RESEARCH ARTICLE

Multi-scale waterfowl habitat conservation planning in Wisconsin, USA

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Abstract

Context The North American Waterfowl Management Plan and the Upper Mississippi River/Great Lakes Joint Venture waterfowl habitat conservation strategy provide continental and regional guidance, respectively, for waterfowl habitat conservation planning. They were not designed to guide watershed-scale waterfowl habitat delivery.

Objective Our goal was to develop a waterfowl habitat decision support framework for the state of Wisconsin using biological and social criteria to guide state and local-scale practitioners with an explicit link to larger scale objectives.

Methods We engaged a core group of wetland and waterfowl experts to decide upon decision support layers relevant to biological and social objectives, evaluate variables, establish weights, and review model outputs for reasonableness and accuracy. We used spatial analyst tools, kernel density estimators, and weighted sums to create spatially explicit models

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to identify landscapes and watersheds important for waterfowl. We identified habitat resources that exist currently (Conservation Capital) and considered potential resources (Conservation Opportunities) which could enhance wetland restoration efforts.

Results We developed a transparent framework to identify and prioritize landscapes for conserving waterfowl habitat at the Hydrologic Unit Code 12 watershed scale in Wisconsin, by maintaining continental and regional priorities, and including local landscape characteristics, biological criteria, and researcher, manager, and biologist expertise.

Conclusions Local detail is critical for implementing waterfowl habitat delivery and making efficient use of limited funds for conservation but can be more abstract in larger regional or continental conservation planning. Our models are science-based, transparent, defensible, and can be modified as social, political, biological, and environmental forces change.

Keywords Conservation planning · Joint venture · Landscape-scale restoration · Waterflow Management Plan · Strategic conservation delivery · Waterfowl · Wetlands · Wisconsin

Introduction

Understanding species distributions in landscapes requires knowledge on ecogeographical preferences (Jones 2011; Noon et al. 2012), timing of seasonal biological life-history events and how these factors interact at various spatial scales (Johnson 1980; Mayor et al. 2009). For example, ducks select a breeding

range based on landscape-level cues (Reynolds et al. 2001; Eichholz and Elmberg 2014), but then select nest sites from local characteristics (Dyson et al. 2019). A central goal of applied ecology is to develop tools that can predict wildlife habitat selection patterns so managers can identify and manage habitat quantity and quality at spatial scales necessary for effective conservation. Wildlife habitat selection assessments are important to management decisions at broad and local scales (McGarigal et al. 2016), and effective conservation planning must go beyond species distribution models (Peterson 2001) and consider multiple objectives including socio-political interests, ecosystem services and stakeholder investment at an appropriate spatial scale.

Decision support tools (DSTs) can assist with choice making or informing decisions for a variety of environmental management or planning actions (Wong-Parodi et al. 2020). Whereas DSTs can be as straight forward as a spreadsheet or decision tree with nodes, they can also incorporate spatially-explicit data. Spatially explicit DSTs can leverage computationally intensive analysis of patterns and processes over large areas and synthesize information into mapping products where priority locations are depicted. They can also identify landscapes most suitable for conservation action and help guide decisions with multiple, sometimes competing, objectives (Garcia and Armbruster 1997; Roloff et al. 1999). As such, wildlife conservation planners are adopting DSTs, especially those identifying priority landscapes for habitat delivery (Soulliere and Al-Saffar 2017; Krainyk et al. 2019a; Ricca and Coates 2020), because they can produce conservation gains with lower costs (Strassburg et al. 2019).

North American waterfowl, as a taxonomic group, are a rare example where wildlife populations are stable or increasing (Rosenberg et al. 2019). One explanation for this trend is habitat planning in North America is aided by conservation actions of the North American Waterfowl Management Plan (NAWMP 1986, 2018). As the name implies, NAWMP has an international focus as waterfowl and their habitats have a continental-scale distribution covering vast landscapes (Baldassarre 2014; Krainyk et al. 2019b). However, scale mismatches can occur when disconnect exists between the extent and resolution of management actions and the ecological system of interest (Guerrero et al. 2013, 2015). To address scale-

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mismatch and to ‘step down’ continental directives, NAWMP goals are refined into measurable regional objectives and then implemented by migratory bird Joint Ventures (JVs). Bird-habitat JVs are 22 regional partnerships established to achieve goals of the NAWMP. These self-directed groups include wildlife agencies, non-government organizations, corporations, tribes, and individuals who accepted responsibility to implement international bird conservation plans within a specific geographic area (see <https://www.fws.gov/birds/management/bird-conservation-partnership-and-initiatives/migratory-bird-joint-ventures.php>). A primary role of JVs is to coordinate and facilitate delivery of bird habitat conservation, stepping down continental bird-conservation plans to JV regions. Whereas the NAWMP provides spatially explicit identification of large critical landscapes for waterfowl (NAWMP 2018; Krainyk et al. 2019b), regional conservation planners have developed and adopted finer scale DSTs to help make resource allocation decisions that connect continental priorities with more regional decisions. For instance, Krainyk et al. (2019b) developed a DST for mottled duck (*Anas fulvigula*) habitat conservation in the western gulf coast of North America. In addition, the Upper Mississippi/Great Lakes (UMGL) JV developed a regional waterfowl habitat DST that uses spatially explicit prioritization to target wetland conservation to achieve multiple goals of NAWMP (Soulliere and Al-Saffar 2017).

The UMGL JV’s conservation planning approach is regional in scale, where there are unique landscapes, biological interactions, and important socio-political influences at large spatial resolutions. Whereas international and regional planning are vital to migratory bird conservation, most habitat delivery (i.e., wetland retention or restoration) and funding operate at local levels usually within state and provincial jurisdictions. Hence, smaller scale tools are needed to account for eco-physiographic variation at the resolution of decision making. For instance, using watersheds as a landscape planning unit not only delineates the spatial modelling extent but also can link physical processes with biological communities (Montgomery et al. 1995). To this end, and to further address scale-mismatches between NAWMP goals and local level planning, we designed a DST to connect continental planning goals with local spatially explicit habitat conservation guidance.

Watershed-scale and state-level conservation prioritization that is linked explicitly to regional and continental habitat goals are largely absent. The nature of how conservation actions scale up to achieve broader goals and objectives have been tacit. Our goal was to develop a state-level and spatially explicit waterfowl habitat DST to facilitate implementation of the NAWMP in Wisconsin, USA. Specific objectives include (a) identify and prioritize Ecological Landscapes and (b) within Ecological Landscapes, identify and prioritize watersheds for fine-scale planning and conservation delivery based on eco-physiographic boundaries. Our approach and resulting maps provide a clear link between granular, within state, conservation planning and implementation (e.g., watersheds) to larger, coarser, continental (NAWMP) and regional (JV) objectives.

Methods

Expert guidance and structure

We structured our DST within the state of Wisconsin for several reasons. First, Wisconsin is one of only four states embedded completely within the UMGL JV which allowed us to ‘step down’ regional goals and approaches (Fig. 1). Second, waterfowl habitat management in Wisconsin has been guided by a conservation strategy that was finalized in 1992 called the Upper Mississippi River and Great Lakes Region Joint Venture—Wisconsin Plan (WDNR 1992). This conservation strategy included spatially explicit landscapes across the state and served as a template for our DST. Third, Wisconsin has vetted and detailed Ecological Landscapes (WDNR 2015) that represent different attributes (e.g., soils, hydrology, vegetation) and are recognized as a contemporary reference for landscape planning (Wisconsin Wildlife Action Plan 2005–2015). Finally, decades of conservation investments in habitat, outreach, and infrastructure (Straub et al. 2019) have engaged many active and passionate stakeholders.

In summer of 2016, we initiated an effort to revise the existing state waterfowl habitat conservation plan (WDNR 1992) as representatives of different agencies including University of Wisconsin Stevens Point (UWSP), Ducks Unlimited (DU), Wisconsin Department of Natural Resources (WDNR), U.S. Fish and

Fig. 1 Depiction of the state of Wisconsin within North America and the Upper Mississippi River and Great Lakes region of USA

Wildlife Service (USFWS), and Natural Resources Conservation Service (NRCS). Collectively, we serve our corresponding agencies as experts in waterfowl habitat planning and deliver waterfowl habitat conservation in Wisconsin. During the subsequent planning phase, we identified a desire to align with goals identified in the recently completed 2017 JV regional waterfowl habitat conservation strategy (Soulliere et al. 2017) and 2018 NAWMP (NAWMP 2018). This process led to development of eight unique spatial layers (see methods below) each representing unique biological or social objectives (Tables 1 and 2). The lead author, J. Straub, G. Soulliere, and M. Al-Saffar initiated design, creation and depiction of spatial layers and then presented them to co-authors for feedback and guidance. Ultimately, all co-authors listed served as an expert panel of waterfowl conservation stakeholders contributing to decisions in the development process of each spatial layer, and final

layers and models represent consensus among co-authors. This included classifying spatial layers into those representing existing habitat resources, termed Conservation Capital (CC), and those that recognize potential (e.g., future) waterfowl habitat termed Conservation Opportunities (CO). Finally, we identified a need to prioritize larger Wisconsin landscapes and smaller resolution local areas for habitat conservation. Therefore, we settled on a two-tiered system to depict statewide waterfowl habitat delivery, starting with Wisconsin's Ecological Landscapes (ELs), modified from those derived from the Wisconsin Wildlife Action Plan (Wisconsin Wildlife Action Plan 2005–2015) and scaled down to 12-digit hydrologic unit code watersheds (hereafter watersheds).

To organize and apply our process, we used a pair of flowcharts (Fig. 2), one each for CC and CO, with the goal of informing an aggregate decision support map in Wisconsin. For each flowchart, we identified

Table 1 Wisconsin conservation planning issues, objectives, scores, and spatial data used to prioritize landscapes for waterfowl conservation based on resources existing on the landscape

Conservation issue (NAWMP/JV/State goal)		Score	Spatial data (model-based maps)
Objective			
Population and species			
Breeding habitat limitation	Identify high quality breeding habitat that maximizes focal species recruitment	0.44	Density and distribution of key breeding duck habitats intersected with key breeding duck abundance estimates (focal species combined and weighted by breeding population composition)
Autumn habitat limitation	Identify habitats that enhance focal species survival and body condition with an emphasis on factors specific to autumn-migrating needs and preferences	0.14	Density and distribution of key Autumn migration duck habitats (focal species combined and weighted by proportion of harvest and wetland area)
Spring habitat limitation	Identify habitats that enhance focal species survival and body condition with an emphasis on factors specific to spring-migrating needs and preferences	0.19	Density and distribution of key Spring migration duck habitats (focal species combined and weighted by proportion of eBird observation)
Conservation supporters and social values			
Resource user—hunters	Identify areas that have the greatest likelihood to maximize waterfowl hunter retention and recruitment	0.1	Harvest distribution for hunting opportunity areas (county-level duck and goose harvest normalized by county size)
Ecological services provided by wetland retention	Identify areas that <i>currently</i> maximize flood abatement, sediment retention, surface water supply, and fish and aquatic habitat and minimize nutrient transformation	0.13	Wetlands by Design: A Watershed Approach combined ecological services score for each watershed
All issues		1	

conservation issues that were pertinent to Wisconsin, the JV, and NAWMP (Tables 1 and 2). Each flowchart includes biological or social objectives (Table 1) in tandem with the corresponding spatial data to represent it at the scale of Wisconsin. Next, we created a spatially explicit map depicting relative density of each biological or social issue of interest. At this stage we presented each to an expanded group of waterfowl and wetland stakeholders within Wisconsin, relative to the authors on this manuscript, and asked them to score each map based on how important they perceived each issue for waterfowl habitat conservation in Wisconsin. Organizations represented on this expanded committee included WDNR, UWSP, USFWS, NRCS, DU, The Nature Conservancy (TNC), Wisconsin Waterfowl Association, and Great Lakes Indian Fish and Wildlife Commission. We instructed each person to provide an importance score for each conservation issue (spatial layer) no less than 0.05 and all layers combined must sum to 1.0. We averaged scores for each layer from all stakeholders

and adopted these as separate statewide surfaces of relative conservation prioritization for CO and CC.

We used spatial analyst extension of ArcMap 10.5.1 (ArcMap 10.5.1, Environmental Systems Research Institute, Redlands California, USA) for each objective derived from the CC and CO decision support flowcharts. Spatial information mapping differed for each objective, depending on available data and the density and distribution each model represented. All spatial layer creation, normalization, and model aggregation followed procedures outlined in Soulliere and Al-Saffar (2017). For each biological or social spatial layer, we applied the fuzzy linear function of Fuzzy Membership tool to its respective raster layer to re-scale values to 0 to 1 (Environmental Systems Research Institute 2018). In addition, all waterfowl habitat suitability considerations and weighting factors (Supplemental Tables) related to the National Wetlands Inventory (NWI) were the product of deliberations and agreement among co-authors and followed Soulliere et al. (2017), where

Table 2 Wisconsin conservation planning issues, objectives, scores, and spatial data used to prioritize landscapes for waterfowl conservation based on restoration potential on the landscape

Conservation issue (NAWMP/JV/State goal)			
Objective		Score	Spatial data (model-based maps)
Population and species			
Breeding habitat limitation	Identify areas that maximize focal species recruitment through the restoration of habitat in proximity to existing core breeding areas	0.48	Density and distribution of potentially restorable wetlands intersected with key breeding duck habitat near areas of greatest breeding duck habitat density
Conservation supporters and social values			
Resource users—all users	Identify areas that maximize waterfowl viewer/recreationist retention and recruitment	0.33	Human distribution relative to population density and locations of low human abundance within areas of high population density
Ecological services needed by wetland restoration	Identify areas that <i>could</i> maximize flood abatement, sediment retention, surface water supply, and fish and aquatic habitat and minimize nutrient transformation		
		0.19	Wetlands by Design: A Watershed Approach combined ecological services score for each watershed
All Issues		1	

Fig. 2 Representative flowchart of the process to synthesize objectives related to waterfowl conservation into a habitat decision support tool in Wisconsin, USA

expert-predicted most-suitable waterfowl habitats were given a score of 100, and secondary suitable habitats were given a score of 80. Areas of lower suitability were not used (see Landscape Suitability Index table in Soulliere et al. 2017).

Developing biological and social layers

Conservation capital spatial layers

Breeding habitat The objective of the breeding habitat spatial layer is to identify high quality breeding habitat that maximizes focal species recruitment. We estimated density and distribution of waterfowl breeding habitat for the four duck species breeding most commonly in the JV region and in Wisconsin: mallard (*Anas platyrhynchos*), wood duck (*Aix sponsa*), blue-winged teal (*Spatula discors*), and ring-necked duck (*Aythya collaris*), (hereafter collectively referred to as focal species). To identify habitat most important during the breeding season (May through August) we developed a breeding season landscape suitability table for all focal species (Supplemental Table 1). We considered breeding habitat as a mix of wetland and upland cover types that would allow for suitable nesting sites and provide adequate brood rearing (Soulliere et al. 2017). We used wetland data from NWI (Federal Geographic Data Committee 2013) and upland cover types (e.g., grassland/herbaceous) from WISCLAND 2 (WDNR 2016) to assess potential habitats for each species. Following guidance and to be consistent with information from the UMGL JV, we assigned locations of greatest suitability a weight of 100 and secondary habitats a weight of 80 (Supplemental Table 1). We converted each wetland polygon derived from our selection analysis to one inside point and used all points in weighted kernel density analysis where suitability scores were weights (Nelson and Boots 2008; Kenchington et al. 2014; Soulliere and Al-Saffar 2017). We performed this kernel density analysis for each species using an average bandwidth of 6.8 km (Supplemental Fig. 1). We performed kernel density analysis on focal species breeding habitat by merging all focal species wetland polygons and standardizing them by breeding abundance compositions for each respective species (e.g., 40% for mallard, 22% for wood duck, 11% for blue-winged teal, 5% for ring-necked duck). We used breeding

composition estimates provided in the 2017 JV waterfowl strategy from 2006 to 2015 for Wisconsin (Soulliere et al. 2017). We used standardized weights in focal species-weighted kernel density analysis to map density and distribution of the most suitable breeding habitats throughout Wisconsin. This analysis produced a smoothed 1-km-cell weighted-density floating-point raster, where areas of relatively greater habitat weight and or density were highlighted as hotspots of important breeding and brood rearing habitat for ducks in Wisconsin.

We supplemented the breeding habitat spatial layer with an additional process that identified where ducks were observed during aerial flights occurring at the onset of the breeding season (Van Horn et al. 2015). WDNR provided breeding abundance estimates for each focal species from their Waterfowl Breeding Population and Habitat Survey (WBPHS; Van Horn et al. 2015). We calculated density of focal species from survey segments ($n = 66$, 400 m wide by 48 km long, Van Horn et al. 2015) and plots ($\sim 2.5 \text{ km}^2$). We spatially joined these estimates to NWI cover types associated with suitable breeding habitat. We converted these suitable cover types to multiple random points with 100-m tolerance in-between and used these points with their weights (associated density data from survey segments) to interpolate density among segments through kriging analysis. We performed interpolation and reduced negative effects of spatial auto-correlation, trends, and directionality. This kriging analysis produced a smoothed 1-km-cell floating-point raster where areas of relatively greater density of focal species were highlighted as hotspots of observed waterfowl during the breeding season.

We combined the raster surface of spatial layer-based breeding habitat and the raster surface of waterfowl abundance during the breeding season through a Fuzzy-product Overlay tool (Environmental Systems Research Institute 2018). Our goal for intersecting the two raster surfaces was to account for potential errors in our designation of breeding habitat and observations of the WBPHS. For example, if a raster cell was designated as > 0 for the NWI-predicted breeding habitat surface and the WBPHS-predicted waterfowl abundance surface, then the product of these two cells was calculated in the subsequent output. If either of the breeding habitat surface or waterfowl abundance surface had a value equal to 0, then regardless of value in the other surface

the subsequent output was 0. The product of the two surfaces represented areas where breeding season habitat was identified, and breeding waterfowl were observed in a 1-km-cell floating-point raster.

Autumn staging habitat The objective of the autumn staging habitat spatial layer is to identify habitats that enhance focal species survival and body condition with an emphasis on factors specific to autumn-migrating needs and preferences. We identified suitable habitat for focal species during the primary autumn staging and migration period (i.e., September through November). Habitat characteristics of these four species reflect the habitats of most waterfowl occurring in the JV region (Soulliere et al. 2017) and in Wisconsin during this non-breeding period. We considered autumn staging habitat as wetland types large enough to enable ducks to congregate and provide adequate foraging resources needed prior to and during migration (Brasher et al. 2007; Stafford et al. 2007). As with the breeding habitat spatial layers, we queried NWI wetland polygons across Wisconsin but incorporated land cover types that waterfowl tend to avoid (e.g., developed areas) from WISCLAND 2.0. We assumed with increasing size of wetlands, opportunities to find refuge improved which can affect use (Stafford et al. 2010; Beatty et al. 2014, Supplemental Table 2) and weighted each wetland by area. We converted each wetland polygon derived from our selection analysis to one inside point and used all points in a wetland area-weighted kernel density analysis size (Nelson and Boots 2008; Kenchington et al. 2014; Soulliere and Al-Saffar 2017). We excluded NWI wetlands associated with Lake Winnebago due to its relatively large size and subsequent weighting it received. We performed this kernel density analysis for each species using an average bandwidth of approximately 11.4 km (Supplemental Fig. 2). We performed kernel density analysis on the focal species autumn staging habitat by merging all focal species wetland polygons and standardizing them by each respective species harvest composition (e.g., 32% for mallard, 22% for wood duck, 7% for blue-winged teal, 3% for ring-necked duck). We used harvest composition estimates provided by WDNR from 2008 to 2016 (WDNR Waterfowl Biologist T. Finger personal communication 2018) and used standardized weights in focal species-weighted kernel density analysis to

map density and distribution of most suitable autumn staging wetlands. This analysis produced a smoothed 1-km-cell weighted density floating-point raster, where areas of relatively greater weight were highlighted as hotspots of important autumn migration habitat.

Spring migration habitat The objective of the spring migration habitat spatial layer is to identify habitats that enhance focal species survival and body condition with an emphasis on factors specific to spring-migrating needs and preferences. Again, we performed an analysis similar to the breeding season and autumn staging spatial layers but for spring migration (February through April). We considered spring migration habitat as wetland types of any size and those that provide adequate foraging resources for waterfowl during migration and preparation for the breeding season (Stafford et al. 2007; Straub et al. 2012). As with the previous two habitat-based spatial layers, we queried NWI wetland polygons across Wisconsin but for this spatial layer we did not incorporate any non-wetland cover types. We assigned wetlands of greatest suitability a weight of 100 and secondary wetlands a weight of 80 (Supplemental Table 3). For spring migration spatial layers, blue-winged teal was the only species that had a secondary wetland type. We converted each wetland polygon derived from our selection analysis to one inside point and used all points in a weighted kernel density analysis (Nelson and Boots 2008; Kenchington et al. 2014; Soulliere and Al-Saffar 2017). We performed this kernel density analysis for each focal species using an average bandwidth of 3.89 km (Supplemental Fig. 3). We performed kernel density analysis on focal species spring migration habitat by merging all focal species wetland polygons and standardizing them by each respective species compositions of eBird observations from March through April of 1995–2014 from traveling checklists greater than 1 km [e.g., 48% for mallard, 20%, for wood duck, 17% for blue-winged teal, 14% for ring-necked duck (eBird Basic Dataset 2018)]. We used eBird observations as our best approximation of composition of focal species abundance during this period (eBird Basic Dataset 2018). We used these standardized weights in focal species-weighted kernel density analysis to map density and distribution of the most suitable spring migration habitat throughout

Wisconsin. This analysis produced a smoothed 1-km-cell weighted density floating-point raster, in which areas of relatively greater weight were highlighted as areas important for spring migration. We did not create a winter season habitat spatial layer due to the relative lack of management opportunities that could be implemented to affect wintering waterfowl habitat.

Density and distribution of waterfowl hunting community For this objective we identified areas to maximize waterfowl hunter retention and recruitment, recognizing the specialized equipment and skills required by waterfowl hunters (and potential hunters) will more likely be found at locations with active waterfowl hunting communities. We assessed level of hunting activity by calculating average harvest of all species of duck and goose per county from 1995 through 2014 and summed averages for all species (Harvest Information Program, USFWS.). We standardized these summed averages by county size and converted polygons to a series of random points. For this application (county-level analysis) and other applications of transferring data to random points bound by a polygon, we fit the greatest number of random points inside each polygon. In summary, we used the random points tool in ArcMap for these analyses with a large, arbitrary number of points per polygon (e.g., one million). The tool maximized the number of points inside the polygon as long as spacing was maintained (i.e., 100 m). This process produced a specific number of random points per polygon depending on polygon size, thus analyses performed using these random points were not biased due to variability of points per polygon. For example, kernel density analyses scanned the entire region using a revolving window, weighting each point based on underlying data rather than number of points per polygon. This 100-m point-spacing decision was a tradeoff between point resolution and computing time. We used standardized summed county averages as weights for the weighted kernel density analysis. We determined bandwidth by averaging the inner radius of the largest county and outer radius of the smallest county in Wisconsin resulting in a bandwidth of 23.7 km. This analysis produced a smoothed 1-km-cell weighted density floating-point raster, highlighting density and distribution of duck and goose harvest across Wisconsin. This spatial layer reflects density of areas where waterfowl hunters have

been successful in the past and where it is most likely to retain and recruit hunters.

Ecological services provided by wetlands The objective of the ecological services provided spatial layer was to identify areas that maximize flood abatement, sediment retention, surface water supply, and fish and aquatic habitat and minimize nutrient transformation (Miller et al 2017). Wetlands protected or restored for waterfowl habitat also provide an array of ecosystem goods and services (EGS) and wetlands provide EGS disproportionately more than other cover types (Costanza et al. 2014). Individual sites vary, however, regarding number and degree of EGS provided. In 2017, TNC and WDNR produced a statewide dataset and DST (Miller et al. 2017) called Wetlands by Design: A Watershed Approach for Wisconsin (www.WetlandsByDesign.org, here after WBD DST), that assessed and ranked wetlands and potentially restorable wetlands for their EGS potential. These data serve as the basis for the EGS component of the Wisconsin DST.

Detailed methods and context are provided in Miller et al. (2017) but an overview of our approach is provided here. For purposes of integrating information from the WBD DST, we considered potential protection sites as current wetlands mapped by Wisconsin Wetland Inventory (WWI, WDNR report) and potentially restorable wetlands (PRW) are former wetlands converted to upland through hydrologic alteration, as mapped by WDNR (<https://dnr.wi.gov/topic/surfacewater/datasets/PRW/>). In Wisconsin, NWI data available statewide were converted from WDNR's original WWI mapping; therefore, WBD wetlands analyses were based on original WWI data. All sites (WWI and PRW polygons) were assessed for their potential to provide five ecosystem services: flood abatement, fish and aquatic habitat, sediment retention, nutrient transformation and surface water supply (i.e., stream baseflow maintenance). Polygons were assessed for ecosystem service potential using NWI-Plus (Tiner 2003, 2005), an approach developed by USFWS and modified for application to Wisconsin. We conducted geospatial analyses to assign four categories of hydrogeomorphic modifiers to all current and restorable wetlands. These categories included landscape position (i.e., relation of site to waterbody), landform (i.e., physical shape and location of site), waterflow path (e.g., inflow, outflow, or through-flow)

and waterbody type (e.g., rivers, streams, or lakes). These factors were combined with WWI data (e.g., hydrologic regime, vegetation type) and additional modifiers (e.g., incision of associated streams, groundwater discharge index). All permutations of factors and modifiers were recorded in tabular format. Each set of possible combinations was then associated with ranks (high, moderate, and not applicable) for each EGS based on literature, best professional judgment of a team of wetland ecologists, and consultation with additional subject matter experts. This enabled ranking of each site for potential to provide each of five EGS.

We aggregated site-level data (sum of WWI acres assessed as high or moderate) for individual EGS within watersheds to consider potential for sites to provide all services combined based on: flood abatement, fish and aquatic habitat, sediment retention, nutrient transformation, and surface water supply. We ranked watersheds against all others by dividing each watershed score by the greatest watershed score, for current services. This process resulted in each watershed having rank value ranging from 0 to 1. We converted these ranks to multiple random points with 30-m tolerance in-between for each watershed. We used these values as the weight of each point in weighted kernel density analysis to map density and distribution of ecological services provided by wetlands throughout Wisconsin. This analysis produced a smoothed 1-km-cell weighted density floating-point raster, where areas of relatively greater weight were highlighted as areas of EGS provided by wetlands.

Conservation opportunities spatial layers

Proximity to core waterfowl breeding habitat The goal of this spatial layer is to identify areas that maximize focal species recruitment through restoration of habitat in proximity to existing core breeding areas. This spatial layer consisted of two parts: areas of potential wetland restoration and areas near most suitable breeding habitat for focal species. The basis for the first part was the PRW layer that was developed by WDNR, which consisted of > 2 million polygons that we converted into inside points and used all points in a non-weighted kernel density analysis. This analysis produced a smoothed 1-km-cell density floating-point raster, in which areas of relatively

greater value were highlighted as areas having greater potential to restore wetlands.

The basis for the second part was the NWI breeding habitat spatial layer that did not include breeding waterfowl abundance data. We used the NWI-based habitat layer to include areas where waterfowl may not have been observed in WBHS but were identified as potential habitat. We reclassified the standardized breeding season habitat layer (i.e., 0–1) into 32 quantiles. We reclassified the top three quantiles to 0 to exclude the area predicted most suitable as breeding habitat and retained the distribution of remaining potential breeding season habitat in proximity.

We combined the raster surface of PRWs and reclassified predicted breeding habitat through the Fuzzy-product Overlay tool. This tool used the product of both surfaces to emphasize areas that were in proximity to already existing and suitable habitat and locations where wetland restoration potential exists (Environmental Systems Research Institute 2018). For example, if a raster cell was designated as > 0 for the reclassified breeding habitat surface and PRW surface then the product of these two cells was calculated in subsequent output. If either of the surfaces had a value equal to 0, then regardless of value in the other surface subsequent output was 0. The product of the two surfaces represented areas where breeding season habitat was identified outside of the area predicted to be most suitable habitat, and restoration potential exists. Density and distribution of these areas were represented in a 1-km-cell floating-point raster.

Conservation opportunities associated with human populations The objective of this layer was to identify areas that maximize waterfowl viewer/recreationist retention and recruitment. This layer mapped distribution of potential waterfowl habitat conservation sites most associated with human populations. The association with human populations was based on a combination of distances from human populations (i.e., accessible considering travel time or distance) and relative density of human populations. We addressed this social objective by developing and combining two spatial layers: (1) potential outdoor recreation around urban areas and (2) potential conservation lands within urban areas.

To model potential outdoor recreation opportunities around urban areas, we assumed locations with greater human populations have more potential

Fig. 3 The 17 Ecological Landscapes (ELs) and boundaries of each associated 12-digit hydrologic unit code (HUC) used for waterfowl habitat conservation planning in Wisconsin, USA

Fig. 4 The five spatial layers combined in weighted overlay analysis to produce density and distribution of Conservation Capital used for waterfowl conservation planning in Wisconsin, USA. Red indicates greatest density and distribution of respective biological or social data, blue indicates least.

recreationists but travel time or distance will limit use of conservation lands (Devers et al. 2017). To produce this spatial layer, we obtained human abundance data per census block (U.S. Census 2010), and converted block polygons to points, where we assigned each point a weight based on number of people in the original block. We used these points and their weights in weighted kernel density analysis to generate 1-km-cell floating-point raster surface that represented density and distribution of human populations in Wisconsin. We reversed cell values, where cells within city centers have low values, then values

increase gradually as distance increased away from cities, reaching greatest values that were assigned to rural and remote areas. Finally, we assigned new values for rural and remote areas as distance increased away from sub-urban landscapes (decreasing gradually values at an increment of 1 km).

To model conservation opportunities within urban centers, we assumed semi-developed sites (e.g., active and deserted golf courses, brown fields, cemeteries, and city parks) with ponds, lakes, and other potential habitats could provide value to waterfowl and people. For example, in addition to waterfowl habitat, urban

conservation lands can provide city dwellers with green space, bird watching opportunities, pollinator gardens, and much more (Elmqvist et al. 2015). To produce this spatial layer, we re-used the raster for density and distribution of human populations in Wisconsin. We assigned zero value to areas overlapping with original U.S. census blocks with ≥ 1 resident (leaving only areas overlapping with blocks having zero residents). We assigned zero value to remote lands outside urban and suburban areas. Finally, we transformed values of each of the two resulting spatial layers (recreation around urban areas and potential conservation lands within urban areas) to 0 to 1 scale using the fuzzy linear function of Fuzzy Membership tool and then combined them with cumulative values to overlapping locations through the Fuzzy-sum Overlay tool.

Ecological services wetlands could provide The objective of the ecological services provided is to identify areas that could maximize flood abatement, sediment retention, surface water supply, and fish and aquatic habitat and minimize nutrient transformation. We used wetland ranks to approximate combined ecosystem service potential of wetlands generated for the WBD DST to identify areas where wetland related EGS have been diminished. We aggregated site-level data (sum of PRW acres assessed as high or moderate)

for individual EGS within watersheds to quantify EGS need for sites combined based on flood abatement, fish and aquatic habitat, sediment retention, nutrient transformation, and surface water supply. We ranked watersheds against all others by dividing each watershed score by the greatest watershed score for restorable services. This process resulted in each watershed having rank value ranging from 0–1. We converted these ranks to multiple random points with 30-m tolerance in-between for each watershed. We used these values as the weight of each point in weighted kernel density analysis that produced a smoothed 1-km-cell weighted density floating-point raster, where areas of relatively greater weight were highlighted as areas of EGS need.

Model aggregation and hierarchical structure

Conservation capital and opportunities raster layers

We combined each set (CC or CO) of objective-based maps by using the weighted sum tool (ArcMap 10.5.1, Environmental Systems Research Institute, Redlands California, USA) and applied scores we agreed on (Table 1 and 2). The weighted sum tool multiplies a field of values (i.e., our agreed upon scores) for each input raster and then adds all input raster values together to produce an output raster map. The CC

Fig. 5 The three spatial layers combined in weighted overlay analysis to produce density and distribution of Conservation Opportunities used for waterfowl conservation planning in Wisconsin, USA. Red indicates greatest density and distribution of respective biological or social data, blue indicates least. **a** Density and distribution of potential areas of waterfowl

breeding habitat that possess greatest restoration potential. **b** Density and distribution of human populated areas expected to receive greatest use by wetland and bird enthusiasts if accessible waterfowl habitats are available **c** Density and distribution of relative restoration potential for wetland ecological goods and services

model consisted of five raster surfaces of standardized values from 0 to 1. For each of three CO raster surfaces, we applied the agreed upon score in weighted sum analysis (ArcMap 10.5.1, Environmental Systems Research Institute, Redlands California, USA.). The CO model set consisted of three raster surfaces of standardized values from 0 to 1. For each of three CO raster surfaces, we applied agreed upon scores in weighted sum analysis (ArcMap 10.5.1, Environmental Systems Research Institute, Redlands California, USA.). We applied the fuzzy linear function of Fuzzy Membership tool to each CC and CO raster layer to re-scale values to 0 to 1 (Environmental Systems Research Institute 2018).

Ecological landscape and watershed prioritization

We applied statewide CC and CO models relative to the 16 ELs of Wisconsin. These ELs represent different ecological attributes (e.g., soils, hydrology, vegetation) across the landscape in Wisconsin and was conceptualized after multi-year, multi-discipline efforts that generated detailed descriptions of each type of landscape. Wisconsin's ELs are recognized as a contemporary reference for landscape planning (Wisconsin Wildlife Action Plan 2005–2015). We created an additional EL that included all watersheds along the Mississippi River along the western border of Wisconsin (Fig. 3). For each of 17 ELs, we summed values of the CC raster model using zonal statistics and then calculated an average value for each EL. We ranked each EL into five quantiles based on their average score and assigned a value of 1 (least priority) through 5 (greatest priority) to each. We applied the same procedure to categorize ELs for the CO model. Finally, we summed scores for every EL by combining scores from CC and CO models and then classified Priority 1 (i.e., greatest priority) Landscapes as those with combined score of 9–10, Priority 2 Landscapes with combined score of 7–8, and Priority 3 Landscapes as those with combined score < 7.

We assigned watersheds to a respective EL whether its centroid was within the EL (Fig. 3). Within each EL independently, we calculated average CC score for each watershed using the zonal statistics tool, then categorized them into four quantiles based on their score. We assigned a value of 0 (bottom quantile) through 3 (top quantile) for all watersheds in Wisconsin (Supplemental Figures 4 and 5). We performed the

Fig. 6 Cumulative Conservation Capital model for waterfowl habitat conservation planning in Wisconsin, USA. Spatial layers include breeding, autumn, and spring habitat needs, levels of waterfowl harvest and ecological goods and services provided by wetlands. Red indicates greatest density and distribution of respective biological or social data, blue indicates least

same summarization and classification for all watersheds using the CO model.

In our final step, we overlaid priority ecological landscapes layer with priority CC and CO watershed layers. Specifically, we summed the priority landscape score (1–3), priority CC watersheds score (0–3) and priority CO watersheds (0–3) which resulted in all watersheds scored from 1 through 9.

Results

Biological and social layers

Within the CC spatial layer set, the breeding waterfowl habitat models identified the greatest density of suitable breeding habitats in southeast glacial plains, forest transition, north central forest, and a portion of northwest sands ELs (Fig. 4a). The autumn habitat spatial layer identified areas of large wetland complexes in the ELs of northern highlands, north central forest, central sand hills, northern Lake Michigan coastal, southeast glacial plains, and areas along the Mississippi River as having greater importance (Fig. 4b). The spring habitat spatial layer identified areas of greatest density of wetlands in the north central forest, forest transition, and northwest sands ELs as having greatest importance. (Fig. 4c). Density and distribution of duck and goose harvest was greatest near the Mississippi River, Green Bay, southeast glacial plains, southern Lake Michigan coastal, and central Lake Michigan coastal ELs (Fig. 4d), indicating areas with greatest potential for waterfowl hunter retention and recruitment. Density and distribution of EGS currently provided on the landscape were greatest within central sand plain and north central forest ELs (Fig. 4e).

Within the CO spatial layer set, proximity to waterfowl breeding habitat had the greatest density in southeast glacial plains, central sand plains and forest transition into north central ELs (Fig. 5a). In

◀**Fig. 7** Cumulative Conservation Opportunities model for waterfowl habitat conservation planning in Wisconsin, USA. Spatial layers include potential areas of breeding habitat restoration, area of potential use by wetland enthusiasts, and distribution of relative need of ecological goods and services of wetlands. Red indicates greatest density and distribution of respective biological or social data, blue indicates least

addition, many of the Mississippi River tributaries were highlighted. Density and distribution of potential outdoor recreational opportunities were greatest surrounding cities where human population was greatest (Fig. 5b). In addition, distinct opportunities for conservation delivery were identified on lands within the cities of Madison and Milwaukee (Fig. 5b). Density and distribution of EGS needed were greatest in central sand plains and portions of east glacial plains and northern Lake Michigan coastal ELs (Fig. 5c).

Conservation capital and opportunity

The aggregate map of CC spatial layers identified areas of greatest current importance. These areas were prominent within forest transition, north central forest, central sand plains, and southeast glacial plains ELs (Fig. 6). The spatial overlay of all the CO spatial layers resulted in an aggregate map depicting areas of greatest importance for waterfowl and wetland restoration practices. These areas were in southeast glacial plains, portions of the forest transition and central sand hills, and many tributaries of the Mississippi River (Fig. 7).

Ecological landscape and watershed prioritization

From our combination process of the CC and CO models we classified three ELs as Priority 1 (i.e., greatest conservation importance), three ELs as Priority 2, and remaining eleven ELs as Priority 3 (i.e., least conservation importance, Fig. 8). Priority 1 Landscapes included southeast glacial plains, central Lake Michigan, and forest transition. Priority 2 Landscapes included central sand hills, southern Lake Michigan Coastal, and northwest lowlands. Priority 3 Landscapes included all remaining regions. The summation of ranks for each watershed per CC, CO, and EL score informed the statewide waterfowl habitat conservation habitat DST. This layer ranked each

watershed from 9 (i.e., greatest conservation importance) to 1 (i.e., least conservation importance, Fig. 9). The watersheds that were ranked to have greatest conservation values occurred within southeast glacial plains, central Lake Michigan coastal, northern Lake Michigan coastal, and forest transition ELs.

Discussion

Summary

We developed a mapping framework to identify the most important ecological landscapes for waterfowl habitat conservation in Wisconsin that links directly to continental and regional conservation initiatives. We based our approach on regional models (Soulliere et al. 2017) and continental directives (NAWMP 2018) but provided greater spatial resolution and developed new relevant layers by coordinating with a large group of stakeholders. We designed waterfowl habitat suitability models to better reflect species known habitat and landscape preferences during spring and autumn migration. In addition, we modeled existing habitat capital and potential opportunities to refine what conservation activities can or should be applied to a landscape. Our DST integrates social and biological considerations at a large landscape and small watershed scale. We integrated spatially explicit ecological goods and services layers to delineate landscapes that can benefit all people (Miller et al. 2017). Furthermore, we produced maps at the scale of ecological landscapes and local watersheds so practitioners can prioritize their conservation activities spatially. Following guidance of the NAWMP (NAWMP 2012, Krainyk et al. 2019b) and JV regional waterfowl habitat conservation strategy (Soulliere et al. 2017), our models are science-based, transparent, defensible, and can be modified easily as social, political, biological, and other environmental forces change. Conservation and management in pixel neighborhoods of greatest values would provide direct benefits to waterfowl, traditional waterfowl enthusiasts, other conservationists, and the public, and assure political and financial support into the future.

Fig. 8 The aggregated Ecological Landscapes (ELs) of Wisconsin used for conservation planning ranked from greatest relative importance of waterfowl habitat conservation (Priority 1) to least (Priority 3)

Conservation capital applications

The CC raster layer is designed to depict areas currently providing greatest density of important wetland resources in Wisconsin based on an amalgamation of three biological and two social data layers. The CC raster is most influenced by the breeding waterfowl habitat distribution layer (0.44 weight) and least influenced by hunter distribution layer (0.10 weight), following objective prioritization by the Wisconsin wetland and waterfowl stakeholder team. The breeding habitat distribution layer was prioritized by stakeholders because Wisconsin harbors high numbers of breeding ducks important to the state's hunters and other waterfowl enthusiasts (March et al. 1973; WDNR 1992; Zuwerink 2001). This layer also combines a theoretical habitat model with existing, ground-truthed, observations of breeding waterfowl. Collectively, breeding, autumn migration, and spring migration habitat made up 0.77 of total weight, reflecting importance by collective stakeholders. In general, the greatest density of existing wetland resources important to waterfowl during breeding and non-breeding periods in Wisconsin occurs along a broad band from the northwest corner to the southeast corner of the state.

The CC layer can inform decisions on waterfowl habitat retention, where wetlands should be acquired, protected, maintained, managed, or enhanced to ensure or grow their value for waterfowl. As an example, WDNR could use the layer to help eliminate (low benefit sites) or increase resource allocation for existing wetlands that need infrastructure upgrades such as dike or levee maintenance or replacement of water control structures (Laughland et al. 2014; Soulliere et al. 2017). In addition, organizations such as DU and other non-governmental organizations, could use this layer for land acquisition planning based on priority ranking of watersheds of greatest benefit to waterfowl and resource users. When stepping down general habitat retention priorities from the JV regional waterfowl strategy, decision processes can

now be considered carefully at landscape and watershed scales.

Conservation opportunities applications

The CO layer depicts density and potential value or restorable waterfowl habitats on the landscape and is an amalgamation of one biological and two social data layers. It is influenced strongly by expanding the core breeding habitat distributions layer (0.48 weight) designed to focus conservation delivery opportunities near or adjacent to existing breeding habitat. This layer complements the breeding distribution layer, but it focuses attention on the periphery of existing habitat and on expanding breeding habitat base with potentially restorable wetlands. The COs associated with human populations layer contributed the second most weight (0.33) and we developed this layer to depict opportunities that might maximize outdoor recreation related to potential waterfowl habitat conservation sites most associated with human populations (i.e., accessible considering distance). This layer identifies opportunities in areas near and within urban centers. Wetland conservation in urban areas can be critical for many reasons (Standish et al. 2013; Elmqvist et al. 2015) and conservation planners are just beginning to explore ways to incorporate these data into their work. Opportunities to create, expand, and restore waterfowl habitat abound in Wisconsin as our models identified high density impact areas in all ELs and in most counties. Finally, the CO map reflects how partners have allocated conservation efforts across Wisconsin traditionally (Pierce et al. 2014; Kahler 2015), but also identified regions of Wisconsin that have received little conservation attention.

The CO layer provides a science-based approach for more effective restoration of waterfowl habitat, including wetlands and associated upland nesting areas. For example, USFWS Partners for Fish and Wildlife Program targets its limited federal resources to aid habitat restoration efforts on private lands (Soulliere et al. 2017). Although the JV defines priority landscapes by Bird Conservation Regions at the regional scale, this finer resolution DST provides biologists the ability to identify watersheds where wetland and upland restoration projects can be implemented. Conservation delivery programs will have the ability to demonstrate multiple benefits of waterfowl habitat to local communities, and the importance of

Fig. 9 Hydrologic Unit Code 12 watersheds of Wisconsin ranked from greatest conservation importance (red; 9) to least (blue; 1) that represent the waterfowl habitat decision support tool for Wisconsin, USA

using science-based tools for allocating congressionally appropriated and other funds.

Ecological landscape and watershed planning and applications

Conservation planning is complex, specifically when determining where to allocate resources across heterogeneous landscapes (Fitzgerald et al. 2009; Wiens 2009). Our objective was to identify priority ELs and watersheds in Wisconsin best suited for waterfowl habitat conservation based on priorities identified by continental and regional guidance. The aggregate conservation landscapes and watershed layers accomplished this objective by spatially guiding conservation delivery activities and accounting for biological and social objectives. The aggregate priority watersheds layer scores all Wisconsin HUC12 watersheds on a 1 to 9 scale. A watershed with a score of 9 indicates the watershed was within a Priority 1 EL and was identified as the top quartile within its respective EL for Conservation Opportunity and Conservation Capital. We believe conservation delivery in a watershed with a conservation score of 9 would yield greater impact to waterfowl conservation relative to other watersheds. It would deliver local-scale results and be embedded in a Priority 1 Landscape. We encourage conservation planners to use our cumulative EL layer when they want to focus resources for landscape-wide initiatives. The watershed map could be used to direct conservation habitat delivery at finer spatial resolution. This level of spatial resolution allows biologists and planners to prioritize conservation delivery at the watershed scale. Overall, this analysis with associated maps can provide users flexibility to decide which application will meet their needs.

Prospects and considerations

We acknowledge there are unlimited combinations of elements and priority weights that can be incorporated into decision support models (e.g., adjusting weights, adding or removing data layers, or altering

methodology we used to build our set of maps). However, because our approach has been vetted by managers and resource users in Wisconsin and model weights were developed by an expert panel, models we present here were deemed most appropriate to meet our goals. We believe the decision support layers will advance the ability of conservation partners to make informed decisions regarding where to deliver waterfowl habitat projects. Through the process of developing the decision support framework we identified existing needs that should be pursued to enhance practical effectiveness of the conservation strategy. For instance, the breeding duck distribution layer is the only layer based on ground-truthed survey transects. All other biological layers are based on theoretical distributions of ducks among their habitats. Having better data on distribution of ducks during autumn and spring migrations, relative to habitat types used, could enhance these decision support layers. In addition, the conservation opportunities associated with human populations layer assumes locations with greater human populations have more potential recreationists, and travel time or distance will limit use of conservation lands (Devers et al. 2017). Work by Devers et al (2017) was based solely on publicly available survey data in the eastern US. The extent this relationship exists in Wisconsin remains unknown, but clearly an expanded understanding of human dimensions would enhance reliability of future modeling and planning efforts.

Finally, we acknowledge potential bias in our methodology for deriving weights of spatial layers. We asked the expert panel to score all spatial layers, relative to one another, only after they had an opportunity to view all spatial layers. This process may have skewed scoring toward areas mapped red (hotspots) where experts wanted or expected to see them. Nevertheless, this large and diverse panel reflected a wide breadth of relevant conservation experience and multiple areas of interest in the evaluation. Additionally, weights we used (Fig. 2) were derived from a similar process used by the UMGL JV (Soulliere et al. 2017, p. 69), overall a methodological approach we were trying to replicate. The extensive representation by the expert panel and replication of the UMGL JV process increases our level of confidence that our process identifies the most impactful regions in Wisconsin. We encourage frequent feedback from groups using our models,

particularly their effectiveness in objective achievement and validity of the decision support framework. Updates to our model objectives and weights should occur if significant changes occur to the NAWMP, JV plans, or other policies that would influence habitat conservation at the state-level.

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