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Optimal water depth management on river-fed National Wildlife Refuges in a changing climate

Sam Nicol · Brad Griffith · Jane Austin · Christine M. Hunter

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Abstract The prairie pothole region (PPR) in the north-central United States and south-central Canada constitutes the most important waterfowl breeding area in North America. Projected long-term changes in precipitation and temperature may alter the drivers of waterfowl abundance: wetland availability and emergent vegetation cover. Previous studies have focused on isolated wetland dynamics, but the implications of changing precipitation on managed, river-fed wetlands have not been addressed. Using a structured decision making (SDM) approach, we derived optimal water management actions for 20 years at four river-fed National Wildlife Refuges (NWRs) in North and South Dakota under contrasting increasing/decreasing (+/−0.4 %/year) inflow scenarios derived from empirical trends. Refuge pool depth is manipulated by control structures. Optimal management involves setting control structure heights that have the highest probability of providing a desired mix of waterfowl habitat, given refuge capacities and inflows. We found optimal seasonal control structure heights for each refuge were essentially the same under increasing and decreasing inflow trends of 0.4 %/year over the next 20 years. Results suggest managed pools in the NWRs receive large inflows relative to their capacities. Hence, water availability does not constrain management; pool bathymetry and management tactics can be greater constraints on attaining management objectives than climate-mediated inflow. We present time-dependent optimal seasonal control structure heights for each refuge, which are resilient to the non-stationary precipitation scenarios we examined. Managers can use this

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S. Nicol · B. Griffith · C. M. Hunter
Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775, USA

B. Griffith
U.S. Geological Survey, Alaska Cooperative Fish and Wildlife Research Unit, Fairbanks, AK 99775-7020, USA

J. Austin
U.S. Geological Survey, Northern Prairie Wildlife Research Center, Jamestown, ND 58401, USA

Present Address:
S. Nicol (✉)
CSIRO Ecosystem Sciences, GPO Box 2583, Brisbane, QLD 4001, Australia
e-mail: sam.nicol@csiro.au

information to provide a desired mixture of wildlife habitats, and to re-assess management objectives in reserves where pool bathymetry prevents attaining the currently stated objectives.

Abbreviations

NWR	National wildlife refuge
PPR	Prairie pothole region
SDM	Structured decision making
SDP	Stochastic dynamic programming

1 Introduction

1.1 Predicted climate changes in the prairie pothole region

The prairie pothole region (PPR) in the north-central United States and south-central Canada constitutes the most important waterfowl breeding area in North America, supporting 50–80 % of the continental breeding duck population (Johnson et al. 2005). Waterfowl abundance in the PPR is a positive function of wetland availability (Johnson et al. 2005; Larson 1995), but dense emergent vegetation cover may reduce wetland value (Weller 1978). Shifts in climate (precipitation and temperature) may affect waterfowl abundance by altering wetland availability and vegetation (Johnson et al. 2005; Poiani et al. 1995).

The Intergovernmental Panel on Climate Change (IPCC) predicts warming of 2.3–5.8 °C over central North America by the year 2100 (Solomon et al. 2007). Precipitation trends in the PPR are difficult to identify because of extreme inter-annual and inter-decadal variation (Covich et al. 1997; Winter and Rosenberry 1998). However, precipitation in the western PPR decreased, while the eastern PPR became wetter during the 20th century (Millett et al. 2009). The future direction of precipitation trends in the PPR is uncertain.

During drought, water levels in isolated pothole wetlands of the PPR decline (Poiani et al. 1995; Winter and Rosenberry 1998), especially during summer and fall. In a warming climate, evaporation may exacerbate drying of potholes (Poiani and Johnson 1993; Sorenson et al. 1998). However, river-fed wetlands may persist because inflows ameliorate evaporative water loss and inflows may remain constant (Millett et al. 2009), or increase due to increased precipitation (Bruce et al. 2003; Solomon et al. 2007) during warming.

1.2 Management objective

U.S. National Wildlife Refuges (NWR) share a common management goal of maintaining biodiversity by manipulating habitats (US Fish and Wildlife Service 2000, 2005, 2006, 2007). Wetlands in river-fed refuges typically consist of a series of interconnected pools (Fig. 1), and management of water depths in pools is one tactic for achieving this goal. Water depths are manipulated with control structures at the downstream ends of pools to create a range of depths that provide habitat for waterfowl species with different ecological requirements. Water depths are also manipulated as a means to limit the density of perennial emergent vegetation because pools with high vegetation density are poor habitat for many waterfowl species (Weller 1978). Managers generally recognize three water depth classes: (1) shallow (<2 ft; <0.6 m); (2) medium (2–5 ft; 0.6–1.5 m); and (3) deep (> 5 ft; >1.5 m) (US Fish and Wildlife Service 2000, 2007). The proportions of a pool in various depth classes are a function of pool bathymetry and water depth at the control structure (pool depth). Three classes of emergent vegetation density are generally recognized: (1) low (< 20 %); (2) medium (20–80 %); and (3) high (> 80 %); density is the percentage of a pool surface that is occupied by emergent vegetation.

We evaluated how wetland management may mitigate potential climate-induced inflow changes for four river-fed NWRs in the PPR: Arrowwood, Lacreek, Sand Lake and Tewaukon (Fig. 1). The common management objective, derived from consultation with staff from all refuges, was to maintain 30 % of the wettable refuge area (the sum of all pool surface areas when pool depths were at maximum control structure heights) in each of the three water depth classes, while limiting density of emergent vegetation to low or medium classes. For each refuge, we used a structured decision making (SDM) approach (Gregory et al. 2012) to find the optimal (i.e., closest to meeting the objective) suite of seasonal control structure heights over a 20-year period with either an increasing or decreasing trend in inflow. Uncertainties incorporated in the optimization included increasing or decreasing inflows, observed historical seasonal inflow variance, and the probability of transitioning among vegetation density classes.

Other studies have used optimization to allocate environmental flows (Yang 2011) and select management responses under different climate projections (Tanaka et al. 2006). Our work differs by including both stochastic inflows and multi-year effects (e.g., prolonged periods of drought) in the optimization. Studies have considered climate uncertainty over multiple years, but have used simulation rather than optimization, so that not all possible outcomes are considered (e.g., Lempert and Groves (2010)). The Markov decision process used in this study is a classic approach to optimize water reservoir releases (Lamond and

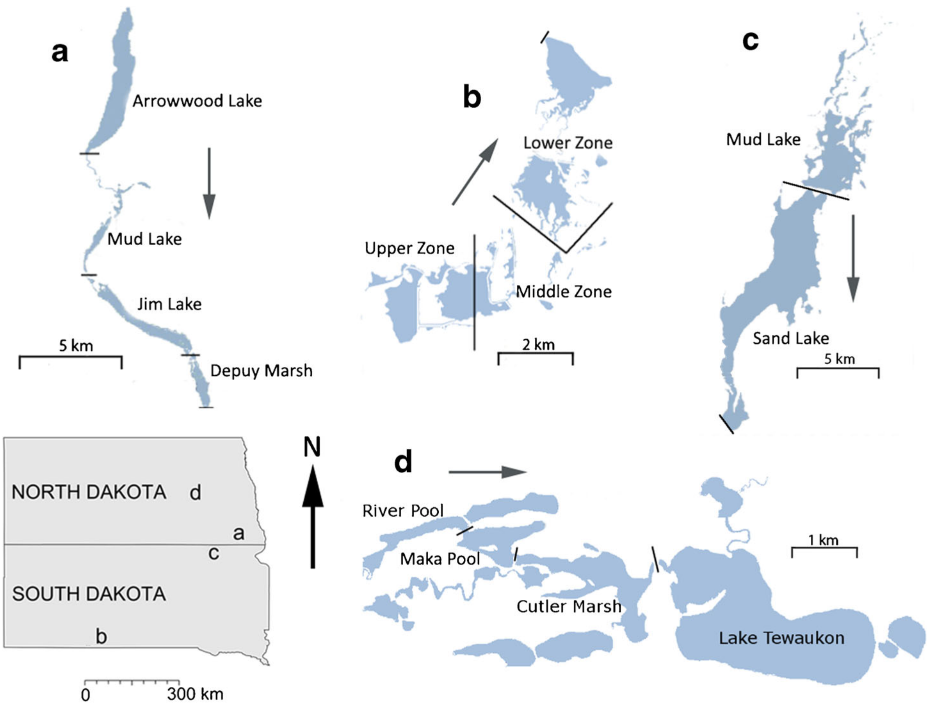

Fig. 1 Modeled pools in four National Wildlife Refuges: **a** Arrowwood, North Dakota; **b** Lacreek, South Dakota; **c** Sand Lake, South Dakota; and **d** Tewaukon, North Dakota. The direction of flow in each refuge is indicated by *arrows*. *Black lines* indicate the locations of control structures (at Lacreek, *lines* denote the boundaries between *upper*, *middle* and *lower* zones)

Boukhtouta 1996) but no reservoir studies to date have included biological constraints (i.e., habitat area and emergent vegetation structure) and the effects of climate on inflows. Our work is unique in providing seasonal control structure heights for water and vegetation management that are optimal over multiple years under contrasting stochastic inflow scenarios.

The goal of this research was to optimize the management of water control structures in NWRs to achieve high-quality waterfowl habitat by providing an approximately equal distribution of three water depth classes, while minimizing high density emergent vegetation under contrasting climate-driven inflow scenarios.

2 Methods

2.1 Management actions

We modeled the effect of raising or lowering control structures to manipulate pool depths provided sufficient inflow was available. In our work, managers could adjust control structure height separately in each pool at the beginning of each season (spring, summer and fall). The heights at which control structures could be set in each pool comprised the set of possible management actions for a refuge (online resource 1).

2.2 Generating inflow scenarios

Because historical inflow records were incomplete and of short duration, we used monthly precipitation records from the U.S. Historical Climatology Network (Menne et al. 2011) to estimate trends in the putative effects of climate on inflow. We first estimated both long-term (1895–2010) and recent (1960–2010) directional trends in regional precipitation from the weather stations nearest each refuge (online resource 2) using a mixed model (Pinheiro and Bates 2000). The mixed model included fixed effects for intercept and year (trend) and a random effect for weather station.

We then applied statistically significant regional precipitation trends to historical seasonal inflows measured directly upstream from each refuge, assuming a gamma distribution for the discretized inflow data. We assumed that the mean of the inflow distribution changed over time at a rate given by the trend derived from regional precipitation and evaluated both an increasing and a decreasing inflow scenario to evaluate the ability of control structure height adjustments to accommodate contrasting inflow scenarios (online resource 2).

2.3 Refuge modeling approach

A model (online resource 3) prescribed how current inflow, pool capacity, control structure height, evaporative losses and vegetation density interacted to determine pool depth, the distribution of water depth classes and vegetation density in the subsequent season (Fig. 2). Each refuge was modeled as a series of pools (Fig. 3). The state of each pool was characterized by two dependent variables: water depth at the control structure (pool depth) and vegetation density (Fig. 2).

Transitions between pool depths were determined by modeling the passage of inflow through a refuge using a water balance model (online resource 3, Eqn. 1). Inflows were obtained from the discretized seasonal inflow probability distributions. The inflows were passed to the deterministic water balance model (online resource 3) and subsequent seasonal and downstream pool depths were computed for all possible control structure heights. Excess

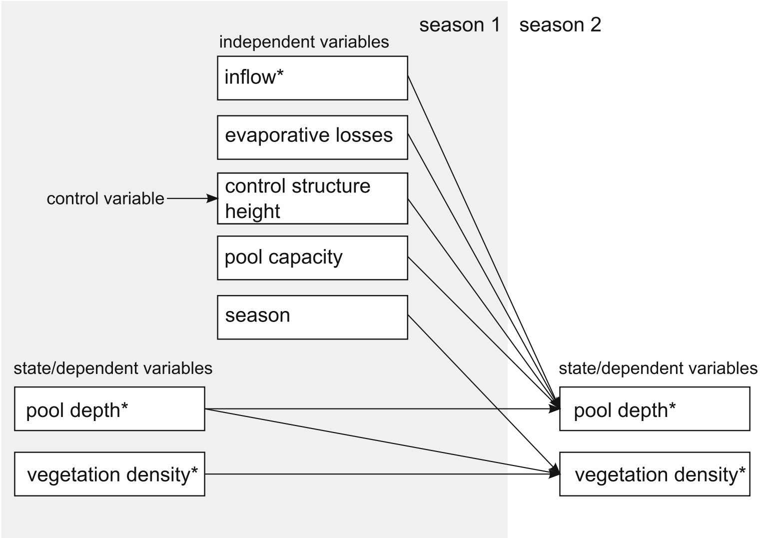

Fig. 2 Influence diagram showing the relationships between variables during a seasonal time step for one pool. The state variables pool depth and vegetation density class are the dependent variables. Control structure height is the control variable. Variables with an *asterisk* are stochastic variables; other variables are deterministic for a given season

water exited downstream from the lowest pool. From this model we generated a matrix of all possible pool depth transition probabilities given inflow and the set of possible control structure heights for each refuge (online resource 3, Eqn. 2). We refer to this as the "pool depth transition matrix". The area of a pool in each of the three depth classes was obtained from pool-specific bathymetry surveys that measured the relationships between area of water depth classes and pool depth at the control structures (online resource 4). These areas were converted to percentages by dividing by the wettable area of each pool. Although evaporation may be affected by climate change, constant seasonal evaporation losses of 20 mm, 115 mm, and 25 mm during the spring, summer and fall respectively (NOAA 2011) were applied because evaporation losses were small compared to refuge inflows (online resource 3).

Season-specific probabilities of transition among three vegetation density classes (low, medium, high) were elicited from refuge managers (see online resource 5 for elicitation sheets). Refuge managers estimated the probabilities that the density class of each refuge pool would change during a season, given the initial refuge-specific water depth class and initial vegetation density. Estimates of change to each of the vegetation density classes were elicited for all combinations of initial depth class and initial vegetation density. From these estimates, we generated a matrix of all possible vegetation transition probabilities given the set of possible control structure heights for each refuge (online resource 3, Eqn. 3). We refer to this as the "vegetation density class transition matrix".

The probability of transitioning between any existing and subsequent state (pool depth and vegetation density) was obtained by multiplying the pool depth transition matrix (online resource 3, Eqn. 2) and the vegetation density class transition probability matrix (online resource 3, Eqn. 3). These transition matrices, and the resulting distribution of water depth classes, constituted the basis for determining optimal control structure heights for a given inflow and vegetation density (online resource 3).

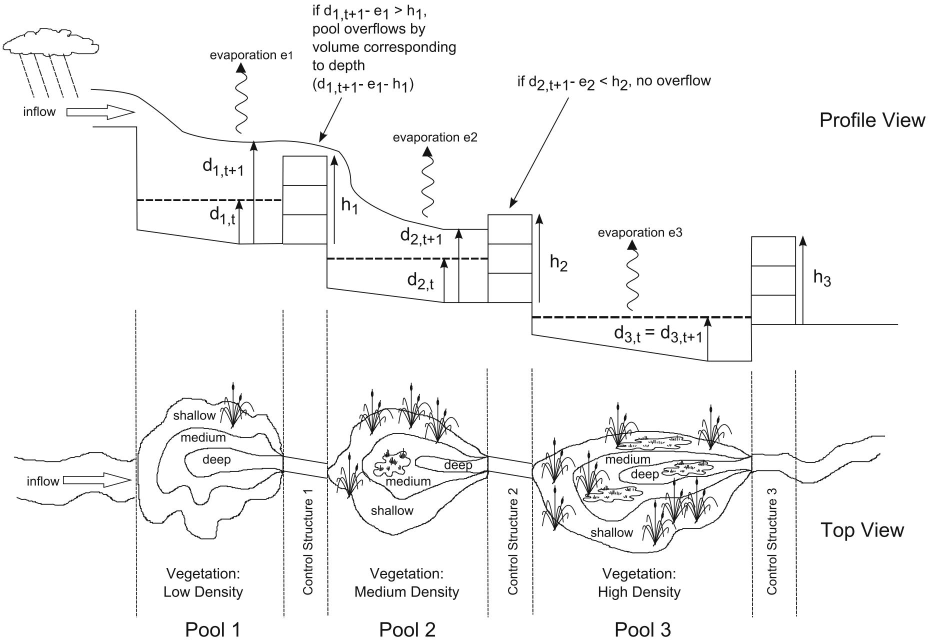

Fig. 3 Schematic model structure for a refuge with 3 pools. Water flows from left to right. In a season, a stochastic inflow passes through the refuge. At each pool, the existing water depth ($d_{i,t}$) is increased by the inflow to the pool and reduced by evaporation. If the new pool depth ($d_{i,t+1}$) is higher than the height of the control structure (h_i), then the depth of flow to the next pool is $d_{i,t+1}$ -e_i – h_i. Managers can manipulate the height of the control structures (h_i) at each pool to control water depth (d_i). The *bottom panel* shows the same three pools from a *top view*. For a given pool depth (d_i), the surface area in each depth class (shallow, medium and deep) is obtained from pool-specific relationships between depth (d_i) and surface area of depth classes. At any season, any pool may have low, medium or high vegetation density

2.4 Generating optimal management actions

Managers cannot control inflow (this is weather dependent), so it is of little use to managers to know how much or how little inflow would provide optimal conditions. Managers need to know how to cope with what flows into their refuge, and how much water to store for drier seasons ahead. The optimal solution tells managers what to do given the uncertainty (i.e., probability distribution) in inflows they are likely to receive under different climate scenarios.

Each pool had a vegetation density (ϕ_i), that was low (ϕ_i=1), medium (ϕ_i=2) or high (ϕ_i= 3) for pool *i*. Let the vector d=(d_1,d_2,…,d_n) represent the depths at the control structure (pool depth) for the *n* pools in the refuge. We defined the wettable area of pool *i* as $\omega(D_i)$ where D_i was the maximum depth of pool *i* at the control structure and ω was a bathymetry-based function relating D_i to pool surface area. Let the surface area of shallow, medium and deep water when the pool depth is d_i be $\omega_1(d_i)$, $\omega_2(d_i)$, $\omega_3(d_i)$, respectively. The refuge-wide area in each depth class was then the sum of the area in that class across all pools. The model is constrained by pool capacity and stochastic inflow (online resource 3, Eqn. 1), which can be converted to pool surface area $\omega(d_i)$ using the bathymetry of the pools.

The optimal solution is obtained by choosing the control structure heights that maximize the expected sum of a reward function over time. Reward is a measure of how well the combined objective of 30 % in each depth class and no high vegetation density was met in a season. We assigned a reward equal to the percentage of the total refuge area in each depth class, up to a maximum of 30 for each class in each season. The maximum reward was 90 points (≥ 30 % in each depth class and no high vegetation density) for each season and 270 points for a year. The objective function was to maximize the expected sum of rewards (E) over time *T*, given by:

$$\max_{d} \mathrm{E}\left(\sum_{t=0}^{T}\sum_{j=1}^{3}\min\left(30, 100\sum_{i=1}^{n}\frac{c(\varphi_{i,t})\omega_j(d_{i,t})}{\omega(D_i)}\right)\right) \tag{1}$$

where T=20 years×3 seasons=60. The index *j* refers to the depth class, where *j*={1,2,3}={shallow, medium, deep} respectively. The term $c(\phi_i)$ is an indicator function that specified if the vegetation density in pool *i* was high, defined as:

$$c(\varphi_i) = \begin{cases} 0 & \text{, if } \phi_i = 3 \\ 1 & \text{, if } \phi_i < 3 \end{cases}$$

If the vegetation density was high, then the pool surface was crowded with vegetation and contribution to the reward from the pool was zero for all depth classes in that season.

The optimal action is the best control structure height to set based on the expected rewards of taking that action. The expectation (E) in Eq. 1 means that extreme inflow events will be weighted by their probability of occurrence when choosing the optimal action.

We used stochastic dynamic programming (SDP) (Bellman 1957; Puterman 2005) to compute the optimal solution for each refuge. The optimal solution was the 20-year-long suite of seasonal pool-specific control structure heights that came closest to satisfying the management objective for the refuge given uncertainties regarding inflow and vegetation density. Value of information analysis (Ades et al. 2004; Runge et al. 2011) was used to test whether the SDP optimization could distinguish between increasing and decreasing inflows. Optimization code was written in MATLAB© 7.11.0. Analysis of inflow data was completed using R©(R Development Core Team 2011). Input data files, M-files, and R-scripts are included in online resource 4.

3 Results

3.1 Inflow scenarios

There was no significant long-term trend in precipitation during 1895–2010. However there was a significant increase in recent annual precipitation from 17.8 to 21.4 in. (452–546 mm) between 1960 and 2010 ($p<0.0001$; Table 3 in online resource 2), approximately 0.4 %/year increase. Because we did not observe a temporal trend in the standard deviation of precipitation (online resource 2), the variance of the inflow distribution was assumed to be constant.

We generated two inflow scenarios from the 1960 to 2010 trend in precipitation. The first imposed a 0.4 %/year increase in inflow, reflecting a continuation of the recent trend in precipitation. The second imposed a 0.4 %/year decrease in inflow, reflecting a return to the long-term average of no change in precipitation. In the absence of reliable historical data for other hydrological variables, both scenarios assumed a direct relationship between precipitation and inflow.

3.2 Value of resolving climate-related uncertainty in inflow

Performance for each refuge was estimated as the cumulative reward attained from implementing the optimal control structure heights divided by the maximum cumulative reward obtained from continuously meeting the objective over 20 years. Performance was expressed as a percentage (recall that the maximum cumulative reward is 5,400=90 points/season×3 seasons/year×20 years). There was little difference in performance regardless of whether the inflow trend was increasing or decreasing (Fig. 4). Value of information analysis demonstrated that resolving the uncertainty between the increasing or decreasing inflow trends increased performance by less than 1 % over 20 years (online resource 6). This inconsequential increase in performance occurred because the large variability in seasonal inflow (online resource 1) swamped the relatively small magnitudes of the contrasting inflow trends.

3.3 Refuge capacities

Spring inflows were generally much larger than the capacity of the refuges because the refuges are located on rivers with large catchments. For both increasing and decreasing inflow scenarios, the annual probability that refuges would flood (i.e., refuge capacity would be exceeded) in spring was always>0.2 (~once every 5 years) and typically > 0.4 (~once every 2.5 years), except at Lacreek (Fig. 5). Flooding in fall was rare for all refuges.

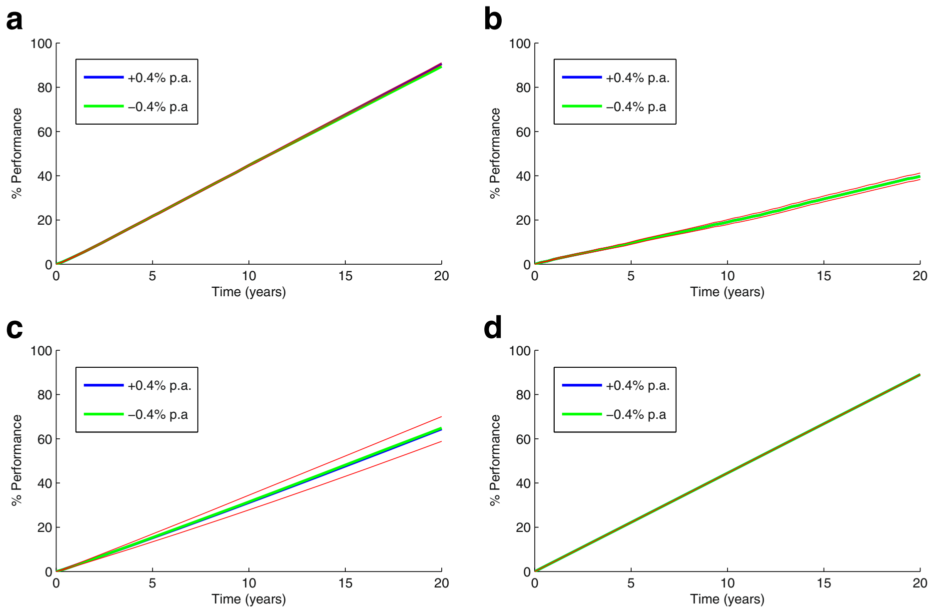

Fig. 4 Performance (accumulated reward from executing the optimal control structure heights divided by the total possible accumulated reward from attaining the objective continuously for 20 years, expressed as a percentage) plots for **a** Arrowwood, **b** Lacreek, **c** Sand Lake and **d** Tewaukon National Wildlife Refuges assuming a +0.4 %/year inflow scenario is the correct model. The *blue* and *green lines* show the performance of optimal management for the increasing (assumed trend correct) and decreasing (assumed trend incorrect) inflow scenarios, respectively. *Red lines* show the 95 % confidence interval on the cumulative reward assuming the correct scenario was managed for

3.4 Optimal management actions

Pool bathymetries prevented the exact attainment of the objective of 30 % in each water depth class for all refuges (Table 1). However, each refuge had a unique suite of control structure heights that came closest to achieving the management objective. We called these heights the achievable configurations. At Arrowwood and Tewaukon, the maximum rewards obtainable from the achievable configurations closely (94 and 97 %, respectively) approximated the maximum rewards if the objective was perfectly met (Table 1). In contrast, at Lacreek and Sand Lake, the achievable configurations yielded maximum rewards only 79 % and 81 %, respectively, of the reward if the objective was met (Table 1). These constraints on achievable rewards occurred because some pool bathymetries were either so shallow (Lacreek) or so deep (Sand Lake) that no combination of control structure heights could achieve maximum rewards.

Because spring inflows were generally larger than refuge capacity, control structure heights could be adjusted to attain the achievable configuration every spring except in the case of a rare low-inflow spring. This routine attainment of the achievable configuration each spring typically resulted in an annually repeating set of optimal seasonal control structure heights for a pool, regardless of whether the trend in inflow was increasing or decreasing (e.g., Fig. 6).

Although achievable configurations resulted in the largest immediate seasonal rewards, it was sometimes optimal to incur a reduced immediate reward to secure subsequent larger rewards. At Sand Lake, it was optimal to maintain the achievable configuration from spring through fall; however, other refuges had unique reasons why it was not optimal to maintain the achievable configuration in summer and fall (online resource 1). For example, at Tewaukon, the objective of 30 % of the refuge in shallow, medium and deep water classes was approximated during spring and summer; however, during the fall there was very little inflow and no configuration could simultaneously achieve the shallow and deep water objectives (online resource 1). The combination of control structure heights that came closest to meeting the depth objective required raising the level of Cutler Marsh to provide

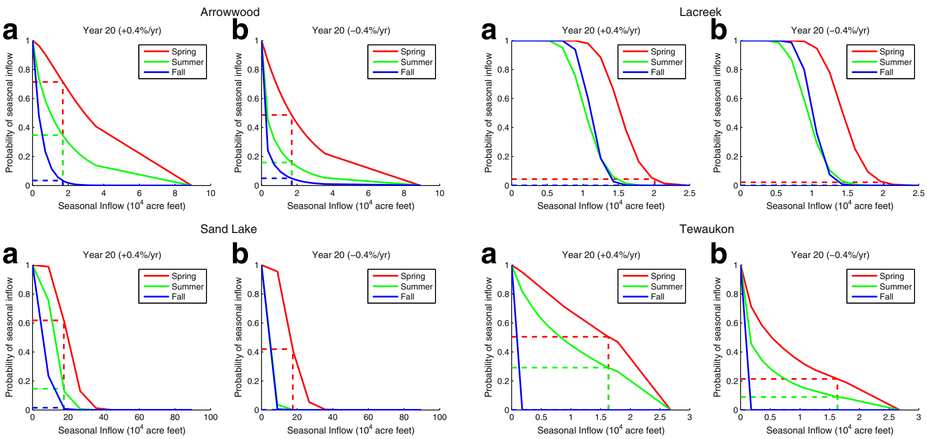

Fig. 5 Probability of attaining a total seasonal inflow (*solid lines*) at 20 years after a continuous **a** increasing or **b** decreasing inflow (±0.4 %) for three seasons at four National Wildlife Refuges in North and South Dakota, USA. Seasonal inflow that constituted flooding is indicated by *vertical dashed lines*. The intersection of *solid* and *dashed lines* denotes flooding and the *horizontal dashed lines* indicate the probability of flooding for a season. Note that the x-axis scales differ among refuges

Table 1 The percentage of potential refuge area in each of 3 depth classes (shallow, < 2 ft [>0.6 m]; medium 2–5 ft [0.6–1.5 m]; deep > 5 ft [>1.5 m]) when all pools are in the achievable pool depth configuration (as close as possible to the objective of 30 % in each depth class) in spring when water is not limiting for four National Wildlife Refuges (NWR) in North and South Dakota, USA

Refuge	Pool name	Control structure height in spring (ft)	% Shallow	% Medium	% Deep	Achievable seasonal reward (% of objective)
Arrowwood	Mud Lake	7	27	34	28	85 (94)
	Jim Lake	6				
	Depuy Marsh	4				
Lacreek	Upper Zone	10	45	39	11	71 (79)
	Middle Zone	3				
	Lower Zone	7				
Sand Lake	Mud Lake	12	18	25	57	73 (81)
	Sand Lake	16				
Tewaukon	River Pool	9	30	33	27	87 (97)
	Maka Pool	12				
	Cutler Marsh	6				

The sum of the percentages across depth classes does not always total 100 % because some of the potential pool areas may be dry. Achievable seasonal reward is the sum of the percentages in all depth classes, subject to the restriction that the reward for any depth class cannot exceed 30 and the seasonal reward may not exceed 90. The achievable seasonal rewards for Arrowwood and Tewaukon NWRs closely approximate the objective of 90, but at Lacreek and Sand Lake NWRs pool bathymetries constrain attainment of the objective

deep water during the low-inflow fall period (Fig. 6). At Arrowwood, high summer evaporation in Depuy Marsh made it optimal to set control structure heights above the level required to meet the deep water objective during summer. At Lacreek, the upper and lower zones were drawn down during the summer to control emergent vegetation via mechanical disturbance and prevent subsequent complete loss of reward due to high vegetation density.

Vegetation density was rarely a constraint on attaining the achievable configuration except at Lacreek. The achievable configuration (Table 1) kept the pools as deep as possible all year. However, at Lacreek competing objectives of sediment removal and moist soil management currently favor summer draw-downs as a means to control emergent vegetation by burning, mowing, disking, or grazing (Fredrickson and Taylor 1982). Thus, the optimal action was to retain deep water during spring and fall, but to decrease pool depth in summer. This reduction in pool depth during summer caused departures from the achievable configuration (online resource 1) and was one of the reasons that Lacreek obtained a cumulative reward that was only 41 % of the objective (Fig. 4).

In contrast, at Arrowwood, Sand Lake and Tewaukon, vegetation density was reduced by increasing control structure heights to drown vegetation (online resource 5). At these refuges, the achievable pool configuration consisted of predominantly deep and medium water (Table 1), so actions producing the achievable configuration also prevented crowded vegetation. Not having to depart from the achievable configuration due to vegetation constraints was one of the reasons that Sand Lake was able to obtain a larger (63 % of the objective) cumulative reward than Lacreek (41 % of the objective; Fig. 4) even though both refuges had bathymetry constraints that prevented them from attaining the objective (Table 1).

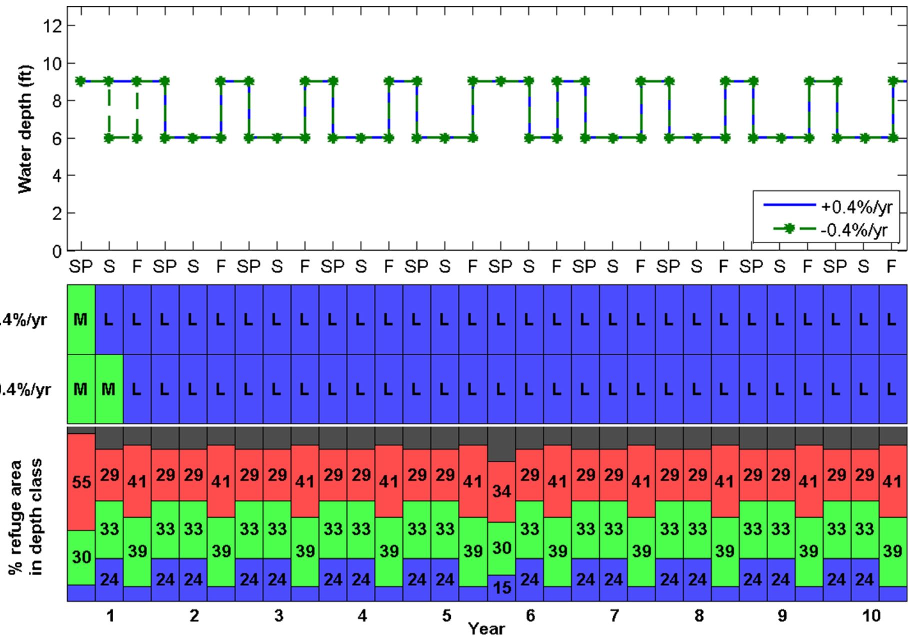

Fig. 6 Ten-year simulation of optimal seasonal (SP = spring; S = summer; F = fall) pool depths under increasing and decreasing (±0.4 %/year) inflow scenarios for the Cutler Marsh pool in Tewaukon National Wildlife Refuge, North Dakota. The *top panel* shows the controlled pool depths and the *middle panel* shows the vegetation density (L = low; M = medium; H = high). The *lowest panel* shows the percentage of water in all managed pools in the refuge in shallow (<2 ft [0.6 m], bottom bar (*blue*)), medium (2–5 ft [0.6–1.5 m], middle bar (*green*)), and deep (>5 ft [>1.5 m], top bar (*red*)) depth classes, assuming that the increasing inflow scenario is correct. *Unlabeled bars* in the lowest panel denote less than 10 %. Percentages do not always add to 100 % because some of the potential pool areas may be dry

4 Discussion

These refuges were designed to provide waterfowl habitat during times of drought and they can easily meet that goal. Sufficient water existed to approximate the management objective of 30 % in each depth class under both plausible climate scenarios over a 20 year period (Fig. 4), provided pool bathymetry did not preclude attainment of the objective. At Sand Lake and Lacreek, it was not possible to approximate the objective because pools were too deep and too shallow, respectively (Table 1, Fig. 4). Lacreek was further constrained from attaining the objective by a vegetation control technique (summer draw-downs as a means to control emergent vegetation by burning, mowing, disking, grazing or chemical treatment) that caused departures from the achievable pool configurations.

Identification and quantification of these non-climate-related constraints on the ability of refuges to attain the management objective were novel results of our analyses. Refuge managers may choose to reassess the objective of 30 % in each depth class to reflect the constraints of pool bathymetries and competing management goals. If the objective is retained: (a) maximum control structure heights or pool bathymetries might be altered to better align the achievable configurations with the objectives, or (b) actions that address competing objectives of moist soil management, sediment removal and pool depth could be optimized simultaneously. Removal of spring flood water from the extremely flat Dakotas was not considered but may constrain the ability of refuges to meet their objectives.

There was a unique suite of optimal seasonal control structure heights for each refuge that yielded rewards as close as possible to the maximum rewards from attaining the objective, but this suite of actions was essentially the same under either an increasing or decreasing trend in inflow of 0.4 %/year over the next 20 years. Refuges were resilient to climate change because their positioning on river systems allowed them to achieve their management goals regardless of climate trend or their ability to identify the direction of climate trend. This result was due to the spring inflows that dominated refuge water balances; inflows dominated because they came from large river catchments that encompassed each refuge. Spring inflows to the refuges remained substantial compared to the capacity of the refuges even if inflows declined by 0.4 %/year over 20 years.

Because spring inflows were generally not limiting under either increasing or decreasing trends in mean inflow, optimal management did not require that the true trend in mean inflow be identified. Although the applied climate trend could sometimes be identified (online resource 1), value of information analysis showed that correctly identifying the direction of the trend would have had a negligible effect on performance (online resource 6). There would have been little benefit to resolving the direction of the trend in inflow unless the magnitude of the trend became much larger than 0.4 %/year. The seasonal variability of the inflow for each refuge (online resource 1) was large enough that it swamped the small magnitude trends that were derived from empirical data.

In our study, evaporative losses from pools were generally minor compared to the magnitude of inflows and only occasionally affected optimal control structure heights during the low inflow fall period (e.g., Depuy Marsh in Arrowwood NWR). This may not be true for isolated shallow potholes in the PPR. Because potholes in the PPR are reliant on localized precipitation for recharge, they are particularly vulnerable to regional changes in evaporation (Eisenlohr 1972; Larson 1995; Poiani and Johnson 1993), which may increase over the PPR (Solomon et al. 2007). If evaporation dominates water balance in potholes, and the net effect of climate change is to reduce the number and size of potholes, the relative contribution of river-fed wetland systems to regional waterfowl habitat may increase with the proportional loss of potholes.

The modeled resolution of pool depth classes and control structure height increments was coarse compared to actual implementation on refuges. On refuges, control structures can be adjusted in 6 in. increments, while increments of ≥2 ft were modeled. Similarly, refuges can adjust control structures in response to individual flow events while we modeled adjustments made once per season. The coarse model resolution was necessary because stochastic dynamic optimization can only be achieved with a small number of alternative states. The model was not intended to replace day-to-day management but to facilitate the strategic setting of seasonal and annual water depth targets in a changing climate.

Traditionally, SDM studies have assumed that the systems being modeled are stationary processes (i.e., the mean and variance of the system are constant in time) and have ignored the effects of climate change. More recently, studies have begun to adapt SDM to make decisions in a changing environment (Martin et al. 2011; Nichols et al. 2011). While climate change exacerbates many sources of uncertainty (Nichols et al. 2011), the primary limitation to using SDM in a changing environment is that we cannot precisely predict the direction and magnitude of system change (structural uncertainty) (Conroy et al. 2011). Our study assumed that the magnitude of changes observed in recent data will continue. While this assumption is acceptable for short-term management, in the longer term it may not hold. If the rate of inflow changes by more than ±0.4 %/year, or is nonlinear, our proposed actions may not be optimal. The model assumed that changes in inflow were directly proportional to precipitation, but inflow may also be affected by anthropogenic wetland drainage in upper catchments, runoff, infiltration, evapotranspiration and evaporation. Historical data for these variables are scarce, but development of a full hydrological budget would increase confidence in an optimal solution.

Ours was one of a small but growing number of studies designed to adapt SDM techniques to problems where the future state of system drivers is unknown. SDM is a powerful tool for these kinds of problems because it is able to incorporate the different types of uncertainty inherent in resource management decisions and give recommendations to achieve objectives in an uncertain future (Johnson et al. 1997). Large inter-annual variance and small magnitude trends are hallmarks of climate change data. We found that, given the small magnitude of trends in precipitation and the large variability in inflow in our system (online resource 2), the expected performance of a suite of optimal control structure heights derived by SDP was essentially unaffected by knowing the true direction of trend in inflow (i.e., the direction of climate change). Thus, performance of the suite of optimal actions was robust to the direction and magnitude of modeled climate change (Fig. 4) but, in half of the refuges, performance in relation to the objective was severely constrained by non-climatic characteristics of the system such as pool bathymetries and vegetation control techniques (Table 1, Fig. 4). Analyses of other sources of uncertainty, such as a) the relationship between the management objective and waterfowl habitat quality, b) the relationship between water depth and vegetation density, or c) the net benefits of competing management goals, would be logical next steps toward enhancing management of river-fed wetlands in refuges.

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