in the late summer. Differences were also observed in nutrient inflow concentrations related to location and source water, with wetlands in the San Joaquin Basin generally receiving higher concentrations of total and nitrate N than those in the Sacramento Basin (Figure 3), as was observed in previous assessments (Mitsch and Gosselink 2015). Comparison by hydrological management type based on loading rates indicates that, while seasonal irrigated and semi-permanent wetlands act as sources of total nitrogen (TN) and phosphorus (P), permanent wetlands in the Sacramento Basin reduced TN loads more than sevenfold and P almost fourfold (Table 2).

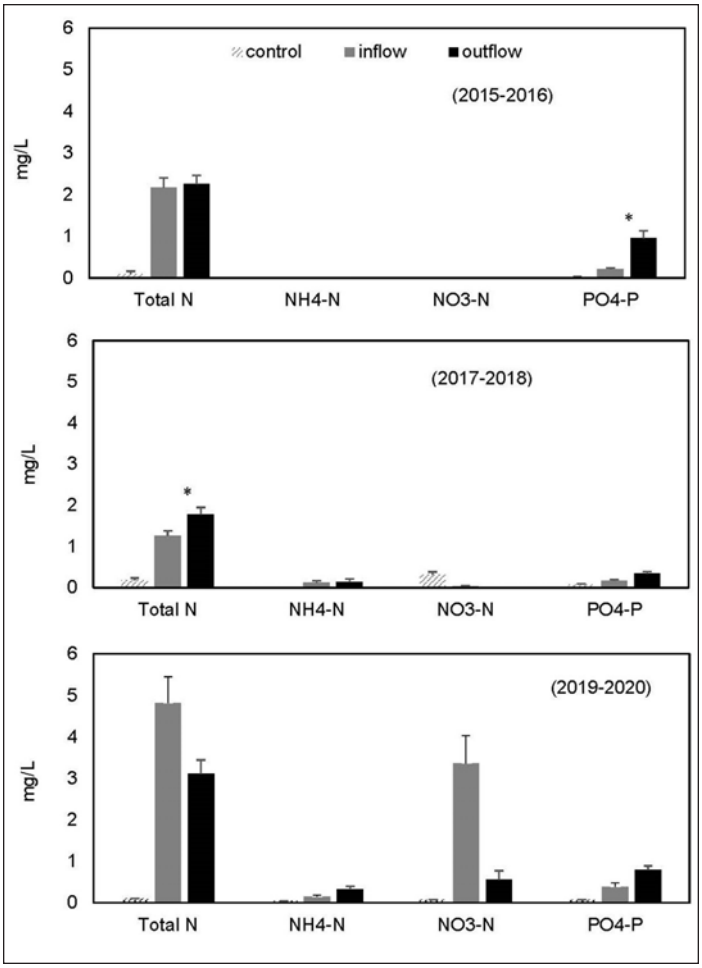

Figure 3. Mean (±S.E.) concentrations of N (total nitrogen [TN], ammonium-nitrogen [NH_4-N], and nitrate-nitrogen [NO_3-N]) and P (soluble phosphates [PO_4-P]) measured at inflows and outflows at 4 managed wetlands on private lands and 13 at the Colusa National Wildlife Refuge during exceptional drought (2015–2016), and above average water conditions (2017–2018). Controls were unopened 500 mL bottles of drinking water. Significant differences (p<0.05) are denoted with an asterisk. In 2019–2020, mean (±S.E.) concentrations were measured at inflows and outflows at the same 4 wetlands on private lands and at 4 wetlands in the San Joaquin River National Wildlife Refuge, also a period of average water conditions.

A review of empirical evidence of nutrient removal by constructed and restored wetlands in agricultural settings in the CCV and elsewhere in the world has demonstrated their effectiveness (O'geen et al. 2010; Madurapperuma et al. 2013). Results from this study indicated that managed wetlands in this area reduced ammonium- and nitrate-N loads but increased TN and phosphate (PO_4) loads slightly at their outflows (Figure 4). Permanent wetlands in the SJNWR did not reduce loads of TN but did for P loads. Removal efficiencies in this study varied by year rather than by wetland type or loading, with wetlands surveyed receiving higher loads of TN in 2015 than in 2018. Removal of up to 30% of N by vegetation has been reported under low loading rates, but uptake declined significantly under higher loads (Cronk and Fennessy 2001).

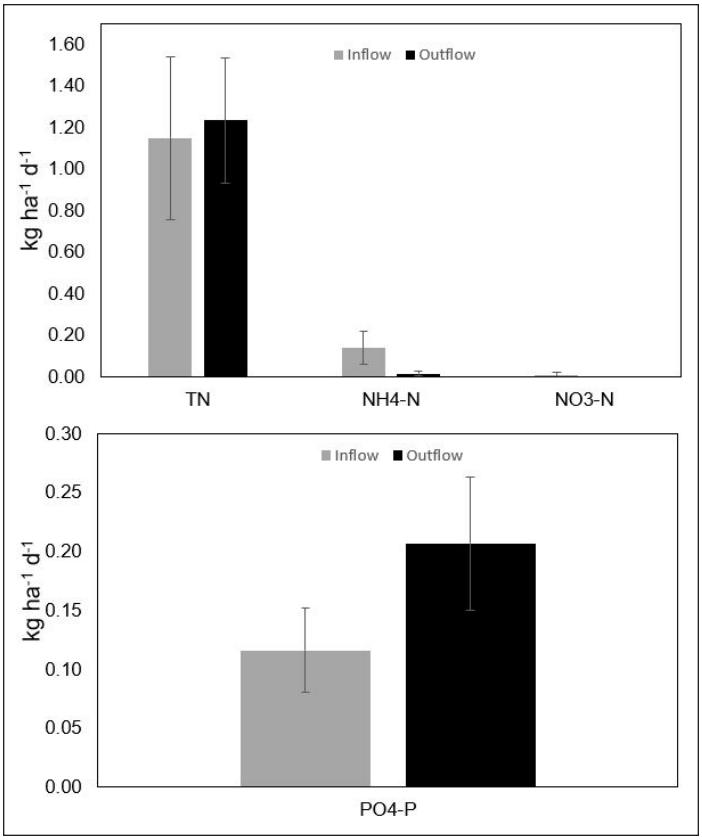

Figure 4. Estimated nutrient yields (mean kg/ha/day+-SE) at the inflows and outflows of managed (seasonal irrigated and semi-permanent) wetlands in the Sacramento Basin in California's Central Valley between 2015 and 2018.

Wetlands surveyed in this study also received higher nutrient loads than is typically recorded in natural waterways of the region. Long-term records collected from multiple stream gauges in the CCV estimate median TN concentrations of 0.31 mg L^{-1} and median total P at 77 µg L^{-1} (Heidel et al. 2006). The mean TN concentrations at the inflow ranged from 1.5–2.6 mg L^{-1}, while inflowing PO_4 ranged between 100 and 270 µg L^{-1}. Interestingly, median concentrations were greater in 2019 than 2020, and further analysis is needed to compare nutrient concentrations in streams to that in irrigation and drainage canals in periods of low flow, such as drought, versus periods of higher flow. One surprising observation in this study resulted from the serial arrangement of wetlands in NWRs. While serial arrangement is a fairly common practice in wastewater treatment systems that typically improves nutrient removal, nutrient concentrations increased in wetlands along the series in

this study, most likely due to evapotranspiration as the water moved through the chain.

While additional research is needed to evaluate the full impact of nutrient loads entering and exiting CCV wetlands, high concentrations are known to have negative effects on sensitive species. For North American amphibians, lethal and sub-lethal effects of nitrates have been detected in the laboratory at concentrations ranging between 2.5–100 mg L^{-1} (Rouse et al. 1999). During this study, nitrate concentrations were detected in excess of 14 mg L^{-1}, mainly at inflows from agricultural canals. Despite increasing concentrations in some management scenarios, long-term biological benefits from the overall reduction in ammonium and nitrate loads to natural waterways and canals should improve habitat for species sensitive to water quality such as fish and amphibians.

Implications for Conservation

Since 1972, the government and industry have expended more than $1 trillion on water pollution abatement in the United States, outstripping expenditures on wetland restoration and other environmental initiatives (Keiser and Shapiro 2019), but water quality improvement goals remain elusive. Increasing ecosystem services through design and management of restored wetlands could provide a broader suite of functions and contribute to making the most out of existing investments in conservation. Improvements in water quality provide economic benefits that include reduced costs of drinking water treatment, public health benefits, and increased recreation spending. As of 2015, USDA alone had spent over $4 billion restoring wetlands nationwide, with upfront restoration costs ranging from a few dollars per acre to more than $3,000/acre depending on location (Hansen et al. 2015).

In California, the consequences of limited water deliveries due to extended droughts and the associated high nutrient loads may be bottlenecks to effective water quality services of wetlands. Between 2011 and 2015, the CCV endured extreme drought conditions, leading to the declaration of a Drought State of Emergency that saw reduced water allocations for agriculture and wetland management. To compensate for dwindling surface water supplies, groundwater extraction increased substantially (Tomscha et al. 2021). Drought conditions eased in the winter of 2015–2016 and precipitation and snowpack levels in northern California were well above average by early 2017, leading to widespread flooding, but these conditions were temporary as the state descended into another severe drought. As the frequency of drought and heatwaves in the region increase (Shi et al. 2021), the number of flooding and irrigation days is expected to decline.

With decreased water availability, the role of hydrology in mediating nutrient removal dynamics must be considered. Plant uptake may also be a significant factor, depending on inflow loads, species, growth rate, and plant age. However, vegetation management for wintering waterfowl include practices that may not align with traditional water treatment goals, including the practice of vegetation removal from seasonal wetlands to create open water areas for waterfowl, typically in late summer. Plants removed prior to plant senescence may limit nutrient removal capacity and, typically, harvested plant material is not removed from the wetland prior to fall flooding, thereby recycling nutrients back into the system rather than eliminating them.

Establishment of fast-growing emergent species at key locations in the wetland, such as outflows and along sloughs, could improve uptake (Vymazal 2007). Emergent plants of the genera *Typha*, *Cyperus*, *Scirpus*, *Juncus*, and *Sagittaria* with relatively fast growth rates and large below-ground biomass are used in constructed wetlands to extract nutrients from pore water and increase nutrient retention (Niswander and Mitsch 1995; Vymazal 2011). These species comprised only about 33% of the area of seasonal wetlands in this study and even less in permanent wetlands. Previous studies found that wetland plants can remove upwards of 4% of N and P but may release P after long periods of inundation. Delayed mowing and removal of harvested biomass could progressively reduce internal nutrient loads in restored wetlands.

Conclusions

This was the first study in the CCV region examining nutrient dynamics in a broad range of restored managed wetlands during drought and flooding periods and highlights the potential for lowering nutrient loads, as well as the complex nature of hydrological and nutrient dynamics in managed wetlands there. Hydrology has changed substantially in the CCV over the last 170 years, with shifting emphasis on artificial or manual water application driven by site-specific management objectives. Wetlands experience frequent water shortages due to drought as well as legislative and management decisions limiting water deliveries when snowpack and reservoir volumes are low.

Differences in source water quality may be the result of agricultural runoff from adjacent croplands flowing into the shared network of irrigation and drainage canals. Increased evapotranspiration with rising temperatures and reduced water availability due to drought may cause nutrient concentrations to increase, particularly in serially connected wetlands where water is held for some period of time. Implementation of vegetation buffers at inflows should be explored as ways to limit inflowing nutrients, with an emphasis on wetland restoration opportunities and collaborations with private landowners. With adequate access to water supplies and technical guidance for hydrological management, wetland restorations can yield multiple ecosystem service benefits.

Sandhill cranes winter in California and other southern states. Findings from this study may support land managers and conservationists in continuing to support the wildlife habitat benefits of wetlands while also capturing and storing nutrients to improve water quality.
Photo By: U.S. Fish and Wildlife Service

Table 1. Mean logged depth and proportion of recordings at <120mm deep, which was considered a state of draw-down. Values are empirically measured, continuously logged water depths in managed wetlands in Colusa and Stanislaus counties, California USA.

Site	Management	Continuous Water Depth Measurements (Days)	Average Logged Depth (mm)	Proportion of Recordings <120 mm (%)
T2A	Permanent	747	1791.8	0%
T1:3	Semi-permanent	735	1749.8	40%
T6:1	Irrigated seasonal	789	330.8	0.3%
T6:2	Irrigated seasonal	782	310.0	25%
T6:3	Irrigated seasonal	778	793.8	17%
T6:4	Irrigated seasonal	482	312.7	32%
T10:1	Unirrigated seasonal	639	277.5	35%
T10:2	Unirrigated seasonal	651	268.5	34%
T10:3	Unirrigated seasonal	602	313.6	40%
T10:4	Unirrigated seasonal	740	423.0	23%
T24:3	Irrigated seasonal	n/a	n/a	n/a
T24:4	Irrigated seasonal	739	443.48	22%
T24:5	Irrigated seasonal	749	221.04	29%
PR2	Unirrigated seasonal	107	15.22	–
PR1	Unirrigated seasonal	557	312.23	0%
PR4	Unirrigated seasonal	904	465.76	0%
PR3	Unirrigated seasonal	577	334.97	0%
SJ14 (Upper White Lake)	Reverse cycle	108	601.1	0%
SJ16 (White Lake)	Permanent	108	952.56	0%
SJ19 (North Vierra)	Seasonal	108	187.35	0%

Table 2. Mean daily yield (kg ha^{-1} d^{-1}) of nutrients measured at managed wetlands under different hydrological management regimes in the Sacramento and San Joaquin Basins of California's Central Valley between 2015 and 2018.

	Mean Daily Yield (kg ha^{-1} d^{-1})							
	TN		NH_4-N*		NO_3-N*		PO_4-P	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Sacramento								
Permanent	16.984	2.321	0.000	7×10^{-6}	0.000	2×10^{-4}	7.069	1.926
Seasonal Irrigated	0.128	0.582	0.003	4×10^{-4}	3×10^{-4}	0.000	0.018	0.079
Semi-permanent	0.004	0.519	0.000	7×10^{-6}	0.000	0.000	0.003	0.352
San Joaquin								
Permanent	0.006	0.009					9×10^{-6}	0.000

*Measurements from 2017–2018 only

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Conservation Effects Assessment Project: Translating Science into Practice

The Conservation Effects Assessment Project (CEAP) is a multi-agency effort led by USDA's Natural Resources Conservation Service (NRCS) to build the science base for conservation. Project findings help guide USDA conservation policy and program development and support farmers and ranchers in making informed conservation choices.

One of CEAP's objectives is to quantify the environmental benefits of conservation practices for reporting at the national and regional levels. CEAP Wetland Assessments complement National Assessments for cropland, wildlife, and grazing lands to support conservation actions on a variety of landscapes.

This project was conducted through a collaborative effort by CEAP and Humboldt State University (now California State Polytechnic University, Humboldt). Primary authors of this Conservation Insight were Drs. Sharon Kahara, current of the University of New Haven and Joseph Prenger, CEAP Wetland Assessment Leader with NRCS.

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For more information, visit www.nrcs.usda.gov/ceap or contact Joe at Joseph.Prenger@usda.gov.