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Hydrology affects shorebirds, waterfowl, and other waterbirds at Bear River Bay, a Globally Important Bird Area

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ABSTRACT. The value of saline lakes and associated wetlands as habitats in the xeric Great Basin is dependent on having water of sufficient quantity and quality to support wetland-dependent birds. To inform conservation and management of these habitats, models are needed to link birds and hydrological changes due to climate and human water use. We modeled seasonal relationships between counts for 35 migratory shorebird, waterfowl, and other waterbird species or taxonomic groups and hydrological metrics at Bear River Bay, a globally Important Bird Area at Utah's Great Salt Lake. We found that increased fall surface flows to the bay increased counts of 13 species, including American Avocets (*Recurvirostra americana*), American White Pelicans (*Pelecanus erythrorhynchos*), American Wigeons (*Mareca americana*), Northern Pintail (*Anas acuta*), Redheads (*Aythya americana*), and Ruddy Ducks (*Oxyura jamaicensis*). Increased spring surface flows increased counts of Forster's Terns (*Sterna forsteri*) and the sandpiper group, whereas intermediate spring flows produced peak counts for American White Pelicans. Thus, conservation or management actions that increase seasonal flows to Bear River Bay are expected to increase bay use by diverse members of the avian community. Counts for 11 species or taxonomic groups responded positively or negatively to the seasonal elevation of Great Salt Lake, and these responses are hypothesized to reflect the relative availability of habitats within the bay versus the lake as a whole. Our models provide tools that allow managers to understand how hydrological changes associated with climate change and human water use will affect birds in Bear River Bay. Addressing lake-wide and regional population implications of changing hydrological conditions at Bear River Bay, Great Salt Lake, and other locations across the Great Basin will require a regionally coordinated assessment of hydrology, habitat, and bird movements in response to changing habitat conditions.

RESUMEN. **La hidrología afecta aves playeras, anátidas y otras aves acuáticas en Bear River Bay, una Área de Importancia Global para las Aves**
El valor como hábitat de los lagos salinos y humedales asociados en el Great Basin xérico depende de tener suficiente calidad y cantidad de agua para dar soporte a las aves dependientes de humedales. Para informar la conservación y el manejo de estos hábitats, se necesitan modelos que vinculen a las aves con los cambios hidrológicos relacionados al clima y el uso humano del agua. Modelamos la relación estacional entre los conteos de 35 aves playeras, anátidas y otras especies acuáticas migratorias o grupos taxonómicos, y métricas hidrológicas en Bear River Bay, un Área de Importancia para las Aves en el Great Salt Lake de Utah. En otoño, encontramos que el incremento de flujos de superficie a la bahía aumentó los conteos de 13 especies, incluyendo a *Recurvirostra americana*, *Pelecanus erythrorhynchos*, *Mareca americana*, *Anas acuta*, *Aythya americana* y *Oxyura jamaicensis*. En primavera, el incremento de los fujos de superficie aumentó los conteos de *Sterna forsteri* y varios playeros, mientras que los flujos intermedios produjeron conteos pico de *Pelecanus erythrorhynchos*. Por ello, se espera que las acciones de conservación o manejo que incrementen los flujos estacionales a Bear River Bay a su vez aumente el uso de la bahía por diversos miembros de la comunidad de aves. Los conteos de 11 especies o grupos taxonómicos respondieron positiva o negativamente a la elevación estacional del Great Salt Lake y tenemos la hipótesis de que estas respuestas reflejan la disponibilidad relativa de hábitats al interior de la bahía versus la del lago completo. Nuestros modelos proveen herramientas que permiten a los gestores entender cómo los cambios hidrológicos asociados con el cambio climático y el uso humano del agua afectarán a las aves en Bear River Bay. Entender las implicaciones del cambio de condiciones hidrológicas en todo el lago y en poblaciones regionales de Bear River Bay, Great Salt Lake, así como en otras localidades a lo ancho del Great Basin, requerirá de una caracterización regionalmente coordinada de la hidrología, hábitat y movimientos de las aves en respuesta a las cambiantes condiciones de sus hábitats.

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Wetland birds rely on saline lakes and associated wetlands as wintering, breeding, and migratory stopover areas in xeric landscapes of the western United States (Aldrich and Paul 2002, Petrie and Vest 2013, Wilsey et al. 2017). For example, Great Salt Lake, Utah, and associated ecosystems are used annually by millions of wetland birds with records of 42 shorebird species, 38 waterfowl species, and 18 species of colonial-nesting waterbirds (Aldrich and Paul 2002, Cavitt et al. 2014, Sorensen and Hoven 2020, J. Neill, pers. observ.). Wetland birds have morphological, physiological, and behavioral traits whose evolution has been driven by water resource conditions (e.g., water depth and salinity) or other habitat resources (e.g., food resources and vegetation composition) affected by water resource conditions (Weller 1999, Sorensen et al. 2020). For example, declining water levels may eliminate islands that provide refuge from terrestrial predators for colonial-nesting birds (Knopf and Evans 2020), or increasing water levels may flood nesting areas (Aldrich and Paul 2002). Water levels also indirectly affect, through changes in salinity, the community composition and abundance of invertebrates (Dana and Lenz 1986, Ma et al. 2010), an important food resource for wetland birds. Securing water supplies of sufficient quantities and qualities at the right times of year and locations is key to maintaining or restoring the value of saline lake and wetland habitat to birds (Aldrich and Paul 2002, Petrie et al. 2013, Thomas and Andres 2013, Wilsey et al. 2017).

Located in terminal basins, saline lakes have water supply budgets that include gains from surface water flows, groundwater flows, and precipitation, and losses through evaporation and seepage to sediments (Williams 2002). Natural short- and long-term changes in precipitation, temperature, and net evaporation affect water budgets with consequences for lake elevation, volume, salinity, and other physical and biological attributes (Alder 2002, Williams 2002). For example, an unusual wet cycle in the 1980s increased Great Salt Lake's elevation from 1280.3 to 1283.7 m, an historic high, by 1987 (Alder 2002). This flooding reduced or eliminated nesting opportunities for colonial waterbirds that nest on the ground or in emergent vegetation (Aldrich and Paul 2002) and presumably also influenced distributions of non-breeding birds (Kadlec and Smith 1989). Anthropogenic water diversions, such as those for irrigated agriculture or municipal and industrial uses, have modified natural climate-driven hydrology and reduced water inflows to, and water cover of, saline lakes and their associated wetlands (Wurtsbaugh et al. 2017, Donnelly et al. 2020, King et al. 2021). Due to anthropogenic consumptive water use, Great Salt Lake's volume in 2015 was 48% less and its elevation 3.6 m lower than values expected without consumptive use (Wurtsbaugh et al. 2017). Anthropogenic climate change is also expected to affect saline lake water budgets (Ficklin and Stewart 2013, Jeppesen et al. 2015). Seasonal minimum air temperatures have increased and hydroperiod durations have decreased in the Great Basin, a region containing Great Salt Lake and several other saline lakes, in recent decades (Haig et al. 2019), and increased evaporative demand has contributed to surface water loss from saline lakes and their associated wetlands (Donnelly et al. 2020). Some lakes may experience more frequent droughts and the potential for volume reductions (Ficklin et al. 2013, Moore 2016). Conservation and management plans have identified the effects of anthropogenic water use and climate change on saline lake water budgets as major threats to wetland birds and their habitats (Thomas et al. 2013, Zimmerman and Ivey 2013, Wilsey et al. 2017).

Concerns about anthropogenic water use and effects of climate change on wetland birds and their habitats have led researchers to model relationships between hydrological and bird habitat use metrics (Sorenson et al. 1998, Timmermans and Badzinski 2008, Wang et al. 2013, Zhang et al. 2016). Hydrological metrics reflecting the magnitude, duration, frequency, timing, and change rate of surface water inputs and lake water levels are ecologically relevant and potentially related to bird use (Poff et al. 1997, Timmermans et al. 2008). Previous studies have revealed connections between wetland bird species and communities and water levels (Bolduc and Afton 2004, DesGranges et al. 2006, Cavitt 2013, Aharon-Rotman et al. 2017), water-level fluctuations (Kingsford and Jenkins 2004, DesGranges et al. 2006, Bellio and Kingsford 2013), and surface water flows to lakes (Cavitt 2013, Wang et al. 2013, Zhang et al. 2016). These studies have shown that bird responses to hydrological metrics vary across guilds, species, and seasons, and these differences may be attributed to differences in foraging habitats and techniques. Modeled relationships between hydrological and bird metrics can help assess potentially negative effects of human water use and climate change and evaluate the effectiveness of conservation and management actions intended to offset or redress negative effects (Jones and Lacey 2009, Wang et al. 2013, Zhang et al. 2016). To maintain or restore bird communities, the needs of species with contrasting and potentially conflicting responses to hydrological metrics must be addressed and balanced.

Efforts are underway to assess impacts of human water use and climate change on the hydrology of Great Salt Lake (e.g., Jacobs Engineering Group Inc. 2019). Our objective was to complement these efforts by producing quantitative models linking hydrological metrics to habitat use by birds in Great Salt Lake's Bear River Bay. Bear River Bay is recognized as a globally Important Bird Area (IBA) given its use by breeding and migrating shorebirds, waterfowl, and other waterbirds (Birdlife International 2020). We modeled relationships between hydrological metrics and counts of wetland birds during spring and fall migration over a 14-year period. Cavitt (2013) reported a mix of negative, positive, and no responses by 11 bird species to increasing surface water flows and lake elevation for Willard Spur, an ecosystem representing 17.4% of our Bear River Bay study area. Here, we build on Cavitt's (2013) study by (1) modeling 35 species and taxonomic groups that included migrants of regional conservation concern, (2) considering the potential for non-linear relationships between bird counts and hydrological metrics, and (3) including the entire unimpounded area of Bear River Bay, an area that, except for water rights related to the Bear River Migratory Bird Refuge, does not currently have a perfected water right for propagation of wildlife and vegetation. Consequently, the area is vulnerable to upstream water development and climate change. We sought to identify hydrological metric(s) most related to the abundance of individual bird species and determine if modeled relationships were positive, negative, or non-linear.

METHODS

Great Salt Lake is a saline lake located in the cold desert environment of northeastern Utah (Fig. 1; Aldrich and Paul 2002). Inflows from the Bear, Jordan, Ogden, and Weber rivers are the dominant freshwater supply for the lake, with smaller sources including precipitation, groundwater, treated sewage flows, and smaller tributaries. Salinities in the lake vary from freshwater up to 280 parts per thousand, with gradients present at multiple spatial scales, including across major bays (Aldrich and Paul 2002). Plants found in freshwater wetlands include cattail (*Typha* spp.), sago pondweed (*Stuckenia pectinata*), and hardstem bulrush (*Schoenoplectus acutus*), whereas plants in relatively saline wetlands include muskgrass (*Chara* spp.) and alkali bulrush (*Bolboschoenus maritimus*) (Aldrich and Paul 2002). Invasive common reed (*Phragmites australis*) is the focus of control efforts at Great Salt Lake (Rohal et al. 2018) and can negatively affect bird habitat (Benoit and Askins 1999).

Bear River Bay (41.3872°N, 112.3169°W) is located in northeastern Great Salt Lake and is geographically delimited by federal, state, and private lands to the north and east, the Promontory Mountains to the west, and industrial areas and Union Pacific Railroad's causeway to the south (Fig. 1) (Aldrich and Paul 2002, Birdlife International 2020). It occupies a position between actively managed wetlands on federal, state, and private lands and the open, hypersaline waters of Great Salt Lake. Designated as a Global IBA, Bear River Bay supports over 1% of the biogeographic populations (IBA criterion A4i) of 14 wetland bird species (Birdlife International 2020). The area also hosts $\geq$ 20,000 waterbirds on a regular basis (IBA criterion A4iii) (Birdlife International 2020). The salinity of Bear River Bay is close to that of the Bear River, its major source of surface water and, as a result, water in the bay is fresh enough to support plants such as sago pondweed (*Ruppia* spp.)

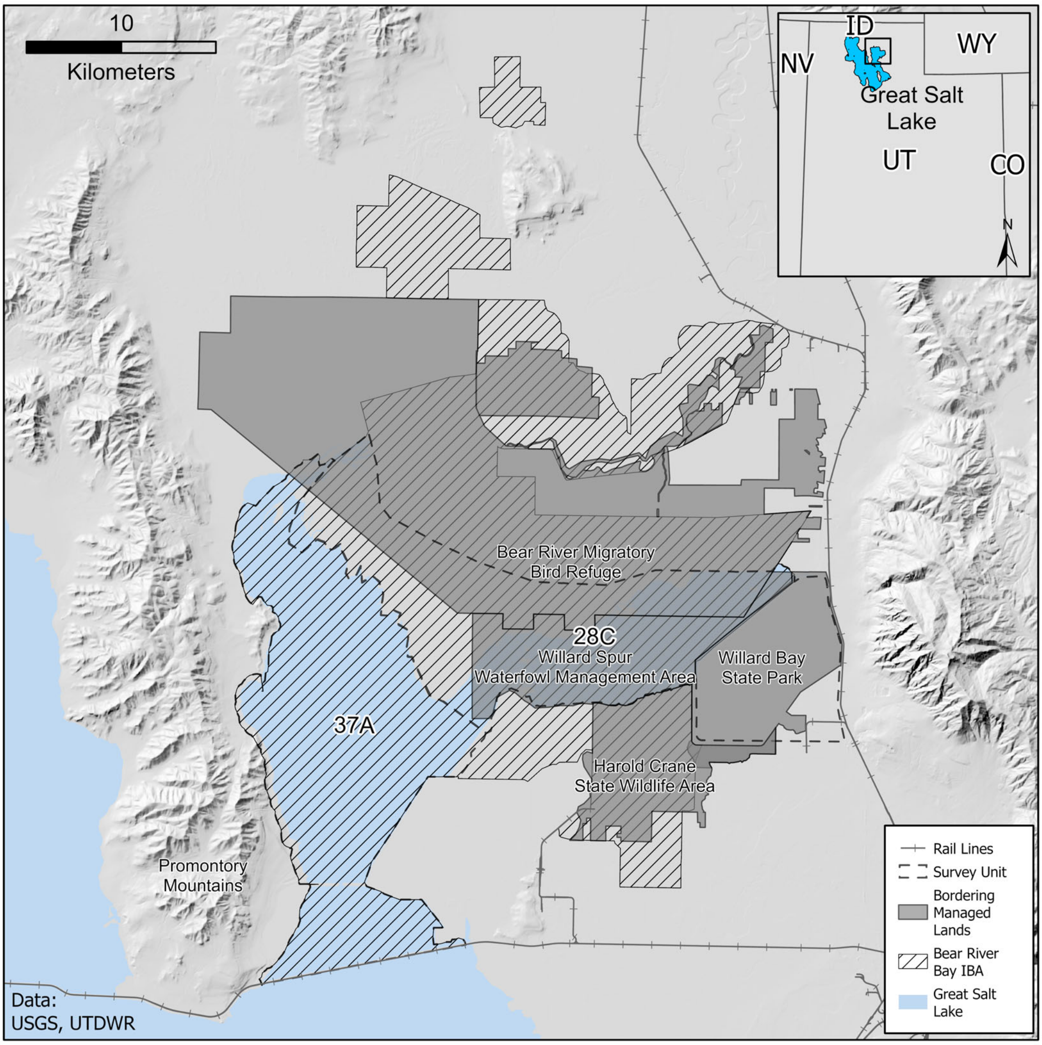

Fig. 1. Locations of survey units 37A and 28C within Bear River Bay where the Great Salt Lake Ecosystem Program conducts long-term surveys for migratory shorebirds, waterfowl, and other waterbirds at Great Salt Lake, Utah. Bear River Bay has been designated as a globally Important Bird Area (IBA).

(Aldrich and Paul 2002) as well as fish species including common carp (*Cyprinus carpio*) and Utah chubs (*Gila atraria*) (Armstrong and Wurtsbaugh 2019).

Bird survey data. Bird data were collected as part of a long-term monitoring program by the Great Salt Lake Ecosystem Program, part of Utah's Division of Wildlife Resources. For two survey units (28C: 19,870.9 ha; 37A: 17,955.2 ha) in Bear River Bay (Fig. 1), observers counted individuals of species in the families Gaviidae, Podicipedidae, Pelecanidae, Phalacrocoracidae, Ardeidae, Threskiornithidae, Anatidae, Rallidae, Gruidae, Charadriidae, Recurvirostridae, Scolopacidae, and Laridae. Biologists counted birds from the air along 463-m wide transects spaced 1852 m apart within survey units. The width and spacing of transects were selected to cover a quarter of each survey unit. During transect flights, two observers counted birds out to 231.5 m on each side of the plane with distances from the plane visually estimated. Flights were at altitudes ranging from

24 to 61 m and speeds of 129–161 km/h in a fixed-wing Cessna 185 Skywagon. Given that altitude varied within and between flights, observers did not use window markings to determine distances. As needed, observers calibrated their visual distance estimates against known landmarks. In aggregate, transects covered a quarter of each survey unit, so we multiplied total counts across all transects for each species and taxonomic group by a factor of four in each survey unit.

From 2004 to 2017, numbers and the timing of surveys differed across two monitoring phases. Until 2007, annual surveys occurred three times in spring (15 April to 14 May) and nine times in fall (8 July to 5 September). Beginning in 2007, there were two spring (10 April to 9 May) and three fall (18 July to 31 August) annual surveys. To reconcile differences in survey numbers and timing, we defined five overlapping survey windows for both monitoring phases, including 10 - 24 April (period 1), 25 April to 9 May (period 2), 18 July to 1 August (period 3), 2 -16 August (period 4), and 17 - 31 August (period 5). We labeled periods 1 and 2 as spring migration counts and periods 3, 4, and 5 as fall migration counts. If multiple counts occurred during the same survey period, we averaged and rounded counts for the period for each survey unit and then summed counts by period and year across survey units. Finally, we took the maximum count across periods within a season to arrive at counts for spring and fall migration seasons.

Several species or taxonomic groups were too rare (i.e., observed on <20% of counts across all years and seasons) to model robustly, so we eliminated their counts from the bird survey dataset. We considered 20 species difficult for observers to distinguish in the field and combined them into seven taxonomic groups (Table 1). Our final bird survey dataset contained 14-year seasonal counts for 28 species (Table S1) and seven taxonomic groups.

Table 1. Groups used to aggregate counts for species difficult to identify during field surveys of Bear River Bay at Great Salt Lake, Utah.

Species	Group
Clark's Grebe	*Aechmophorus*
Western Grebe	
Clark's/Western Grebe	
Greater Scaup	*Aythya*
Lesser Scaup	
Ring-necked Duck	
Unidentified Scaup	
Cattle Egret	Egrets
Great Egret	
Snowy Egret	
Unidentified egret	
California Gull	Gulls
Ring-billed Gull	
Unidentified gull	
Red-necked Phalarope	*Phalaropus*
Wilson's Phalarope	
Unidentified phalarope	
Baird's Sandpiper	Sandpipers
Least Sandpiper	
Sanderling	
Semipalmated Sandpiper	
Spotted Sandpiper	
Western Sandpiper	
Unidentified sandpiper	
Greater Yellowlegs	Yellowlegs
Lesser Yellowlegs	
Unidentified yellowlegs	

Hydrological metrics. To quantify surface water inflows, we combined river, reservoir release, and treated sewage flow datasets. We quantified Bear River surface water inflows using mean daily discharge (cubic feet per second) records from the U.S. Geological Survey's (USGS) gage near Corinne, Utah (site number 10126000). We accessed the discharge records using the R package dataRetrieval (De Cicco et al. 2018) in R 4.0.2 (R Core Team 2020). Releases from Willard Bay Reservoir represent an intermittent source of surface water inflow to Bear River Bay. Weber Basin Water Conservancy District provided daily flow release records for the reservoir (Chris Hogge, pers. comm.), and we added these to the USGS daily flows.

Publicly owned treatment works (POTW), or sewage treatment facilities, also provide surface flows into Bear River Bay. Utah's Division of Environmental Quality makes available the locations of permitted POTWs via an interactive web interface (https://enviro.deq.utah.gov/). Using these spatial data, we identified three facilities (permit numbers UT0025721, UT0020931, and UT0022365) that (1) discharge directly into Bear River Bay or (2) discharge below the previously identified USGS gaging station into rivers or canals flowing into the bay. We accessed flow records (2004–2017) for these facilities from Discharge Monitoring Reports (DMR) available from the U.S.

Environmental Protection Agency's Enforcement and Compliance History Online system (echo.epa.gov). All three facilities reported flow as monthly or 30-day averages. One monitored flow of gross effluent, one monitored flow of raw sewage influent, and the monitoring location of the final facility was unreported. Two facilities operated from 2004 to 2017 and the third began operation in March 2011. For each POTW, we calculated median monthly flow values by year and assumed that daily discharge equaled the median monthly value. When a monthly flow value was unreported in a given year, we used a monthly value equal to the median of available values for that month from 2004 to 2017. In some instances, facilities indicated that "No Discharge" prevented reporting of monthly discharge values and, in these cases, we assumed zero flow for the month.

We joined and summed river, reservoir, and POTW daily discharge data to produce a final dataset of daily surface water inflows. Using this dataset, we calculated total cumulative flow from the start of the water year (October of the preceding calendar year) through the end of each migration season (spring: 9 May; fall: 31 August). This produced annual estimates of spring and fall cumulative flows. Like Wang et al. (2013), we assumed cumulative flow reflected or was correlated with overall supplies of water, nutrients, and sediments.

We downloaded Great Salt Lake surface elevation data (National Geodetic Vertical Datum of 1929) from the USGS's gage at Saltair Boat Harbor, Utah (10010000) using the R package dataRetrieval (De Cicco et al. 2018) in R 4.0.2 (R Core Team 2020). We calculated the median Great Salt Lake surface elevation during the spring (10 April to 9 May) and fall (18 July to 31 August) survey periods for each year.

Statistical analysis. We analyzed the effects of hydrological metrics on species and taxonomic group counts separately and seasonally. We modeled the expected count, μ_t, in year t as a function of standardized surface water inflows, Great Salt Lake elevation, and year using negative binomial regression. A variance inflation factor analysis revealed scores ≥ three indicating collinearity among our fall predictor variables (Zuur and Ieno 2010) caused by a negative correlation between year and Great Salt Lake elevation (adjusted r^2 = 0.20). To address this correlation, we regressed year against lake elevation and used the resulting residuals as a predictor in lieu of year for both spring and fall seasons. We used year residuals as a predictor for both seasons to maintain a consistent modeling approach facilitating inter-season comparisons. With year residuals as a predictor, variance inflation factors for spring and fall did not exceed three.

We considered models representing the interaction and all possible quadratic and linear combinations of surface water inflows and Great Salt Lake elevation (Table 2). We compared competing models using Bayes factors that summarized the support for one statistical model versus another (Kass and Raftery 1995) based on models' marginal likelihoods. We identified the model (M_0) with the greatest marginal likelihood and calculated Bayes factors relative to this model:

$$B_{01} = \frac{p(y|M_0)}{p(y|M_1)}, \qquad (1)$$

where B_{01} is the Bayes factor comparing support for model M_0 to M_1 and where the numerator and denominator represent the marginal likelihoods of models M_0 and M_1, respectively. After Kass and Raftery (1995), we considered a Bayes factor ≥10 to be evidence of "strong" support for model M_0 over

Table 2. Statistical models relating bird species and taxonomic group counts to hydrological metrics and survey year for Bear River Bay, Utah. Metrics included surface water flows (S), Great Salt Lake elevation (E), and year (Y). Prior to model fitting, year was regressed against lake elevation, and the resulting residuals were used as the year predictor to remove collinearity between year and lake elevation. An intercept term (α) was included in each model. μ_t is the expected count during year *t*. The number of species or taxonomic groups for which each model performed best is reported by season.

Models	Spring	Fall
$\log\mu_t = S{*}E + S + E + Y + \alpha$	0	0
$\log\mu_t = S^2 + S + E^2 + E + Y + \alpha$	0	0
$\log\mu_t = S^2 + S + E + Y + \alpha$	0	0
$\log\mu_t = S + E^2 + E + Y + \alpha$	0	0
$\log\mu_t = S^2 + S + Y + \alpha$	1	0
$\log\mu_t = E^2 + E + Y + \alpha$	0	0
$\log\mu_t = S + E + Y + \alpha$	0	0
$\log\mu_t = S + Y + \alpha$	15	24
$\log\mu_t = E + Y + \alpha$	16	11

M_1 whereas we considered a Bayes factor <10 as evidence that M_0 and M_1 were competitive. Pairwise Bayes factors were computed for all competing models and used to identify competitive models by species or taxonomic group and season. Within models, we identified a parameter estimate as statistically significant if its Bayesian credible interval did not overlap zero.

We used a Bayesian approach to fit models via the INLA 20.04.18 package (Rue et al. 2017) for R statistical computing software (R Core Team 2020). For all model fixed effects, we assigned a normal prior distribution with a mean of zero and precision equal to 0.001. We assumed a negative binomial distribution for expected counts to account for potential overdispersion (median dispersion parameter $k = 0.65$). To evaluate model fit, we examined distributions of conditional predictive ordinates looking for uniformity (Czado and Gneiting 2009). We also calculated correlations between observed and predicted counts per site, year, and season and found that models had reasonable predictive ability (median $r_s = 0.54$). Models did not converge for Killdeer (*Charadrius vociferus*), yellowlegs, or *Phalaropus* in spring.

RESULTS

Across years, surface flows varied from 0.45 to 1.75 km^3 (median = 0.70 km^3) in the spring and from 0.54 to 2.30 km^3 (median = 0.88 km^3) in the fall. Great Salt Lake elevation ranged from 1278.3 to 1279.8 m (median = 1278.9 m) in spring and from 1278.1 to 1279.6 m (median = 1278.6 m) in fall.

Across seasons, the number of competitive models (Bayes factor <10) ranged from one to three (median = two). In spring and fall, the best models for the greatest number of species or taxonomic groups included either a linear effect of surface water inflows or a linear effect of Great Salt Lake elevation (Table 2). Parameter estimates for surface water inflows and lake elevation were not always significant (Figs. 2 and 3). Significant, linear responses to surface water were positive in spring and in fall (Fig. 2). There were positive and negative significant, linear responses to lake elevation in spring and fall (Fig. 3). The only best model that was non-linear showed counts of American White Pelicans responding in a significantly concave fashion to spring surface water flows (maximum abundance at an intermediate flow of 1.07 km^3). Credible intervals for parameters of all other best models overlapped zero.

DISCUSSION

For Bear River Bay, we found that increasing fall surface water flows increased counts for 13 species including American Avocets, American White Pelicans, American Wigeons (*Mareca americana*), Northern Pintails (*Anas acuta*), Redheads (*Aythya americana*), and Ruddy Ducks (*Oxyura jamaicensis*), all species of regional conservation focus (Petrie et al. 2013, Thomas et al. 2013, Zimmerman et al. 2013, Wilsey et al. 2017). These species have varied foraging habitats, techniques, and food resources, so increasing flows during fall benefits a broad segment of the avian community. Increased surface flows apparently create diverse and abundant habitats during fall, a season when bay water cover is relatively low. When water cover is greater in spring, we observed fewer relationships between bird counts and surface water flows. Counts for Forster's Terns (*Sterna forsteri*) and the sandpiper group increased with increased spring flows whereas counts of American White Pelicans peaked at intermediate spring flows. Increasing spring flows may create foraging habitat for Forster's Terns in deeper, unimpounded areas with fish and lead to additional shallow water and mudflat habitat for the sandpiper group. As with Forster's Terns, American White Pelicans benefit from increasing spring flows that may create foraging habitat in unimpounded areas of Bear River Bay, but, as spring flows continue to increase, pelicans may move to exploit emerging foraging opportunities in managed areas, reducing their counts in the unimpounded areas. Using our models, policy makers and resource managers can consider explicitly the degree to which water management and use decisions that reduce seasonal flows will negatively affect bird species and taxonomic groups in Bear River Bay.

We found that increased Great Salt Lake elevation during spring decreased bay counts for five species and increased counts for one species, whereas increased lake elevation during the fall increased counts for one species

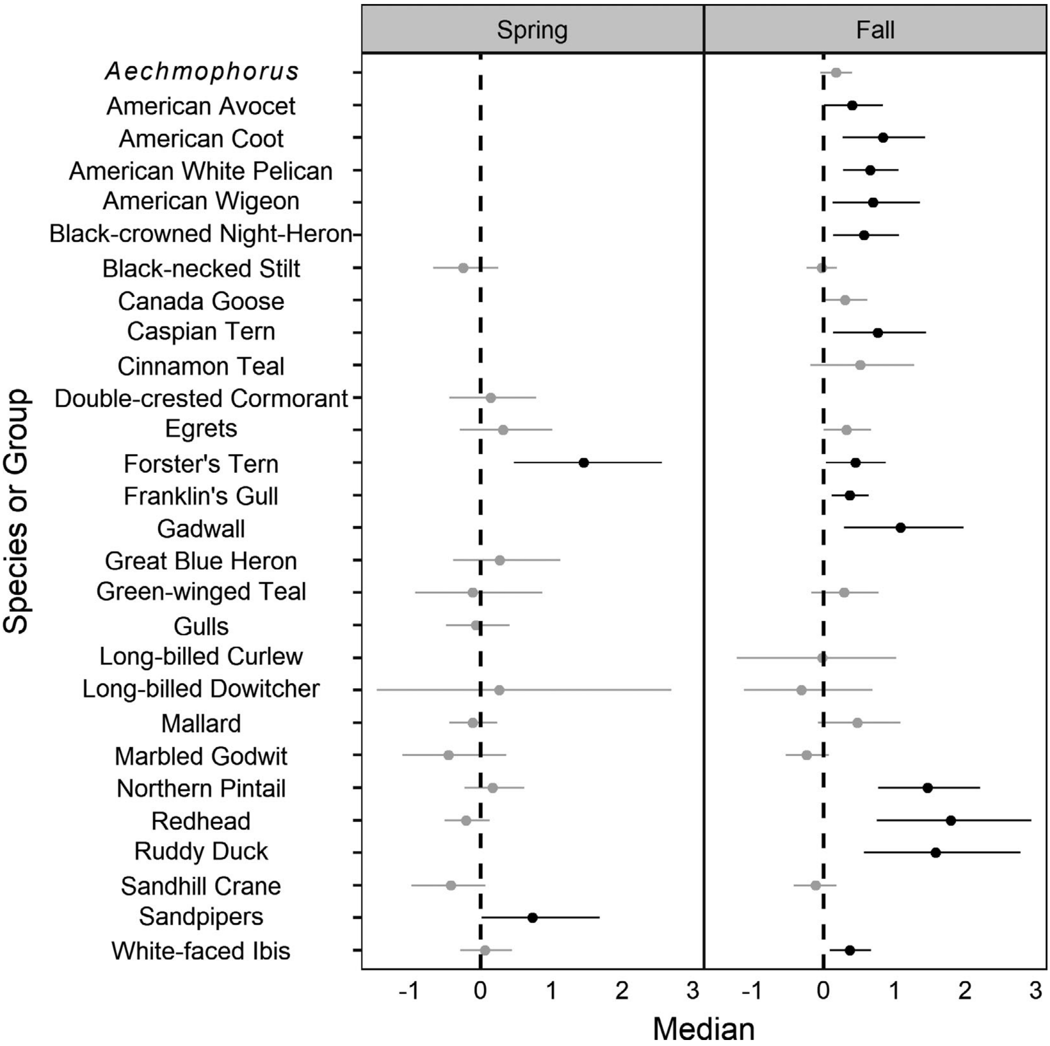

Fig. 2. Seasonal surface flow parameter estimates for shorebird, waterfowl, and other waterbird species or taxonomic groups in Great Salt Lake's Bear River Bay (Utah, USA). Estimates are provided where a seasonal, linear effect of surface flow was the best model for a species or taxonomic group. Point estimates represent the median of posterior distributions, and bars represent the 95% Bayesian credible intervals. Significant positive estimates are in dark gray, and non-significant estimates are in light gray.

and two taxonomic groups and decreased counts for two species. Eared Grebes (*Podiceps nigricollis*), a species of regional conservation focus during its migration (Zimmerman et al. 2013), were among those species that declined in numbers in Bear River Bay with increased lake elevation in fall. The elevation of Great Salt Lake reflects and affects the types, distributions, and areas of wetlands across the lake (Aldrich and Paul 2002, Roberts and Conover 2016). Use of a wetland by migrating birds depends on local and landscape habitat conditions (Farmer and Parent 1997, Webb et al. 2010); thus, we hypothesize that bird use of Bear River Bay reflects the influence of lake elevation on bay and lake-wide wetland habitats. For example, with increasing lake elevation during fall and additional habitat available, migrating Eared Grebes may use other areas of the lake thereby reducing numbers in Bear River Bay. During fall migration, Eared Grebes tend to

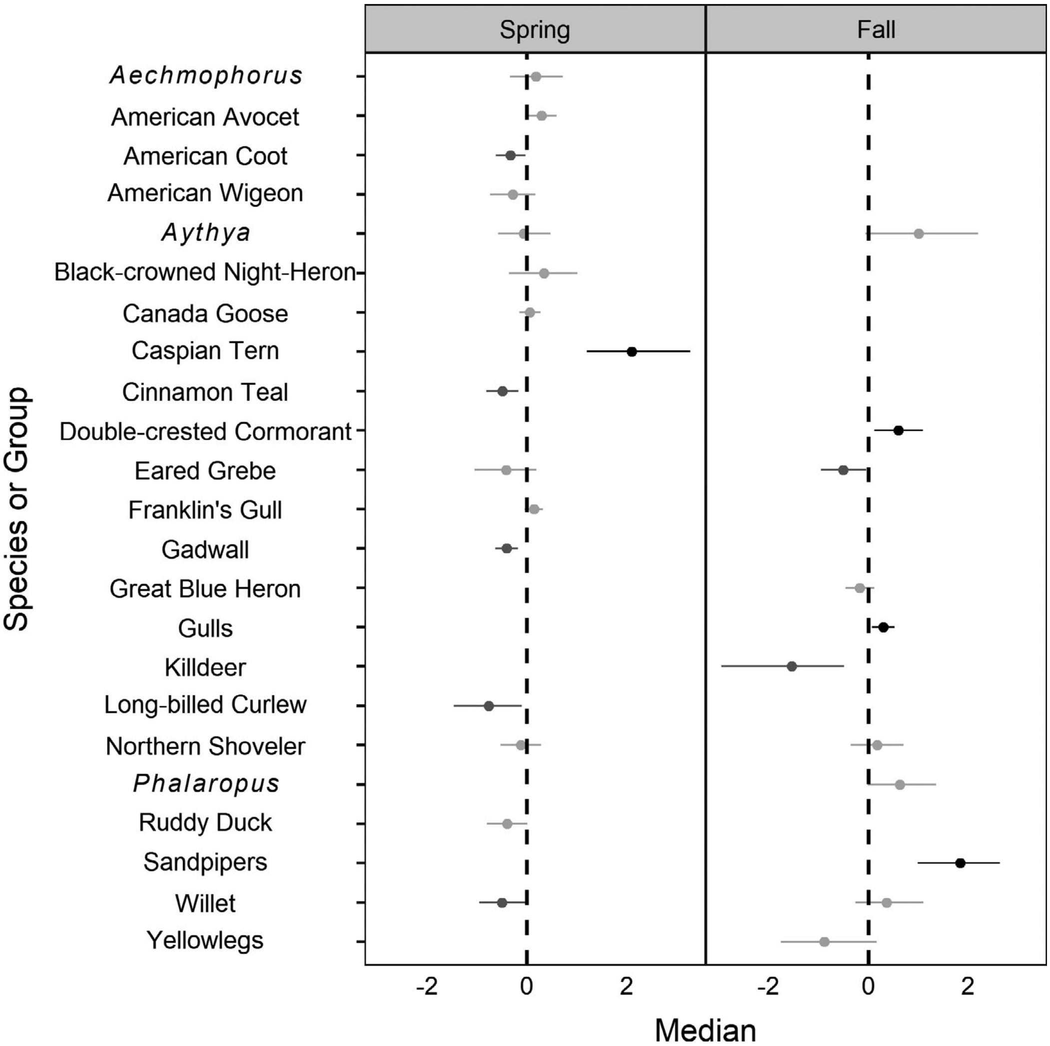

Fig. 3. Seasonal lake elevation estimates for shorebird, waterfowl, and other waterbird species or taxonomic groups in Great Salt Lake's Bear River Bay (Utah, USA). Estimates are provided where a seasonal, linear effect of Great Salt Lake elevation was the best model for a species or taxonomic group. Point estimates represent the median of posterior distributions, and bars represent the 95% Bayesian credible intervals. Significant positive estimates are in dark gray, significant negative estimates appear medium gray, and non-significant estimates are in light gray.

be found in more saline waters of the lake with abundant brine shrimp on which they forage while molting and preparing for further migratory movements (Caudell and Conover 2006). Utah's Division of Forestry, Fire and State Lands (UDNR FFSL 2013), in cooperation with partners, identified lake elevations ranging from 1279.6 to 1281.7 m as benefitting birds foraging in salt or fresh water, nesting on islands, and foraging or nesting in wetlands, in shallow water, or on shorelines/mudflats. Although useful for lake-wide assessments, this elevation range does not apply to specific areas, including Bear River Bay. This is evidenced by the fact that, despite lake elevations in our study generally falling below 1279.6 m in spring and fall, increasing lake elevation resulted in a decrease in Bear River Bay counts for species and taxonomic groups that use varied foraging habitats, techniques, and food resources. Understanding how the elevation of Great Salt Lake affects seasonal bird use of specific bays will require future studies that explicitly model how lake elevation affects the types, distributions, and areas of wetland habitats across the entire lake. Notwithstanding the need for such wetland modeling, relationships reported in our study can be used to evaluate and consider how changes in lake elevation affect Bear River Bay counts for species and taxonomic groups.

Cavitt (2013) analyzed relationships between counts of 11 bird species or taxonomic groups and surface water inflows and lake elevation for Willard Spur, an ecosystem comprising 17.4% of our Bear River Bay study area. Using Willard Spur bird counts (1999–2012) from the Great Salt Lake Ecosystem Program, Cavitt (2013) reported negative relationships between Great Salt Lake elevation and fall counts for the *Aechmophorus* group, Black-necked Stilt (*Himantopus mexicanus*), California Gull (*Larus californicus*), Cinnamon Teal, and White-faced Ibis (*Plegadis chihi*) and a positive relationship for American Avocets. We do not attempt to compare these lake elevation results to those in our study primarily because Cavitt (2013) did not include survey year as a model predictor. We found that including survey year —specifically, its residual after controlling for correlations with lake elevation—as a predictor affected which species and taxonomic groups responded to lake elevation and changed the relative numerical balance of positive and negative relationships (B. Tavernia, unpubl. data). Given that our dataset spanned 14 years (2004–2017), we believed it appropriate to include survey year to account for temporal changes in counts. Using surface flows from the USGS gage near Corrine, Cavitt (2013) reported a positive effect of flows on fall counts of American Coots (*Fulica americana*), a negative effect on spring counts of White-faced Ibis, and no effect of fall or spring flows on counts of American Avocets, American White Pelicans, or Forster's Terns in Willard Spur. For our Bear River Bay study area, we found more responses to surface water flows, including positive responses for American Avocets, American Coots, American White Pelicans, Forster's Terns, and White-faced Ibis to increased fall surface water flows, a positive response of Forster's Tern to increased spring surface flows, and maximum counts of American White Pelicans at intermediate spring surface flows. In many years, Willard Spur retains some standing surface water when other areas of Bear River Bay have none (B. Tavernia, pers. observ.), and this may, in part, explain the few relationships between surface water flows and bird counts reported by Cavitt (2013). Nonetheless, surface flows and water connections among Willard Spur, Bear River Bay, and Great Salt Lake are important for the long-term ecological health of Willard Spur and its bird habitat (CH2M Hill Inc. 2016, Low 2018).

Long-term bird monitoring programs do not always collect a suite of local habitat data concurrent with bird counts (e.g., O'Connor et al. 2000), and without habitat data, explaining bird distributions, abundances, and trends is impossible. In this paper, we developed hydrological measures—surface water inflows and Great Salt Lake elevation—for Bear River Bay hydrology by relying largely on long-term USGS hydrological monitoring data. Although we found relationships between bird counts and these hydrological metrics, our ability to model bird counts would be enhanced by temporally and spatially comprehensive data representing potentially important habitat characteristics including water depth (specific to Bear River Bay), vegetation structure and composition, salinity, and food resources (Ma et al. 2010). Such characteristics may be significant correlates of counts including for those species that did not respond to either surface flows or lake elevation in our study. Some habitat data gaps could be addressed by pairing a feasible habitat monitoring protocol with ongoing Great Salt Lake Ecosystem Program bird surveys, and guidance exists to develop habitat survey protocols for nonbreeding season surveys (e.g., Program for Regional and International Shorebird Monitoring 2018). For isolated projects, remote sensing datasets and image classification techniques have shown promise in addressing habitat-related ecosystem attributes, including the invasive *Phragmites australis* (Long et al. 2017) and chlorophyll concentrations (Bradt 2012). Continued scientific refinement of these techniques and institutional support for their ongoing application at Great Salt Lake would provide important habitat data.

Despite a desire for additional habitat metrics, we deliberately considered our hydrological metrics because they offer potential linkages to scenario-based projections of surface flows (Serago et al. 2020) and lake elevation at Great Salt Lake (Jacobs Engineering Group Inc. 2019). Our models can be used to evaluate bird responses to projections that are within the range of surface flows and lake elevations used in model construction. Projection efforts and associated models are still in their relative infancies, but these preliminary projections suggest that lake elevations will decline outside the range observed in the data used to build our models (Jacobs Engineering Group Inc. 2019). If our models are extrapolated to assess effects of surface flows and lake elevations not included in modeled data, such assessments should acknowledge that the models have been extrapolated. To obviate the need for extrapolation, continued monitoring and modeling can update our models to incorporate bird responses to lake elevations and surface flows that have no analog in currently modeled data.

In our analyses, we assumed that a constant proportion of individuals was counted regardless of lake elevation, surface flows, or year. This requires that detection probability, or the chance of confirming an individual animal is present within a survey unit over a defined time (Thompson and White 1998), remains unchanged. Factors affecting detection probability include observer identity and experience, survey method, time of day, weather conditions, habitat conditions, and other variables (Thompson et al. 1998). In our study, wildlife biologists conducted counts, and most surveys (76%) were conducted by the same two observers (J. Neill, unpubl. data). Surveys were consistently conducted by air following a protocol that detailed the acceptable timing and weather conditions for flights. Because our study area consisted primarily of open water or mudflats, we assumed, as did Vest (2013), that habitat did not affect bird visibility. Therefore, we do not believe that detection probability biased observed relationships between counts, lake elevations, surface flows, and year.

Bear River Bay is an integral part of a habitat network at Great Salt Lake and other western hemisphere saline lakes and wetlands, and this network supports wetland-dependent birds as they complete their annual cycles. Declining habitat quality or availability at critical locations within a habitat network can have disproportionate effects on migratory bird populations (Iwamura et al. 2013), so it is important to secure sufficient water resources for Bear River Bay and other locally, regionally, and internationally recognized sites for bird conservation. Conserving and increasing seasonal surface water flows now and in the future will increase numbers of shorebirds, waterfowl, and other waterbirds using Bear River Bay. Ultimately, successful bird conservation will require coordinated management and monitoring of hydrology, habitats, and bird populations across the network of saline lakes and their associated wetlands.

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LITERATURE CITED

AHARON-ROTMAN, Y., J. MCEVOY, Z. ZHAOJU, H. YU, X. WANG, Y. SI, Z. XU, Z. YUAN, W. JEONG, L. CAO, AND A. D. FOX. 2017. Water level affects availability of optimal feeding habitats for threatened migratory waterbirds. Ecology and Evolution 7: 10440–10450.

ALDER, W. 2002. The National Weather Service, weather across Utah in the 1980s, and its effect on Great Salt Lake. In: Great Salt Lake: an overview of change (J. W. Gwynn, ed.), pp. 295–301. Utah Department of Natural Resources and Utah Geological Survey, Salt Lake City, UT.

ALDRICH, T. W., AND D. S. PAUL. 2002. Avian ecology of Great Salt Lake. In: Great Salt Lake: an overview of change (J. W. Gwynn, ed.), pp. 343–374. Utah Department of Natural Resources and Utah Geological Survey, Salt Lake City, UT.

ARMSTRONG, T., AND W. A. WURTSBAUGH [online]. 2019. Impacts of eutrophication on benthic invertebrates and fish prey of birds in Farmington and Bear River bays of Great Salt Lake. Utah

Division of Forestry, Fire, and State Lands. <https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2121&context=wats_facpub> (Accessed 20 July 2021).

Bellio, M., and R. T. Kingsford. 2013. Alteration of wetland hydrology in coastal lagoons: implications for shorebird conservation and wetland restoration at a Ramsar site in Sri Lanka. Biological Conservation 167: 57–68.

Benoit, L. K., and R. A. Askins. 1999. Impact of the spread of *Phragmites* on the distribution of birds in Connecticut tidal marshes. Wetlands 19: 194–208.

BirdLife International [online]. 2020. Important Bird Areas factsheet: Bear River Bay UT02. <http://www.birdlife.org> (Accessed 23 April 2020).

Bolduc, F., and A. D. Afton. 2004. Relationships between wintering waterbirds and invertebrates, sediments and hydrology of coastal marsh ponds. Waterbirds 27: 333–341.

Bradt, S. R. 2012. Development of bio-optical algorithms to estimate chlorophyll in the Great Salt Lake and New England lakes using *in situ* hyperspectral measurements. Ph.D. dissertation, University of New Hampshire, Durham, NH.

Caudell, J. N., and M. R. Conover. 2006. Behavioral and physiological responses of Eared Grebes (*Podiceps nigricollis*) to variations in brine shrimp (*Artemia franciscana*) densities. Western North American Naturalist 66: 12–22.

Cavitt, J. 2013. Avian population analysis of the Willard Spur. Utah Division of Water Quality. <https://deq.utah.gov/legacy/destinations/g/great-salt-lake/willardspur/docs/2015/10Oct/SpurAvianPopulationAnalysis.pdf> (Accessed 7 April 2021).

Cavitt, J. F., S. L. Jones, N. M. Wilson, J. S. Dieni, T. S. Zimmerman, R. H. Doster, and Howe W. H. 2014. Atlas of breeding colonial waterbirds in the interior western United States. U.S. Department of the Interior, Fish and Wildlife Service, Denver, CO. <https://www.fws.gov/mountain-prairie/migbirds/species/birds/western_colonial/Atlas_WCWS_interior_1-23-2014_FINAL.pdf> (Accessed 7 April 2021).

CH2M Hill Inc [online]. 2016. Hydrology assessment of Willard Spur, Great Salt Lake, 2011-2013: development of water quality standards for Willard Spur. Utah Division of Water Quality. https:deq.utah.gov/legacy/destinations/g/great-salt-lake/willard-spur/docs/2016/01jan/finaldraft_ws_report_2016-1-7%20rep_only.pdf (Accessed 7 April 2021).

Czado, C., T. Gneiting, and L. Held. 2009. Predictive model assessment for count data. Biometrics 65: 1254–1261.

Dana, G. L., and P. H. Lenz. 1986. Effects of increasing salinity on an *Artemia* population from Mono Lake, California. Oecologia 68: 428–436.

De Cicco, L. A., D. Lorenz, R. M. Hirsch, and W. Watkins. 2018. dataRetrieval: R packages for discovering and retrieving water data available from U.S. federal hydrologic web services. U.S. Geological Survey. Version 2.7.5. DOI:https://doi.org/10.5066/P9X4L3GE

DesGranges, J., J. Ingram, B. Drolet, J. Morin, C. Savage, and D. Borcard. 2006. Modelling wetland bird response to water level changes in the Lake Ontario – St. Lawrence River hydrosystem. Environmental Monitoring and Assessment 113: 329–365.

Donnelly, J. P., S. L. King, N. L. Silverman, D. P. Collins, E. M. Carrera-Gonzalez, A. Lafón-Terrazas, and J. N. Moore. 2020. Climate and human water use diminish wetland networks supporting continental waterbird migration. Global Change Biology 26: 2042–2059.

Farmer, A. H., and A. H. Parent. 1997. Effects of the landscape on shorebird movements at spring migration stopovers. Condor 99: 698–707.

Ficklin, D. L., I. T. Stewart, and E. P. Maurer. 2013. Effects of projected climate change on the hydrology in the Mono Lake Basin, California. Climate Change 116: 111–131.

Haig, S. M., S. P. Murphy, J. H. Matthews, I. Arismendi, and M. Safeeq. 2019. Climate-altered wetlands challenge waterbird use and migratory connectivity in arid landscapes. Scientific Reports 9: 4666.

Iwamura, T., H. P. Possingham, I. Chadès, C. Minton, N. J. Murray, D. I. Rogers, E. A. Treml, and R. A. Fuller. 2013. Migratory connectivity magnifies the consequences of habitat loss from sea-level rise for shorebird populations. Proceedings of the Royal Society B 280: 20130325.

Jacobs Engineering Group Inc. 2019. Great Salt Lake Integrated Model (GSLIM): an integrated water resource management tool for the Great Salt Lake Watershed. Phase II – GSLIM Evaluation. Report to the Great Salt Lake Advisory Council, Jacobs Engineering Group, Taylorsville, UT.

Jeppesen, E., S. Brucet, L. Naselli-Flores, E. Papastergiadou, K. Stefanidis, T. Nõges, P. Nõges, J. L. Attayde, T. Zohary, J. Coppens, T. Bucak, R. F. Menezes, F. R. S. Freitas, M. Kernan, M. Søndergaard, and M. Beklioğlu. 2015. Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. Trends in Aquatic Ecology 750: 201–227.

Jones, S., P. Lacey, and T. Walshe. 2009. A dynamic hydrological Monte Carlo simulation model to inform decision-making at Lake Toolibin, Western Australia. Journal of Environmental Management 90: 1761–1769.

Kadlec, J. A., and L. M. Smith. 1989. The Great Basin marshes. In: Habitat management for migrating and wintering waterfowl in North America (L. M. Smith, R. L. Pederson, and R. H. Kaminski, eds.), pp. 451–474. Texas Tech University Press, Lubbock, TX.

Kass, R. E., and A. E. Raftery. 1995. Bayes factors. Journal of the American Statistical Association 90: 773–795.

King, S. L., M. K. Laubhan, P. Tashjian, J. Vradenburg, and L. Fredrickson. 2021. Wetland conservation: challenges related to water law and farm policy. Wetlands 41: 54.

Kingsford, R. T., K. M. Jenkins, and J. L. Porter. 2004. Imposed hydrological stability on lakes in arid Australia and effects on waterbirds. Ecology 85: 2478–2492.

Knopf, F. L., and R. M. Evans. 2020. American White Pelican (*Pelecanus erythrorhynchos*), version 1.0. In: Birds of the world (A. F. Poole, ed.). Cornell Lab of Ornithology, Ithaca, NY.

Long, A. L., K. M. Kettenring, C. P. Hawkins, and C. M. U. Neale. 2017. Distribution and drivers of a widespread, invasive wetland grass, *Phragmites australis*, in wetlands of the Great Salt Lake, Utah, USA. Wetlands 37: 45–57.

Low, G. [online]. 2018. Willard Spur CAP workshop: summary report. <https://documents.deq.utah.gov/water-quality/standards-technical-services/gsl-website-docs/wetlands-program/gsl-wetland-cap/DWQ-2018-005270.pdf> (Accessed 21 July 2021).

Ma, Z., Y. Cai, B. Li, and J. Chen. 2010. Managing wetland habits for waterbirds: an international perspective. Wetlands 30: 15–27.

Moore, J. N. 2016. Recent desiccation of western Great Basin saline lakes: lessons from Lake Abert, Oregon, U.S.A. Science of the Total Environment 554–555: 142–154.

O'Connor, R. J., E. H. Dunn, D. H. Johnson, S. L. Jones, D. Petit, K. Pollock, C. R. Smith, J. L. Trapp, and W. Welling. 2000. A programmatic review of the North American Breeding Bird Survey: report of a peer review panel. USGS Patuxent Wildlife Research Center, Laurel, MD.

Petrie, M., J. Vest, and D. Smith. 2013. Waterfowl. Intermountain West Joint Venture. 2013 Implementation Plan – Strengthening science and partnerships. Intermountain West Joint Venture., Missoula, MT.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. BioScience 47: 769–784.

Program for Regional and International Shorebird Monitoring [online]. 2018. Standards for monitoring nonbreeding shorebirds in the Western Hemisphere. Program for Regional and International Shorebird Monitoring (PRISM). <https://www.shorebirdplan.org/wp-content/uploads/2018/10/Nonbreeding-Shorebird-Monitoring-Standards-PRISM-Oct-2018.pdf> (Accessed 7 April 2021).

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Roberts, A. J., M. R. Conover, and J. L. Vest. 2016. Environmental influences on wintering duck abundance at Great Salt Lake, Utah. Western North American Naturalist 76: 18–26.

Rohal, C. B., K. M. Kettenring, K. Sims, E. L. G. Hazelton, and Z. Ma. 2018. Surveying managers to inform a regionally relevant invasive *Phragmites australis* control research program. Journal of Environmental Management 206: 807–816.

Rue, H., A. Riebler, S. H. Sorbye, J. B. Illian, D. P. Simpson, and F. K. Lindgren. 2017. Bayesian computing with INLA: a review. Annual Reviews of Statistics and Its Applications 4: 395–421.

Serago, J. M., C. K. Baldwin, D. J. Hoekema, E. T. Geisler, C. Burton, and D. W. Neumann. 2020. Impacts on Bear Lake storage under alternative high-runoff management operations. <https://water.utah.gov/wp-content/uploads/2020/12/BearLakeReport.pdf> (Accessed 21 July 2021).

Sorensen, E. D., H. M. Hoven, and J. Neill. 2020. Great Salt Lake shorebirds, their habitats and food base. In: Great Salt Lake biology: a terminal lake in a time of change (B. K. Baxter and J. K. Butler, eds.), pp. 263–309. Springer, Cham, Switzerland.

Sorenson, L. G., R. Goldberg, T. L. Root, and M. G. Anderson. 1998. Potential effects of global warming on waterfowl populations breeding in the northern Great Plains. Climatic Change 40: 343–369.

Thomas, S., B. Andres, and J. Vest. 2013. Shorebirds. In: Intermountain West Joint Venture. 2013 Implementation Plan – Strengthening science and partnerships. Intermountain West Joint Venture, Missoula, MT.

Thompson, W. L., G. C. White, and C. Gowan. 1998. Monitoring vertebrate populations. Academic Press Inc., San Diego, CA.

Timmermans, S. T. A., S. S. Badzinski, and J. W. Ingram. 2008. Associations between breeding marsh bird abundances and Great Lakes hydrology. Journal of Great Lakes Research 34: 351–364.

UDNR Ffsl (Utah Department of Natural Resources Division of Forestry, Fire and State Lands). [online]. 2013. Final Great Salt Lake Comprehensive Management Plan and Record of Decision. Prepared by SWCA Environmental Consultants. Salt Lake City, UT.

Vest, J. L. 2013. Winter ecology of waterfowl on the Great Salt Lake, Utah. Ph.D. dissertation, Utah State University, Logan, UT.

Wang, Y., Y. Jia, L. Guan, C. Lu, G. Lei, L. Wen, and G. Liu. 2013. Optimising hydrological conditions to sustain wintering waterbird populations in Poyang Lake National Natural Reserve: implications for dam operations. Freshwater Biology 58: 2366–2379.

Webb, E. B., L. M. Smith, M. P. Vrtiska, and T. G. LaGrange. 2010. Effects of local and landscape variables on wetland bird habitat use during migration through the Rainwater Basin. Journal of Wildlife Management 74: 109–119.

Weller, M. W. 1999. Wetland birds. Cambridge University Press, Cambridge, UK.

Williams, W. D. 2002. Environmental threats to salt lakes and the likely status of inland saline ecosystems in 2025. Environmental Conservation 29: 154–167.

Wilsey, C. B., L. Taylor, N. Michel, and K. Stockdale. 2017. Water and birds in the arid west: habitats in decline. National Audubon Society, New York, NY.

Wurtsbaugh, W. A., C. Miller, S. E. Null, R. J. DeRose, P. Wilcock, M. Hahnenberger, F. Howe, and J. Moore. 2017. Decline of the world's saline lakes. Nature Geoscience 10: 816–821.

Zhang, C., Y. Yuan, G. Zeng, J. Liang, S. Guo, L. Huang, S. Hua, H. Wu, Y. Zhu, H. An, and L.

ZHANG. 2016. Influence of hydrological regime and climatic factor on waterbird abundance in Dongting Lake Wetland, China: implications for biological conservation. Ecological Engineering 90: 473–481.

ZIMMERMAN, T., G. IVEY, AND J. VEST [ONLINE]. 2013. Waterbirds. In: Intermountain West Joint Venture. 2013 Implementation Plan – Strengthening Science and Partnerships. Intermountain West Joint Venture, Missoula, MT.

ZUUR, A. F., E. N. IENO, AND C. F. ELPHICK. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1: 3–14.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website.

Table S1. Species with counts modeled as a function of surface water flows, Great Salt Lake elevation, and survey year for Bear River Bay, Utah.