Articles

Waterbird Habitat in California’s Central Valley Basins Under Climate, Urbanization, and Water Management Scenarios

Elliott L. Matchett,* Joseph P. Fleskes

E.L. Matchett, J.P. Fleskes
U.S. Geological Survey - Western Ecological Research Center, 800 Business Park Drive, Suite D, Dixon, California 95620

Abstract

California’s Central Valley provides critical, but threatened habitat and food resources for migrating and wintering waterfowl, shorebirds, and other waterbirds. To assist in conservation planning, the Central Valley Joint Venture identified nine basins in the Valley. The basins vary in composition and extent of habitats, which primarily include croplands and wetlands that rely on water supplies shared with other competing human and environmental uses. Changes in climate, urban development, and water supply management are uncertain and could reduce future availability of water supplies supporting waterbird habitats and limit effectiveness of wetland restoration planned by the Central Valley Joint Venture to support wintering waterbirds. We modeled 17 plausible scenarios including combinations of 3 climate projections, 3 urbanization rates, and 5 water-supply management options to promote agricultural and urban water uses, with and without wetland restoration. Our research examines the reduction in quantity and quality of habitats during the autumn migration–wintering period by basin under each scenario, and the efficacy of planned wetland restoration to compensate for reductions in flooded areas of wetland habitats. Scenario combinations of projected climate, urbanization, and water-supply management options reduced availability of flooded cropland and wetland habitats during autumn–winter and degraded the quality of seasonal wetlands (i.e., summer irrigation for improved forage production), though the extent and frequency of impacts varied by basin. Planned wetland restoration may substantially compensate for scenario-related effects on wetland habitats in each basin. However, results indicate that Colusa, Butte, Sutter, San Joaquin, and Tulare basins may require additional conservation to support summer irrigation of seasonal wetlands and winter flooding of cropland habitats. Still further conservation may be required to provide sufficient areas of flooded seasonal and semipermanent wetlands in San Joaquin and Tulare basins during autumn–winter. The main objective of this research was to provide decision support for achieving waterbird conservation goals in the valley and to inform Central Valley Joint Venture’s regional conservation planning.

Keywords: climate change; urbanization; waterbirds; water management; wetland restoration

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* Corresponding author: ematchett@usgs.gov
Introduction

Despite the loss of >90% of its historical wetlands, the Central Valley of California is one of the most important wintering regions for waterfowl (i.e., ducks, geese, and swans), shorebirds, and other waterbirds in North America (Figure 1; Gilmer et al. 1982; Shuford et al. 1998; Hickey et al. 2003; Fleskes 2012; Shuford 2014). Central Valley wetlands, rice and corn agriculture, as well as a variety of crops that are flooded after harvest in the Tulare Lake bed of the Tulare Basin, provide critical habitat where waterbirds can feed and rest before the next breeding season. Managed inundation of seasonally flooded (i.e., seasonal) wetlands and cropland habitats provides important plant and invertebrate foods for waterbirds during the wintering period (CVJV 2006; Fleskes 2012; Fleskes et al. 2012, 2013). Rice fields, which replaced most historical wetlands in the Sacramento Valley (Colusa, Butte, Sutter, American, and Yolo basins; Figure 1), provide important waterbird habitat, especially when flooded after harvest (CVJV 2006). For waterfowl (and likely other waterbirds as well), an increase in area of managed habitat (particularly winter-flooded croplands and wetlands) is linked to improved body condition in the valley (Fleskes et al. 2016), which in turn can influence population demographics (Conroy et al. 1989; Fleskes et al. 2002; Morrison et al. 2007; Devries et al. 2008; Warren et al. 2014).

The availability of water for wetland management and postharvest flooding of certain crops in the valley may be limited by competition from urban and other agricultural users, instream flow requirements for fish, and drought. Scarcity of water can result in fallowing of agricultural lands that would otherwise have been planted in rice and other crop habitats, restrict summer irrigations of wetlands to limit seed production, reduce winter flooding of seasonal wetlands and harvested cropland habitat, and limit flooding of semipermanent wetlands (Gilmer et al. 1982; Petrie et al. 2016). A mismatch in amount and timing of wintering waterbird food supplies and requirements resulting in a food energy deficit would likely compromise body condition, survival, and reproduction of waterbirds (Conroy et al. 1989; Raveling and Heitmeyer 1989; Fleskes et al. 2016). Effects of water scarcity on habitats and food resources of wintering waterbirds may vary substantially by basin depending on regional sources of water supplies and dominant habitat types.

Croplands and wetlands in the Central Valley vary in reliability, quality, and function as habitat for waterbirds. Socio-economic factors, such as high water prices, can lead to cropping practices that diminish the area or quality of agricultural fields as waterbird habitat (CVJV 2006; Petrie et al. 2016). Additionally, high property value near metropolitan areas can lead to urban conversion of cropland habitats. By contrast, most wetlands are protected by government policies and conservation easements (CVJV 2006; Environmental Law Institute 2008; Zollitsch and Christie 2015). Compared with rice, seasonal wetlands provide more diverse and abundant food resources (approximately 50% more food energy) per hectare for waterfowl and potentially other herbivorous waterbird species in the Central Valley (CVJV 2006). Moreover, many seasonal wetlands are irrigated in summer; this practice greatly improves production of seeds by wetland plants (Naylor 2002; Brown 2013), which are made available to foraging waterfowl and other waterbirds by flooding during August–March (i.e., “winter flooding”). Thus, as available foraging habitat, seasonal wetlands presumably are more reliable and higher quality than winter-flooded rice. Wetlands that retain water throughout most or all months (i.e., semipermanent or permanent; hereafter, “semipermanent”) provide waterfowl roosting habitat, and foraging and nesting habitat for some waterfowl and other waterbirds (CVJV 2006; Shuford and Dybala 2017).

As a consequence of its value to waterbirds and challenges facing waterbird conservation, the Central Valley is the focus of major continental and regional initiatives and programs (Hickey et al. 2003; NAWMP 2004, 2012; CVJV 2006; Shuford 2014). Consequently, conservation partners, lead primarily by the Central Valley Joint Venture (CVJV), have developed plans to restore seasonal wetlands across the Central Valley. The CVJV is 1 of 22 Migratory Bird Joint Ventures representing most of the United States, Canada, and Mexico, and function as cooperative, regional partnerships of public and private organizations focused on conserving habitat for birds. Each Migratory Bird Joint Venture works to address bird habitat conservation challenges specific to its region (Migratory Bird Joint Ventures 2017).

The CVJV is a self-directed partnership of nongovernmental conservation groups, state and federal natural resource agencies, and one corporation that aims to restore, protect, and enhance habitats adequate to support goal populations of waterbirds (CVJV 2006; Gardali et al. 2017). Population goals are established for each of nine basins that were defined by the CVJV to assist in conservation planning (Figure 1; CVJV 2006). Wetland restoration objectives formalized in the North American Waterfowl Management Plan (NAWMP 2004) and scaled-down for each planning basin were based on wetlands that provide ≥50% of all food energy needs of waterfowl, with the remaining food energy needs supported by croplands (CVJV 2006). Additional objectives for waterbird populations and habitats were based on published recommendations and on CVJV experts of bird groups, and were developed for planning basins or regions that combined planning basins (CVJV 2006; Dybala et al. 2017; Shuford and Dybala 2017). Planned area of seasonal wetland restoration according to CVJV habitat objectives (hereafter, “CVJV goal” wetland restoration) varies between 0 (Suisun Basin) and 86 (Tulare Basin) km² by basin and totals 439 km² across the valley.

Changing climate has the potential to greatly impact water resources (Hayhoe et al. 2004; Diffenbaugh et al. 2015) and reduce availability of waterbird habitats in the valley (CVJV 2006, 2009; Singh 2015; USBR 2016a). Urban development in the Central Valley is predicted to increase substantially (EPA 2009; Radeloff et al. 2010, 2012), threatening sustainability of waterbird habitats.
Figure 1. The Central Valley of California including nine planning basins (bold text); major rivers, lakes, and reservoirs that are part of the surface-water supply system; and important waterbird habitats. Habitats include managed wetlands, rice fields (corn not shown) in the Sacramento Valley and Sacramento-San Joaquin River Delta (Delta), and flooded fields in the Tulare Lake (dry) bed existing in 2005.
through conversion of cropland habitat and increased competition for water supplies (Hickey et al. 2003; CVJV 2006; Fleskes 2012). Given the high competition for limited water supplies, proposals to revise management of water supplies in the valley are common (Hanák et al. 2011; CDWR and USBR 2015; USBR 2016b). Changes that result in less water available for managing waterbird habitats have the potential to adversely affect waterbirds. Modeling the combined and potentially synergistic effects of water supply management and other important factors including climate change and land conversion is crucial for fully understanding impacts of water management decisions on waterbird habitats. Our recent research indicated that combined climate change, urbanization, and water-supply management options that further agricultural and urban water uses could cause substantial habitat degradation across the Central Valley (Matchett and Fleskes 2017), which may vary regionally.

Our current research builds on this previous research, and based on output from the same 17 scenarios evaluated by Matchett and Fleskes (2017), examined the extent of potential habitat reduction during the autumn migration–wintering period for individual basins within the valley. The current research also evaluated the efficacy of wetland restoration for compensating reductions in flooded areas of wetland habitats under scenarios by basin, similar to the valley-wide analysis of wetland restoration performance by Matchett and Fleskes (2017). The main objectives of this research were to provide decision support for achieving waterbird conservation goals in the valley and to inform CVJV’s regional conservation planning.

**Study Area**

The Central Valley encompasses approximately 52,000 km² extending 640 km north–south from the city of Red Bluff to the Tehachapi Range near the city of Bakersfield and 48–112 km east–west between the foothills of the Sierra Nevada and Pacific Coastal Ranges (Fleskes 2012; Figure 1). The Sacramento Valley is the primary (>95%) rice-growing region in California (USDA 2015), and rice fields provide approximately 63% of the flooded wintering habitat in the Sacramento Valley (CVJV 2006). Rice and corn fields are also important waterbird habitats in the Sacramento–San Joaquin River Delta (hereafter, “Delta Basin”; CVJV 2006). Most postharvest flooding of other crops that provide valuable wintering habitat occurs in the Tulare Lake bed of Tulare Basin located in the southern part of the Central Valley (Figure 1; Fleskes et al. 2013). Existing managed wetlands provide wintering habitat area to a varying extent among the nine basins. Approximately 90% of the area of managed wetland habitat in the Central Valley is seasonal wetland, of which approximately 60–70% is summer-irrigated (CVJV 2006; Brown 2013). In contrast with the Sacramento Valley basins and Delta Basin, managed wetlands provide the substantial majority of habitat in Suisun, San Joaquin, and Tulare basins during winter (CVJV 2006). Climate in the Central Valley is generally characterized as Mediterranean with warm, dry summers and cool, wet winters (Fleskes 2012). Precipitation in the valley varies substantially among years, and the valley is relatively drier as it extends south (Birdsall et al. 2008; Fleskes 2012). Most water supplies in the valley are provided by mountain snowmelt and rainfall runoff draining to storage reservoirs, rainfall on the valley floor, return flows from crop irrigation, and groundwater pumping, which is more extensive when surface supplies are lacking (Hanak et al. 2011).

**Methods**

We modeled scenarios to project areas of habitats during August–April, when the majority of waterfowl and shorebirds migrate to and winter in the Central Valley. Although migrating shorebirds begin arriving in the valley during July, an estimated 10% of staging or wintering shorebirds arrive then and we do not report habitat areas for July (CVJV 2006). We calculated basin-specific results for effects of climate change, urbanization, water-supply management options, and CVJV goal wetland restoration on habitats using raw data from our previous modeling of valley-wide impacts (Matchett and Fleskes 2017).

We modeled scenarios utilizing the Water Evaluation and Planning (WEAP) Software (Yates et al. 2005a, 2005b; Young et al. 2009; Matchett and Fleskes 2017). The WEAP Software provides an intuitive framework for modeling scenarios for user-defined water-management systems. We updated and expanded a WEAP model previously developed for the Central Valley and adjoining watersheds (i.e., WEAP-CV; Yates et al. 2009; Joyce et al. 2010, 2011). The WEAP-CV model represents ground and surface hydrology, water storage and conveyance infrastructure and management, and competing water uses (e.g., agriculture, urban, fisheries, and managed wetlands), and accounts for changing evapotranspiration rates and water demands of vegetation (e.g., crops) due to changing climate.

Our model (hereafter, “WEAP-CV_{wu}”) was modified from WEAP-CV to include primary waterbird habitats, related water supplies, and projections of future urbanization of cropland in the valley through year 2099 (Matchett et al. 2015; Matchett and Fleskes 2017). In the WEAP-CV_{wu} we defined contiguous spatially explicit polygons of variable size (tens of km²) and shape covering and draining to the Central Valley, each of which represented land units with unique biophysical characteristics (termed “catchments” in WEAP Software; Yates et al. 2009). These catchments represented variability in land cover or land use (including waterbird habitats), climate, surface and groundwater hydrology, and water resources infrastructure and management important for waterbird habitats in each basin. The WEAP-CV_{wu} calculates the water balance for each water supply source and water use (represented as a fractional land-use area of the total catchment area; Yates et al. 2009) within each catchment, and then allocates
available water supplies to water uses on a monthly time step.

For each scenario and corresponding rates of urbanization and wetland restoration, WEAP-CV_{wh} accounts for interannual and spatially varying changes in urban, crop, and wetland areas in its calculations of supply availability and water allocations for water uses. In scenario simulations, WEAP-CV_{wh} used data sets of urbanization and wetland restoration projections that we developed, to adjust (on the start of each year) areas of crop, urban, and wetland water uses and corresponding hydrologic and water management characteristics of model catchments (see “Scenario descriptions” section for more detail). Similarly, WEAP-CV_{wh} used data sets of air temperature and precipitation projections that varied monthly and among catchments in estimation of water requirements and allocations. User-defined water-supply priorities in WEAP-CV_{wh} determine the relative order in which each water use receives (from a shared water source) its full water requirement as estimated in WEAP-CV_{wh}. Water supply priorities in WEAP-CV_{wh} are used to represent variable access to water supplies among water uses based on economic principles (i.e., profitability of one water use vs. another) or government policy and regulations, and priorities can be adjusted to model assumed changes in access to supplies.

The WEAP-CV_{wh} models the dynamics of water availability and water requirements related to the complex and interactive effects of climate (including effects on air temperature, rain, snow accumulation, snow melt, and evapotranspiration), land cover or land use, watershed runoff, groundwater recharge, surface reservoir storage, groundwater–surface water interactions, and water use withdrawals, using equations in Yates et al. (2005a, 2009). The optimization routine in WEAP-CV_{wh} maximizes allocation to fulfill requirements for all water uses conditional on availability, supply priorities of water uses, and other constraints (e.g., reservoir operational limits, physical capacity of reservoirs and canals, or regulatory stream-flow requirements). In its simulations, WEAP-CV_{wh} models the propagation of water accretions and depletions (e.g., in reservoir storage, stream flow, or groundwater) between monthly intervals, and models the flows of surface water supplies within and among catchments from upstream to downstream directions. For each scenario, the modeled temporal propagation of water supply depletion, combined with model constraints (e.g., supply priority), determines the projected quantity of water allocated to waterbird habitats in each year by basin. Thus, WEAP-CV_{wh} water allocation projections for wetlands and crop habitats can vary spatially by basin and through time depending on severity and longevity of modeled drought conditions and on supply priority or other model constraints that determine relative access to water supplies.

Following Matchett and Fleskes (2017), 17 scenarios represented projected conditions under different combinations of 3 climates (2 future and 1 recent historical), 3 urbanization rates, 5 water-supply management options, and 1 level of wetland restoration (Table 1). We processed WEAP-CV_{wh} output for water supplies and requirements to compute monthly and annual availability of each waterbird habitat for all scenario, year (2006–2009), and basin combinations following Matchett et al. (2015, 2017). In processing, we initially summed the output from WEAP-CV_{wh} for water supply requirements and water allocations across all catchments by each combination of habitat, scenario, year, and basin. Next, for each basin, scenario, and year combination we computed the proportion of each habitat type supported by water supplies as water allocation per km²/water supply requirement per km². Then, to compute final projected annual areas for basin, scenario, year, and habitat combinations, we multiplied the resulting fractions by corresponding annual areas of habitats previously adjusted by urbanization and wetland restoration rates modeled in our scenarios.

In our calculations of annual areas, we further distinguished periods for growing vs. winter flooding of rice, corn, and Tulare fields, and for summer irrigation vs. winter flooding of seasonal wetlands, which was necessary to understand effects of scenario conditions on quality as well as quantity of habitat. We used model output to compute projected habitat areas based on realistic assumptions for water management on post-harvested flooded crop fields and managed wetlands. We assumed for rice and corn that allocated water was first used for growing and then remaining water supplies were used for winter flooding. If water allocation was insufficient to fulfill the winter-flooding water requirement, we reduced winter-flooded area by the proportion of water unavailable for winter flooding (i.e., one minus the proportion supported by water supplies). For calculating monthly areas of winter-flooded rice and corn (Figure S1, Supplemental Material), we assumed that farmers did not delay winter flooding; and if water supplies were inadequate to fully meet winter flooding requirements, we reduced winter flooding by an equal proportion in each month. If modeled annual water allocation was insufficient for growing rice or corn as well as winter flooding, we reduced the area of dry habitat (i.e., area of fields that were fallowed) by the proportion water unavailable for growing. We followed the same process for Tulare field crops that were flooded after harvest, but instead used monthly modeling estimates to calculate winter flooding because water demand varied among crops each month (Fleskes et al. 2013). Using a similar process as for winter-flooded crops, we modeled available area of summer-irrigated seasonal wetlands conditional on first having sufficient available water for winter flooding based on typical seasonal wetland management in the Central Valley (G. Yarris, CVJV Science Coordinator; personal communication). Similar to winter-flooded rice and corn, we modeled a reduction in area by an equal proportion each month for seasonal and semipermanent wetlands (Figure S1, Supplemental Material).

We mainly report peak annual areas of managed wetlands and flooded cropland (Figures 2–4; Table A1, Archived Material), but also provide monthly information on habitat areas including for dry postharvested
Table 1. Scenarios modeled to evaluate projected impacts on habitats of wintering waterbirds. Climate and urbanization projections, water-supply management options, and wetland restoration levels included in scenarios used to estimate annual water supplies and area of wintering waterbird habitats that could be supported with those water supplies in the Central Valley of California during 2006–2099.

| Scenario | Climate* | Urbanizationb | Water managementc | Wetland restorationd |
|----------|-----------|---------------|-------------------|----------------------|
| 1        | Recent    | No additional | Existing          | No additional        |
| 2        | GFDL A2   | Expansive     | Existing          | No additional        |
| 3        | GFDL A2   | Current trend | Existing          | No additional        |
| 4        | PCM B1    | Current trend | Existing          | No additional        |
| 5        | PCM B1    | Strategic     | Existing          | No additional        |
| 6        | GFDL A2   | Expansive     | Existing          | CVJV goal            |
| 7        | GFDL A2   | Current trend | Existing          | CVJV goal            |
| 8        | PCM B1    | Current trend | Existing          | CVJV goal            |
| 9        | PCM B1    | Strategic     | Existing          | CVJV goal            |
| 10       | GFDL A2   | Current trend | Reduced priority-rice, Tulare fields | CVJV goal |
| 11       | PCM B1    | Current trend | Reduced priority-rice, Tulare fields | CVJV goal |
| 12       | GFDL A2   | Current trend | Reduced priority-rice, wetlands | CVJV goal |
| 13       | PCM B1    | Current trend | Reduced priority-rice, wetlands | CVJV goal |
| 14       | GFDL A2   | Current trend | CWFSTR             | CVJV goal            |
| 15       | PCM B1    | Current trend | CWFSTR             | CVJV goal            |
| 16       | GFDL A2   | Current trend | CWFSTR + reduced priority-rice, Tulare fields, wetlands | CVJV goal |
| 17       | PCM B1    | Current trend | CWFSTR + reduced priority-rice, Tulare fields, wetlands | CVJV goal |

* Recent = recent historical climate replicating 1971–2000 conditions in 2006–2035, 2036–2065, and 2066–2095 (1971–1974 conditions were replicated in 2006–2009). The GFDL A2 and PCM B1 climate projections produced from global circulation models were bias-corrected and scaled down to 12 × 12 km² resolution (USBR 2013; USBR et al. 2013). Compared with recent historical climate, GFDL A2 represents a much warmer and drier future and PCM B1 represents a warmer climate and little change in precipitation.

b The “strategic” = slow, “current trend” = moderate, and “expansive” = high rates of urbanization.

c Existing = recent (as of 2005) management of water supplies. Reduced priority = Reduction in water supply priority for managed waterbird habitats relative to competing water uses. CWFSTR = approximate water management under the proposed California WaterFix (north Delta tunnels water-diversion project) to facilitate conveyance and redistribution of water for human use, and Suisun Marsh tidal wetland restoration resulting in approximately 16% (24 km²) less area of managed freshwater wetland used by waterfowl in Suisun Basin.

d Represents CVJV goal wetland restoration of 421-km² in the Central Valley to compensate for potential reduction in flooded area of wetlands.

cropland used by wintering ducks and geese (Table A2, Archived Material; Figure S1, Supplemental Material). In Figures 2–4, we report annual area for each type of wetland and winter-flooded crop in the month when area is typically the greatest during autumn–winter (January for wetlands and winter-flooded rice and corn, September for “other” winter-flooded cropland). We report interannual variation (years 2006–2099) in available area by habitat, scenario, and basin as a series of box–whisker plots (Figures 2–4 and S1 [Supplemental Material]). We compare area of waterbird habitats for each scenario with the area of waterbird habitats that existed just before the start of the modeled time series (hereafter referred to as “recent” areas; Table 2) to analyze the frequency and extent of area reduction by habitat, scenario, and basin.

Recent areas of habitats that existed before the modeled time series varied greatly by basin overall and depending on habitat type (Table 2). There was insufficient available information for modeling summer irrigation of seasonal wetlands in Delta and Suisun basins, so we simplified our analysis by representing all seasonal wetland area as nonsummer-irrigated for these basins. Because semipermanent and permanent wetlands are both relatively deeply flooded to provide functionally similar habitat for wintering waterbirds and because the majority of these are semipermanent (CVJV 2006, p. 28), we further simplified our analysis by representing their combined areas as semipermanent wetland.

Scenario descriptions

Like the “recent” habitat landscape described previously, Scenario 1 represented a historical baseline useful to compare with projected changes in climate, urbanization, water management, and wetland restoration included in Scenarios 2–17. For Scenario 1, we fixed the urban footprint at year 2005, wetland habitat area at the most recent available estimate (i.e., year 2003; M. Petrie, Ducks Unlimited, Inc., unpublished data; CVJV 2006), and the water-delivery system mechanics and water-supply priorities of 2005. Urban and wetland areas have increased since 2005, but likely not enough to change our results significantly. However, rather than a static ‘snapshot’ of waterbird habitats existing just before the start of the 2006–2099 time series, we allowed precipitation and air temperatures in Scenario 1 to vary in the range and yearly sequence of the recent historical climate replicating 1971–2000 conditions in 2006–2035, 2036–2065, and 2066–2095 (1971–1974 conditions were replicated in 2006–2009). Thus, in Scenario 1, water availability varied among years and resulted in annual variation in area of waterbird habitats supported by that water.

Climate. In addition to the recent historical climate included in Scenario 1, we evaluated two climate change
Figure 2. Box–whisker plots of annual peak areas (km$^2$) for flooded waterbird habitats in the Colusa, Butte, American, and Delta planning basins in the Central Valley of California and that are available during the autumn–winter period for each of 17 projected scenarios (years 2006–2099). Scenarios consisted of various climate, urbanization, water management, and wetland restoration levels (see Table 1 for scenario descriptions). Flooded habitats were seasonal wetland (either summer-irrigated or not), semipermanent wetland, winter-flooded rice, and winter-flooded corn. We calculated the peak area of each habitat from the month when the area was typically the greatest during each autumn–winter period of the time series (January for wetlands, winter-flooded rice, and winter-flooded corn). Habitat areas existing in year 2005 (for comparison with scenarios) are represented by the horizontal blue dotted line.
Figure 3. Box-whisker plots of annual peak areas (km²) for flooded waterbird habitats in the Sutter and Yolo planning basins in the Central Valley of California and that are available during the autumn–winter period for each of 17 projected scenarios (years 2006–2099). Scenarios consisted of various climate, urbanization, water management, and wetland restoration levels (see Table 1 for scenario descriptions). Flooded habitats were seasonal wetland (either summer-irrigated or not), semipermanent wetland, and winter-flooded rice. We calculated the peak area of each habitat from the month when the area was typically the greatest during each autumn–winter period of the time series (January for wetlands and winter-flooded rice). Habitat areas existing in year 2005 (for comparison with scenarios) are represented by the horizontal blue dotted line.
Figure 4. Box–whisker plots of annual peak areas (km²) for flooded waterbird habitats in the San Joaquin and Tulare planning basins in the Central Valley of California and that are available during the autumn–winter period for each of 17 projected scenarios (years 2006–2099). Scenarios consisted of various climate, urbanization, water management, and wetland restoration levels (see Table 1 for scenario descriptions). Flooded habitats were seasonal wetland (either summer-irrigated or not), semipermanent wetland, and other winter-flooded cropland. We calculated the peak area of each habitat from the month when the area was typically the greatest during each autumn–winter period of the time series (January for wetlands and September for other winter-flooded cropland). Habitat areas existing in year 2005 (for comparison with scenarios) are represented by the horizontal blue dotted line.
Table 2. Recent historical areas (km²) of habitats used during autumn–winter by waterbirds in the Central Valley as represented in modeling and by planning basin. We calculated the area of each habitat from the month when the area was typically the greatest during autumn–winter (January for wetlands, winter-flooded rice, and winter-flooded corn, and September for other winter-flooded cropland). Years indicates the time periods of the data that were used to derive recent baseline areas of habitats for modeling, and to compare with results from climate, urbanization, and water management scenarios.

| Habitat                        | Years    | American | Butte | Colusa | Delta | Suisun | Sutter | Tulare | Yolo | Total |
|-------------------------------|----------|----------|-------|--------|-------|--------|--------|--------|------|-------|
| Seasonal wetland (not SI)     | 2003     | 5        | 38    | 36     | 25    | 99     | 130    | 3      | 33   | 14    | 383   |
| Seasonal wetland (SI)         | 2003     | 8        | 57    | 54     | 0     | 148    | 0      | 5      | 49   | 21    | 342   |
| Semipermanent wetland         | 2003     | 3        | 17    | 16     | 9     | 27     | 23     | 4      | 3    | 9     | 311   |
| Winter-flooded corn           | 1995–2004| 0        | 0     | 0      | 67    | 0      | 0      | 0      | 0    | 67    |
| Winter-flooded rice           | 1995–2004| 197      | 434   | 376    | 23    | 0      | 113    | 0      | 37   | 1,180 |
| Other winter-flooded cropland | 2005–2006| 0        | 0     | 0      | 0     | 0      | 24     | 0      | 24   |
| Unplowed winter-dry rice      | 1995–2004| 6        | 11    | 62     | 224   | 0      | 10     | 0      | 21   | 334   |
| Unplowed winter-dry rice      | 1995–2004| 121      | 139   | 331    | 9     | 0      | 75     | 0      | 13   | 688   |
| Total                         | 340      | 696      | 875   | 357    | 274   | 153    | 210    | 115    | 109  | 3,129 |

* Recent areas used in modeling generally were derived from CVJV (2006) and Brown (2013) for wetlands; CVJV (2006), CDWR (2016 and unpublished data), and M. Reiter of Point Blue Conservation Science (unpublished data) for winter-flooded and unplowed winter-dry rice and corn; and Fleskes et al. (2013) for other winter-flooded cropland (i.e., postharvest flooded fields in the Tulare Lake bed). Abbreviation “SI” = “summer-irrigated”.

projections in Scenarios 2–17 (Table 1). Climate projections used in Scenarios 2–17 are based on output of two global circulation models that have been bias-corrected and scaled down to 12 × 12 km² resolution (USBR 2013; USBR et al. 2013). These two climate projections were GFDL-CM2.1 A2 (hereafter, “GFDL A2”) and NCAR-PCM1 B1 (hereafter, “PCM B1”), which represented a range of potential future climate conditions and are a subset of projections previously selected to investigate climate change impacts on California (Cayan et al. 2008, 2009). GFDL A2 represents a much warmer and drier future and PCM B1 represents a warmer climate and little change in precipitation compared with recent historical climate; respectively, GFDL A2 and PCM B1 projected annual air temperature and precipitation changes in northern California of +4.5°C and −18%, and +1.5°C and 0%, by 2100 compared with means for the recent historical period 1961–1990 (Cayan et al. 2008).

Urbanization. Scenarios 2–17 include “strategic,” “current trend,” or “expansive” (i.e., slow, moderate, or high, respectively) rates of urbanization (Table 1). To develop urbanization projections for modeling, we initially obtained data for projections of cropland conversion to urban areas that were created independently for water management planning by the State of California (CDWR 2009). Projections varied regionally among relatively large areas (each intersecting multiple counties) across the valley and temporally for years 2005–2100. Strategic, current trend, and expansive urbanization rates (i.e., before initiating simulations of scenarios), respectively, accounted for 0–43%, 0–100%, and 18–100% total cropland reduction among valley regions by year 2100. Using those projections, which represented conversion of the combined area of crops for each region, we developed projections for each of 20 annual and 7 perennial (i.e., orchard) crops represented in WEAP-CVwh by year. Projections for individual crops (i.e., the proportion of area urbanized for a crop relative to area in 2005) were equal by region and year combination (Matchett and Fleskes 2017). Extent of urbanized dry unplowed and postharvest flooded rice and corn and Tulare field habitats directly corresponded with projections of urban conversion of total cropland.

Water supply management. We assumed recent (as of 2005) management of water supplies in Scenarios 1–9 and evaluated possible options in water supply management in Scenarios 10–17 (Table 1). Water-supply management options included in scenarios were the reduction in water supply priority for managed waterbird habitats (Scenarios 10–13), development and management of specific water-delivery infrastructure (i.e., CWFSTR = approximate water management conditions that would occur under the proposed California WaterFix and Suisun Marsh tidal wetland restoration, see Matchett and Fleskes 2017; Scenarios 14–15), or both (Scenarios 16 and 17). For scenarios that included reduced habitat priorities, we adjusted supply priority coefficients in WEAP-CVwh for individual habitats to represent the reduced likelihood of these habitats receiving water supplies relative to other competing agricultural and urban outdoor water uses. This change to the model structure allowed us to represent realistic shifts in agroeconomics or government policy and regulations that would favor less allocation of water for habitats than for other uses when water supplies are limited.

By contrast, the CWFSTR option represents development and management of the proposed California WaterFix north Delta tunnels water-diversion project to improve water delivery from the Sacramento River system to the existing State Water Project and Central Valley Water Project pumping facilities in the Sacramento–San Joaquin River Delta (Figure 1; CDWR and USBR 2015; USBR and CNRA 2015). For scenarios that included CWFSTR, we modified WEAP-CVwh by constructing necessary model-diversion linkages, a stream flow requirement on the Sacramento River for mitigating operations of the proposed tunnels, and other capacity and regulatory flow constraints specific to California.
Waterbird Habitat in Central Valley Basins Under Landscape Change Scenarios

E.L. Matchett and J.P. Fleskes

WaterFix (see Matchett and Fleskes 2017 for more detail). The CWFSTR option would enable greater quantities of water to be conveyed and redistributed for human use (i.e., supplying crops, urban residences, businesses, and manufacturing) south of the Delta, potentially reducing access of waterbird habitats to water. This may be especially true when combined with lowered supply priority of waterbird habitats (Scenarios 16 and 17). Despite potential benefits to the Delta aquatic ecosystem, restoration of approximately 16% (24 km²) of managed freshwater wetland area to tidal wetlands in Suisun Marsh under CWFSTR will reduce the concomitant area of wetlands managed for waterfowl there, and therefore represented a loss of wetland habitat in our analysis.

For Scenarios 10–13, 16, and 17, which represented lowered water-supply priority for managed waterbird habitats, the relative priorities of some water uses and habitats were the same as for Scenarios 1–9. Consistent with Scenarios 1–9, supply priorities for wetland summer irrigation or growing and winter flooding of all crop and wetland habitats in Scenarios 10–13, 16, and 17 were higher than reservoir filling for hydropower generation and water storage, and flood bypass systems (reflecting filling of flood management bypasses with excess stream flow that is not allocated for other uses). Also like Scenarios 1–9, supply priorities of all crop and many wetland (i.e., those not identified in the Central Valley Project Improvement Act [CVPIA; USBR 2017]) habitats in Scenarios 10–13, 16, and 17 were lower than stream flow requirements and urban indoor use.

In Scenarios 10 and 11, water supply priorities for rice habitats in the Sacramento Valley basins and Delta Basin during both the growing (May–Sep) and winter flooding (Oct–Mar) periods were lowered relative to priorities of other crops, urban outdoor use, and some public and many private wetlands to represent the fallingow of rice fields that often occurs in these regions during drought years (USDA 2015; Petrie et al. 2016). Water supply priorities for wetlands or for irrigation of crops other than rice were not changed in Scenarios 10–11, but water supply priority for postharvest flooding of crop fields in Tulare was lowered relative to priorities of other crops, urban outdoor use, and some public and many private wetlands. All crop habitats retained water supply priorities below many public and some private wetlands receiving water supplies contracted through the CVPIA.

In Scenarios 12 and 13, water supply priorities for summer irrigation and winter flooding of all wetlands, and growing and winter flooding of rice, were reduced to below the priority for other crops and urban outdoor use (but still above priority for reservoir filling and flood bypass systems). Scenarios 14–17 approximate water management conditions that would occur under CWFSTR, and for Scenarios 16 and 17 we also specified that water supply priorities for wetlands, growing and winter flooding of rice, and winter flooding of Tulare fields were identical to each other, and similar to Scenarios 10–13, they were reduced below priorities of other crops and urban outdoor use.

**Wetland restoration.** To evaluate the potential for CVJV goal wetland restoration to compensate reduction in flooded area of wetlands resulting from scenarios (Table 1), we used wetland areas existing in 2005 as a benchmark with which to compare scenario results. According to projections of CVJV goal wetland restoration (Matchett and Fleskes 2017), 421 km² of seasonal wetlands and an additional 15 ha of semipermanent wetlands for every 100 ha of seasonal wetlands (total of 60 km²) were restored in Scenarios 6–17. The 421-km² restoration objective represented wintering waterfowl needs and sufficiently approximated (i.e., 96% of) total seasonal wetland restoration planned for all waterbirds. Although lack of funds or opportunities (i.e., participating landowners with suitable land) could limit the area of wetlands that are actually constructed in the future, in our analysis we assumed the wetland area constructed under CVJV goal restoration to be fully achieved.

**Results**

**Effects of changing climate, urbanization, and water-supply management options**

**Overall patterns.** With few exceptions among cropland and wetland habitats, changes in climate, urbanization, and water supply management at levels we evaluated reduced habitat areas in each basin (Figures 2–4 and Figure S1 [Supplemental Material]). Wetland restoration planned by the CVJV appeared to substantially compensate scenario effects, but not in all years of the projected time period or for all basins (Figures 2–4). Overall, among the nine basins, scenarios reduced wetland areas in Tulare Basin the most, and those in Suisun the least, relative to areas existing in 2005 (Figure 4 and Figures S1F, I [Supplemental Material]). Effects on habitat areas in the other basins varied more substantially depending on scenario.

**Crop habitats in Sacramento Valley and Delta basins.** Among the scenarios we analyzed, conditions in the Sacramento Valley basins and Delta Basin reduced areas of crop habitats in more years, and to greater extent, than for wetland habitats (Figures 2 and 3). With respect to crop habitats, scenario conditions reduced area of winter-flooded rice the most, followed by area of winter-flooded corn (in the Delta Basin). Scenarios that included GFDL A2 climate, and particularly those with both GFDL A2 climate and water-supply management options, substantially reduced area of winter-flooded rice in Colusa, Butte, Sutter, and Delta basins (Scenarios 2, 3, 10, 12, 14, and 16; Figures 2 and 3). By contrast, those scenarios reduced areas of winter-flooded rice in American and Yolo basins more moderately (Figures 2 and 3). Regarding areas of unplowed dry rice and corn, scenarios projected marked reductions in these habitats in some years, although the extent varied substantially by basin and scenario (Figure S1, Supplemental Material).
Crop habitats in Tulare Basin. In the Tulare Basin, the only other basin that contained substantial areas of crop habitats used by waterbirds, scenario results projected substantial reductions of winter-flooded crop habitats (Figure 4 and Figure S11 [Supplemental Material]). Winter-flooded area of Tulare fields was reduced by ≥50% in approximately half of all years for most scenarios. Likewise, for many scenarios, flooded areas of these croplands were completely eliminated in some years (Figure 4).

Wetland habitats in Sacramento Valley, Delta, and Suisun basins. Across all Sacramento Valley and Delta basins, scenarios reduced summer-irrigated area of seasonal wetland, area of semipermanent wetland, and winter-flooded area of seasonal wetland in order of greatest to least, respectively (Figures 2 and 3). Scenarios reduced area (relative to recent) of summer-irrigated seasonal wetland in descending order of effect in the Sutter, Butte, and Colusa basins, respectively. Consistent with relatively moderate reductions of winter-flooded rice area in the American and Yolo basins, scenarios reduced summer-irrigated area of seasonal wetlands the least compared with other basins within Sacramento Valley. For the Sacramento Valley, scenarios that excluded CVJV goal restoration or included goal restoration, GFDL A2 climate, and lowering of wetlands water-supply priority resulted in the greatest reduction in summer-irrigated area of seasonal wetlands (Scenarios 1–5, 12, and 16; Figures 2 and 3).

For Sacramento Valley basins, generally those scenarios that excluded wetland restoration (Scenarios 1–5; Figures 2 and 3) also reduced flooded areas of semipermanent wetlands the most. In contrast with semipermanent wetlands and summer-irrigated area of seasonal wetlands, scenario results indicated no reduction in winter-flooded area of seasonal wetlands in Sacramento Valley basins through 2099 (Figures 2 and 3). Similarly, for Delta and Suisun basins, areas of semipermanent wetlands and winter-flooded area of seasonal wetlands were affected little by the scenarios evaluated based on WEAP-CVwh assumptions of regionally secure water supplies supported by riparian water rights related to extensive land area contiguous with tidally influenced streams in these basins (Figure 2 and Figure S1F [Supplemental Material]). Solely scenarios that included CWFSTR marginally reduced areas of semipermanent and seasonal wetlands (winter-flooded only) in Suisun Basin as a result of conversion of wetlands primarily managed as waterfowl habitat to restored tidal wetland in Suisun Marsh (Scenarios 14–17; Figure S1F, Supplemental Material).

Wetland habitats in San Joaquin and Tulare basins. Similar to Colusa, Butte, Sutter, American, Yolo, and Delta basins, scenario conditions in the San Joaquin and Tulare basins reduced summer-irrigated area of seasonal wetlands the most, and winter-flooded area of seasonal wetlands the least (Figure 4). However, scenarios combining future climate projections and water-supply management options reduced summer-irrigated area of seasonal wetlands to a greater extent and in more years (relative to recent) there than for the Sacramento Valley basins (12–17; Figure 4). Even such scenarios that included combinations with PCM B1 climate resulted in many years of marked reduction in summer-irrigated area of seasonal wetlands for San Joaquin and Tulare basins (Scenarios 11, 13, 15, 17; Figure 4). Among all basins, summer-irrigated area of seasonal wetlands was most severely reduced in Tulare Basin (i.e., by approximately 50–100% in half of all years across all scenarios; Figure 4).

Some scenarios reduced winter flooding of seasonal wetlands and flooding of semipermanent wetlands in San Joaquin and Tulare basins more than in Sacramento Valley basins and Delta Basin. Specifically, scenarios that included combinations of future climate projections (especially GFDL A2), CWFSTR, and lowered wetlands water-supply priority, resulted in moderate to substantial reductions in winter-flooded area of seasonal wetlands and flooded area of semipermanent wetlands in San Joaquin and Tulare basins (Scenarios 12–17; Figure 4).

Wetland restoration performance

Wetland habitats in Sacramento Valley and Delta basins. In Sacramento Valley basins and Delta Basin, CVJV goal wetland restoration was mostly effective at compensating for reductions in wetland area under various scenarios (Figures 2 and 3). In Sacramento Valley, CVJV goal wetland restoration greatly compensated for reductions in summer-irrigated area of seasonal wetlands and flooded area of semipermanent wetlands related to climate change and urbanization combined (Scenarios 6 vs. 2, 7 vs. 3, 8 vs. 4, and 9 vs. 5; Figures 2 and 3) and additional water-supply management options (Scenarios 10–17; Figures 2 and 3). For all scenarios, goal wetland restoration combined with the shift in management from summer irrigation to solely winter flooding (i.e., as nonsummer-irrigated seasonal wetland), compensated for potential reductions in winter-flooded area of seasonal wetlands in Sacramento Valley (Figures 2 and 3). Across all scenarios, goal wetland restoration compensated for the marginal reductions in flooded areas of semipermanent and nonsummer-irrigated seasonal wetlands in the Delta Basin (Figure 2).

Despite CVJV goal restoration, two scenarios that included combinations of GFDL A2 climate and lowered wetlands water-supply priority resulted in many years of substantial reductions (relative to recent) in summer-irrigated area of seasonal wetlands in Sacramento Valley basins (Scenarios 12 and 16; Figures 2 and 3). For example, for Scenario 16, in 25% of years summer-irrigated area of seasonal wetlands was reduced by ≥16% (9 km²), 35% (7 km²), 59% (32 km²), and 79% (4 km²) for Butte, Yolo, Colusa, and Sutter basins, respectively. There was disproportionately greater wetland restoration for achieving conservation objectives in American Basin; therefore, substantial reduction in
summer-irrigated area of seasonal wetland was relatively less frequent there than for other basins (Figure 2).

**Wetland habitats in San Joaquin and Tulare basins.** Goal wetland restoration compensated projected reductions in wetland areas notably less for the San Joaquin Basin than for Sacramento Valley basins and Delta Basin (Figure 4). In San Joaquin Basin, goal wetland restoration mostly compensated for reduction in summer-irrigated area of seasonal wetlands and flooded area of semipermanent wetlands related to climate change and urbanization (Scenarios 6 vs. 2, 7 vs. 3, 8 vs. 4, and 9 vs. 5; Figure 4). However, scenarios that included specific water-supply management options (especially when combined with GFDL A2 climate) reduced flooding for all three types of managed wetland in San Joaquin Basin despite goal wetland restoration (Scenarios 12–17; Figure 4). For example, conditions for five scenarios (12 and 14–17), which included the addition of lowered wetlands water-supply priority and CWFST to projected climate, eliminated nearly all summer irrigation of seasonal wetland area in 25% of years. Furthermore, in as many as half of the years, summer-irrigated area in San Joaquin Basin was eliminated by between 51% (75 km²) and 86% (127 km²) among three scenarios (12, 13, and 16; Figure 4). Similarly, in 25% of years, flooded area of semipermanent wetlands in San Joaquin Basin was eliminated by between 21% (5.8 km²) and 42% (11.5 km²) among Scenarios 14, 16, and 17 (Figure 4). With respect to seasonal wetland that is solely winter-flooded, combined GFDL A2 climate, lowered wetlands water-supply priority, and CWFST (Scenario 16), eliminated 30% (30 km²) of the flooded area in 25% of years (Figure 4).

For Tulare Basin, CVJV goal restoration compensated scenario-based reduction in areas (relative to recent) of flooded wetlands less than for other Central Valley basins (Figure 4). Similar to other basins, goal restoration in Tulare Basin fully compensated for impacts on semipermanent and nonsummer-irrigated seasonal wetlands related to climate change and urbanization combined (Scenarios 6 vs. 2, 7 vs. 3, 8 vs. 4, and 9 vs. 5; Figure 4). However, effectiveness of goal restoration to compensate reduction in summer-irrigated area of seasonal wetlands related to climate change and urbanization was more limited there than for other basins. The addition of CWFST and lowering of wetlands water-supply priority further limited the capacity of goal wetland restoration to compensate reduction in summer irrigation of seasonal wetlands in Tulare Basin (Scenarios 12–17; Figure 4). In particular, the two scenarios that included both lowered wetlands water-supply priority and CWFST, eliminated essentially all summer-irrigated area of seasonal wetland in Tulare Basin through year 2099 (Scenarios 16 and 17; Figure 4).

As for San Joaquin Basin, goal wetland restoration in Tulare Basin partially compensated for the additional effect of water-supply management options on flooded areas of semipermanent wetlands and seasonal wetlands that were solely winter-flooded. In Tulare Basin, four scenarios (14–17) that combined projected climate, lowered wetlands water-supply priority, and CWFSTR, eliminated ≥50–80% (4.5–7.3 km²) of semipermanent wetland flooding in 25% of years, and up to 100% of the flooding in some years (Figure 4). With respect to seasonal wetland that is solely winter-flooded, combined projected climate, lowered wetlands water-supply priority, and CWFST, eliminated ≥22% (7 km²) of the flooded area in the Tulare Basin in 25% of years (Scenario 16), and up to 95% of the flooding in some years (Scenarios 17; Figure 4).

### Discussion

Scenario combinations of projected climate and urbanization significantly reduced area of flooded waterbird habitats in planning basins during some years. The addition of water-supply management options that promoted agricultural and urban water uses exacerbated effects of urbanization and projected climate (especially the warmer, drier GFDL A2 climate) on availability of flooded habitats. Goal wetland restoration planned by the CVJV varied from marginal to fully effective for compensating impacts of scenarios on wetland habitats relative to wetland areas existing in 2005. Our analysis indicated that, for all basins, CVJV goal wetland restoration could substantially compensate for reduction in wetland habitats related to scenario conditions. Despite goal wetland restoration, however, our findings also indicated that for several basins (Colusa, Butte, Sutter, San Joaquin, and Tulare) additional conservation may be required to support summer irrigation of seasonal wetlands during many of the years in the projected future. Similarly, the frequent and extensive reductions in winter flooding of cropland habitats in the basins where they occurred indicate that improvement in water supply availability is needed for winter-flooded cropland. Under our scenarios, future water scarcity for wetlands in San Joaquin and Tulare basins and for winter flooding of croplands in Tulare Basin was the most severe, and habitats in these basins will likely require significant planning for the development of effective strategies to mitigate potential impacts to habitats.

### Demographic effects of habitat loss or degradation

Petrie et al. (2016) modeled bioenergetics of wintering waterfowl in the valley under scenarios approximating recent drought (year 2014) effects on waterfowl habitats. They concluded that the goal population of nonbreeding waterfowl (established for the CVJV in the North American Waterfowl Management Plan) would encounter mid- to late-winter food deficits in the valley. Other efforts to quantify habitat objectives for nonbreeding shorebirds and other waterbirds (Dybala et al. 2017; Shuford and Dybala 2017) determined that even during nondrought, wetland and crop habitats may not provide sufficient food resources to support population goals of these birds. Our scenarios projected urbanization and water-supply management impacts in addition to
potentially worse drought deficits than in 2014; thus, even greater food energy deficits for several basins are likely to result in the future than those described in these recent findings. Therefore, our findings indicate that meeting habitat conservation objectives for wintering waterbirds in the Central Valley may be challenged under future climate change, urbanization, and water-supply management scenarios.

Conservation planning that develops strategies that explicitly address potential frequent and substantial loss of summer-irrigated (and to a lesser extent semipermanent and nonsummer-irrigated seasonal) wetland in San Joaquin and Tulare basins would be most useful. Sustaining goal waterbird populations in these basins may be particularly challenging in the future based on scenario projections and given current limitations in obtaining water supplies for habitats (CVJV 2000, 2006). The projected reduction of all three types of wetlands as well as winter-flooded cropland in Tulare Basin would presumably result in reduced available food energy and increased food energy costs related to less feeding habitat for waterbirds. Also, projected reductions in Tulare and San Joaquin Basin wetlands used for roosting by waterfowl during the hunting season (approximately October–January) would likely increase flight distances to feeding sites by waterfowl and lead to declines in body condition for these species (Hamilton and Watt 1970; Baveco et al. 2011).

Our study illustrated the potential vulnerability of conservation efforts aiming to support goal populations of waterbirds in the Sacramento Valley. Impacts on waterbird food resources caused by moderate reductions in habitats projected in scenarios may be efficiently mitigated by areas of winter-flooded and unplowed, winter-dry rice fields combined with goal wetland restoration. However, neither wetland restoration nor recent expansive areas of rice habitat are likely to sufficiently buffer substantial reductions in habitats projected under severe GFDL A2 climate and lowering of water supply priorities of habitats. Among basins in Sacramento Valley, it may be most challenging to achieve population goals for ducks in the Colusa, Butte, and Sutter basins under these circumstances.

Water management strategies for habitats
Management of water supplies to manipulate timing, depth, and areal extent of flooded habitats could be adjusted to mitigate scenario impacts on a variety of waterbirds in the valley, and support population goals for each. A great majority of the winter flooding of seasonal wetlands and rice fields occurs well before the December peak in waterfowl abundance and after many shorebirds have arrived (Figure S1, Supplemental Material; CVJV 2006; Dybala et al. 2017). Correspondingly, bioenergetics modeling predicted the depletion of food energy supplies beginning mid-December for waterfowl in drought scenarios (Petrie et al. 2016), whereas food deficits for shorebirds are likely to occur in late July–September and mid-March–late April (Dybala et al. 2017). Therefore, improved timing of habitat flooding to precisely correspond with waterfowl and shorebird migration chronology could substantially enhance food resources for waterfowl and shorebirds when food energy deficits are most likely a result of drought or other factors restricting water supplies (e.g., climate or changes to water supply management). Similarly, improved spatial allocation of water resources has the potential to provide flooded habitats where they are likely to benefit waterbirds the most (e.g., where at a given time, there is the least available flooded habitat relative to waterbird abundance). More effective collaboration and coordination among natural resource and regulatory agencies (e.g., facilitating greater water reuse or water transfers among users) could help habitat managers provide optimally timed and located, highly productive habitats for various waterbirds. Identifying improved timing, spatial allocation, and agency collaboration of water management constitute a suite of actions to achieve water use efficiency that could be highly effective for mitigating potential habitat reductions across all evaluated scenarios (or “no regret” actions).

Depth of flooding is critical for determining accessibility of food resources for waterbirds and requires effective coordination among conservation practitioners. Water management of postharvested rice fields could be better focused to provide both deeply flooded fields (maintained at 26 cm) for ducks and fields that are shallowly flooded once during the year to an unmaintained depth of 8–11 cm (i.e., water depth decreasing naturally) for shorebirds, and to conserve water supplies (Strum et al. 2013). Across expansive areas (within and among basins), effective coordination is essential to implement an appropriate balance of deeply and shallowly flooded areas of winter-flooded rice to support population goals among multiple clades of waterbirds.

Multiple available strategies that promote winter flooding of cropland will make conservation more robust to future uncertainty. Under the future scenarios we modeled, projected areas of unplowed, winter-dry rice and corn were generally less affected than winter-flooded rice. Therefore, as a mitigation strategy, there may be opportunity in some years and in basins containing relatively substantial rice area to incentivize winter flooding of otherwise unplowed, dry rice. Other “plowed” dry rice and corn fields, when flooded, could further supplement the available area of flooded habitat, particularly for shorebirds and many other waterbirds that don’t require access to seeds. Such incentive-based strategies are already an element of CVJV conservation objectives and have been applied in recent years in the Sacramento Valley, but could be expanded to include more area in targeted months and years of extended drought periods, and to other basins. Conservation incentives to winter-flood Sacramento Valley rice and
Delta corn fields could be expanded to crop and range land in the San Joaquin Valley (Canright 2014), which would increase the portfolio of adaptation strategies there.

However, winter-flooding expansive areas of rice and corn could have negative consequences for some waterbird species. Wintering sandhill cranes *Antigone canadensis* frequently roost in flooded rice and corn fields but prefer to feed in dry ones nearby (Shuford and Dybala 2017). Efforts to increase area of winter-flooded fields for other waterbirds could better accommodate cranes by leaving some fields dry nearby.

**Wetland enhancement**

Scenario impacts could be mitigated through more frequent or expansive wetland enhancement, as habitat managers can leverage land management activities to optimize use of available water supplies for providing food resources for many waterbird species. Complementary wetland enhancement practices may include diking pond vegetation in summer–autumn, allocating water for summer irrigation (although potentially reducing water for flooding during autumn–winter), and pond enhancement to create topographically varied water depths and extend shallow-flooded or moist pond edge (Isola 2000; Naylor 2002; Colwell and Taft 2002; Taft et al. 2002; Olson 2011; Reiter et al. 2015). This example of a combined “no regrets” enhancement approach could help improve availability and accessibility, and encourage greater use of wetland food resources for a variety of waterbirds, thereby improving use efficiency of limited water supplies.

**Identification and establishment of new water supplies**

Results of this study indicate that conservation planners could consider actively identifying opportunities for developing, negotiating, and acquiring new regional or local water supplies for Central Valley habitats (see also Downard and Endter-Wada 2013). Future habitat water supplies could derive from sources of recycled urban wastewater, captured stormwater runoff, and groundwater recharge through negotiations and strategic partnerships with urban and agricultural interests (Hanak et al. 2011; Bland 2015; Hertel 2016). Conservation planners could identify these types of opportunities early in order to secure respective water sources for addressing future uncertainty in water supplies and avoiding growing competition for water. Funding is already limited (relative to the cost of water) to address current water-supply deficits for habitats (CVJV 2006), and projected increases in water demand relative to water supply based on scenarios (2–5) suggests an increase in the future cost of water. Thus, solutions that address future uncertainty likely will require additional funding and potentially new funding mechanisms (e.g., endowment funds) to develop alternative water supplies or purchase water.

**Research considerations**

Evaluating performance of potential conservation and climate adaptation strategies under future uncertainty may help guide the development of habitat conservation objectives robust to and compensating for projected habitat changes. Subsequent research evaluating future biological impacts of scenarios presented herein on waterbird populations could inform the extent to which other conservation strategies may be required. We suggest further research evaluating future impacts of scenarios on bioenergetics of waterbirds and ability of food resources to sustain waterbird population goals in the Central Valley, especially using bioenergetic models for waterfowl and shorebirds (see Miller et al. 2013; Petrie et al. 2016; Dybala et al. 2017).

We anticipate new water-supply management proposals, policies, actions for supporting growing human and aquatic ecosystem demands for water, and extensive agricultural land-use change. As demonstrated herein (i.e., Scenarios 10–17), our approach could be used to evaluate options for future water-supply management that might restrict the use of potential new (e.g., urban recycled or stormwater runoff), as well as existing, habitat water supplies. The approach could aid natural resource managers and conservationists to understand whether new or proposed supply management options present a threat to waterbird habitats, and the robustness of conservation strategies under future options. Our results indicated that an increase in competition for water from agriculture could substantially limit area of waterbird habitat (Scenarios 10–13). Permanent crops (e.g., orchards and vineyards) provide little habitat value to waterbirds and are much less likely to be fallowed during drought than annual crops (Howitt et al. 2015; Shuford and Dybala 2017). Thus, the conversion of annual crops to permanent ones would reduce the potential area of waterbird habitat, and during drought would likely increase the competition for water. Similar research is needed to evaluate the potential future reduction in valley waterbird habitat resulting from the expansion of permanent crops. Our modeling approach currently provides a tool to evaluate the potential effects of various water-supply management, land use changes, climate projections, and alternative conservation strategies on habitats for breeding and wintering waterbirds, and other wetland-dependent species in the valley.

**Supplemental Material**

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**Figure S1.** Box–whisker plots of available habitat area (km²) projected through years 2006–2099 for each of 17 scenarios and by habitat type, month of the continuous autumn migration–wintering period, and planning basin within the Central Valley of California. Habitat areas existing in year 2005 (for comparison with
scenarios) are represented by the horizontal blue dotted line. A limited area (420 ha) of permanent wetland in Sutter, American, and Delta basins are managed specifically for giant garter snake Thamnophis gigas, which is listed as “threatened” pursuant to the U.S. Endangered Species Act (ESA 1973, as amended). Therefore, we chose to present results for these specific wetlands (areas indicated in August and September for semipermanent wetlands), herein, to accommodate future analysis of scenario impacts on the biology of the giant garter snake. Scenarios consisting of various climate, urbanization, water management, and wetland restoration levels (see Table 1 for scenario descriptions). Central Valley planning basins included A. Colusa, B. Butte, C. Sutter, D. American, E. Yolo, F. Suisun, G. Delta, H. San Joaquin, and I. Tulare basins in the Central Valley of California. (Shaded box = 50% of years [horizontal line in box = median]; whiskers = 25% of years).

Found at DOI: http://dx.doi.org/10.3996/122016-JFWM-095.S1 (264 KB PDF).

Reference S1. Cayan DR, Tyree M, Dettinger MD, Hidalgo H, Das T, Maurer EP, Bromirski P, Graham N, Flick R. 2009. Climate change scenarios and sea level rise estimates for the California 2009 climate change scenarios assessment. Sacramento: California Energy Commission. Report CEC-500-2009-014-F.

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Reference S3. [EPA] U.S. Environmental Protection Agency, Global Change Research Program, National Center for Environmental Assessment. 2009. Land-use scenarios: national-scale housing-density scenarios consistent with climate change storylines. Washington, D.C.: Environmental Protection Agency. Report EPA/600/R-08/076F.

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Table A1. Comma-separated (CSV) text file containing data that summarize annual peak abundance (km²) of Central Valley flooded waterbird habitats (i.e., wetland and flooded cropland types) that are available between August and March (of the following year) for each of 17 projected scenarios (years 2006–2099) by planning basin, scenario, and habitat. Data represent the extent and frequency of annually available habitat areas that were used to graph box–whisker plots in Figures 2–4. We calculated the area of each habitat from the month when the area was typically the greatest during autumn–winter (January for wetlands, winter-flooded rice, and winter-flooded corn, and September for other winter-flooded cropland). Data columns are (a) scenario (descriptions correspond with combinations of variables in Table 1 herein), (b) scenario_num (Scenario number 1–17), (c) basin (Central Valley planning basin), (d) habitat (waterbird habitat), (e) month (August–April period), (f) existing_km2 (recent habitat representing a “snapshot” [approximately year 2005] of habitat areas unaffected by historical drought or scenario impacts and approximating fully available habitat in km²), (g) minimum_km2 (minimum available area of habitat [km²] for years in time series), (h) percentile25_km2 (value of available area of habitat [km²] ≥25% of years in time series), (i) quantile50_km2 (value of available area of habitat [km²] ≥50% of years in time series), (j) quantile75_km2 (value of available area of habitat [km²] ≥75% of years in time series), (k) maximum_km2 (maximum available area of habitat [km²] for years in time series).

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Table A2. Comma-separated (CSV) text file containing habitat areas projected through years 2006–2099 for each of 17 scenarios and by scenario, planning basin, habitat, and month representing values used to graph box–whisker plots in supplemental Figure S1. Columns are (a) scenario (descriptions correspond with combinations of variables in Table 1 herein), (b) scenario_num (Scenario numbers 1–17), (c) basin (Central Valley planning basin), (d) habitat (waterbird habitat), (e) month (August–April period), (f) existing_km2 (recent habitat representing a “snapshot” [approximately year 2005] of habitat areas unaffected by historical drought or scenario impacts and approximating fully available habitat in km²), (g) minimum_km2 (minimum available area of habitat [km²] for years in time series), (h) percenti-
le25_km2 (value of available area of habitat [km²] ≥ 25% of years in time series), (i) quantile50_km2 (value of available area of habitat [km²] ≥ 50% of years in time series), (j) quantile75_km2 (value of available area of habitat [km²] ≥ 75% of years in time series), (k) maximum_km2 (maximum available area of habitat [km²] for years in time series).

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