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RESEARCH

Wetland Availability and Salinity Concentrations for Breeding Waterfowl in Suisun Marsh, California

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ABSTRACT

Availability of wetlands with low salinities during the breeding season can influence waterfowl reproductive success and population recruitment. Salinities as low as 2 ppt (3.6 mScm^{-1}) can impair duckling growth and influence behavior, with mortality occurring above 9 ppt (14.8 mScm^{-1}). We used satellite imagery to quantify the amount of available water, and sampled surface water salinity at Grizzly Island, in the brackish Suisun Marsh, at three time-periods during waterfowl breeding (April, May, July) over 4 years (2016–2019). More water was available and salinity was lower during wetter years (2017, 2019) than during drier years (2016, 2018), and the amount of water in wetlands decreased 73%–86% from April to July. Across all time-periods and years, the majority (64%–100%) of wetland habitat area had salinities above what has been shown to negatively affect ducklings (> 2 ppt), and up to 42% of wetland area had salinities associated with duckling mortality (> 9 ppt). During peak duckling production in May, 81%–95% of available water had salinity above 2 ppt, and 5%–21% was above 9 ppt. In May of the driest year (2016), only 0.5 km^2 of low-salinity water (< 2 ppt) was available to ducklings in the study area, compared to 2.6 km^2 in May of the wettest year (2017). Private duck clubs own the majority of wetland habitat at Grizzly Island and consistently had a greater percentage of land flooded during summer than did publicly owned wetlands, but private wetlands generally had higher salinities than public wetlands, likely because they draw from higher-salinity water sources. By July, few wetlands remained flooded, and most had salinities high enough to impair duckling growth and survival. Local waterfowl populations would benefit from management practices that provide fresher water during peak duckling production in May and retain more water through July.

KEY WORDS

seasonal wetland, canal, salinity, waterfowl, duck, duckling, brood habitat, water management, Grizzly Island, conductivity

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INTRODUCTION

Wetlands provide critical ecosystem services, including habitat for many species (Williams and Dodd 1978; Wilen and Frayer 1990). Wetlands

are also among the habitats most vulnerable to anthropogenic change (Williams and Dodd 1978), with global wetland losses estimated as high as 87% (Davidson 2018). The largest loss of wetlands on the west coast of North America has occurred in California (Wilen and Frayer 1990), where wetlands have been reduced as a result of diking and drainage for agricultural use and other development, and diversion of freshwater inputs for consumption and irrigation (Nichols et al. 1986; Van Dyke and Wasson 2005). Wetlands are particularly important for migratory waterfowl, which rely on them for both wintering and breeding habitat. Maintaining sufficient wetland habitat to sustain abundant waterfowl populations will require coordination between public entities and private land owners (Brasher et al. 2019). Generally, wetland conservation and management for waterfowl has focused more on migration stop-overs and wintering habitat and less on the availability and quality of wetlands during the spring and summer breeding season.

Wetland habitat is important to breeding waterfowl during both the nesting and brood-rearing periods. Although dabbling ducks, such as mallard (*Anas platyrhynchos*) and gadwall (*Mareca strepera*), typically nest in upland habitat, hens take daily incubation breaks to forage in nearby wetlands and may also assess those wetlands as future brood-rearing sites (Casazza et al. 2020; Croston et al. 2020; Croston et al. 2021). Shortly after hatch, hens move ducklings to nearby wetland habitat suitable for brood rearing (Mauser et al. 1994a; Peterson et al. 2019). The accessibility and quality of available wetland habitats are important factors that influence duck reproductive success (Mauser et al. 1994b). For example, duckling survival is positively related to the area of available wetland habitat (Krapu et al. 2006; Amundson and Arnold 2011). In some cases, low water levels may force hens and ducklings to travel farther over land from the nest site to brooding habitat, potentially increasing duckling exposure to predators (Krapu et al. 2006). Furthermore, ducklings require water of relatively low salinity. Salt glands allow ducks to excrete excess salt ingested in drinking water (Cooch 1964); however, their salt glands are not fully functional until approximately 6 days post-hatch (Ellis et al. 1963; Riggert 1977). Therefore, younger ducklings are particularly vulnerable to high salinity levels in surface waters (Schmidt–Nielsen and Kim 1964; Moorman et al. 1991). Even sea ducks require fresh drinking water when first hatched (DeVink et al. 2005). Salinity concentrations as low as 2 ppt can impair duckling growth and influence behavior, with lethal effects occurring above 9 ppt (Krista et al. 1961; Schmidt–Nielsen and Kim 1964; Swanson et al. 1984; Mitcham and Wobeser 1988a,b; Barnes and Nudds 1991; Moorman et al. 1991; Stolley and Meteyer 2004; DeVink et al. 2005).

California breeding sites produce a large proportion of the dabbling ducks within the Pacific Flyway, and account for 60% of mallard, 53% of cinnamon teal (*Spatula cyanoptera*), and 49% of gadwall harvested by hunters in California (de Sobrino et al. 2017). Suisun Marsh, in the Sacramento–San Joaquin Delta, is one of the largest contiguous brackish marshes in the western US and contains 12% of the remaining natural wetlands in California (Ackerman et al. 2014b). It is an important migratory stop-over site along the Pacific Flyway and provides wintering habitat for more than 60,000 waterfowl every year (Ackerman et al. 2014b), although numbers remain well below Central Valley Joint Venture Implementation Plan peak population objectives (CVJV 2020). Suisun Marsh also provides important breeding habitat for dabbling ducks, with nesting densities among the highest in California (McLandress et al. 1996; Ackerman et al. 2014b). However, local mallard, gadwall, and cinnamon teal breeding populations are 61% below the CVJV objective (CVJV 2020). Suisun Marsh is a highly managed system of natural wetlands, most of which are diked and managed as seasonal wetlands adjacent to tidal marsh habitats. The amount of water and salinity concentrations vary, depending on the net outflow of freshwater from the Delta to the San Francisco Bay, and the decisions of local water managers. Salinity concentrations in Suisun Marsh are monitored and managed to meet legally mandated salinity standards based on time of year (higher salinity concentrations are

allowed in summer and fall, lower concentrations in winter) and drought conditions (SWRCB 2018). Within Suisun Marsh, approximately 50% of the seasonal wetland habitat is located on Grizzly Island and the adjacent areas south and west of Montezuma Slough (hereafter "Grizzly Island"; Figure 1). The habitat at Grizzly Island is managed for a number of purposes (details below), but the maintenance of spring/summer wetland habitat for waterfowl breeding has generally not been a priority.

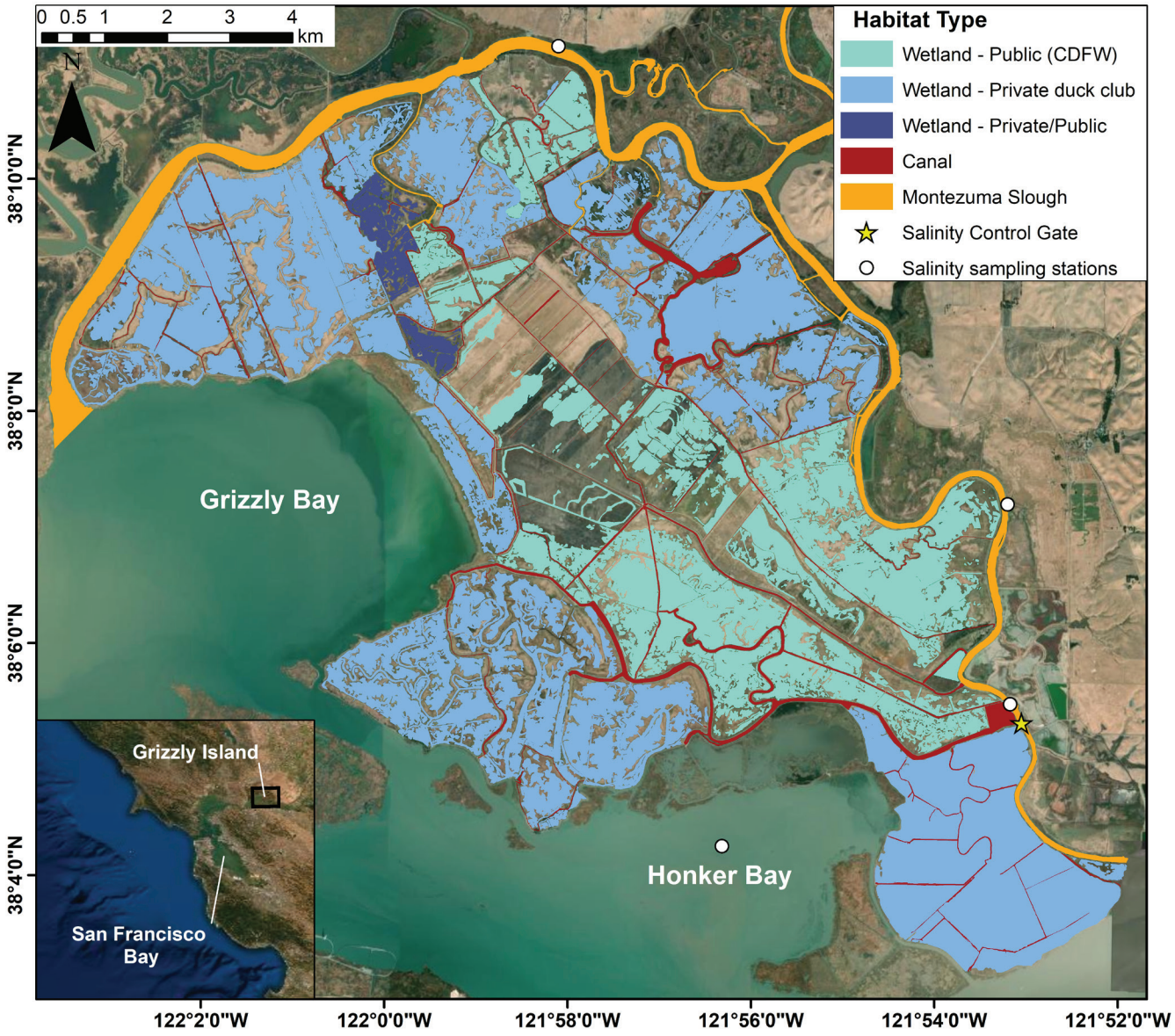

Figure 1 Study area map showing total maximum water extent (April–July) for each wetland unit over the course of the study (2016–2019). Wetland units are color-coded to show ownership (private vs public [California Department of Fish and Wildlife: CDFW]). Private/Public units were private in 2016–2017 and changed to public ownership in 2018–2019. Montezuma Slough and connected smaller sloughs (*orange*) and canals (*red*) are also shown, as well as the location of the California Department of Water Resources (CDWR) Salinity Control Gate (*star*). CDWR salinity sampling stations (CDEC 2020) are marked with *white circles* (three in Montezuma Slough, and one in Honker Bay). *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

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Our objectives for this study were to: (1) quantify the amount of water available to breeding waterfowl during the spring and summer at Grizzly Island, and investigate how water availability varies among years and over the course of the waterfowl breeding season; (2) determine the salinity concentrations of available water at Grizzly Island, and assess if salinity could affect ducklings; and (3) compare salinity concentrations and availability of water in publicly- and privately-owned wetlands. To do this, we used satellite imagery to delineate water present within seasonal wetlands during the waterfowl breeding season in each of three time-periods (April to July) for 4 years (2016 to 2019). We also measured salinity at 191 wetlands and canals at Grizzly Island during the same time-periods and years.

MATERIALS AND METHODS

Study Area

Grizzly Island (38°09′N, 121°58′W; Figure 1) is located in the center of Suisun Marsh, California, and comprises a mosaic of managed wetlands and upland habitat on both privately- and publicly-owned land (McLandress et al. 1996; Ackerman et al. 2003a). Montezuma Slough is a horseshoe-shaped channel that separates Grizzly Island from the mainland and is the primary source of water for wetlands (Figure 1). The eastern end serves as an input to Suisun Marsh, with freshwater from the Sacramento and San Joaquin rivers; the western end provides more saline water, from Grizzly Bay (Figure 1). Much of the island was diked and drained for agricultural purposes in the mid-1800s, but high soil salinity made cultivation difficult, and parcels are now owned and managed primarily by private duck-hunting clubs and the state of California. Freshwater flow into Suisun Marsh has been altered extensively since the 1930s as a result of the development of the federal Central Valley Project and the State Water Project, which resulted in increased upstream diversions (Kimmerer 2002). On public land, the California Department of Fish and Wildlife (CDFW) manages the Grizzly Island Wildlife Area and focuses on providing habitat for resident and migratory wildlife populations, public access, and hunting opportunities. Wetland habitat for over-wintering waterfowl is a priority, as is upland habitat for spring- and summer-nesting waterfowl, pheasants, and elk calving, and the maintenance and operation of water-delivery infrastructure for seasonal wetlands. Private land management, with the assistance of the Suisun Resource Conservation District (SRCD), focuses on providing wetland habitat for migrating and wintering waterfowl during the hunting season (October–January), after which the diked wetlands must be drained and flushed to reduce salt accumulation in the soil, and promote the growth of food plants for waterfowl as part of moist soil seasonal wetland management practices (Ackerman et al. 2014b). However, many private duck-hunting clubs lack sufficient resources and/or water control infrastructure to adequately drain or pump out the remaining high-salinity water applied in October.

Study Design

We divided the waterfowl breeding season into three time-periods to capture the full range of conditions experienced by nesting ducks (Table 1):

1. April (sampling from approximately April 4 to April 13): early nesting season, with 13% of nests initiated by April 8 (Ackerman et al. 2003a, 2003b; Ackerman et al. 2020, unpublished data, see “Notes”);

2. May (sampling from approximately May 14 to May 25): middle of the nesting season and onset of peak duckling production, with 77% of nests initiated and 22% of nests hatched by May 19 (Ackerman et al. 2003a, 2003b; Ackerman et al. 2020, unpublished data, see “Notes”)

3. July (sampling from approximately July 9 to July 20): late nesting season, with 100% of nests initiated and 98% of nests hatched by July 14, but most ducklings not yet fledged (Ackerman et al. 2003a, 2003b; Ackerman et al. 2020, unpublished data, see “Notes”).

During each time-period, we sampled surface water salinity in as many accessible bodies of

Table 1 Dates for seasonal conductivity sampling and corresponding satellite imagery used to delineate available water within Suisun Marsh, California

Year and time-period	Dates of conductivity sampling	Dates of satellite imagery used to delineate water	Dates of Landsat imagery used to validate open water
2016			
April	NA	April 15, April 20[a]	March 3
May	May 13–June 16	June 1	May 10, May 26
July	June 21–July 29	July 10[a], July 14	July 13, Aug 14
2017			
April	March 27–April 18	April 10, April 14[a]	April 27
May	May 17–June 29	May 17	May 13, June 14
July	July 14–July 21	July 13	July 16
2018			
April	April 2–April 13	April 2[a], April 13	April 14
May	May 13–May 24	May 18, May 21[a]	June 1
July	July 9–July 20	July 16, July 19[a]	July 19, August 4
2019			
April	April 3–April 17	April 14	April 17
May	May 11–May 25	May 5, May 12[a]	June 4
July	July 8–July 19	July 15	July 22

a. Primary imagery used.

water as possible. Rainfall data from the study period (total precipitation October 1 to April 30 at the Fairfield and Napa weather stations; CDEC 2020) showed that our study occurred during 2 relatively dry years (even years: 2016 and 2018) and 2 relatively wet years (odd years: 2017 and 2019), with local rainfall in the 2 wetter years averaging 72% higher than that in the drier years (CDEC 2020).

To determine areas used (and not used) by waterfowl and ensure appropriate sampling locations for water salinity levels, we mapped nest locations, and tracked breeding hens and ducklings. We used standard nest-searching techniques, modified from McLandress et al. (1996), to find mallard, gadwall, and cinnamon teal nests in upland habitat from March to July during 2016 to 2019. We recorded GPS coordinates for all nests found (1,232 mallard, 1,001 gadwall, and 78 cinnamon teal). We used GPS–GSM transmitters (Ecotone GPS-GSM SAKER L [Ecotone Telemetry, Gdynia, Poland] and Ornitela Ornitrack 15 [Ornitela, Vilnius, Lithuania] transmitters; details in Casazza et al. 2020) to track 172 hens (82 mallard, 65 gadwall, and 25 cinnamon teal) from April to June during 2016 to 2019. GPS–GSM tags transmit location data over the GSM (Global System for Mobile Communications) cellular network. We included only location data from hens during the breeding season in which they were captured and tagged on the nest (known breeders). We began monitoring hen movement as soon as they were tagged (13 Apr–22 June); however, to be conservative and ensure that hen locations represented use of wetlands during the breeding season, we excluded all locations after 28 June, when only 10% of radio-marked ducklings remained alive at Grizzly Island (Ackerman et al. unpublished data).

We also radio-marked and tracked a total of 563 ducklings (365 mallard and 198 gadwall) from 287 broods from April to July during 2016 to 2019. To do so, we attached very high-frequency (VHF) radio transmitters (model BD-2T, Holohil Systems, Ontario, Canada) to two ducklings in each brood immediately after hatch and before leaving the nest, following a similar protocol to Ackerman et al. (2014a). We tracked radio-marked ducklings daily (with a few exceptions) using a truck with a dual 4-element Yagi null-peak antenna system (AVM Instrument Co., Livermore, CA, USA). Each time a duckling was located, we obtained three bearings and used triangulation software (Location of a Signal, version 3.0.1, Ecological Software Solutions, Urnäsch, Switzerland) to calculate Universal Transverse Mercator (UTM) coordinates (e.g., Takekawa et al. 2002; Ackerman et al. 2006). We also tracked radio-marked ducklings using fixed-wing aircraft with dual side-view 4-element Yagi antennas and a left–right control box (Advanced Telemetry Systems, Inc., Isanti, MN, USA; Gilmer et al. 1981). Here, we included only locations of live ducklings (determined based on movement and data from thermistors built into the tags, verified visually if ambiguous).

Wetland Area

For the purposes of this study, wetland units consisted of seasonal or permanent non-tidal

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bodies of standing water, and included within the wetland any ditches that were within the maximum water extent of the wetland and would overflow into the wetland at high water levels and dry out at low water levels. Wetted area refers specifically to the amount (km^2) of visible surface water present in these wetland units, which changes within and among years. Canals were defined as water transportation ditches along the outside of or in between wetlands that were larger and were more permanent. We did not differentiate between water supply ditches and drainage ditches, but supply ditches generally have lower salinity concentrations than drainage ditches. We used four data sources to delineate wetted habitat at Grizzly Island.

- First, we used multi-spectral satellite imagery (RapidEye and PlanetScope) from the Planet Open California Data portal (Planet Team 2017) and visually interpreted the satellite imagery, outlining any visible water in ArcGIS 10.5.0 (Environmental Systems Research Institute, Redlands, CA, USA).

- Second, we used both an open-water raster layer derived from Landsat 8 imagery (Reiter et al. 2015; Point Blue 2020) and lower-resolution multi-spectral Sentinel satellite imagery (Copernicus 2020) obtained through the USGS Earth Resources Observation and Science Center (EROS) as a validation for our water delineation. Because of a gap in coverage from other sources, we relied primarily on Sentinel data (Copernicus 2020) for a section of the study area in April 2016.

- Third, we added narrow linear habitat features (canals)—such as channels that transport water throughout Grizzly Island—to the layer. These narrow features are less detectable in satellite imagery because the satellite-derived imagery had a pixel size of 6.5 m (RapidEye–Planet Team), 3.7 m (PlanetScope–Planet Team), 30 m (Point Blue), and 20 m (Sentinel). Consequently, we extracted previously digitized water channels (i.e., fluvial ditches and fluvial channels) and sloughs from the Bay Area Aquatic Resources Inventory base map for Grizzly Island (San Francisco Estuary Institute and Aquatic Science Center 2017).

- Fourth, we used local expertise and ground truthing by our field staff to add additional smaller channels that were not previously mapped, but which often contain water during April through July. The water channel layer was then merged with the satellite-derived visible water layer to provide a layer of wetted habitat (UTM Zone 10 projection). We repeated this process for each of the three-time periods (April, May, and July; defined above) from 2016 to 2019, using the clearest available imagery from within (or as close as possible to) the water sampling time-period for that year (Table 1). For general mapping purposes, we merged all the seasonal shapefiles to create one layer that showed the total maximum water extent across the 4 years of the study (Figure 1). We used this layer to calculate the total area potentially available for wetland habitat (not including canals) during the study.

When digitizing wetted habitat, we used aerial imagery, local expertise, and land ownership divisions (i.e., CDFW wetland units and SRCD units for private duck-hunting clubs; Figure 1) to separately identify the individual wetlands and canals within Grizzly Island. We labeled each wetland unit and canal with a unique identifier, which was associated with each data point within that unit (see below). For analyses, we categorized canals based on canal width: small (< 10 m), medium (10 to 20 m), or large (> 20 m), and we categorized wetlands based on whether they were privately owned (managed by private duck-hunting clubs in partnership with the SRCD) or publicly owned (managed by the CDFW).

Salinity Sampling

To quantify the salinity of water available to waterfowl at Grizzly Island during the breeding season, we selected monitoring sites in as many accessible bodies of water (wetland and canals) as possible, adding additional sites in each year of the study if new areas were flooded (314 sampling sites in 2016, 380 in 2017, 414 in 2018, 457 in 2019). We chose monitoring sites that were in

open water, obviously contiguous with the main body of water, accessible from the shoreline, and deep enough to insert the probe (see below). These repeatedly-sampled sites encompassed 191 uniquely identified bodies of water. Whenever possible, larger bodies of water were sampled at multiple sites to ensure that data were representative of that body of water. We measured conductivity and temperature at each of these sites during each of three time-periods in every year (Figure 1; Table 1), unless the site was dry or otherwise inaccessible during that period. We also included some opportunistic measurements associated with duckling observations. These measurements did not necessarily fall within our defined sampling periods (Table 1), but were included when taken within 7 days of those sampling periods if there would otherwise be no measurements for a particular body of water during that time-period.

We measured conductivity ($mS\,cm^{-1}$) and temperature (°C) in surface water using a FieldScout Direct Soil EC Meter probe (Spectrum Technologies Inc, Aurora, IL, USA), calibrated at least once a month using a standard solution ($2.76\ mS\,cm^{-1}$). For bodies of water with conductivity $< 2\ mS\,cm^{-1}$, we re-calibrated the probe to a lower standard ($1.41\ mS\,cm^{-1}$) to maintain accuracy. Samples with conductivity above $19.99\ mS\,cm^{-1}$ were diluted with deionized water (volumes and ratio recorded) and re-measured, and the actual conductivity value was calculated based on the dilution. We rinsed the probe with deionized water and then dried the probe between each sample. At each sampling location we also recorded the precise location, in UTM coordinates, using hand-held GPS units (Garmin Ltd, Schaffhausen, Switzerland). Each sample was associated to a specific wetland or canal. In cases where a wetland unit had no visible water in satellite imagery, but we measured conductivity and temperature—indicating that water was present when the measurement was taken—we included a 3-m × 3-m square around the sample point in the digitized GIS layer to indicate water presence that was not able to be seen within the satellite imagery, which had a best-case precision of 3.7-m (see "Wetland Area," p. 5).

We calculated the salinity concentration (ppt) for each sample, using paired conductivity and temperature measurements and the formulas in Fofonoff and Millard (1983). When multiple measurements were taken in the same unit during a time-period, we calculated the arithmetic mean for that unit, which was used for visualization and analysis. To determine the change in salinity concentration in wetlands over the course of the breeding season, we calculated the absolute change in salinity concentration within each individual unit between April and July. These calculations excluded any units for which we did not have salinity measurements during both time-periods (e.g., any units that dried out completely by the July sampling time-period).

To determine biologically relevant salinity benchmarks for data visualization and analysis, we conducted a literature review of experimental studies that tested the effects of various salinity concentrations on duckling growth and survival (Krista et al. 1961; Schmidt–Nielsen and Kim 1964; Swanson et al. 1984; Mitcham and Wobeser 1988a, 1988b; Barnes and Nudds 1991; Moorman et al. 1991; Stolley and Meteyer 2004; DeVink et al. 2005). Based on the literature, we defined the following six categories of salinity concentrations associated with negative effects on ducklings. Because salinity objectives used by managers in Suisun Marsh are expressed in terms of conductivity, rather than salinity, we provide approximate conversions (in parentheses below) based on the mean temperature of sampled wetlands in May (23 °C).

1. < 2 ppt ($3.6\ mS\,cm^{-1}$): no detectable negative effects on growth or survival;

2. 2–6 ppt ($3.6–10.1\ mS\,cm^{-1}$): sub-lethal effects, including reduced growth rates, reduced feather growth, and delayed molt to juvenile plumage;

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3. 6–9 ppt (10.1–14.8 mS cm^{-1}): sub-lethal effects, including severely impaired growth and lethargy;

4. 9–12 ppt (14.8–19.2 mS cm^{-1}): sub-lethal effects on growth and some observed mortality;

5. 12–21 ppt (19.2–32.1 mS cm^{-1}): higher incidence of mortality; and

6. > 21 ppt (32.1 mS cm^{-1}): typically rapid mortality.

Statistical Analysis

We conducted two separate sets of statistical analyses to assess the factors influencing (1) the amount of available water, and (2) the salinity concentration of available surface water. We conducted all analyses in the program R v. 3.6.0 (R Core Team 2019). We examined wetted area by year, time-period, and ownership type (public versus private) using general linear models, where area of water was summed across all wetland units within each time-period and year for each ownership type (n = 24). The model included fixed effects for time-period, year, and ownership. Because of the small sample size, we approached the interaction effects hierarchically, testing each two-way interaction separately, starting with the most biologically relevant interaction of time-period × year. We made pairwise comparisons within each factor using least squares means (R package *emmeans*, Lenth 2020). Canals were assumed not to change substantially in area over time, and therefore were not included in wetland area summaries or analysis.

We used linear mixed effects models (R package *lme4*, Bates 2015) with restricted maximum likelihood, Type II Wald F-tests and Kenward–Roger degrees of freedom (R packages *car*, Fox and Weisberg 2019; *afex*, Singmann et al. 2020) to examine patterns in the salinity concentration of wetlands, with year, time-period, ownership, and a year × time-period × ownership interaction as fixed effects and wetland unit identification as a random effect to account for repeated sampling of the same body of water. The distribution of salinity data was highly skewed, so we $\log_e$-transformed salinity concentrations before analysis. We used the model to make best linear unbiased predictions (Henderson 1975) for each wetland unit in each time-period and year. We then back-transformed the predicted values. Because large wetland units provided more duckling habitat than small units, we calculated weighted averages and variances for each ownership type in each time-period and year, using wetted area as a weighting factor, and conducted planned *a priori* pairwise comparisons of the weighted averages using Welch's *t*-tests for unequal variance (R package *BSDA*, Arnholt and Evans 2017). This approach slightly underestimates the variance used in our statistical comparisons, since it incorporates only the among-unit variance, not the within-unit variance inherent in the best linear unbiased predictions. The magnitude of the within-unit variance would be small relative to the among-unit variance, but this limitation should be considered when interpreting the results.

We ran a comparable model to examine the salinity concentration of canals, with time-period, year, size (small, medium, and large canals), and a year × time period × size interaction as fixed effects and canal identification as a random effect. Unlike wetlands, canals of any size provided suitable duckling habitat only at the edges; the majority of the surface area of larger canals consisted of deep water with no emergent vegetation. Therefore, we did not use weighted averages for the canal model. Where interaction effects were significant, we conducted planned *a priori* pairwise comparisons using least squares means. Model-estimated least squares means were back-transformed for figures and summary tables, with standard errors derived using the delta method (Seber 1982).

For comparison with wetlands and canals, we used the California Department of Water Resources (CDWR) conductivity and temperature data (CDEC 2020) from three fixed sampling stations in Montezuma Slough downstream of the Salinity Control Gates (Montezuma Slough at Roaring River, National Steel, and Beldon Landing, which are 0.4 km, 4.4 km, and 18.6 km

downstream of the Salinity Control Gates, respectively), and one station in Honker Bay (CDEC 2020; Figure 1). To ensure comparability with our data, we used only measurements taken during the day (0700–1700 hours) within the same time-periods described above (Table 1). Because most wetland managers can only draw water from the slough at higher tides (when salinity concentrations in the slough are also higher because of bay-water intrusion), we further limited the Montezuma Slough data to measurements taken within 1 hour of the daytime high tide (as measured at each of these three stations). For the slough, we calculated means using a similar method as the canal model above, treating each sampling station as a unit. For the bay, we calculated the arithmetic mean within the single sampling station for each time-period.

RESULTS

Monitored nests were concentrated in the upland habitat in the center of Grizzly Island, and duckling habitat use was primarily in wetted habitat close to the nesting habitat (Figure 2). GPS-marked hens used nearby wetland habitat and canals as well. Within wetland and canal habitat (excluding locations in upland habitat), 96.9% of duckling locations and 96.0% of hen locations were in units that we sampled for salinity at least once. The large wetlands (8.9 km^2) on the south side of the island that we were unable to sample were not used by tagged ducklings during the study period and were used only minimally by GPS-tagged hens (2.3% of tagged hens; Figure 2). Therefore, we were confident that the wetlands and canals we sampled for salinity concentrations represented those available to and used by the majority of ducklings each year.

Wetland Area

The total area of Grizzly Island potentially available as wetland habitat (covered by water at some point between April and July of 2016 to 2019 and excluding tidal marshes, lagoons, and canals) was 64.0 km^2 (Figure 1). In 2016 and 2017, 29.5% of this area was owned and managed by the state of California (public) and 70.5% by private duck clubs (Figure 1). As a result of the transfer of some parcels from private to public ownership in 2018, publicly-owned wetland area increased to 31.6% for 2018 and 2019. There was no significant

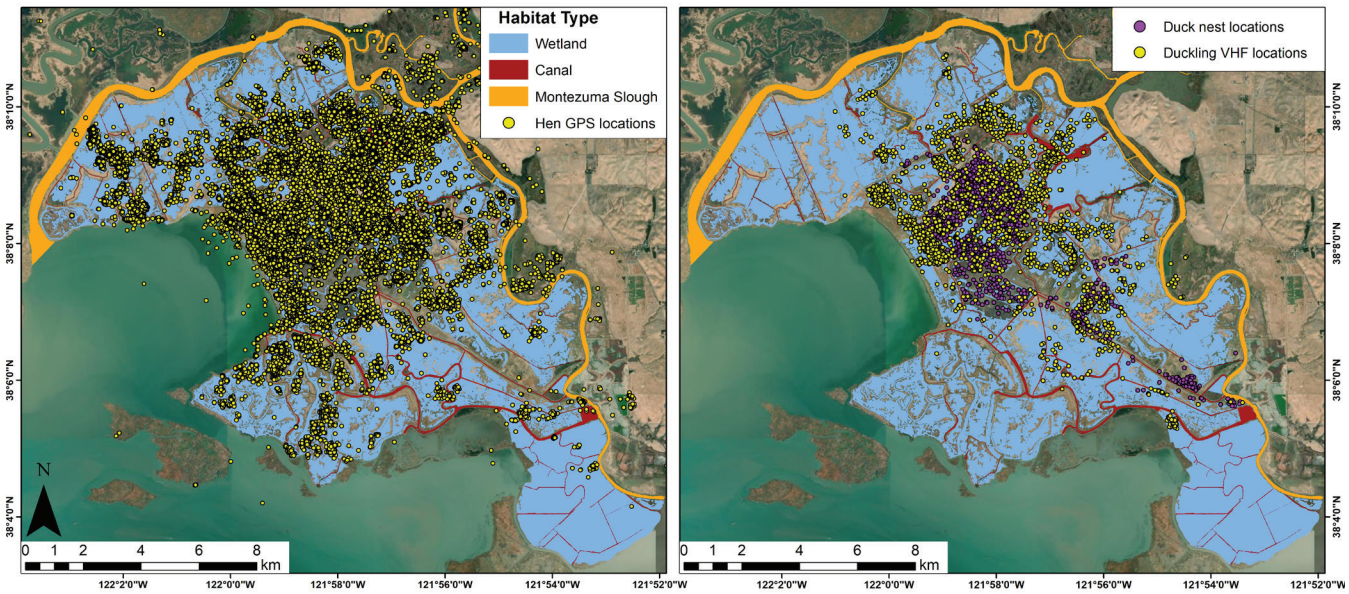

Figure 2 Duck use of Grizzly Island within Suisun Marsh, California during 2016–2019, overlaid on habitat type (total maximum water extent). **Left:** GPS locations of hens captured on the nest during the nesting and brooding period (April–June). **Right:** Locations of monitored duck nests and locations of live, radio-marked (VHF) ducklings. All data are specific to the study period (2016–2019). *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

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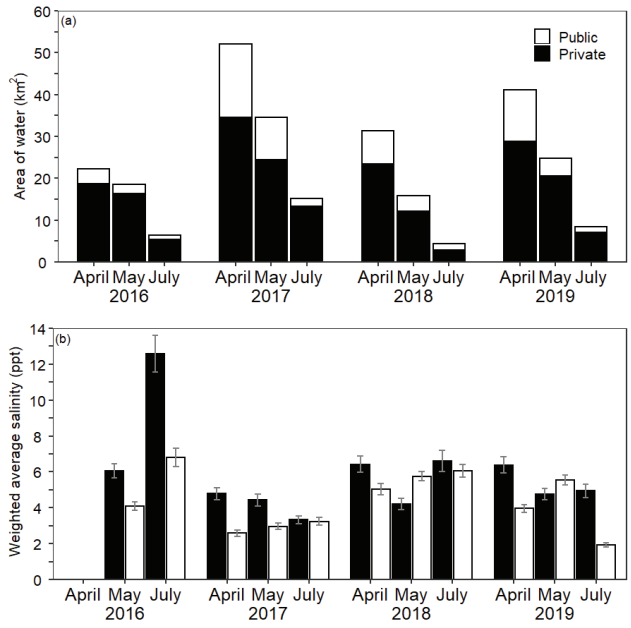

Figure 3 (**A**) Wetted area of wetland habitat (raw data) and (**B**) weighted average salinity (model-estimated) of public (*open bars*) and private (**filled bars**) wetlands at Grizzly Island within Suisun Marsh, California during 2016–2019. Salinity was not sampled in April 2016. Error bars represent standard errors based on weighted variance.

interaction effect of time-period × year ($F_{6,11} = 0.8$, $p = 0.59$), or ownership × year ($F_{3,14} = 0.7$, $p = 0.59$). The time-period × ownership interaction was significant ($F_{2,15} = 7.4$, $p < 0.01$), so we proceeded with a model that included only that two-way interaction. There was a significant main effect of year ($F_{3,15} = 7.4$, $p < 0.01$). Main effects of time-period ($F_{2,15} = 15.8$, $p < 0.001$) and ownership ($F_{1,15} = 108.3$, $p < 0.001$) were also significant, but could not be interpreted in isolation because of the significant interaction. Detailed results for least squares means comparisons are provided in Table A1.

Year

The total wetted area of wetland habitat at Grizzly Island in April was largest in 2017 (52.1 km^2), followed by 2019 (41.2 km^2), 2018 (31.3 km^2), and 2016 (22.4 km^2). Wetted area (averaged across time-period and ownership) was significantly greater in the wettest year (2017) than in the 2 driest years. Specifically, wetted area in 2017 was 115.2% greater than in 2016 ($t_{15} = 5.7$, $p < 0.001$; Figures 3A, 4, 5) and 97.7% greater than in 2018 ($t_{15} = 8.4$, $p < 0.001$; Table 2, Figures 3A, 4, 6). Wetted area in 2019 was not significantly different from other years (Table A1), although it was marginally lower than 2017 ($t_{15} = 4.5$, $p = 0.053$) and greater than 2016 ($t_{15} = 4.5$, $p = 0.054$).

Time-Period

When averaged across years, wetted area decreased by 86.0% (8.9 km^2) in publicly-owned wetlands ($t_{15} = 4.6$, $p < 0.001$; Figures 3A, 4–7, 8, A1) and 72.7% (19.2 km^2) in privately-owned–wetlands ($t_{15} = 1.8$, $p < 0.001$; Figures 3A, 4–7, 8, A1) over the course of the waterfowl breeding season (April to July). The lack of a significant interaction effect of time-period × year ($F_{6,11} = 0.8$, $p = 0.59$) shows that although there was generally less water in dryer years than in wetter years, the seasonal pattern within years did not differ.

Ownership

For any given time-period and year, 77.9% ± 8.2% (mean ± SD) of the wetted area was privately-owned and 22.1% ± 8.2% was publicly-owned (Table 2). Privately-owned wetlands had significantly larger wetted area than publicly-owned wetlands in all time-periods ($t_{15} > 2.9$, $p < 0.01$; Table A1). Availability of potential wetland habitat was greater on private land than on public land during the spring and summer breeding season, so those differences do not necessarily reflect differences in management. However, 38.9% ± 21.6% of the potentially available wetland habitat on private land was covered in water, compared to 28.8% ± 27.5% on public land.

The seasonal decrease (in terms of percent of water lost) in wetted area from April to July was similar for private and public lands in drier years (2016: 71.2% and 69.5%, respectively, and 2018: 87.5% and 81.4%, respectively), but the water available on private lands decreased proportionally less than on public lands in wetter years (2017: 61.3% vs. 89.6% and 2019: 75.2% vs. 88.8%). By July, < 2 km^2 of water was available to ducklings in publicly-owned wetlands, whereas privately-owned wetlands provided 2.9 km^2 to 5.4 km^2 in drier years and 7.1 km^2 to 13.4 km^2 in wetter years (Table 2).

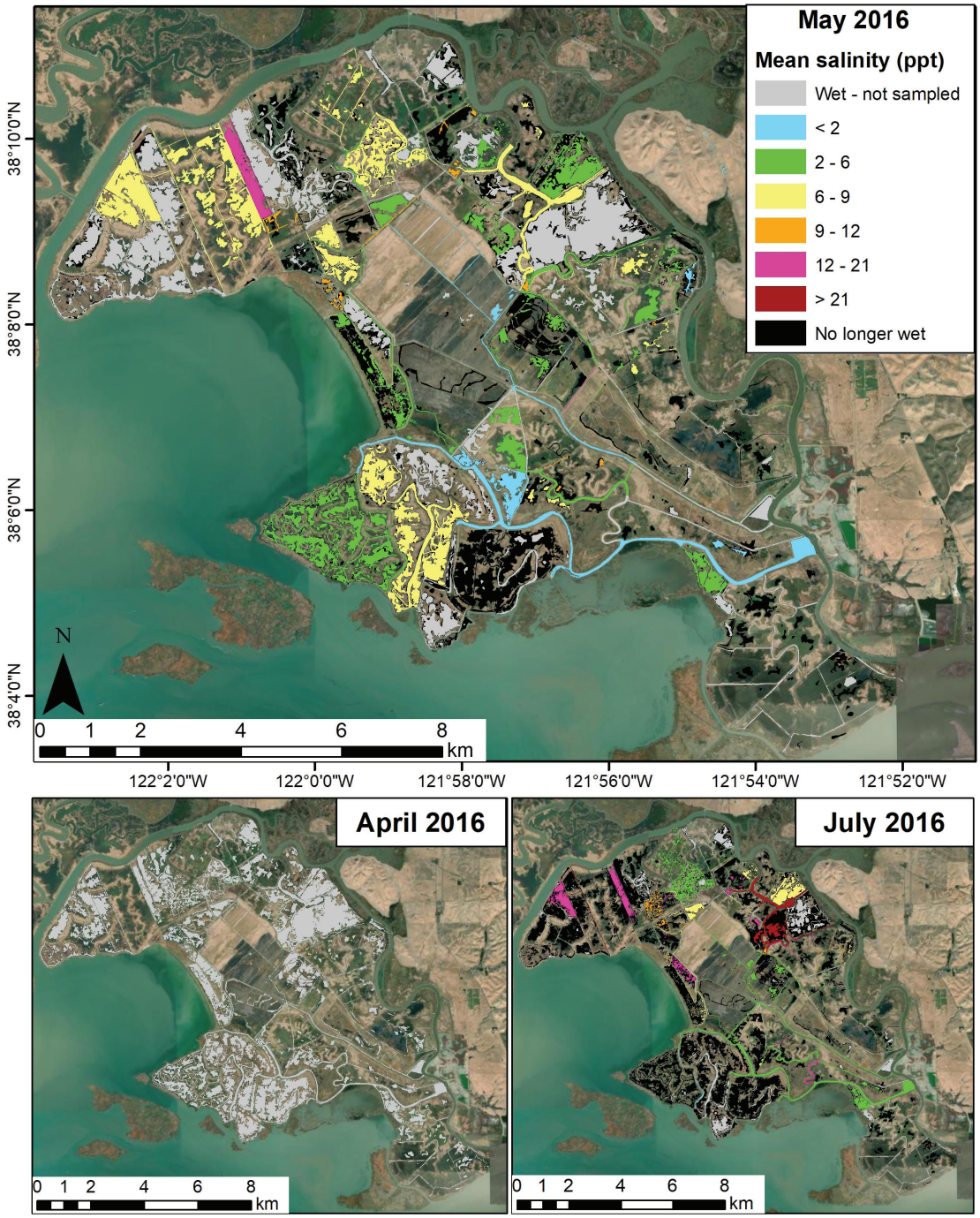

Figure 4 Seasonal extent of wetted areas in wetlands and canals, and mean salinity concentration of sampled bodies of water at Grizzly Island within Suisun Marsh, California during 2016. Sampling dates are provided in Table 1. Salinity concentrations were divided into categories based on studies that tested the effects of salinity on duckling growth and survival: ranging from no detectable negative effects (< 2 ppt) to rapidly lethal effects (> 21 ppt), with the severity of effects increasing with each colored bin (*see references cited in "Materials and Methods" in the text*). Areas in *black* were wet earlier in the breeding season (April or May) but dried up later in the season (May or July), thus providing no habitat for ducklings. *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

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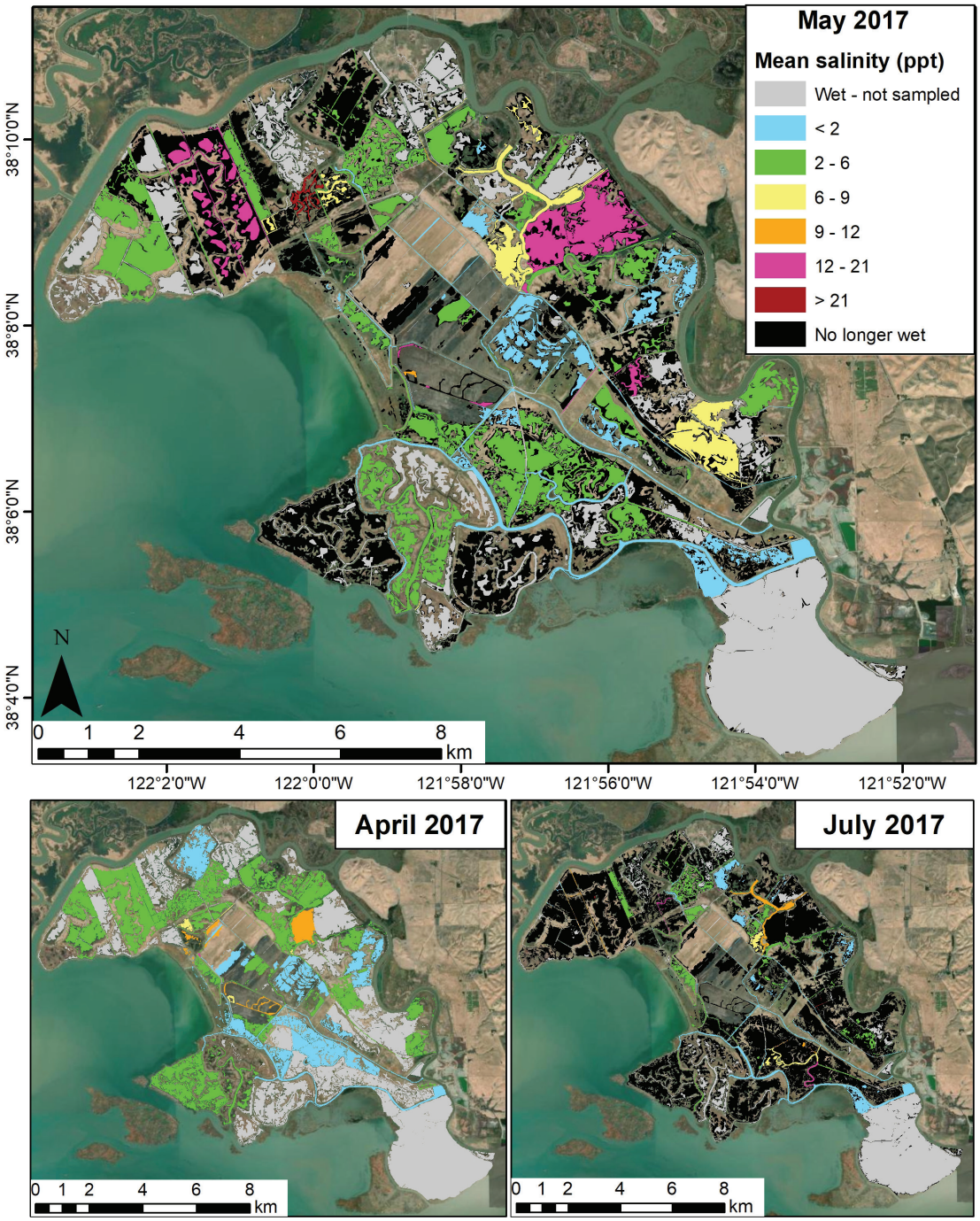

Figure 5 Seasonal extent of wetted areas in wetlands and canals and mean salinity concentration of sampled bodies of water at Grizzly Island within Suisun Marsh, California during 2017. Sampling dates are provided in Table 1. Salinity concentrations were divided into categories based on studies that tested the effects of salinity on duckling growth and survival: ranging from no detectable negative effects (< 2 ppt) to rapidly lethal effects (> 21 ppt), with the severity of effects increasing with each colored bin (*see references cited in "Materials and Methods" in the text*). Areas in black were wet earlier in the breeding season (April or May) but dried up later in the season (May or July), thus providing no habitat for ducklings. *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

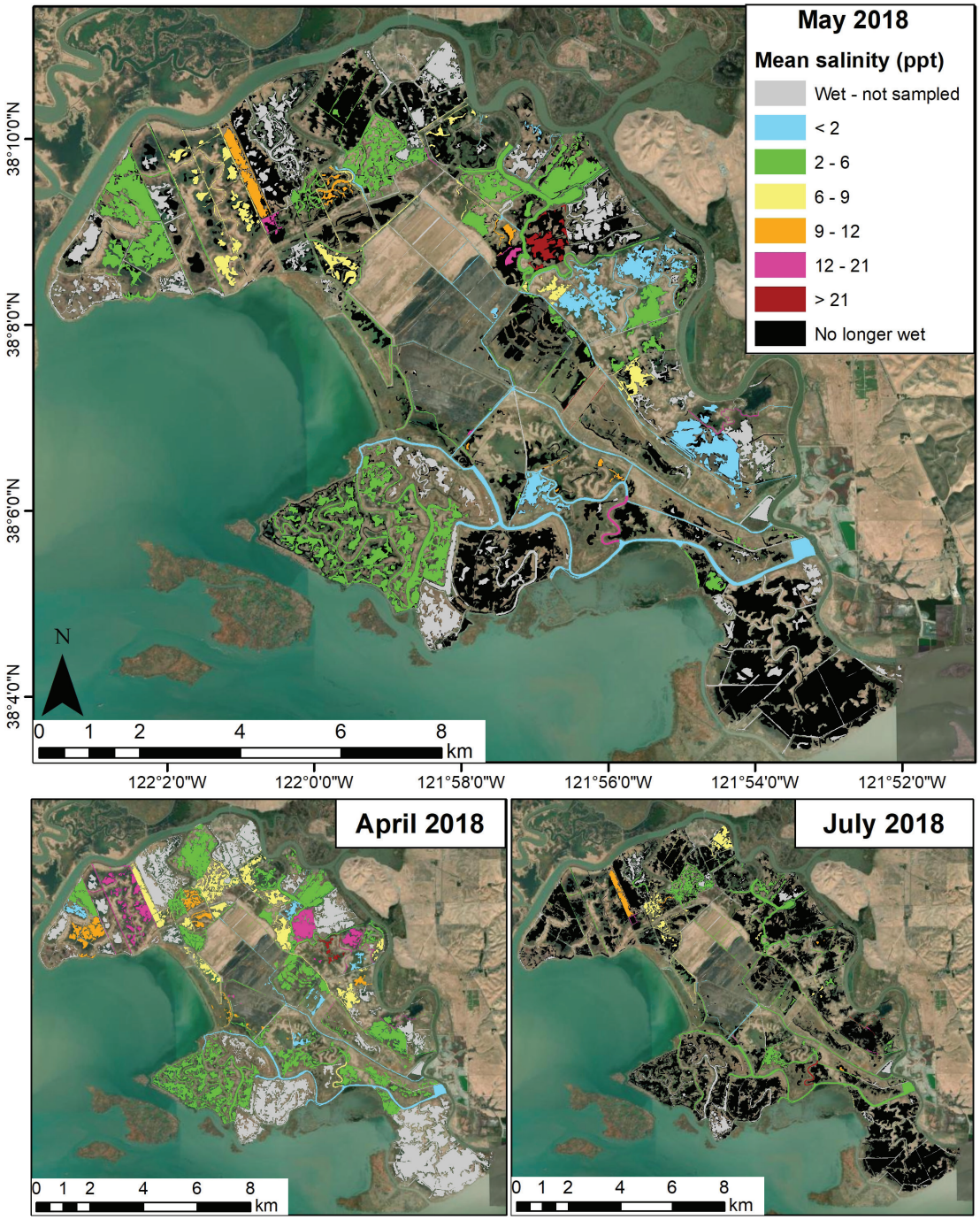

Figure 6 Seasonal extent of wetted areas in wetlands and canals, and mean salinity concentration of sampled bodies of water at Grizzly Island within Suisun Marsh, California during 2018. Sampling dates are provided in Table 1. Salinity concentrations were divided into categories based on studies that tested the effects of salinity on duckling growth and survival: ranging from no detectable negative effects (< 2 ppt) to rapidly lethal effects (> 21 ppt), with the severity of effects increasing with each colored bin (*see references cited in "Materials and Methods" in the text*). Areas in *black* were wet earlier in the breeding season (April or May) but dried up later in the season (May or July), thus providing no habitat for ducklings. *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

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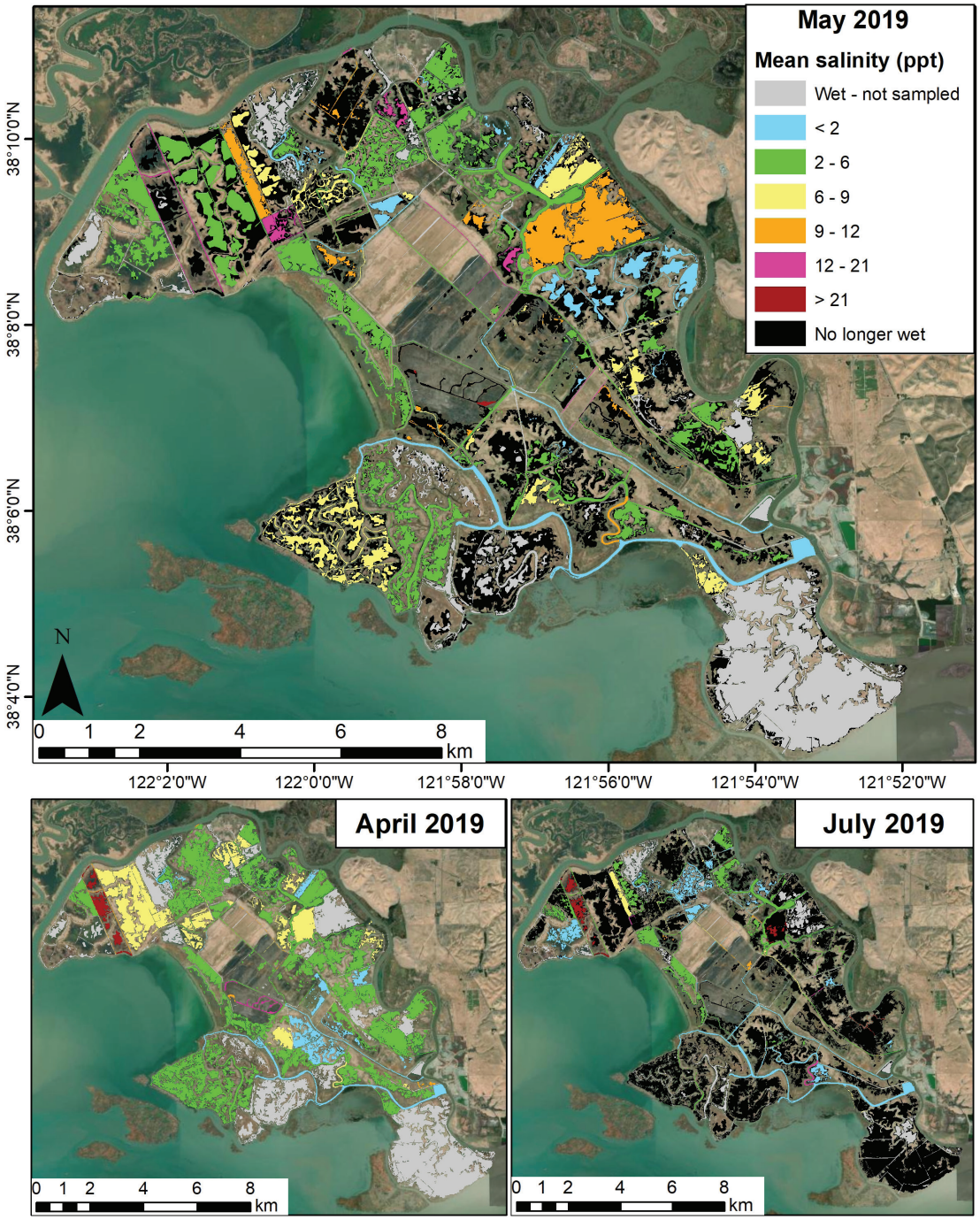

Figure 7 Seasonal extent of wetted areas in wetlands and canals, and mean salinity concentration of sampled bodies of water at Grizzly Island within Suisun Marsh, California during 2019. Sampling dates are provided in Table 1. Salinity concentrations were divided into categories based on studies that tested the effects of salinity on duckling growth and survival: ranging from no detectable negative effects (< 2 ppt) to rapidly lethal effects (> 21 ppt), with the severity of effects increasing with each colored bin (*see references cited in "Materials and Methods" in the text*). Areas in *black* were wet earlier in the breeding season (April or May) but dried up later in the season (May or July), thus providing no habitat for ducklings. *Background imagery source: ESRI DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.*

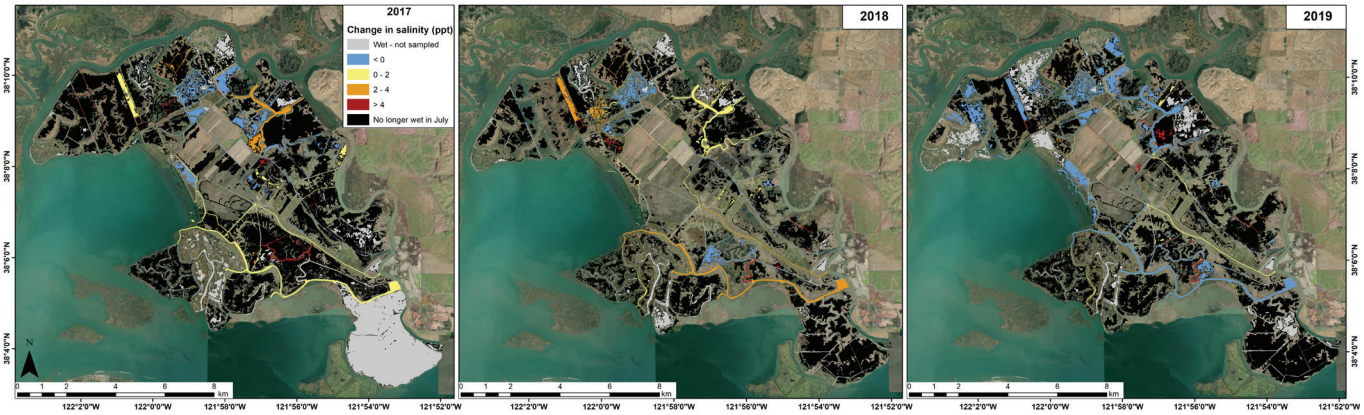

Figure 8 Change in water area (wetlands) and salinity (wetlands and canals) from April (early waterfowl nesting season) to July (late waterfowl nesting season) at Grizzly Island, Suisun Marsh, California during 2017–2019. Areas in *black* were wet in April but dry in July. Water remaining in July is color-coded based on the magnitude and direction of the change in surface water salinity concentrations (from April to July).

Table 2 Summary of wetted area and salinity concentrations (weighted averages) in wetlands by time-period, year, and land ownership at Grizzly Island, Suisun Marsh, California. (*NA indicates that salinity was not sampled during that time-period.*)

		April		May		July	
Year		Public	Private	Public	Private	Public	Private
2016[a]							
	Total area of water (km^2)	3.6	18.7	2.2	16.3	1.1	5.4
	Wetland area sampled (km^2)	0	0	1.4	8.5	0.6	3.6
	Percent sampled	0	0	63.6	52.1	54.5	66.7
	Weighted average salinity (ppt)	NA	NA	4.1	6.0	6.8	12.6
2017[b]							
	Total area of water (km^2)	17.6	34.5	10.0	24.5	1.8	13.4
	Wetland area sampled (km^2)	9.2	16.0	7.1	10.4	0.9	2.8
	Percent sampled	52.3	46.4	71.0	42.4	50.0	20.9
	Weighted average salinity (ppt)	2.6	4.8	3.0	4.4	3.2	3.3
2018[a]							
	Total area of water (km^2)	7.9	23.4	3.6	12.2	1.5	2.9
	Wetland area sampled (km^2)	5.1	11.4	2.0	8.4	1.2	1.4
	Percent sampled	64.6	48.7	55.6	68.9	80.0	48.3
	Weighted average salinity (ppt)	5.0	6.3	5.8	4.2	6.1	6.6
2019[b]							
	Total area of water (km^2)	12.4	28.8	4.1	20.6	1.4	7.1
	Wetland area sampled (km^2)	10.8	15.4	3.4	12.2	1.2	4.4
	Percent sampled	87.1	53.5	82.9	59.2	85.7	62.0
	Weighted average salinity (ppt)	4.0	6.4	5.5	4.8	1.9	4.9

a. Drier year.
b. Wetter year.

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Salinity

Overview

During peak duckling production in May, the weighted average salinity concentration in wetlands at Grizzly Island (regardless of ownership) was 5.8 ppt in 2016, 3.8 ppt in 2017, 4.5 ppt in 2018, and 5.0 ppt in 2019 (Figure 9). The mean salinity concentration of canals was 1.2 ppt to 3.1 ppt in May (Figure 9). During all but one time-period (July 2018), the salinity concentration in wetlands (3.3–11.8 ppt) was higher than in canals (1.2–6.0 ppt), Montezuma Slough (0.3–4.4 ppt), or Honker Bay (0.1–6.5 ppt; Figure 9). The mean salinity concentration in Montezuma Slough (the source of fresher water for Grizzly Island, other than precipitation; Figure 1) remained at or below 2 ppt during April and May in all 4 years of this study (Figure 9; CDEC 2020). In July, the mean salinity concentration in Montezuma Slough remained below 2 ppt in wetter years (2017, 2019), but averaged 4.3–4.4 ppt in drier years (2016, 2018; Figure 9).

Wetland Salinity Analysis

The unweighted global model showed significant interaction effects of time-period × year × ownership ($F_{5,632.8} = 3.1$, $p < 0.01$), time-period × year ($F_{5,633.3} = 7.8$, $p < 0.001$), and time-period × ownership ($F_{2,642.9} = 6.6$, $p < 0.01$), a non-significant year × ownership interaction ($F_{3,648.3} = 0.8$, $p = 0.48$), as well as significant main effects of year ($F_{3,648.6} = 39.8$, $p < 0.001$) and ownership ($F_{1,136.0} = 9.7$, $p < 0.01$). Time-period was not a significant factor in the unweighted global model ($F_{2,643.7} = 1.1$, $p = 0.34$). We used best linear unbiased predictions (Henderson 1975) estimated by the model and then weighted by wetted area to make pairwise comparisons within each of the main effects while accounting for the other co-factors. Detailed results for pairwise comparisons are provided in Table A1.

Year. Generally, for most time-periods in both publicly- and privately-owned wetlands, salinity concentrations were lowest during the 2 wetter years (2017 and 2019), and highest during the 2 drier years (2016 and 2018; Table 2, Table A1, Figure 3B. The clearest trends occurred in July, where salinity concentrations in drier years were 33.9%–277.4% higher than in wetter years (Table A1).

Time-Period. Salinity concentrations over the course of the breeding season did not follow a consistent pattern (Table 2, Table A1, Figures 3B, 8, A1). The magnitude and direction of change were highly

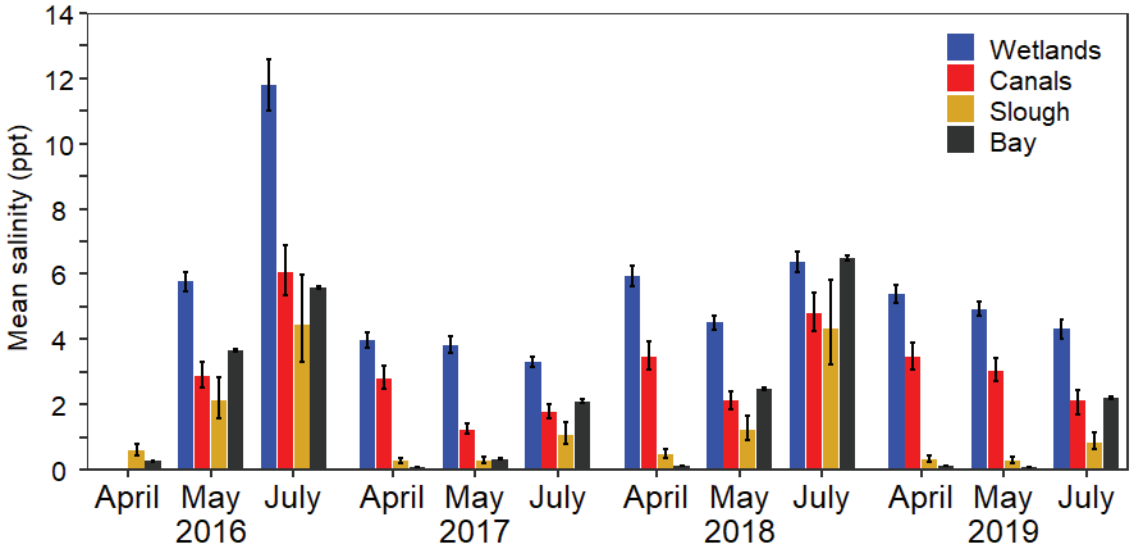

Figure 9 Average salinity concentration for wetlands, canals, sloughs (Montezuma Slough), and the bay (Honker Bay) at Grizzly Island, Suisun Marsh, California during 2016–2019. *Note: this figure presents overall weighted means for wetlands, not split by ownership as in* Figure 3B. Wetlands and canals were not sampled in April 2016. *Error bars* represent standard error.

variable among wetland units (Figures 8, A1), ranging from a decrease of 11.4 ppt to an increase of 39.0 ppt from April to July.

Ownership. The overall salinity concentration (weighted average) in privately-owned wetlands was generally higher than in publicly-owned wetlands (in 7 of 11 time-period–year combinations; $t > 2.2$, $p < 0.03$; Table 2, Table A1, Figure 3B). Differences were most consistent in April, when salinity concentrations in privately-owned wetlands were 25.7%–85.4% higher than in publicly-owned wetlands ($t > 2.2$, $p < 0.03$; Table 2, Table A1, Figure 3B). The salinity concentration in publicly-owned wetlands was significantly higher than in privately-owned wetlands in only one time-period–year combination (37.1% higher in May 2018; $t_{31.5} = 3.8$, $p < 0.001$; Table 2, Table A1, Figure 3B). There were no differences for the remaining time-period–years ($t < 1.9$, $p > 0.07$; Table A1).

Canal Salinity Analysis

After removing all non-significant interactions (year × time period × canal size: $F_{10,493.5} = 1.0$, $p = 0.48$; time period × canal size: $F_{4,493.6} = 2.1$, $p = 0.08$; year × canal size: $F_{6,496.8} = 0.5$, $p = 0.78$), salinity concentrations in canals were influenced by a significant interaction of year × time-period ($F_{5,513.8} = 13.4$, $p < 0.001$). Main effects of year ($F_{3,517.3} = 43.5$, $p < 0.001$) and time-period ($F_{2,513.8} = 31.6$, $p < 0.001$) were also significant, but could not be interpreted in isolation because of the significant interaction. Therefore, we conducted pairwise comparisons of least squares means to look specifically at the effects of year and time-period. Detailed results for pairwise comparisons are provided in Table A1. Canal size was not a significant factor ($F_{2,63.6} = 1.4$, $p = 0.24$), so least squares means were averaged across canal size for all pairwise tests (Table A1).

Year. Salinity concentrations in canals followed the same general pattern of wetter years vs. drier years seen in the wetland data (above), although the details varied (Figure 9, Table A1). In April, there was no significant effect of year ($t < 1.8$, $p > 0.8$). In May, salinity concentrations in canals were lowest in 2017 ($t > 4.1$, $p < 0.01$), with no significant differences among other years ($t < 3.1$, $p > 0.1$). In July, the 2 drier years (2016 and 2018) had salinity concentrations that were 124.7%–182.5% higher than the 2 wetter years (2017 and 2019; $t > 6.2$, $p < 0.001$). The magnitudes of the differences among years were highest in July (mean 3.0 ppt), followed by May (mean 1.6 ppt), and then April (mean 0.7 ppt).

Time-period. Patterns in canal salinity over the course of the breeding season were not consistent across years. Salinity concentrations were generally highest in April and lowest in May, but specifics varied (Figure 9, Table A1). The magnitude and direction of change was highly variable among canals, ranging from a decrease of 10.5 ppt to an increase of 23.1 ppt from April to July.

Salinity Concentrations and Duckling Toxicity Benchmarks

As expected for a brackish marsh, the majority (63.7%–100%) of wetland habitat (by area) that was sampled at Grizzly Island was above the benchmark for observable negative effects on ducklings (> 2 ppt) in all time-period–year combinations of this study (Table 3, Figures 4–7). Privately-owned wetlands had a greater proportion of wetted area above 2 ppt than publicly-owned wetlands in 9 of 11 time-period and year combinations (private: 89.3% ± 12.9%; public: 75.3% ± 22.6%). In May of the wettest year (2017), during peak duckling production, 85.4% of available water had salinity concentrations above 2 ppt, leaving 2.6 km^2 of low-salinity water (< 2 ppt) available to ducklings, 58.6% of which was on public land (Table 3, Figure 5). In May of the driest year (2016), 95.1% of available water had salinity concentrations above 2 ppt, leaving only 0.5 km^2 of low-salinity water, 91.8% of which was on public land (Table 3, Figure 4). The distinction between wet years and dry years was even more evident in July. In wetter years (2017 and 2019), 63.7%–66.7% of available water had salinity concentrations above 2 ppt, leaving 1.3 km^2– 2.0 km^2 of low-salinity water, 11.6%–33.8% of which was on public land (Table 3, Figures 5, 7). In July of drier years (2016 and 2018), more than 99.9% of available water had salinity concentrations above 2 ppt, leaving less than

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Table 3 Percent of the total area of wetted wetland habitat by time-period and year within each of the six defined salinity categories for duckling health at Grizzly Island, Suisun Marsh, California

Year	Effect on ducklings	Salinity range	April	May	July
2016[a]					
	No detectable effect	< 2 ppt	NA	4.9	0.0
	Sub-lethal effects: mild	2-6 ppt	NA	38.2	33.2
	Sub-lethal effects: severe	6-9 ppt	NA	51.2	24.9
	Lethal effects: uncommon	9-12 ppt	NA	1.8	6.2
	Lethal effects: common	12-21ppt	NA	4.0	27.7
	Lethal effects: certain	> 21ppt	NA	0.0	8.0
		Area sampled	0 km^2	9.8 km^2	4.1 km^2
		Total wetted area	22.4 km^2	18.4 km^2	6.5 km^2
2017[b]					
	No detectable effect	< 2 ppt	30.7	14.6	33.3
	Sub-lethal effects: mild	2-6 ppt	63.7	58.4	57.0
	Sub-lethal effects: severe	6-9 ppt	0.6	9.9	7.8
	Lethal effects: uncommon	9-12 ppt	5.0	0.1	1.0
	Lethal effects: common	12-21ppt	0.0	16.3	0.6
	Lethal effects: certain	> 21ppt	0.0	0.8	0.4
		Area sampled	25.3 km^2	17.5 km^2	3.8 km^2
		Total wetted area	52.1 km^2	34.5 km^2	15.2 km^2
2018[a]					
	No detectable effect	< 2 ppt	4.2	18.8	0.1
	Sub-lethal effects: mild	2–6 ppt	59.2	62.4	49.4
	Sub-lethal effects: severe	6–9 ppt	18.6	10.1	33.1
	Lethal effects: uncommon	9–12 ppt	7.3	5.2	16.1
	Lethal effects: common	12–21 ppt	9.9	1.0	1.4
	Lethal effects: certain	> 21 ppt	0.8	2.5	0.0
		Area sampled	25.3 km^2	17.5 km^2	3.8 km^2
		Total wetted area	52.1 km^2	34.5 km^2	15.2 km^2
2019[b]					
	No detectable effect	< 2 ppt	8.1	7.8	36.3
	Sub-lethal effects: mild	2–6 ppt	64.9	52.8	45.2
	Sub-lethal effects: severe	6–9 ppt	23.9	18.9	7.0
	Lethal effects: uncommon	9–12 ppt	0.2	18.3	0.8
	Lethal effects: common	12–21 ppt	0.5	2.1	0.3
	Lethal effects: certain	> 21 ppt	2.3	0.1	10.3
		Area sampled	26.2 km^2	15.6 km^2	5.5 km^2
		Total wetted area	41.3 km^2	24.7 km^2	8.5 km^2

a. Drier year.
b. Wetter year.

0.05 km^2 of low salinity water, all of which was on public land (Table 3, Figures 4, 6). Wetland salinity concentrations above 9 ppt, which are associated with duckling mortality, were common, with up to 41.9% (July 2016) of wetted area above that benchmark (Table 3, Figure 4). In any given year, 36 to 55 individual wetland units were sampled in both April and July (excluding 2016, for which we have no April samples). Of those, 11.1%–36.6% (4 to 15 units) had salinity concentrations below 2 ppt in April. In 2018 (drier year), none of those units were still below 2 ppt in July. In 2017 and 2019 (wetter years), 40.0% and 57.1% of wetland units, respectively, were still below 2 ppt in July.

Small canals (< 10 m wide) represented a small portion (0.29 km^2) of the available habitat at Grizzly Island, but were potentially important for ducklings, especially in July when there was relatively little wetted area remaining in wetlands. In July of wetter years (2017 and 2019), 51.0%–56.4% of small canal area sampled fell above the benchmark for observable negative effects on ducklings (> 2 ppt) and 3.6%–9.2% fell above the benchmark where mortality starts to occur (> 9 ppt). In July of drier years (2016 and 2018), 83.0%–100.0% of small canal area had salinity concentrations above 2 ppt and 4.4%–40.1% was above 9 ppt.

DISCUSSION

Within Suisun Marsh, waterfowl nest in upland habitats, particularly within the 52 km^2 publicly-owned Grizzly Island Wildlife Area, where managers maintain a large block of upland vegetated habitat for nesting ducks (8 km^2) and flood seasonal wetlands during the fall and winter for migratory waterfowl (Figure 2; McLandress et al. 1996; Ackerman et al. 2014b). Private duck-hunting clubs own the majority of the seasonal wetland habitat, where management is primarily focused on providing food resources and habitat that will support high densities of wintering waterfowl during the hunting season (October to January). Wetlands are flooded in late September and early October before the start of the waterfowl hunting season, when salinity concentrations in source water are still relatively high (CDEC 2020). Land managers typically try to maintain some water flow through the wetlands during the winter, such as allowing water to enter on the high tide and exit on the low tide, thereby maintaining a certain amount of circulation over the course of the hunting season. However, the degree to which that is possible varies among wetland units. Because source water salinity concentrations are generally lowest in late winter and early spring (CDEC 2020), managers recommend draining the high-salinity water that remains from flooding in October immediately after the hunting season ends in late January, and completing a series of leach cycles of flooding and draining with the lower-salinity water that is available in February. This process minimizes soil salinity and promotes the growth of important food plants for waterfowl (Ackerman et al. 2014b; SRCD 2017). Some land owners, however, lack the infrastructure to quickly (< 2 weeks) flood or drain their wetland units. These units may retain saltier water delivered in October that has since experienced substantial evaporation, leading to even higher wetland salinity concentrations.

Because of the costs and logistical difficulties involved in sourcing and moving water, and the prioritization of winter wetland habitat, less consideration has been given to wetland availability during the spring and summer waterfowl breeding season (April to July). Yet, high-quality wetland habitat in spring and summer is important for breeding ducks. Breeding hens take incubation breaks to feed and drink in nearby wetland habitat (Figure 2; Casazza et al. 2020; Croston et al. 2020, 2021) and then leave the nest with their ducklings within 2 days of hatch (Peterson et al. 2019) and move their brood to nearby wetland habitats (Casazza et al. 2020; Figure 2). These wetlands are brackish and highly managed within the marsh, and their salinity concentrations vary extensively, which has important implications for the survival and growth of ducklings (Krista et al. 1961; Schmidt–Nielsen and Kim 1964; Swanson et al. 1984; Mitcham and Wobeser 1988a,b; Barnes and Nudds 1991; Moorman et al. 1991; Stolley and Meteyer 2004; DeVink et al. 2005).

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The amount of water available to waterfowl in Suisun Marsh varies from year to year, and can change significantly over the course of a single breeding season. Our study took place during 2 relatively dry years (2016 and 2018) and 2 relatively wet years (2017 and 2019), with 133% more wetted area in April of the wettest year (2017) than in the driest year (2016; Figure 3A). Although there was less water in drier years than in wetter years, the seasonal pattern within years was similar. The amount of water present in seasonal wetlands decreased by 73%–86% during the waterfowl breeding season for each of the 4 years of this study (Figure 3A). Private duck-hunting clubs owned more of the potential wetland habitat at Grizzly Island (69%) than the state of California (31%; CDFW). Private clubs, on average, also had a greater proportion (39%) of their available land flooded than the state (29%) throughout the waterfowl nesting and brood rearing time-period. To a certain degree this could be because some private clubs lack the infrastructure to actively remove water from wetlands after the duck-hunting season and before the breeding season, rather than actively managing the wetlands for increased summer brooding habitat. Regardless, the majority of the wetted area available during spring and summer at Grizzly Island was on private land (78% on average). Over the course of the breeding season, water levels consistently decreased (Table 2), whether due to evaporation or active water management. In drier years, publicly- and privately-owned wetlands dried up at similar rates (average decrease in flooded wetland extent from April to July was 77%), but, in wetter years, privately-owned wetlands dried up less by July (68% decline in water area) than publicly-owned wetlands (89% decline in water area; Figure 3A). By July of each of the 4 years, less than 2 km^2 of water remained available to ducklings in publicly-owned wetlands, whereas privately-owned wetlands provided 2.9 km^2 to 5.4 km^2 of water area in drier years and 7.1 km^2 to 13.4 km^2 in wetter years (Table 2). Having more water on the landscape during peak duckling production (especially adjacent to the upland nesting habitat) reduces the distance young ducklings must travel overland to reach suitable brooding habitat, which could reduce exposure to predators (Mauser et al. 1994b; Krapu et al. 2006; Chouinard and Arnold 2007). Duckling survival has been shown to be positively related to the amount of inundated wetland habitat available (Krapu et al. 2006; Amundson and Arnold 2011), with higher survival in seasonal wetlands (flooded March to August) than permanent wetlands (Mauser et al. 1994a, 1994b; Chouinard and Arnold 2007). Older ducklings are less vulnerable to the predation risk that is associated with moving longer distances between wetlands, and for that reason other studies have recommended that draining water from seasonal wetlands should be delayed until at least 10 to14 days after hatch (Mauser et al. 1994a, 1994b).

Salinity concentrations at Grizzly Island were highly variable among individual wetlands and canals. Generally, wetlands (3–12 ppt) had higher average salinity concentrations than canals (1–6 ppt), and other nearby water sources in the estuary, including Montezuma Slough (0.3–4.4 ppt) and Honker Bay (0.1–6.5 ppt; Figure 9). Overall, salinity concentrations in wetlands and canals were higher in drier years (2016 and 2018) than in wetter years (2017 and 2019; Figures 3b, 9). These differences were most consistent in July, late in the duck breeding season (dry years had 34%–274% higher salinity), when there was also less water available. We found no consistent patterns of change in salinity over the course of the breeding season from April to July. In a natural system, we would expect to see a general increase in salinity concentration throughout the spring and summer, as water is lost to evaporation. In contrast, changes in the salinity concentration of individual diked wetlands at Grizzly Island varied in magnitude and direction (Figure 8), and likely depended on many factors, most notably water management actions taken at different times throughout the year (e.g., adding fresher water or draining wetlands). Salinity concentrations in canals tended to be highest early in the season (April) and lowest mid-season (May). This pattern may relate to the timing of management actions, such as the gradual drawing down of higher salinity water (applied in October) through drainage canals in Febrary after the duck-hunting season. As with wetlands, we found

high variability in the salinity concentration of canals, although in this case that could partially be a result of differences between supply (lower salinity) and drainage (higher salinity) canals. Although we did not directly assess salinity concentrations in supply versus drainage canals, we did assess canal size (often correlated with supply or drainage) and found no effect. Salinity concentrations in privately-owned wetlands were typically higher than in publicly-owned wetlands, especially early in the waterfowl breeding season (26%–85% higher in April; Figure 3B). Water management could, in part, explain why the differences were most evident early in the breeding season (as with the canals). In addition, private duck clubs on the northwest side of the island obtain higher-salinity water from their diversion points off of Grizzly Bay (CDEC 2020), whereas the state managers primarily source water from the lower salinity-portions of Montezuma Slough to the southeast (upstream). To mitigate the effects of other regional water projects by providing lower-salinity conditions, salinity control gates (Figure 1) were installed in 1988 at the eastern side of Montezuma Slough. The gates function as a tidal pump, maintaining a net flow of water toward the bay, and reducing saltwater incursion. This could help maintain the availability of lower-salinity water to wetlands during the spring and summer, especially at the upstream end of the slough. However, the salinity control gates only operate from October to May, as needed to meet salinity standards measured at monitoring stations in Suisun Marsh. Thus, there is currently salinity mitigation via the gates only during the early portion of the waterfowl breeding season, but not from June to August, although a pilot program in 2018 tested the feasibility of operating the gates in August to maintain suitable habitat for the endangered Delta Smelt (*Hypomesus transpacificus*; Beakes et al. 2021).

Ducklings, especially in the first week post-hatch, require access to low-salinity drinking water (Ellis et al. 1963; Riggert 1977; Moorman et al. 1991). Salinity concentrations greater than 2 ppt negatively affect duckling growth and behavior, which, even when not directly fatal under controlled experimental conditions, would likely cause reduced survival rates in a more natural setting (Moorman et al. 1991). There is high-quality water (salinity concentration ≤ 2 ppt) consistently available in Montezuma Slough throughout April and May, and even into July during wetter years (Figure 9). However, the wetlands and canals that were available to ducklings tended to have surface water salinity concentrations that were > 2 ppt (Figures 3B, 9). During drier years (2016 and 2018), only 14%–29% of the wetland area available in April was still inundated in July (Table 2, Figure 8) and > 99% of the water sampled in July had salinity concentrations high enough to negatively affect duckling growth and survival (> 2 ppt; Table 3). Even during wetter years (2017 and 2019), only 21%–29% of the April wetland area was still inundated in July (Table 2, Figure 8), and 64%–67% of the July water had salinity concentrations > 2 ppt (Table 3). Although the majority of ducklings would be older than 2 weeks in July, and may therefore be able to tolerate a greater range of salinity concentrations than could younger ducklings, higher salinity concentrations (≥ 15 ppt; approximately 23.6 mS cm^{-1}) have been shown to cause mortality in older ducklings as well (Swanson et al. 1984; Barnes and Nudds 1991). Importantly, even when more water was available to waterfowl during peak duckling production in May, 81%–95% of water in wetlands had salinity concentrations above the benchmark for observable negative effects on ducklings (2 ppt) and 5%–21% had salinity concentrations known to cause mortality (> 9 ppt; Table 3). In May of the driest year (2016), only 0.5 km^2 of low-salinity water (< 2 ppt) was available to young ducklings in the study area, compared to 2.6 km^2 in May of the wettest year (2017; Table 3). Publicly-owned wetlands had less water available, but, in most time-periods, a greater proportion of that water was of suitably low salinity concentrations (25% of public wetland area had salinity concentrations < 2 ppt versus 11% of private wetland area).

Because a large proportion of ducks harvested in California are produced at breeding sites within the state (Ackerman et al. 2014b; de Sobrino et al. 2017), local wintering populations may also benefit from increased availability of high-quality

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(low-salinity) wetland habitat in Suisun Marsh during peak duckling production and brooding from May through July. Especially important is the critical period when the greatest number of young (≤ 7 days) ducklings are on the brooding habitat, which occurred between May 26 and June 26 during the years of this study (Ackerman et al. 2020, unpublished data, see "Notes"). After this period, older ducklings (> 7 days) can tolerate higher salinity concentrations. Currently, most brooding habitat consists of high-salinity water, either left over from winter flooding or from spring irrigations conducted as part of the seasonal wetland leach cycles designed to reduce soil salinities. Future efforts could focus on improvements to infrastructure and management practices that allow for the targeted maintenance and addition of water in spring and summer, especially in wetlands that are located near upland nesting sites and whose managers have access to lower-salinity water sources. The effort and infrastructure required to move and hold more fresh water at Grizzly Island would necessitate additional expenditure, and changes to the timing of wetland inundation may lead to trade-offs with current, moist-soil plant management. In addition, future sea level rise from climate change is likely to increase levee maintenance costs and make drainage of brackish water more difficult, while more frequent and prolonged drought conditions will make lower salinities more difficult to maintain (Parker et al. 2011). The holding of more water into the summer months could be facilitated by programs like the California Waterfowl Habitat Program (Presley Program), established by the CDFW in 1993 to improve habitat conditions for waterfowl on private lands by providing monetary incentives to encourage land owners to increase the number of summer-flooded wetlands across the interior of California. Our results suggest that habitat management which provides: (1) low-salinity brood water during peak production of young ducklings in May and June, and (2) increased water (regardless of salinity) through July for older ducklings, would likely increase population recruitment, benefit local breeding waterfowl populations, and increase the number of ducks present in the region during the winter.

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