Examining alternative water management strategies to support Rio Grande Silvery Minnow conservation within and across years

Timothy E. Walsworth[1,2]

and

Phaedra Budy[3,1]

[1] Department of Watershed Sciences, Utah State University, Logan, UT
[2] The Ecology Center, Utah State University, Logan, UT
[3] U.S. Geological Survey Utah Cooperative Fish and Wildlife Research Unit, Utah State University, Logan, UT

A report to the U.S. Bureau of Reclamation

Upper Colorado Region

Albuquerque Area Office

January 17, 2022

Executive Summary

Rio Grande Silvery Minnow (RGSM) are currently constrained to only 5% of their historic range, and their persistence is threatened by highly altered and impaired habitat conditions (Bestgen and Platania 1991). These habitat conditions have resulted from reduced spring and summer flows due to natural variability and anthropogenic water development and extraction, which have resulted in substantial geomorphic changes (Swanson et al. 2011). Successful conservation of this endangered species will require determination of how available flows can be managed to provide conditions supporting growth, reproduction, and survival of RGSM within and across a variety of water years. Previous research has identified that years with large spring high flow events and years with higher summer base flows support greater densities of RGSM during fall surveys (Dudley and Platania 2007; Archdeacon 2016; Walsworth and Budy 2021). However, given that years with large spring high flows also tend to have greater summer base flows, it remains unclear whether spring or summer flows (or both) are more critical to successful conservation of RGSM.

While experimental manipulation of annual flows could test the relative effectiveness of supplementing spring versus summer flows, such an experimental manipulation would take many years to reveal trends, potentially delaying the implementation of effective conservation strategies as suboptimal options are tested and eliminated. Simulation models provide a rapid means of examining the expected relative effectiveness of multiple proposed alternative management strategies simultaneously (Sainsbury et al. 2011; Smith et al. 2013), while not requiring the actual manipulation of flows that can result in missed ecological, cultural, social, or economic opportunities.

Here, we use an empirical model fit to the observed relationship between annual hydrographs of the Middle Rio Grande and autumn RGSM densities in a simulation framework to examine the expected relative benefit of implementing alternative water management strategies for RGSM conservation. We envision the results of this report being used to compare the expected performance of alternative flow management strategies under different hydrologic conditions to inform managers of broad patterns in when alternative management strategies are likely to provide the most benefit for RGSM conservation. Specifically, we address the following questions: (1) what generalized single-year water management strategy provides the best performance across a range of randomized hypothetical hydrographs, (2) what generalized multi-year water management strategy maximizes the likelihood of meeting RGSM management targets across years, (3) how is the probability of meeting RGSM management targets impacted by the extent of summer drying, and (4) how is the benefit provided by adding discretionary flows during the spring high flow period impacted by the total amount of discretionary water available? Further, as an example case study, we examined the expected performance of stakeholder-submitted alternative flow management strategies for the 2021 forecast hydrograph.

We examined a suite of alternative management strategies against generalized single-year and multi-year combinations of hydrographs, in which a given percentage of flows were temporarily stored for later release, discretionary flows were added, or water was stored to be used in later years (in the multi-year analysis only). We ran each of these scenarios across a range of proportions of water stored per day, discretionary water availability, and storage availability, as well as across a range of randomized hypothetical hydrographs. To examine the effect different summer drying conditions on the probability of meeting management targets (the “self-sustaining population” target of at least 1 RGSM per $100m^2$ and the down-listing target of at least 5 RGSM per $100m^2$), we applied a range of specified summer

drying intensities (mile-days dry in the San Acacia and Isleta reaches) to randomized hydrographs representing low-water years. Similarly, to examine the effect adding different amounts of discretionary water to the spring high flow period on the probability of meeting management targets, we applied a range of discretionary water volumes to the spring high flow period of randomized hydrographs representing low-water years. We then examined the predicted probabilities of achieving management targets across the range of drying intensity or discretionary water availabilities specified. For the analysis of alternative water management strategies for the 2021 forecast hydrograph, we examined the relative benefits to the RGSM population provided by 66 alternative strategies provided by stakeholders and managers following a simulation model workshop in January 2021. Given the inherent uncertainties of forecasting, all results are more robust when interpreted in a relative fashion. Specifically, examining which water management strategy (or strategies) performs better than the other strategies across many simulations is more appropriate than concentrating on the exact predicted probabilities of meeting management targets for each strategy.

Notably, water management throughout the Rio Grande watershed, including in the Middle Rio Grande discussed in this report, is subject to multiple international, interstate, and intrastate laws and agreements. The rights, priorities, and restrictions imposed by the different agreements influence the timing and magnitude of water releases from dams and extractions from diversions. Those restrictions are not explicitly incorporated into the generalized analyses presented herein. As the model used in the following analyses requires only the input of an annual hydrograph, requirements of the different water agreements can be incorporated by the user during the generation of alternative hydrographs under exploration. Further, the ability of our simulations to examine scenarios outside of those currently legal or feasibly implemented may allow stakeholders to identify and consider policy or infrastructural changes that may benefit RGSM conservation, while considering trade-offs with other management goals within the MRG.

Our generalizable single-year management analysis, in which alternative flow management strategies were applied to randomized hydrographs, revealed that the RGSM population is likely to meet management targets regardless of the management strategy adopted in high and medium water years, and that choice of management strategy matters most in low water years. When the amount of discretionary water available was low, strategies focused on increasing summer flows performed best, but as more discretionary water became available, those strategies focusing on increasing spring high flow periods performed best. Strategies combining both the addition of discretionary water and shifting flows across months (by temporarily storing water) consistently provided the best opportunities for meeting management targets. Across all scenarios, each of the top five performing strategies incorporated the use of discretionary water additions, two of the top five included adding these flows to spring months only, one added flows to summer months only, and two added flows to both spring and summer periods.

Our generalizable multi-year management analysis applied to randomized five-year sequences of hydrographs identified storing water for use across years as a beneficial approach for RGSM meeting RGSM management goals. The top performing strategies incorporated storing water during high water years to be used for supplementing flows during low water years. Strategies incorporating the storage of water during high water years for use in low water years were able to substantially increase the probability of meeting management targets across more years compared to the “no action” strategy. Additionally, fifteen of the top 20 strategies included supplementing flows during summer months (seven of these sixteen also included supplementing spring flows). By increasing the probability of meeting management targets within individual years as well as across multiple years, such across-year management strategies may be capable of limiting the negative impacts of low water years on the MRG population of RGSM.

We examined the relationship between drying severity (mile-days dry) and probability of achieving management targets in years characterized by randomized hydrographs representative of low water years. These simulations identified that the probability of achieving RGSM CPUE targets declines rapidly as drying severity increases from 500 mile-days dry to 1,200 mile-days dry. These simulations also suggest that small reductions in either the extent (miles) or duration (days) of summer channel drying can increase the probability of meeting management targets substantially when drying severity is near this threshold severity.

Our analysis of the impacts of supplementing spring high flow periods during low water years suggest that such additions of discretionary water will have limited impact until nearly 50,000 AF are available. In scenarios in which summer drying severity was high, much larger volumes of discretionary water were required to meaningfully increase the probability of meeting management targets. These results suggest that small amounts of discretionary water released during spring high flow periods may not be sufficient to have a large impact on rearing habitat availability for RGSM, while large volumes of discretionary water are better able to connect the main channel to the floodplain and low velocity off channel habitats.

Our example analysis of alternative management applied to the 2021 forecast hydrograph suggested that finding approaches to limit summer drying extent would provide greater probabilities of meeting management targets than those focusing on supplementing only spring high flows. When the specified drying extent was near the expected upper limit for the summer base flows realized with each managed hydrograph, nearly every management strategy submitted had a zero percent predicted probability of meeting the management target of 1 RGSM per $100m^2$ in October surveys. However, one strategy that capped spring high flows for later release to maintain modest summer flows performed well across all drying scenarios. As the 2021 forecast hydrograph was for a low water year, the results of this example support the results of our generalized management strategy analyses where supplementing summer low flows is most beneficial in low water years, and the relative benefit of supplementing spring high flows depends on a large volume of water being available for supplementation.

Our simulation analyses highlight three major results for managing flows to conserve RGSM. First, limiting the extent and duration of summer drying appears to be critical to meeting management targets in low water years. In the single year management simulations, strategies supplementing flows during the summer low flow period as at least part of their approach performed well, particularly when less than 30,000 AF of discretionary water was available. In the multi-year analysis, all the top models incorporated supplementing summer flows, while those incorporating only spring supplementation performed relatively poorly. Second, the relative performance of strategies supplementing spring high flows increases substantially when much larger volumes of water are shifted between months or when larger volumes of discretionary water is available. Third, the ability to manage water across years and extend the benefits of periodic large flows can greatly increase the probability of meeting RGSM management targets within single years as well as across a sequence of years. The results of these simulation analyses can provide managers and stakeholders with a starting point for discussions regarding both the short-term and long-term flow management options for RGSM conservation in the MRG. Further, this report makes the simulation model code available for use by stakeholders to compare alternative flow management options of interest.

Major Takeaways

- Single year management simulations
    - Incorporating both shifts in flow timing and additions of discretionary water outperforms strategies incorporating only one of these methods.
    - When limited amounts of discretionary water are available and there is a low capacity to shift flows across time, strategies focusing on supplementing summer or both spring and summer flows perform best.
    - As the amount of discretionary water available and capacity for shifting flows across time increases to very high levels, strategies focusing on supplementing spring high flows perform better than those focusing on summer low flows.
    - Choice of management strategy matters most in low water years.
- Multi-year management strategy simulations
    - The ability to store water in high flow years for use in later low and medium water years is a highly effective strategy relative to those strategies focusing only on in-season management.
    - Fifteen of the 20 top-performing strategies incorporated supplementing summer flows in low water years as at least part of their approach.
    - Performance of strategies supplementing flows only during spring high flow periods is highly sensitive to the volume of discretionary water available.
- Impact of summer drying intensity
    - During low water years, the probability of meeting RGSM population targets declines rapidly between 500 and 1200 mile-days dry.
    - Reducing either the extent or duration of drying within this region can greatly increase the probability of achieving annual population goals.
- Impact of adding discretionary water to the spring high flow period
    - Adding discretionary water to spring high flow periods had a limited impact until nearly 35,000 – 40,000 AF of water was added in years with low or moderate summer drying intensities.
    - In years with high summer drying intensities, even larger volumes of discretionary water were required to register a meaningful increase in the probability of meeting density targets.

Background

Natural resource management decisions are often plagued by multiple sources of uncertainty; including, but not limited to, uncertainty regarding future conditions, ecosystem structure, relationships between ecosystem components, and human behavioral response to management decisions (Mills et al. 2013; Allen et al. 2011; Göthe et al. 2019). Uncertainty can lead to delaying management decisions while more data are gathered. However, delaying management can result in lost opportunities to improve ecosystem conditions, which can be particularly damaging if management is focused on the conservation of highly imperiled endangered species. Continuing "business-as-usual" while gathering additional data may result in continued or even more rapid declines in endangered species or continued reductions in habitat, and additional data collection may not reduce uncertainties, or may reveal additional uncertainties. A commonly promoted approach to dealing with uncertainty in natural resource management is to adopt an adaptive management framework (Walters and Hilborn 1978; Walters 1986; Chen and Olden 2017). Adaptive management explicitly acknowledges that we do not fully understand how ecosystems function currently or how they may function in the future, but instead uses management actions as experiments to reveal underlying ecosystem properties (Allen et al. 2011). An iterative process, adaptive management requires periodic analysis of ecosystem response to management actions, which then feeds back into informing subsequent management decisions. Determining which management actions to implement in this experimental framework can be informed by simulation modeling (Walters 1986; Sainsbury et al. 2000).

Due to the inherent uncertainties in complex ecosystems, diverse sets of stakeholders and managers will often have a large set of alternative management options they would like examined, and simulation models provide a valuable means for reducing the number of strategies considered for real-world implementation. For large ecosystems, paired simultaneous experiments are not possible, and individual actions may take a long time to demonstrate a response due to non-linear dynamics, or stochastic variation in climatic, geomorphic, or biological conditions masking any management effects (e.g., Walsworth and Schindler 2016). As management can have substantial ecological, social, and economic consequences, it may not be socially acceptable to implement costly experimental management strategies for long enough to observe their impact on the target ecosystem (Evans et al. 2015; Walsh et al. 2020). Simulation models provide a means to rapidly examine many alternatives simultaneously and without demanding substantial opportunity costs (Walters et al. 2000; Walsworth et al. 2019; Walsworth and Budy, 2021). Ultimately these simulations allow managers to identify which management actions are likely to be most effective, such that they can then be explored with adaptive management experiments in the most cost effective and efficient manner (e.g., Walters and Hilborn 1978).

Globally, many native fishes have become imperiled due to the development of water resources via dams and diversions, particularly in arid regions where water storage is critical to maintaining reliable water resources for agricultural and municipal uses (Minckley and Deacon 1991; Olden and Poff 2005; Dudley and Platania 2007). As native fishes' life histories are adapted to the natural flow regimes of their native rivers, there have been increasing calls to reinstate or mimic a more natural flow regime in highly altered rivers as a means to bolster imperiled populations (Pennock et al. 2021). Recently, researchers have examined the concept of designer flows, in which alternative daily flow patterns for full years are compared for their expected benefits to native fish populations (e.g., Chen and Olden 2017). These studies use empirical models of the relationships between fish populations and seasonal discharge dynamics to identify flow patterns that are beneficial for native fishes and other taxa (Tonkin et al. 2020). Additionally, designer flows that hinder the proliferation of non-native species have been examined in conjunction with those benefiting native fishes (Tonkin et al. 2020). The results of designer flow analyses can then be used by stakeholders and managers to determine the preferred management strategy moving forward.

The Rio Grande Silvery Minnow (*Hybognathus amarus*; hereafter "RGSM") is an endangered species native to the Rio Grande Basin (Pflieger 1980), and has experienced a 95% reduction in range due largely to habitat alterations. The RGSM is currently limited to the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir in central New Mexico, USA (Bestgen and Platania 1991; Treviño-Robinson 1959). Water development upstream and within the Middle Rio Grande challenge the continued persistence of RGSM (Dudley and Platania 2007). Storage and extraction of flows in Colorado for irrigation reduce the amount of water that eventually reaches the MRG, while irrigation diversions within the MRG further reduce flows during irrigation season as well as fragmenting habitats resulting in extreme geomorphic and hydrological modification (Makar and Aubuchon 2012; Archdeacon 2016; Blythe and Schmidt 2018). Flood control dams, such as Cochiti Dam, reduce the magnitude of spring high flows, though they can extend high flow periods further into summer under some conditions (Junk et al. 1989; Poff et al. 1997; Naiman et al. 2008). Spring high flow events have been demonstrated to be critical to RGSM productivity, as inundated low velocity off-channel habitats provide valuable rearing conditions for larval and juvenile RGSM (Archdeacon 2016; Dudley et al. 2018; USFWS 2016; Pease et al. 2006; Medley and Shirey 2013; Valdez et al. 2019). Additionally, low-velocity off-channel habitats slow the downstream transport of RGSM eggs, larvae, and juveniles, maintaining populations upstream of diversion dams (Dudley and Platania 2007). Reduced summer base flows due to upstream and local water withdrawals have led to extensive channel drying in the MRG (Blythe and Schmidt 2018). Channel drying events lead to stranding of RGSM in isolated pools that eventually dry up if low flow periods are not relieved by monsoon precipitation or increased releases from upstream reservoirs and dams. Large drying events lead to high mortality rates, as RGSM cannot access wetted habitats (Archdeacon 2016; Archdeacon and Reale 2020; Archdeacon et al. 2020).

While water development presents many challenges to RGSM populations, the infrastructure in place may provide opportunities to manage water in ways that support RGSM persistence (Walsworth and Budy, 2021). Discretionary water (such as water leased from the San Juan-Chama Project) can be used by managers to supplement flows during specific times of year. Alternatively, dams designed for flood control may be able to temporarily store water for release during spawning or juvenile rearing season, to increase the area or duration of inundated off-channel habitats, or during summer base flows to reduce the extent and duration of channel drying. While flows during both seasons are known to be important for RGSM populations (Dudley and Platania 2007; Medley and Shirey 2013; Archdeacon and Reale 2020), it remains unclear whether supplementing spring flows or summer flows would be more beneficial across a range of hydrologic conditions. Both high spring flows and higher summer flows are correlated with greater RGSM densities in the autumn, but they are also highly correlated with each other (Walsworth and Budy, 2021). Thus, managers are challenged to identify when to deploy any supplementary flows available to them to increase benefits for RGSM conservation. Further, managers are limited by legal, institutional, and physical constraints on how much and when water can be stored or released. However, examining strategies currently unrealistic for implementation may be able to identify changes stakeholders may wish to consider in the future.

Here we use a simulation modeling approach developed from empirical relationships between MRG flows and RGSM population densities to examine the relative benefits of implementing alternative water management actions for RGSM conservation. Specifically, we address the following questions:

1. What generalized (i.e., applicable to any hydrograph), single-year water management strategy provides the best conditions to support the RGSM population under different water year types?
2. What generalized multi-year water management strategies provide the best conditions to maintain target densities of RGSM across multiple years of varying water availability?
3. Is there a threshold level of summer drying at which probability of meeting management targets declines rapidly?
4. How is the benefit provided by adding discretionary water during the spring high flow period impacted by the total amount of discretionary water available?

Additionally, we examine a case study using the 2021 forecast hydrograph as an example of how the model can be used to examine which of a suite of proposed alternative water management strategies are expected to provide the best opportunities to meet RGSM management goals under anticipated hydrologic conditions. Finally, we provide the computer code necessary to run the simulation model for a forecast hydrograph, so that managers and stakeholders can examine alternative approaches to increase RGSM conservation benefits in future years. By examining the effectiveness of alternative management approaches for both specific (2021) and generalized short (single year) and long term (multiple year) scenarios, our analyses provide managers with valuable information for determining both tactical (specific and near-term) and strategic (general and longer-term) management decisions. Given the inherent uncertainties in the relationship between annual flows and RGSM densities (Walsworth and Budy 2020, 2021), differences in the predicted performance of alternative management strategies should primarily be considered on a relative basis (e.g., which strategy is expected to perform best across multiple simulations) rather than focusing on exact probabilities (e.g., strategy *X* is expected to provide a 98.7% chance of meeting a management target).

Methods

Data

Historical discharge data were gathered from the U.S. Geological Survey Albuquerque water monitoring station (USGS Gage #08330000 Rio Grande at Albuquerque , New Mexico; *hereafter* "Albuquerque Central Gage"). We converted these discharge data collected at 15-minute intervals to daily mean values for our analyses. Discharge data are available from 1991 to 2021, and where data were missing (e.g., due to equipment failure or maintenance), we linearly interpolated the missing values between the preceding and following data points. Forecast hydrographs for 2021 were developed by the U.S. Bureau of Reclamation Upper Colorado Basin - Albuquerque Area Office (*hereafter* USBR) in March 2021. We examined the hydrographs representing the 50% and 70% exceedance probabilities (Boroughs 2013) in our analysis.

Simulation model

The simulation model developed by Walsworth and Budy (2021) is built on an empirical model of the relationship between historical RGSM October catch per unit effort (CPUE) data and annual flow conditions at the Albuquerque Central Gage (Fig. 1; Walsworth and Budy 2020, 2021). The RGSM CPUE data used to fit the empirical model were collected from multiple sampling sites within each reach of the Middle Rio Grande from 1993 through 2019 (Dudley et al. 2020). While fewer sites (5 in Angostura, 6 in Isleta and 11 in San Acacia) were sampled each year prior to 2017, ten sample sites within each of the three monitored reaches of the MRG have been sampled each October since 2017 to generate the October CPUE index against which management targets are measured. In the simulations presented herein, we simulate sampling from ten locations within each reach of the MRG to mimic the data generation pattern. The simulation model is built on an empirical hurdle model that predicts both the probability of encountering RGSM at a site given annual flow conditions, as well as the expected CPUE of RGSM given they are encountered (Walsworth and Budy 2020, 2021). Annual hydrologic conditions used to predict RGSM CPUE are an integrated metric of multiple measurements of spring high flow magnitude, duration, timing, and the extent of summer channel drying. Summer drying data were collected by the RiverEyes Program (a U.S. Bureau of Reclamation funded effort to monitor the daily extent and location of channel drying during the low flow season; e.g., McKenna 2019). Additionally, the underlying model incorporates reach-specific responses of RGSM to annual flow conditions using a mixed-effects model structure. While the empirical model underlying our simulations is not mechanistic but rather correlative between annual hydrology and observed RGSM CPUE, it is able to reproduce observed interannual changes in RGSM CPUE in the MRG across the period of observation, as well as the among-site variance in CPUE within years. For full model details, please see Walsworth and Budy (2020; link to pdf in reference list) and Walsworth and Budy (2021).

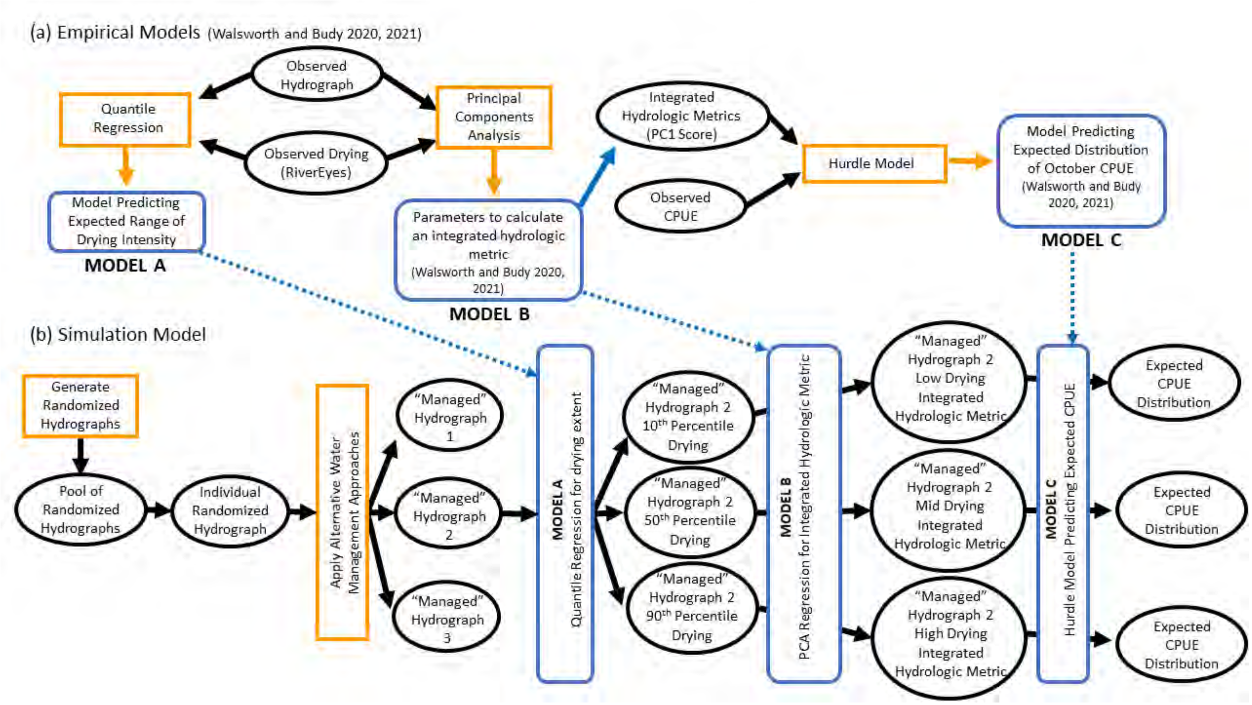

Figure 1. Conceptual model demonstrating the approach used to fit the empirical models (a; Phase 2 of this project; Walsworth and Budy 2020, 2021) that are used in this report to simulate the expected response of RGSM to alternative hydrographs given the historically observed relationships.

Generating randomized hydrographs

To simulate the response of RGSM to alternative water management strategies across a range of plausible hydrologic scenarios, we generated a large number of hypothetical, randomized hydrographs. To ensure the randomized hydrographs were realistic in terms of flow timing and magnitude, we developed the randomized hydrographs from the range of total discharge and hydrograph shapes observed in the historical data. Specifically, we:

1. Selected a total flow volume from the observed data set.
2. Multiplied the total flow volume by a random value with a mean of 1 and standard deviation of 0.05.
3. Randomly selected an annual hydrograph from the observed record and scaled the daily flow volumes to match the annual flow volume generated in steps 1 and 2.
4. Repeated steps 1-3 10,000 times to produce 10,000 randomized hydrographs.
5. Ranked the flow volume within each day across all randomized hydrographs (i.e., each daily flow within each hydrograph was ranked from 1-10,000, relative to flows on the same day in other hydrographs).
6. Generated a hydrograph by randomly sampling an integer between 1 and 10,000, selecting the January 1 daily flow volume with the selected integer's rank from the pool of hydrographs generated in step 4.
7. For each subsequent day of the year, we selected the ranked flow of the previous day's integer plus a random integer with mean 0 and standard deviation of 500 (forcing integers outside of the range from 1 – 10,000 back to the bounds). This process allowed the generation of unique

hydrograph shapes not previously observed in the data set, but still matching the general seasonal flow patterns typical of the Middle Rio Grande at the ABQ Central gage.

8. We repeated steps 6-7 of this process 10,000 times to generate a pool of 10,000 potential hydrographs from which to select (hereafter, "randomized hydrographs").

We categorized hydrographs based on their total flow volume: low water years were the bottom 25% of annual flow volumes, high water years were the top 25% of annual flow volumes, and medium water years were the middle 50%. The total flow volumes of these categories generally align with the bimodal distribution of low water and high water years identified in Appendix A of the USFWS Biological Opinion of 2016 (USFWS 2016) from the 1940-2015 Otowi Gage record (USGS Gage 08313000). Low water years had total flow volumes less than approximately 600,000 AF, while high water years had total flow volumes greater than approximately 1,300,000 AF.

Simulating summer drying extent and duration for randomized hydrographs

The hydrobiological model developed by Walsworth and Budy (2020, 2021) incorporates two metrics of summer drying, the mile-days dry in the San Acacia reach and the mile-days dry in the Isleta reach. As summer drying extent and duration cannot be extracted directly from the hydrograph at the Albuquerque Central Gage, we used quantile regression between the minimum summer flow value and the number of mile-days dry observed in the Isleta and San Acacia reaches to estimate the median, 10th percentile, and 90th percentile drying extents for each summer low flow scenario (Fig. 2). Variation in drying extent at the same minimum flow volume can be due to interannual differences in soil moisture, precipitation, irrigation withdrawals, or hydrologic losses downstream of the Albuquerque Central Gage, among other potential drivers. By examining the expected response of RGSM under low, median, and high drying scenarios for a given hydrograph, we can determine the range of potential responses by the RGSM population that would be expected given historic relationships.

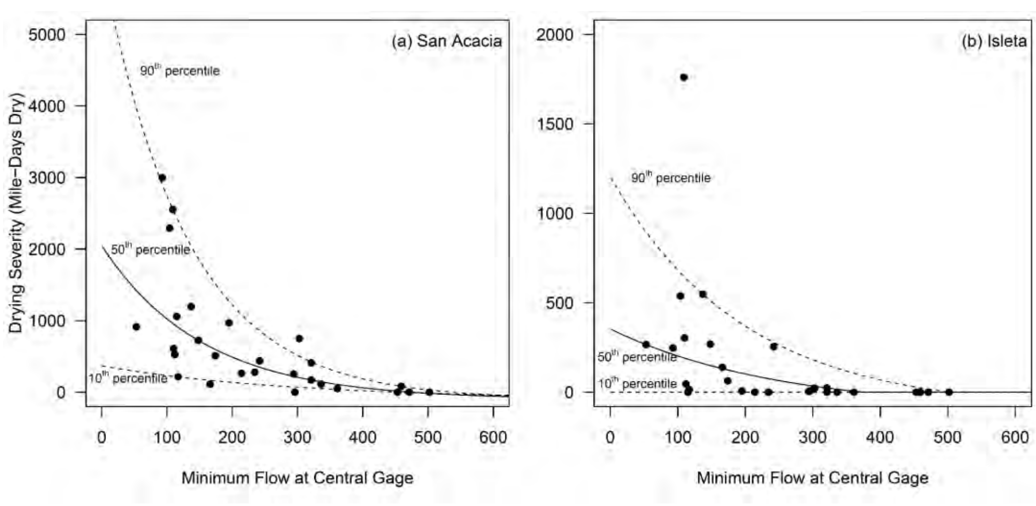

Figure 2. Quantile regression fits for the observed relationship between the minimum flow at the USGS Gage in Albuquerque and the mile-days dry observed by the RiverEyes monitoring program in the San Acacia (a) and Isleta (b) reaches.

Comparing Alternative Water Management Strategies

We applied water management strategies to the randomized hydrographs, increasing or decreasing daily flows according to the specified management plan. Flows are manipulated in the simulations by adding discretionary water (representing supplemental water available to managers, such as water leased from the San Juan-Chama Project), by temporarily storing native Rio Grande flows, and by releasing temporarily stored water. It is important to recognize that while water management in the Rio Grande is constrained by interstate agreements, these constraints are not explicitly incorporated into the generalized analyses presented herein. However, the simulation model requires only the input of an annual hydrograph, and thus requirements of the relevant policies and agreements can be incorporated by the user during the generation of alternative hydrographs to be explored. For our exploration of generalized strategies applied to randomized hydrographs, the ability of the model to examine scenarios outside of those currently able to be legally or feasibly implemented allows us to identify those strategies that would best support RGSM conservation. Managers, stakeholders, and policymakers can then use the information to consider the policy or infrastructural changes that may benefit RGSM conservation, while considering trade-offs with other management goals within the MRG.

The resultant modified hydrographs were then used to calculate integrated flow metrics from measurement of spring high flow timing and magnitude, summer low flow magnitude and the extent and duration of summer drying in the Isleta and San Acacia Reaches (Walsworth and Budy 2020, 2021). Using the simulation model presented in Walsworth and Budy (2021), we then calculated the expected distribution of sample site-level RGSM CPUE for each flow management strategy and its resultant integrated flow metric within each of the three reaches of the MRG. We sampled ten random values from each of the reach-specific distributions to simulate the ten sample sites within each reach (30 samples total). We then calculated the mean CPUE within each reach from these ten samples and for the full MRG mean CPUE from the samples across all reaches. Finally, we examined the expected probability of meeting different management targets, defined as the proportion of simulations in which RGSM CPUE was greater than 1 (the "self-sustaining population" target; USFWS 2016) or 5 (the down-listing target; USFWS 2016) RGSM per $100m^2$, depending on target being assessed. We finally calculated the rank-performance of all management strategies considered relative to each other.

We developed a suite of generalized single-year water management strategies capable of being applied to a range of annual hydrographs (Table 1). These strategies focused on storing or releasing different proportions of available water, as opposed to set volumes of water, across different months. By focusing on proportions, the strategies could be applied to both low and high water-years without storing more water than is actually available (e.g., trying to store 100 acre-feet of water per day when only 90 acre-feet are flowing per day). While generalizable across a range of water-year types, many of these strategies reflect the broad approaches developed by stakeholders during and following the workshop (see *Case Study: 2021 Forecast Hydrograph* below).

We examined the performance the generalized single-year management strategies (Table 1) against 200 hydrographs randomly selected from the pool of randomized hydrographs described above. Randomized hydrographs were identified as high (top 25% of spring flow volumes), medium (within the interquartile range of spring flow volumes), or low (bottom 25% of spring flow volumes) water years. For each hydrograph, we simulated RGSM CPUE 100 times, with each simulation using unique model parameter values sampled from posterior distributions estimated from the model developed in Walsworth and Budy (2020, 2021) updated to include data through 2020.

Additionally, we produced a suite of generalized multi-year management strategies that combined different single-year strategies, implementing them conditional on annual flows (Table 2). Each multi-year management strategy specifies an approach for each of the following: low water years, medium water years, high water years, low water years following high water years, low water years following medium water years, and medium water years following high water years. The multi-year strategies differed from simply being sequences of single-year strategies in one critical way: water was allowed to be stored from one year and used in subsequent years. Not all strategies incorporated across-year storage to allow an evaluation of such an approach relative to single-year actions.

We examined the performance the generalized multi-year management strategies (Table 2) against 200 different 5-year hydrograph sequences randomly selected from the pool of randomized hydrographs described above. For each multi-year hydrograph, we simulated annual RGSM CPUE 100 times, with each simulation using unique model parameter values sampled from posterior distributions estimated from the model developed in Walsworth and Budy (2020, 2021) updated to include data through 2020.

For both the single-year and multi-year randomized hydrograph analyses, we examined different levels of water storage available (25,000 AF, 50,000 AF, and 100,000 AF), discretionary water available (10,000 AF, 30,000 AF, and 100,000 AF), and proportions of daily flow stored during periods of storage (0.1, 0.25, and 0.5). We refer to the different combinations of these conditions as “management intensity scenarios”. While some of these scenarios are currently infeasible due to legal, infrastructural, and institutional constraints, examining their results my identify change stakeholders and managers may wish to consider in the future.

Table 1. Generalized single year water management strategies indicating monthly changes to simulated annual hydrographs. Values of -1 (red shading) indicate months in which flow is stored for later release. Values of 1 (blue shading) indicate months in which stored flows are released evenly across all days. Values of zero indicate no change to the hydrograph within those months. Values of -1 (red shading) in the Discretionary column indicate years in which discretionary water is also applied to months receiving stored flows. Letters at the beginning of strategy names indicate whether flows are shifted from one month to another (S), added from discretionary water supplies (A), both shifted between months and added from discretionary supplies (B), or harvested from spring high flows to be used in later months (H). The end of strategy names indicate where stored flows are subsequently released (Spring = May and June, Summer = July through September, Both = May through September, other strategies indicate specific months). The amount of water stored and thus moved among months varied among simulation scenarios (*see methods*).

		Month												
Strategy	**Description**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Discretionary**
0	NoAct	0	0	0	0	0	0	0	0	0	0	0	0	0
1	S Spring	0	0	-1	-1	1	1	0	0	0	0	0	0	0
2	S Summer	0	0	-1	-1	0	0	1	1	1	0	0	0	0
3	S Both	0	0	-1	-1	1	1	1	1	1	0	0	0	0
4	H Summer	0	0	0	0	-1	-1	1	1	1	0	0	0	0
5	S AugSept	0	0	-1	-1	0	0	0	1	1	0	0	0	0
6	S Sept	0	0	-1	-1	0	0	0	0	1	0	0	0	0
7	S Aug	0	0	-1	-1	0	0	0	1	0	0	0	0	0
8	S JulyAug	0	0	-1	-1	0	0	1	1	0	0	0	0	0
9	S July	0	0	-1	-1	0	0	1	0	0	0	0	0	0
10	S JulySept	0	0	-1	-1	0	0	1	0	1	0	0	0	0
11	A Spring	0	0	0	0	1	1	0	0	0	0	0	0	-1
12	A Summer	0	0	0	0	0	0	1	1	1	0	0	0	-1
13	A Both	0	0	0	0	1	1	1	1	1	0	0	0	-1
14	B Spring	0	0	-1	-1	1	1	0	0	0	0	0	0	-1
15	B Summer	0	0	-1	-1	0	0	1	1	1	0	0	0	-1
16	B Both	0	0	-1	-1	1	1	1	1	1	0	0	0	-1
17	A AugSept	0	0	0	0	0	0	0	1	1	0	0	0	-1
18	A Sept	0	0	0	0	0	0	0	0	1	0	0	0	-1
19	A Aug	0	0	0	0	0	0	0	1	0	0	0	0	-1
20	A JulyAug	0	0	0	0	0	0	1	1	0	0	0	0	-1
21	A July	0	0	0	0	0	0	1	0	0	0	0	0	-1
22	A JulySept	0	0	0	0	0	0	1	0	1	0	0	0	-1
23	B AugSept	0	0	-1	-1	0	0	0	1	1	0	0	0	-1
24	B Sept	0	0	-1	-1	0	0	0	0	1	0	0	0	-1
25	B Aug	0	0	-1	-1	0	0	0	1	0	0	0	0	-1
26	B JulyAug	0	0	-1	-1	0	0	1	1	0	0	0	0	-1
27	B July	0	0	-1	-1	0	0	1	0	0	0	0	0	-1
28	B JulySept	0	0	-1	-1	0	0	1	0	1	0	0	0	-1

Table 2. Multi-year water management strategies examined with the simulation model. As in Table 2, negative values (red shading) indicate months in which water is stored for later release, positive values (blue shading) indicate months in which water is released from storage, and zero values indicate no manipulation of the hydrograph. Values of -1 (red shading) in the Discretionary column indicate years in which discretionary water is also applied to months receiving stored flows. Values of 1 in the storage column (blue shading) indicate water is stored for use in subsequent years, while values of -1 in the storage column (red shading) indicate interannually stored water is released this year. Water-year types *midlow* and *highlow* indicate low-flow years following either a medium or high flow year, respectively, while *highmid* water years are medium flow years following a high flow year. Letters preceding strategy descriptions indicate whether discretionary flow is added (A), flow is shifted across months within year (S), flow is stored during spring high flows in high water years for use in subsequent years (HH), or flow is stored during spring high flows in both high and medium flow years for use in subsequent years (HM). The middle of strategy descriptions indicates when flows are released (Spring = May and June, Summer = July through September, Both = May through September). The last word in strategy descriptions indicates the types of water years in which flow manipulations other than interannual storage occur (Low = only in low water years, LowMed = in both low and medium water years).

			Month													
Strategy	**Description**	**Water Year Type**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Discretionary**	**Storage**
0	NoAction	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	A Spring Low	low	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	A Both Low	low	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	S Spring Low	low	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	S Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	A Summer Low	low	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	S Both Low	low	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2 (continued).

			Month													
Strategy	**Description**	**Water Year Type**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Discretionary**	**Storage**
7	S+A Spring Low	low	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	S+A Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	HH Spring Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
10	HH Summer Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
11	HH Both Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
12	HH+A Spring Low	low	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
13	HH+A Summer Low	low	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
14	HH+A Both Low	low	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
15	HH+S Spring Low	low	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1

Table 2 (continued).

Strategy	Description	Water Year Type	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Discretionary	Storage
16	HH+S Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
17	HH+S Both Low	low	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
18	HH+S+A Spring Low	low	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
19	HH+S+A Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
20	HH+S+A Both Low	low	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
21	HM Spring Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	1	1	0	0	0	0	0	0	0	-1
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
22	HM Summer Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	1	1	1	0	0	0	0	-1
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
23	HM Both Low	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	1	1	1	1	1	0	0	0	0	-1
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
24	HM+A Spring Low	low	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	-1
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1

Table 2 (continued).

			Month													
Strategy	Description	Water Year Type	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Discretionary	Storage
25	HM+A Summer Low	low	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	-1
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
26	HM+A Both Low	low	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	-1
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
27	HM+S Spring Low	low	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	-1
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
28	HM+S Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	-1
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
29	HM+S Both Low	low	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	-1
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
30	HM+S+A Spring Low	low	0	0	-1	-1	1	1	0	-1	0	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	-1
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
31	HM+S+A Summer Low	low	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	-1
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
32	HM+S+A Both Low	low	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	-1
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		highmid	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
33	HH+A Spring LowMed	low	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	0	0	1	1	0	0	0	0	0	0	-1	0
		highmid	0	0	0	0	1	1	0	0	0	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1

Table 2 (Continued).

Strategy	Description	Water Year Type	Month												Discretionary	Storage
			Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec		
34	HH+A Summer LowMed	low	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	0	0	1	1	1	0	0	0	-1	0
		highmid	0	0	0	0	0	0	1	1	1	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
35	HH+A Both LowMed	low	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	0	0	1	1	1	1	1	0	0	0	-1	0
		highmid	0	0	0	0	1	1	1	1	1	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
36	HH+S Spring LowMed	low	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	-1	-1	1	1	0	0	0	0	0	0	0	0
		highmid	0	0	-1	-1	1	1	0	0	0	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
37	HH+S Summer LowMed	low	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	-1	-1	0	0	1	1	1	0	0	0	0	0
		highmid	0	0	-1	-1	0	0	1	1	1	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
38	HH+S Both LowMed	low	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	-1	-1	1	1	1	1	1	0	0	0	0	0
		highmid	0	0	-1	-1	1	1	1	1	1	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
39	HH+S+A Spring LowMed	low	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		highlow	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	-1
		mid	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	0
		highmid	0	0	-1	-1	1	1	0	0	0	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
40	HH+S+A Summer LowMed	low	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		highlow	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	-1
		mid	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	0
		highmid	0	0	-1	-1	0	0	1	1	1	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
41	HH+S+A Both LowMed	low	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		midlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		highlow	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	-1
		mid	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	0
		highmid	0	0	-1	-1	1	1	1	1	1	0	0	0	-1	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1

Table 2 (continued).

Strategy	Description	Water Year Type	Month												Discretionary	Storage
			Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec		
42	HH Spring LowMed	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	1	1	0	0	0	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	1	1	0	0	0	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
43	HH Summer LowMed	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	0	0	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	0	0	1	1	1	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1
44	HH Both LowMed	low	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		midlow	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highlow	0	0	0	0	1	1	1	1	1	0	0	0	0	-1
		mid	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		highmid	0	0	0	0	1	1	1	1	1	0	0	0	0	-1
		high	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1

Assessing threshold drying extent

As in-season management actions may be able to impact the duration and extent of channel drying in the Isleta and San Acacia reaches, we examined the relationship between channel drying intensity and probability of meeting the sustainable population CPUE target of 1 RGSM per $100m^2$. For this analysis, we examined 1,000 hydrographs selected from the randomized hydrographs with the 25% lowest total flows (representing low water years in which drying is most likely to be extensive). For each selected hydrograph, we calculated the 25 integrated hydrologic metrics, each using different drying intensity values (mile-days dry in the Isleta and San Acacia reaches), ranging from 0 mile-days dry to the value corresponding with 1.5 times the 90^{th} percentile of expected drying for that randomized hydrograph as determined by the quantile regressions described above. This approach allowed us to examine how drying extent alone is expected to impact RGSM densities, while keeping the specified drying intensities within the realm of possibility for each hydrograph. We then used these integrated hydrologic metrics to simulate the expected RGSM CPUE for each hydrograph and drying intensity combination with the simulation model described above. We ran 1,000 stochastic simulations for each hydrograph x drying intensity combination.

Assessing threshold discretionary water impacts

Under current management for the conservation of RGSM, managers lease water annually to be used as discretionary or supplemental flows (hereafter, “discretionary water”) to be added to MRG flows to provide improved habitat conditions for RGSM spawning, rearing, or survival. As with the drying threshold analysis above, we examined 1,000 hydrographs selected from the randomized hydrographs with the 25% lowest total flows (representing low water years in which drying is most likely to be extensive). For each selected hydrograph, we applied the “A Both” single year management strategy (Table 1) in which discretionary flows are added evenly across the months of May and June. We examined the effect of 20 different levels of discretionary water available, ranging from 0 AF to 200,000 AF. After adding the discretionary flows to the randomized hydrographs, we calculated the integrated hydrologic metrics under low (10^{th} percentile), median (50^{th} percentile), and high (90^{th} percentile) drying intensity (mile-days dry in the Isleta and San Acacia reaches) values derived from the quantile regressions predicting expected drying for each randomized hydrograph as described above. We then used these integrated hydrologic metrics to simulate the expected RGSM CPUE for each hydrograph and drying intensity combination with the simulation model described above. We ran 1,000 stochastic simulations for each hydrograph by drying intensity combination.

Case Study: 2021 Forecast Hydrograph

To demonstrate the use of the simulation model for evaluating alternative management strategies, we held a virtual workshop in January 2021 in cooperation with USBR, during which interested stakeholders were able to see how the simulation model works and to gain experience developing hypothetical water management strategies in small groups. During the workshop, the strategies developed by participants were then applied to a hypothetical hydrograph and the performance of the different strategies developed by all groups in attendance were compared. Following the workshop, interested attendees were asked to submit flow management strategies they were interested in examining for the 2021 forecast hydrograph with the model (see description below, as well as Figs. 3,4 ad Supp. Figs. S1, S2). We examined these submitted strategies as an example of how the model can be applied to a single year's hydrograph to compare the relative performance of alternative flow management strategies.

The USBR produces pre-season flow forecasts in late winter and spring to allow managers and stakeholders to plan water actions for the year. We applied the alternative management strategies supplied by stakeholders following the simulation model workshop held in January 2021 to two of these forecasts, one representing the 50% exceedance probability (Figs. 3,4; Table 3) and one representing a 70% exceedance probability (Supplemental Fig. S1, S2). Some of the scenarios submitted for the 50% exceedance scenario (highlighted in orange in Supplemental Figs. S1, S2, and identified in Table 3) could not easily be applied for the 70% exceedance scenario, given the much lower daily discharge values in the 70% exceedance scenario. For example, the strategy *ISC.1a* aims to cap spring high flows at 1,999 cfs and uses the stored flows to extend the period of spring high flows into summer, but the 70% exceedance forecast has no daily mean discharge values greater than approximately 1200cfs. Thus, this strategy does not alter the forecast hydrograph in the 70% exceedance scenario. As such, we focus our discussion on the results of the 50% exceedance scenario simulations. We present the results for the 70% exceedance scenario as well, but urge caution when interpreting the performance of strategies not tailored to 70% exceedance flows.

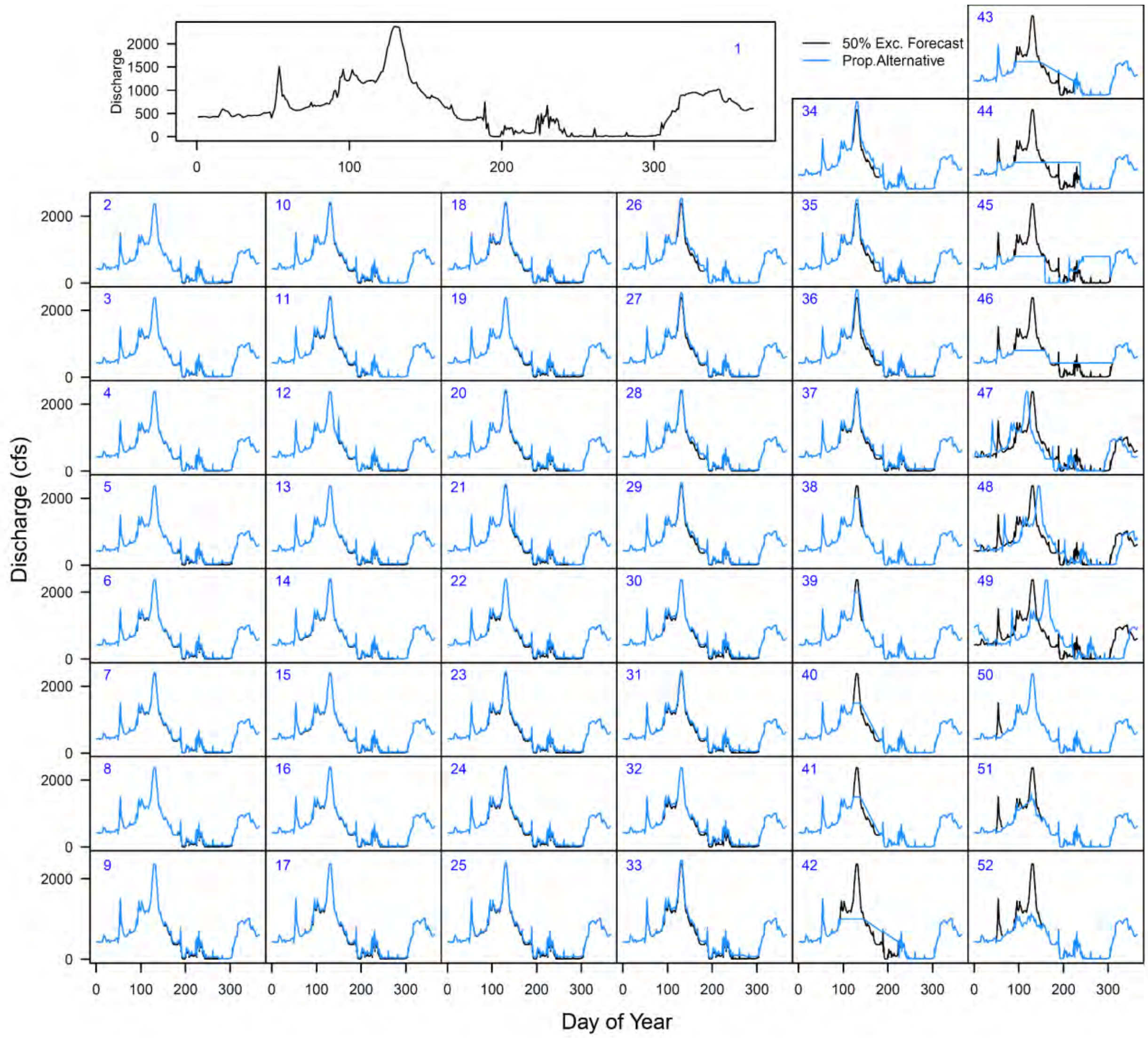

Figure 3. Forecast 2021 hydrograph for the 50% exceedance scenario (top panel with blue number 1 in top left), as well as the hydrographs proposed for exploration as alternative management actions submitted by stakeholders following the winter 2021 workshop. Each alternative hydrograph is identified by the blue number at the top left of each panel, whose descriptions can be found in Table 3. The blue lines represent the alternative hydrographs proposed while the black line represents the forecast hydrograph.

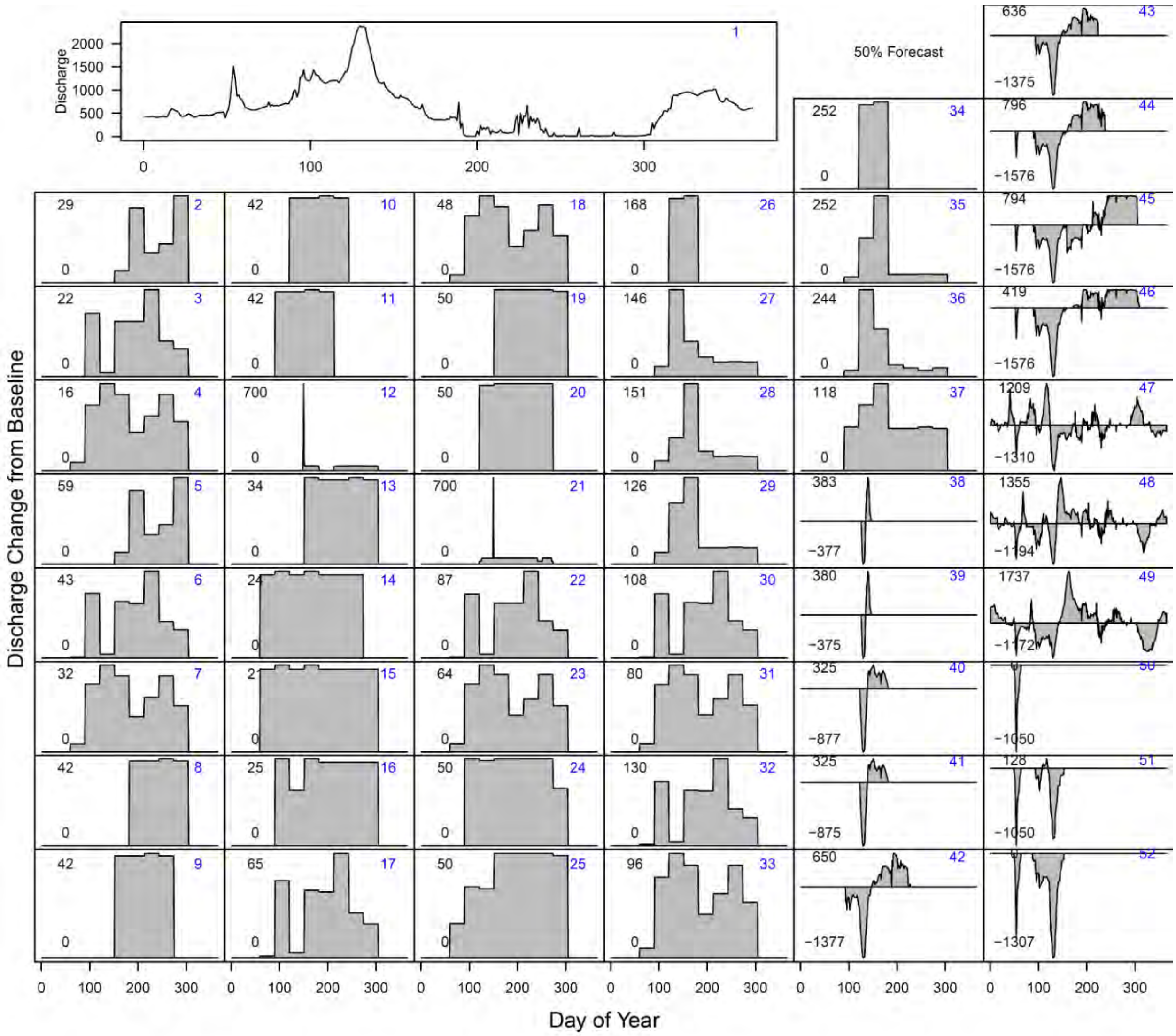

Figure 4. Forecast 2021 hydrograph for the 50% exceedance scenario (top panel with blue number 1 in top right), as well as deviations from the forecast for the different management actions submitted by stakeholders following the winter 2021 workshop. Each alternative hydrograph is identified by the blue number at the top right of each panel. The maximum and minimum deviations are indicated in black numbers on the left side of each panel.

Table 3. Descriptions of the different flow management strategies submitted by stakeholders following the January 2021 workshop. ID numbers match the hydrographs and hydrograph deviations in Figs. 3,4,17 and Supplemental Figs. S1,S2. Strategy names match those on the x-axis of Figs. 13-16 and Supp. Figs S15-S18. ID numbers marked with an asterisk indicate those strategies developed for the 50% exceedance scenario whose goals are incompatible with the 70% exceedance scenario. While these simulations were still run, their results should be interpreted with caution. These strategies are also noted with orange coloring in Supp. Figs. 1,2.

ID #	Name	Description
1	Forecast	US BOR forecast hydrograph for the Rio Grande at USGS Gage #08330000 in Albuquerque.
2	5K_Avg	5,000 acft of discretionary water are added to the flows beginning in June and increasing through October, with an initial peak in July.
3	5K_Dry	5,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.
4	5K_VDry	5,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
5	10K_Avg	10,000 acft of discretionary water are added to the flows beginning in June and increasing through October, with an initial peak in July.
6	10K_Dry	10,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.
7	10K_VDry	10,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
8	10K_Jul_to_Oct	10,000 acft of discretionary water are added to the flows relatively evenly across all days from July through October.
9	10K_June_to_Sep	10,000 acft of discretionary water are added to the flows relatively evenly across all days from June through September.
10	10K_May_to_Aug	10,000 acft of discretionary water are added to the flows relatively evenly across all days from May through August.

Table 3. (Continued)

ID #	Name	Description
11	10K_April_to_July	10,000 acft of discretionary water are added to the flows relatively evenly across all days from April through July.
12	10K_June_to_Oct_Jiggle	10,000 acft of discretionary water are added to the flows relatively evenly across all days from June through October, while also including a large pulse during June to trigger spawning activity.
13	10K_June_to_Oct	10,000 acft of discretionary water are added to the flows relatively evenly across all days from June through October.
14	10K_March_to_Sep	10,000 acft of discretionary water are added to the flows relatively evenly across all days from March through September.
15	10K_March_to_Oct	10,000 acft of discretionary water are added to the flows relatively evenly across all days from March through October.
16	10K_April_to_Oct	10,000 acft of discretionary water are added to the flows relatively evenly across all days from April through October.
17	15K_Dry	15,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.
18	15K_VDry	15,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
19	15K_June_to_Oct	15,000 acft of discretionary water are added to the flows relatively evenly across all days from June through October.
20	15K_May_to_Sep	15,000 acft of discretionary water are added to the flows relatively evenly across all days from May through September.
21	15K_May_to_Oct_Jiggle	15,000 acft of discretionary water are added to the flows relatively evenly across all days from May through October, while also including a large pulse during June to trigger spawning activity.
22	20K_Dry	20,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.

Table 3. (Continued)

ID #	Name	Description
23	20K_VDry	20,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
24	20K_Apr_to_Oct	20,000 acft of discretionary water are added to the flows relatively evenly across all days from March through September, with additions reduced by approximately half in October.
25	20K_March_to_Oct	20,000 acft of discretionary water are added to the flows beginning in March, increasing in April and May, and increasing again in June before remaining relatively even across all days from June through October.
26	20K_May_June	20,000 acft of discretionary water are added to the flows evenly across the months of May and June.
27	20K_May_Plus_to_Oct	20,000 acft of discretionary water are added to the flows relatively evenly across all days from April through October, with a large pulse through the month of May and receding to baseline additions through June and July.
28	20K_June_Plus	20,000 acft of discretionary water are added to the flows all days from April through October, with slightly higher flows in May before large additions in June, before receding to background addition levels in July.
29	20K_May_June_Plus	20,000 acft of discretionary water are added to the flows all days from April through October, with higher flows in May before an additional increase to additions in June, before receding to background addition levels in July.
30	25K_Dry	25,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.
31	25K_VDry	25,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
32	30K_Dry	30,000 acft of discretionary water are added to the flows, with an initial pulse of added water in April, limited additions in May, and large additions from June through October.

Table 3. (Continued)

ID #	Name	Description
33	30K_VDry	30,000 acft of discretionary water are added to the flows, with flow additions being largely split between two pulses: one during spring high flows from April through June and the other during summer low flows, with peaks in May and September.
34	30K_May_June	30,000 acft of discretionary water are added to the flows evenly across the months of May and June.
35	30K_May_Plus_to_Oct	30,000 acft of discretionary water are added to the flows all days from April through October, with slightly higher flows in May before large additions in June, before receding to background addition levels in July.
36	30K_June_Plus	30,000 acft of discretionary water are added to the flows relatively evenly across all days from April through October, with a large pulse through the month of May and receding to baseline additions through June and July.
37	30K_May_June_Plus	30,000 acft of discretionary water are added to the flows across the months of April through October, with releases in May being approximately 50% higher and those in June being approximately 100% higher than background additions.
38*	ISC.1.A	Flows are stored during spring high flow pulse to limit peak discharge at 1,999 cfs. Stored water is released so flows tail off through the summer.
39*	ISC.1.B	Flows are stored during spring high flow pulse to limit peak discharge at 2,001 cfs. Stored water is released so flows tail off through the summer.
40*	ISC.2.A	Flows are stored during spring high flow pulse to limit peak discharge at 1,499 cfs. Stored water is released so flows tail off through the summer.
41*	ISC.2.B	Flows are stored during spring high flow pulse to limit peak discharge at 1,501 cfs. Stored water is released so flows tail off through the summer.
42*	ISC.3.A	Flows are stored during spring high flow pulse to limit peak discharge at 999 cfs. Stored water is released so flows tail off through the summer.
43*	ISC.3.B	Flows are stored during spring high flow pulse to limit peak discharge at 1,001 cfs. Stored water is released so flows tail off through the summer.

Table 3. (Continued)

ID #	Name	Description
44*	ISC.4	Flows capped at 800 cfs during RGSM spawning period. A no magnitude, static duration hydrograph with a steep drop in late summer. Captured flows from spring runoff are released during the early summer
45*	ISC.5	Flows capped at 800 cfs during RGSM spawning period. A no magnitude, static duration hydrograph with a steep drop in mid-June. Captured flows from spring runoff are released during the early fall.
46	ISC.6	Flows capped at 800 cfs during spring and then are maintained at a constant 425 cfs through October (maintained at 100cfs in 70% exceedance scenario). Stored flows are stretched to prevent any drying.
47	ISC.7	Entire hydrograph shifted earlier by 14 days to test timing of peak.
48	ISC.8	Entire hydrograph shifted later by 14 days to test timing of peak.
49	ISC.9	Entire hydrograph shifted later by 31 days to test timing of peak.
50*	ISC.10	Deletes the February high flow pulse, no other changes. Reduces the total water supply by 10,000 acft without affecting anything else relative to main spring runoff magnitude, duration, or timing.
51*	ISC.11	Deletes the February high flow pulse, and lowers the peak magnitude down to approximately 1,500 cfs in May, reducing the total water supply by about 40,000 acft.
52*	ISC.12	Deletes the February high flow pulse, and lowers the peak magnitude down to approximately 1,000 cfs in May, reducing the total water supply by about 70,000 acft.

All simulations and analyses were conducted in the R Statistical Computing Environment (R Core Team 2020). Simulation model code is available in Appendix A.

Results and Discussion

Single-year Randomized Hydrographs

Most of the generalized alternative management strategies improved the probability of successfully meeting management targets relative to taking no action across all storage, discretionary water, and proportional management scenarios (Fig. 5, Supp. Figs. S3, S4). However, the improvements were generally smallest in high water years and were largest in low water years. Increasing the proportion of water moved across months and the amount of discretionary water available each allowed for greater relative success rates of top strategies, particularly in low water years. Interestingly, when the amount of discretionary water available and the ability to move flows across months was low, strategies focused on increasing summer flows performed best, but as more discretionary water became available and more water was shifted between months, those strategies focusing on increasing spring high flow periods' performed best. Under the highest discretionary water availability scenario and highest proportional management scenario, the best strategy (*B Spring*, in which both natural flow is shifted to and discretionary water is added to May and June flows) had a nearly 40% increase in the probability of success than taking no action in low water years (Fig. 5).

When examined across all storage capacity, discretionary water, and proportional management scenarios, all strategies, including *No Action*, were highly likely to meet the management target of 1 RGSM per $100m^2$ in both high water years (all median probabilities > 0.98; Fig. 6) and in medium water years (all median probabilities > 0.8). Even in low water years, the worst performing strategy (H Summer) demonstrated a median probability of success greater than 0.6. All strategies were also likely to meet the down-listing target of 5 RGSM per $100m^2$ in high water years (all median probabilities > 0.9; Fig. 7). The probabilities of meeting the down-listing target in medium water years was between 0.5 and 0.8, depending on management strategy, while in low water years, the probabilities of meeting the down-listing target were only between 0.15 and 0.25. As the probability of meeting management targets is relatively high in high flow years, choice of strategy has a generally smaller impact on the likelihood of success compared to low and medium water years, and therefore management efforts focusing on how to increase production and survival in low flow years may provide the most conservation benefit. However, those strategies supplementing water in spring high flow months as at least part of their strategy (*B Spring*, *B Both*, *A Both*, *A Spring*, *S Both*, and *S Spring*) consistently improved the probability of meeting management targets in medium flow years relative to the *No Action* strategy. These results suggest that in medium water years, those strategies either supplementing both spring high flows and summer low flows or those supplementing spring high flows only may provide consistent conservation benefits.

Of the top five performing strategies in low water years across all storage, discretionary water, and proportional management scenarios, four included supplementing flows during summer low flow periods, two included supplementing flows during spring high flow periods, and one included supplementing flows in both periods (Figs. 6,7). The strategy including both shifting (from March and April) and adding discretionary water to spring (May and June) months and summer low flow months (July through September; strategy *B Both*) demonstrated the highest median performance for meeting both the 1 and 5 RGSM per $100m^2$ targets. The strategy *B Spring,* which both shifted and added discretionary water to May and June only had the second highest median performance, but was highly variable due to its sensitivity to the volume of discretionary water available (Fig. 5). The strategy both shifting and adding discretionary water to only summer months was outperformed only by the *B Both* strategy when considering the worst-case ranking (i.e., the lowest ranking observed for the scenario across all scenarios and stochastic iterations). This suggests that supplementing summer flows with both shifted and discretionary water is a consistently strong strategy in low water years. The strategy of "harvesting" spring (May and June) high flows and shifting them to summer months (*H Summer*) performed consistently poorly (Figs. 6,7), decreasing the probability of meeting management targets relative to the *No Action* strategy, particularly in scenarios in which large proportions (50%) of daily flows are stored for later release (Fig. 5). These results further reinforce that supplementing both spring high flows and summer low flows are valuable, though the benefit to supplementing spring flows is dependent on the amount of water available to be added.

Our results indicate that strategies that use both discretionary water and water stored from before spring high flow periods to increase flows in later months provide the best opportunities for meeting management targets across a range of flow conditions. The top performing model when considering both expected performance and variance in performance across all storage, discretionary water, and proportional management scenarios increased flows in both spring (May and June) and summer (July through September) months. Such a strategy would theoretically increase both the production of juveniles during spring high flows and the survival of RGSM through summer dry periods. Interestingly, whether it is better to provide additional flows to spring or summer months depends on how much water can be moved or added (via discretionary water) to the system. When discretionary water volume is limited and only a smaller amount of daily flow can be stored in late winter months, adding flows to summer or both spring and summer performs better than adding flows to spring only. However, when a large volume of discretionary water is available or a large proportion of daily flow can be moved across months, increasing spring flows becomes more beneficial. While our underlying model is correlative and cannot definitively determine causation, this observation may be due to the large, sustained increases in flow required to inundate off-channel rearing habitats during low flow years. Whereas a relatively small amount of additional discharge may be able to reduce the extent and duration of summer channel drying, large increases in daily discharge may be required to increase spring flows enough to inundate these off-channel habitats for sufficient periods during low water years. We explore this dynamic in further depth in the "*Assessing Discretionary Water Impacts"* section below.

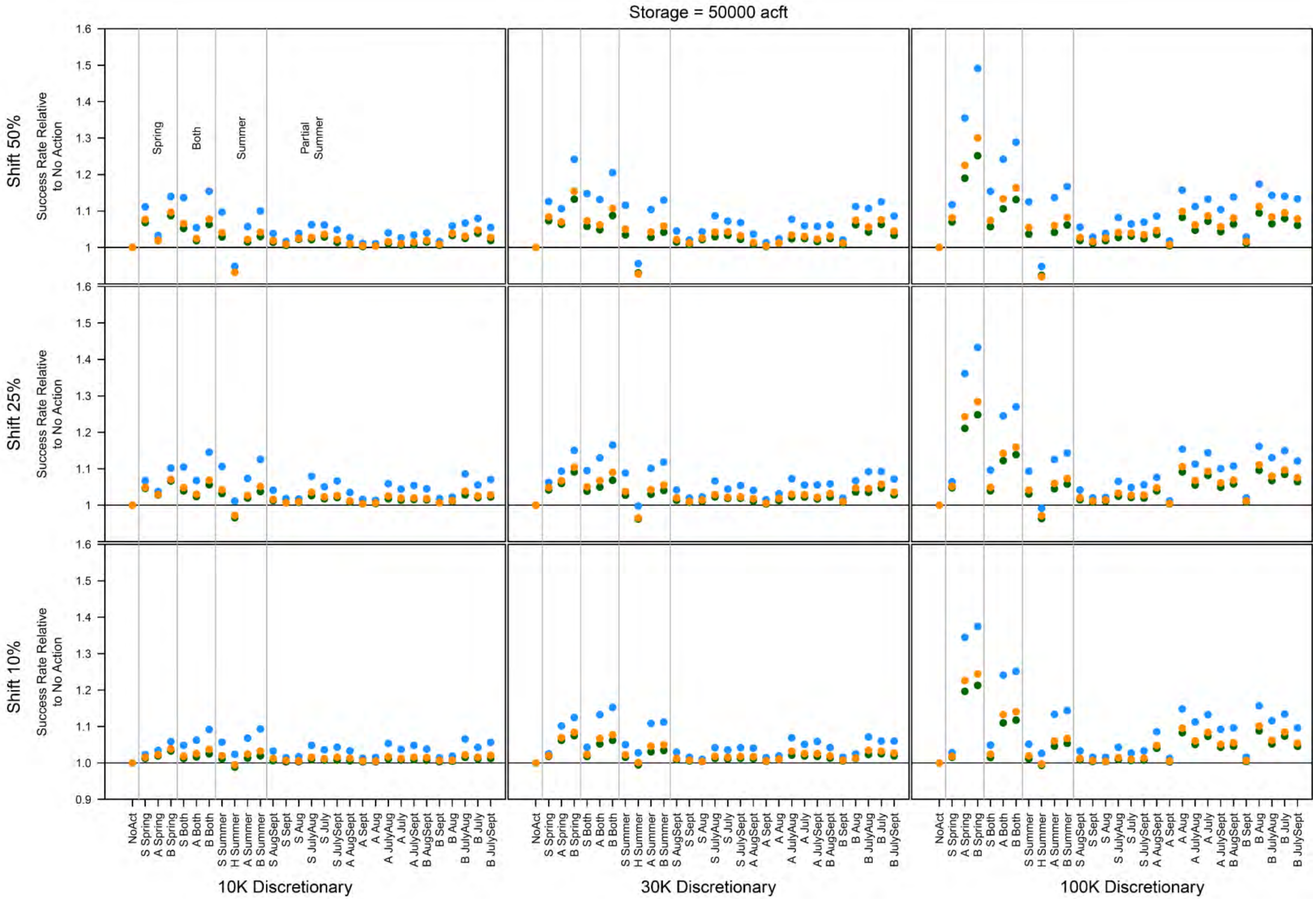

Figure 5. (*Caption on following page*)

Figure 5. (*Previous page*) Success rates of alternative water management strategies relative to no action across different discretionary water availability (columns) and proportional management (rows) scenarios when 50,000 AF of temporary storage is available. Blue points represent relative performance in low water years, orange points represent medium water years, and green points represent high water years. Values of 1 indicate that the alternative management strategy does not improve the probability of successfully meeting management targets compared to taking no action. A value of 1.1 indicates that the probability of success for a management strategy is 10% greater than that of the no action strategy. Vertical grey lines separate strategies supplementing flows in spring only, both spring and summer, summer only, or combinations of individual summer months ("partial summer").

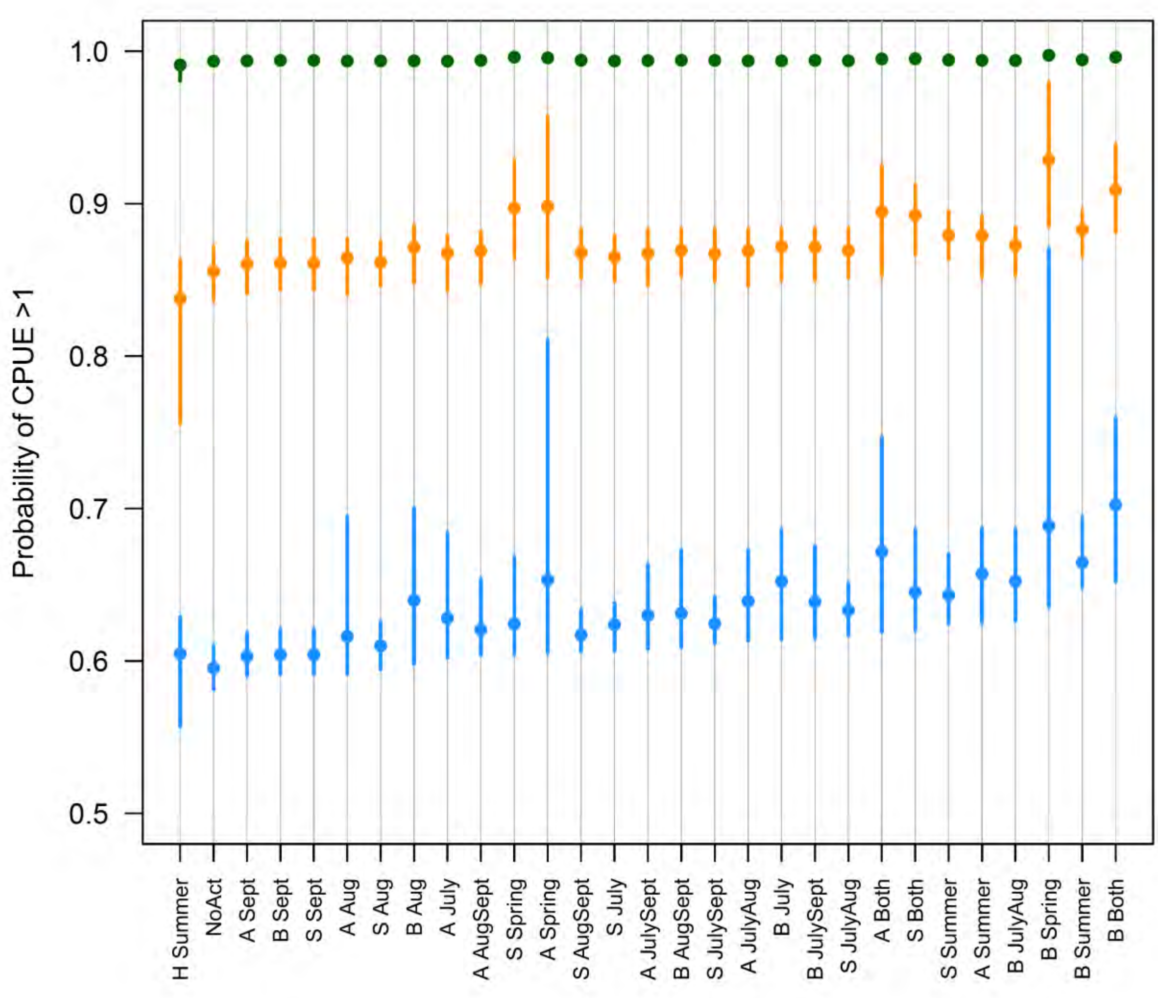

Figure 6. Probability of successfully meeting a management target of 1 RGSM per $100m^2$ for each management strategy across all water storage availability, discretionary water availability, and proportional management scenarios. Blue points represent relative performance in low water years, orange points represent medium water years, and green points represent high water years. Vertical lines indicate 90% prediction interval of performance within strategies among management intensity scenarios.

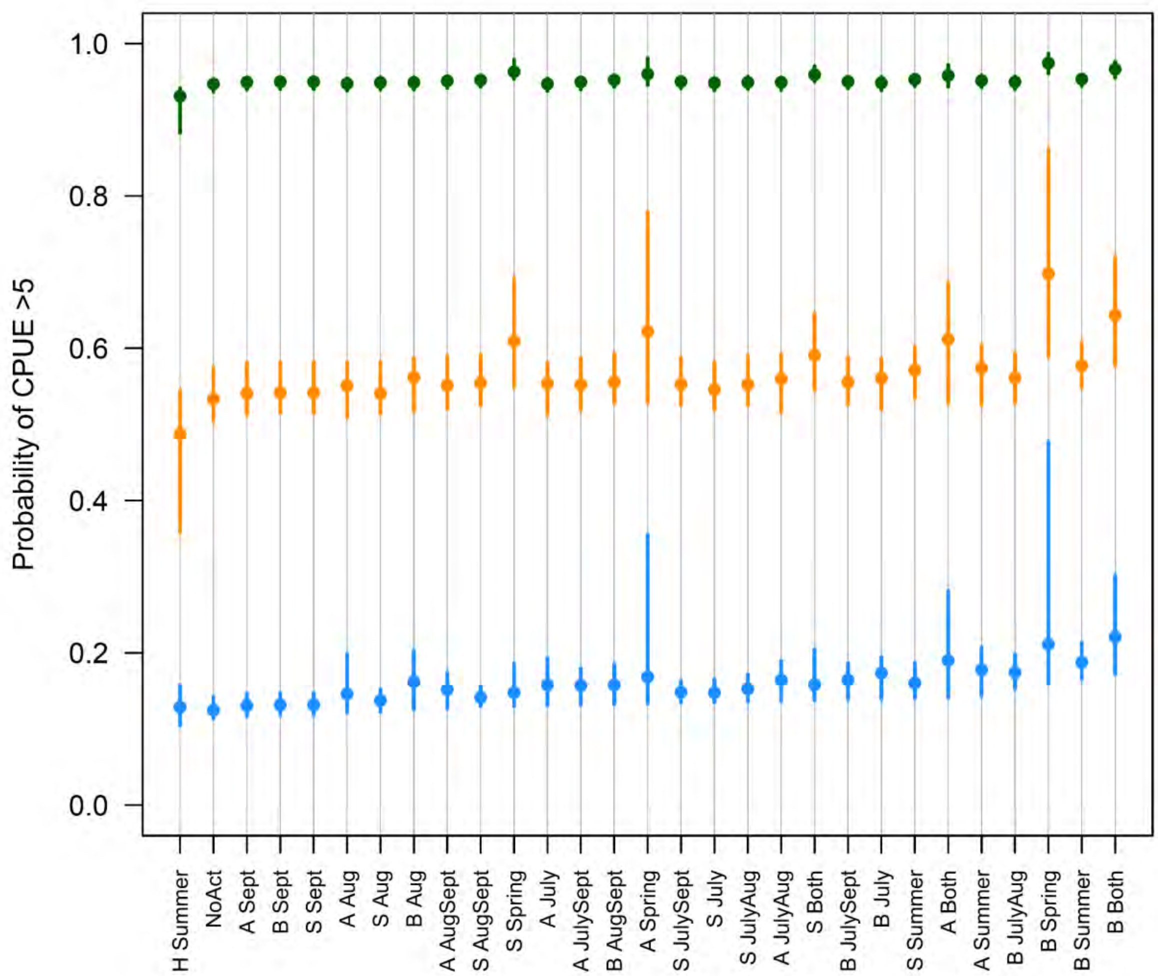

Figure 7. Probability of successfully meeting a management target of 5 RGSM per 100m^2 for each management strategy across all water storage availability, discretionary water availability, and proportional management scenarios. Blue points represent relative performance in low water years, orange points represent medium water years, and green points represent high water years. Vertical lines indicate the 90% prediction interval for performance within strategies among management intensity scenarios.

Multi-year Management Simulations Using Generalized Strategies

All multi-year water management strategies (Table 2) had high probabilities (greater than 0.8) of meeting the management target of 1 RGSM per 100 m^2 in at least two of the five years simulated for the multi-year simulation analysis (Fig. 8). However, the probability of meeting management targets for additional years out of the five years simulated decreased rapidly. Even the best performing strategies (*HH+S+A Both LowMed* and *HH+S+A Spring LowMed*) only met management targets all five years in less than 40% of simulations, except in the highest discretionary water scenarios in which *HH+S+A Spring*

LowMed met the management target in all five years in over 50% of simulations (Fig. 8, Supp. Figs. S5, S6). For most strategies, there were only minor differences in probabilities of meeting management targets at different frequencies across the range of storage capacities, discretionary water volumes, and proportional flow manipulations we examined. However, the top performing strategies increased their predicted performance as discretionary water availability and proportional flow manipulations increased. As was detected in the single-year simulations, the relative performance of strategies focusing on supplementing spring high flows increased in scenarios with more discretionary water available and larger proportions of flows were shifted across months (Fig. 8). In scenarios with limited discretionary water and limited ability to shift flows across months, supplementing both spring and summer flows during low and medium water years was the top performing strategy.

The choice of water management strategy drove major differences in the number of years in which management targets were met relative to the *No Action* strategy (Fig. 9, Supp. Figs. S7-S14). The top performing strategies (*HH+S+A Both LowMed* and *HH+S+A Spring LowMed*) increased the probability of meeting management targets in at least 4 out of 5 years by between 10-30%, with the largest impact when storage capacity, discretionary water volume, and proportional flow manipulation were at the highest values examined. Both of these strategies stored water during spring high flow periods of high water years and added these interannually stored flows, as well as discretionary water and flows stored during late winter within low and medium flow years to spring high flow periods in low and medium flow years, though the *HH+S+A Both LowMed* strategy also supplemented the flows during summer low flow months (Table 2). Interestingly, many of the strategies storing water in both high and medium flow years (represented by green lines in Fig. 9) decreased the probability of meeting management targets relative to the *No Action* strategy. The worst performing of these strategies (HM Spring Low) stores water during spring high flow periods of both high and medium water years and releases the stored water during spring months of low water years, yet does not manage water in low flow years that follow low flow years.

One strategy (*HH+S+A Both LowMed*) consistently outperformed all others in the multi-year simulations (Fig. 10), except in the highest discretionary water availability scenarios in which the *HH+S+A Spring LowMed* was consistently best (Figs. 8, 9; Supp. Figs. S5-S14). Of the top 20 strategies, 8 incorporated supplementing only summer low flows, 7 supplemented flows during both spring high flow and summer low flow periods, and 5 supplemented flows only during spring high flow months. Six strategies had lower "worst-case" rank performance (i.e., the lowest observed rank performance across all scenarios and iterations) than the *No Action* strategy. Five of these strategies stored flows during spring high flows in both high and medium water years. Four of these strategies only supplemented flows in the spring high flow period of low water years. While the *HM+A Spring Low* strategy had a lower worst-case rank performance than the *No Action* strategy, it had high variation in performance across scenarios and stochastic iterations, with a much higher best-case performance than the *No Action* strategy. The consistently high ranking of strategies incorporating supplementation of summer flows as at least part of their approach demonstrates the importance of maintaining suitable habitat during this season.

Given that each of the top nine and 12 out of the top 15 performing strategies involved storing water during high water years for use during low water years, it is apparent that managing water across years as opposed to strictly on a year-to-year basis can provide major conservation opportunities for RGSM. These approaches increased the expected probability of meeting management targets in any given year, as well as the frequency at which management targets were met. By dampening the negative effects of low flow years on the RGSM population in the MRG, such multi-year management strategies may be valuable to long-term persistence of this endangered species. Notably, the estimated benefit of multi-year water management from our simulation model is likely conservative (i.e., the benefits could be greater than predicted here), as our correlative model does not mechanistically include population carry-over effects across years (though temporal autocorrelation in the model will generate some carry-over effects; Walsworth and Budy 2020, 2021). By reducing the negative effects of low water years with supplemental water stored during antecedent higher flow years, managers may be able to increase survival of large year classes produced during high flow years, thus maintaining larger populations of RGSM for longer time periods. Alternatively, low survival in low flow years could negate the benefits realized from preceding large recruitment years. Models incorporating mechanistic population dynamics are currently being developed by other research groups (C. Yackulic, *personal communication*) and could be incorporated into a similar simulation analysis as that presented herein. However, as the empirical model underlying our simulation analysis is fit to and capable of reproducing observed RGSM CPUE trends from annual flows at the Central Gage, we expect a more mechanistic model would arrive at qualitatively similar results to those presented here.

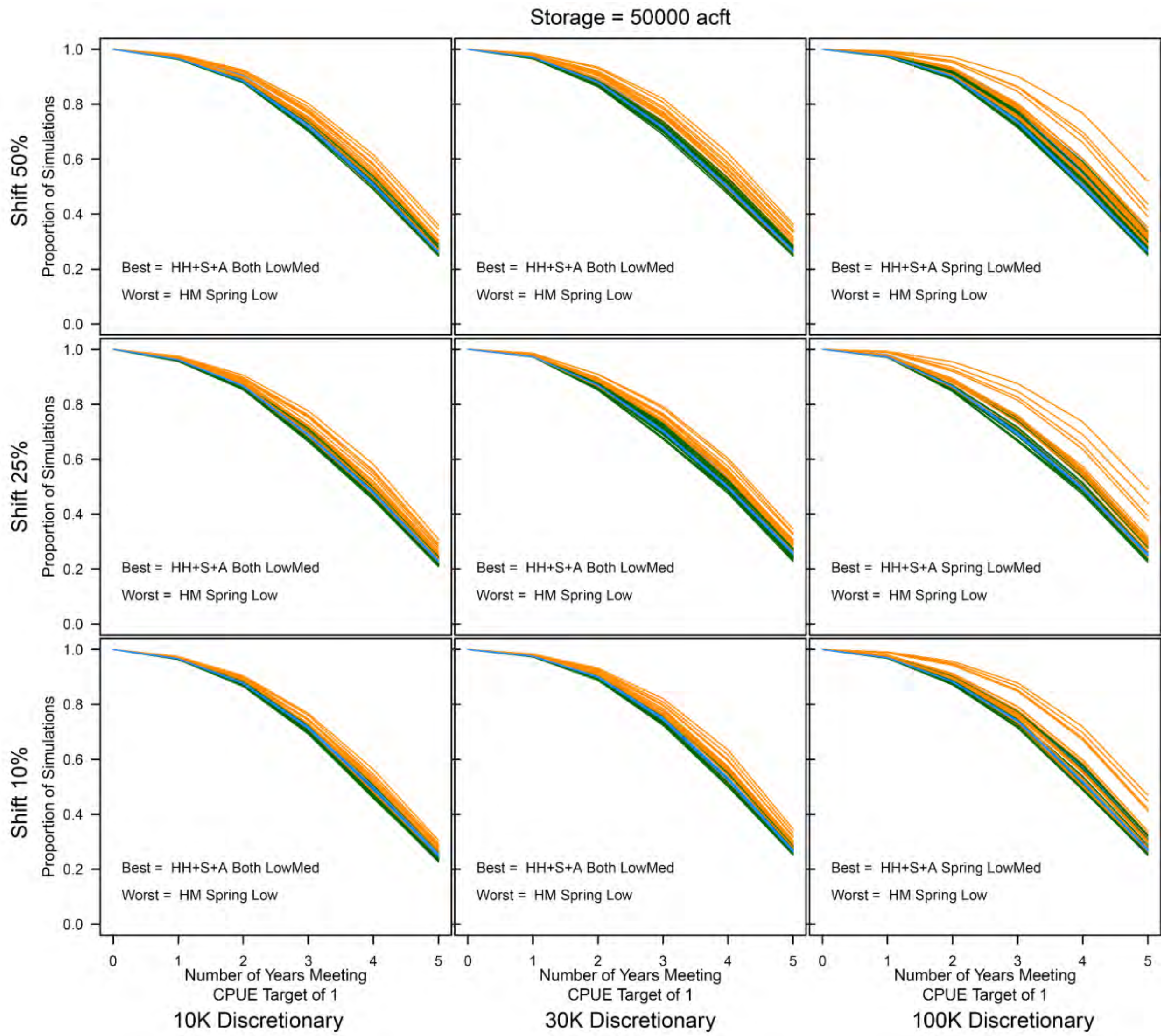

Figure 8. Proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per $100m^2$ successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 50,000 AF of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

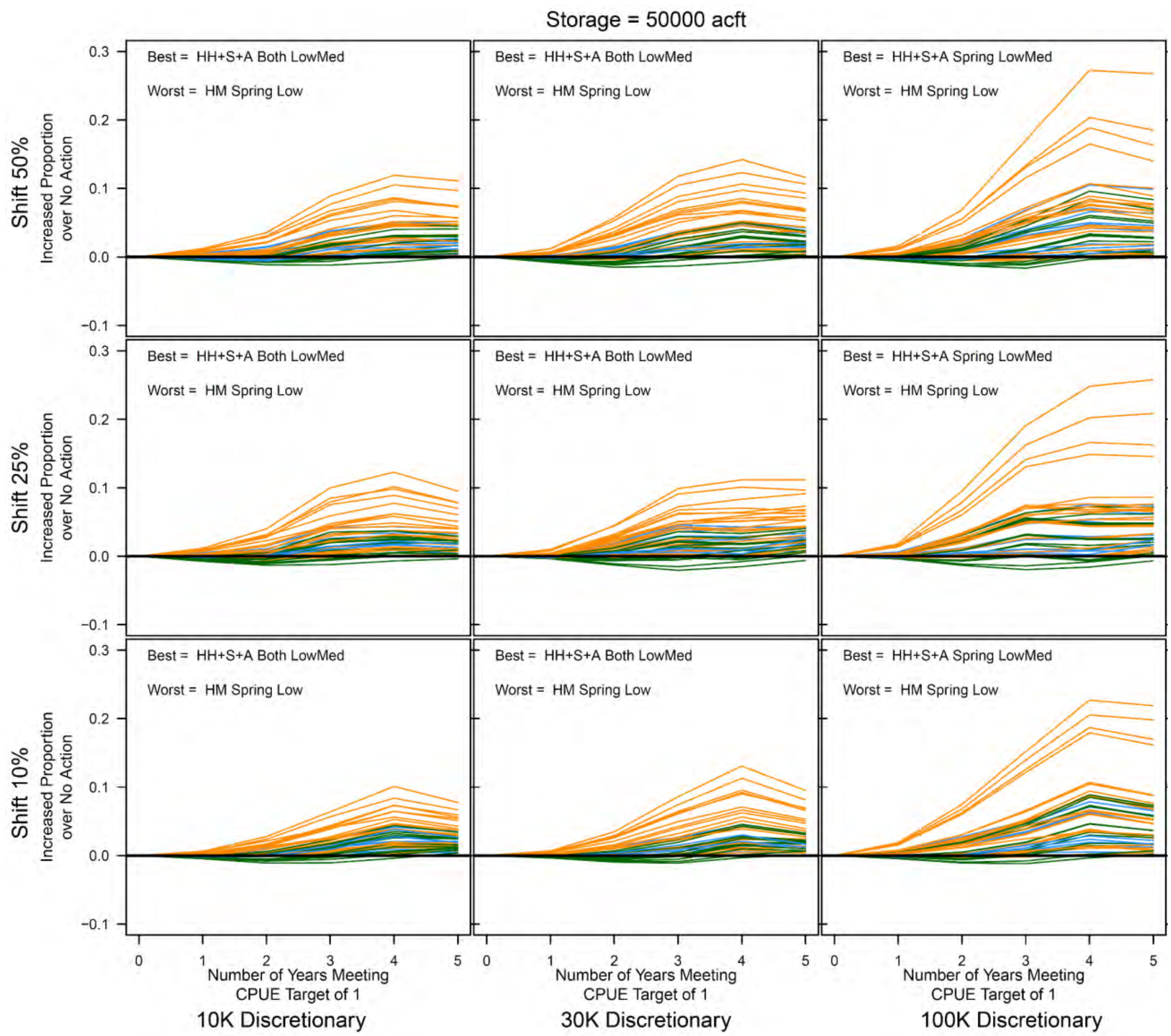

Figure 9. Change in the proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per 100m^2 successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 50,000 AF of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

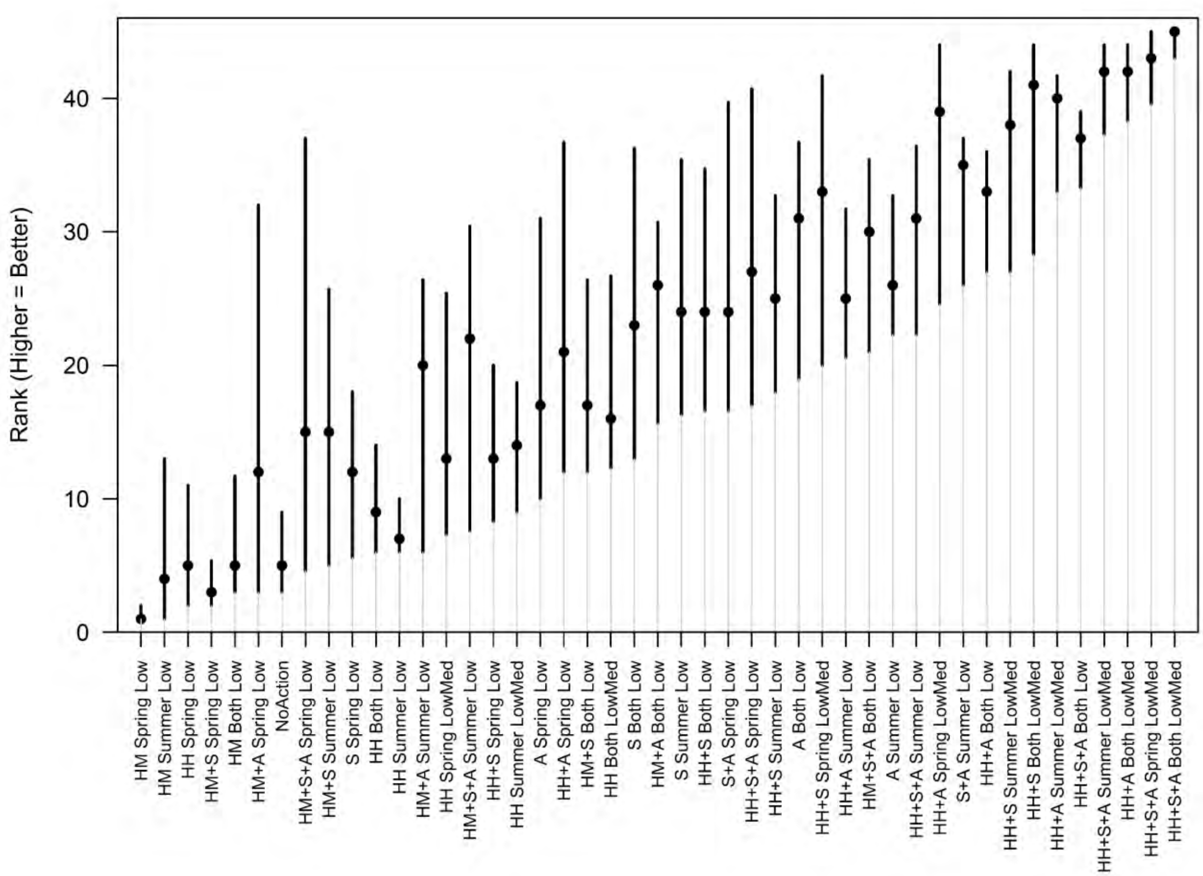

Figure 10. Rank performance of different multi-year management strategies across all storage, discretionary water, and proportional management scenarios, ranked by each strategy's lowest-ranked performance across all iterations and scenarios. Higher ranks indicate higher probabilities of meeting management targets across more years in the multi-year simulations relative to other strategies. Points indicate the median rank performance, while vertical bars indicate the range of ranks across management intensity scenarios and stochastic iterations. Thin grey lines extending from the x-axis are intended only to help the reader identify which strategy is associated with which point.

Assessing threshold drying impacts

The probability of achieving a CPUE goal of 1 RGSM per 100m^2 declined with increasing drying severity across all simulated hydrographs examined (Fig. 11a). In the relatively low flow years examined, even completely avoiding drying did not guarantee meeting the CPUE target, as probabilities of meeting the CPUE target ranged from 0.51 to 0.95 with a mean of 0.76 when the mile-days dry in San Acacia was specified to be zero. The mean expected probability of achieving the CPUE target declines below 50% once the San Acacia reach experiences 625 mile-days dry.

The rapid decline in probability of achieving management targets as drying intensity increases suggests that management actions that can reduce either the spatial extent or temporal duration of drying by a small number of miles or days may be able to substantially increase the probability of meeting management targets (Fig. 11b). However, under extreme drying conditions that would be expected to cause many miles dry for many days, much larger management actions that could reduce drying extent or duration would be required to have a meaningful impact on the probability of meeting CPUE targets.

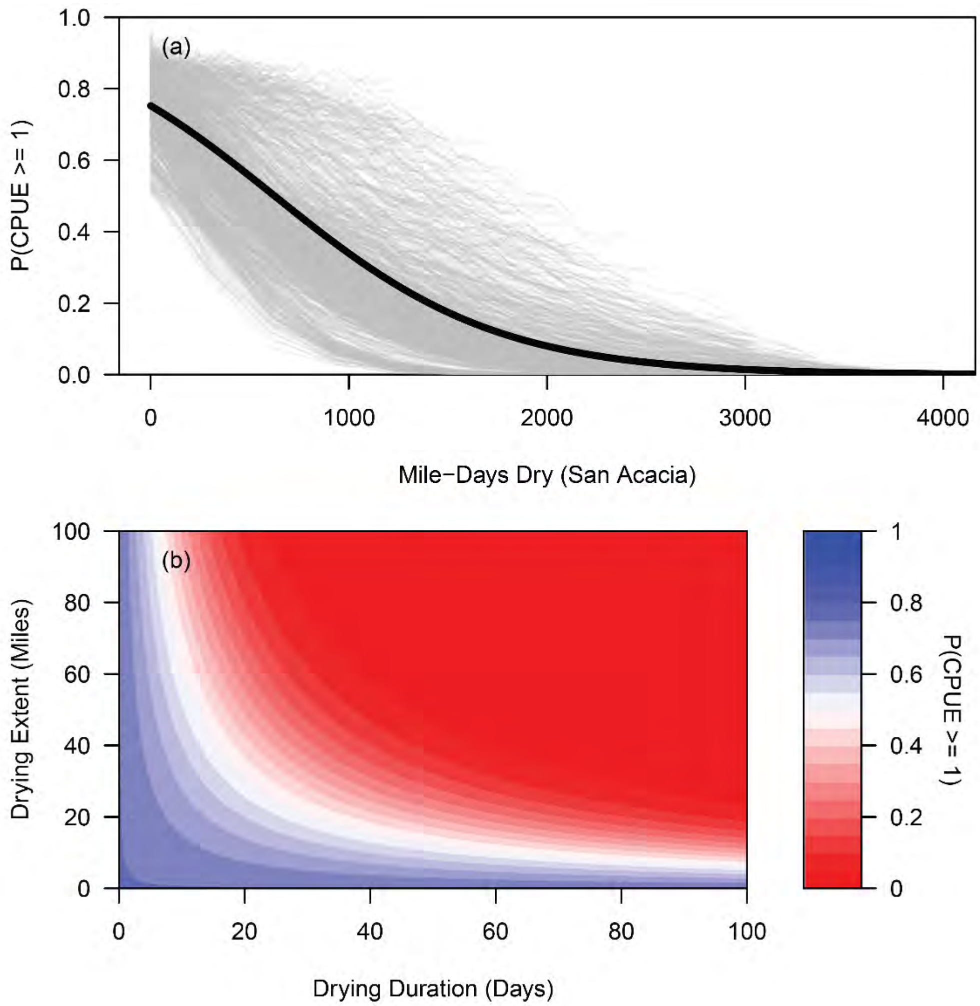

Figure 11. (a) Relationship between drying intensity in the San Acacia reach (mile-days dry) and the probability of meeting a CPUE target of 1 RGSM per $100m^2$. The thin grey lines indicate the results from individual randomized hydrographs across a range of specified drying intensities, while the thick black line indicates the relationship across all randomized hydrographs examined. (b) Probability of meeting a CPUE target of 1 RGSM per $100m^2$ across different combinations of drying extents (miles) and durations (days). Red colors indicate probabilities less than 50%, while blue colors indicate probabilities greater than 50%.

Assessing Discretionary Water Impacts

The relative effectiveness of adding different volumes of discretionary water during May and June to increase the magnitude and duration of spring high flows demonstrates a saturating relationship under low, medium, and high drying conditions across the randomized hydrographs examined (Fig. 12).

Under low drying conditions (10^{th} percentile predicted drying extent for a specific hydrograph), the median probability of meeting the CPUE target of 1 RGSM per $100m^2$ is over 75%, even when no discretionary water is added to the spring flows (Fig. 12a). However, there is very limited increase in the probability of meeting this CPUE target until approximately 40,000 AF of discretionary water is added (Fig. 12b). Adding 40,000 AF of water to May and June flows is predicted to increase the probability of meeting the CPUE target by 10% relative to adding zero discretionary water. While the probability of meeting the CPUE target continues to increase with additional discretionary water, diminishing marginal benefits were realized beyond the addition of 60,000 AF.

Under median drying conditions (50^{th} percentile predicted drying extent for a specific hydrograph), the median probability of meeting the CPUE target of 1 RGSM per $100m^2$ is approximately 56% when no discretionary water is added to the spring flows (Fig. 12c). As under low drying conditions, small amounts of discretionary water had limited impact on the probability of meeting the CPUE target (Fig. 12d). A 10% increase in the probability of meeting CPUE target was only realized when approximately 34,000 AF of discretionary water was added to May and June flows. As observed in the low drying simulations, diminishing marginal benefits were realized beyond the addition of 60,000 AF.

Under high drying conditions (90^{th} percentile predicted drying extent for a specific hydrograph), the median probability of meeting the CPUE target of 1 RGSM per $100m^2$ is 28% when no discretionary water is added to the spring flows (Fig. 12e). Additionally, no meaningful increase in the probability of meeting the CPUE target is expected until 38,000 AF of water is added to May and June flows, and it is not until 52,000 AF of water are added to May and June flows that the median probability of meeting the CPUE target achieves 50%. Nearly 80,000 AF are required for the median probability of achieving a management target of 1 RGSM per $100m^2$ to surpass 90%.

The observation that large amounts of discretionary water are required for spring additions to have meaningful impacts in low water years is due to the integrated hydrologic metric used in the model is driven, in part, by the number of days above different threshold discharge levels (i.e., 1500 cfs, 2000 cfs, 2500 cfs, and 3000 cfs). Adding discretionary water in during the spring months that does not raise daily discharge rates above these thresholds will not increase the value of these metrics, and thus has limited impact on the integrated hydrologic metric (though there will still be a benefit from the increased mean daily discharge and total volume of flow in spring). This is not to say that RGSM will not benefit from flows that are increased but do not reach these specific threshold values, but the benefits of additional discharge during spring high flow periods are likely to be limited if the additional flows are insufficient to connect the main channel to the floodplain and create low velocity retention and rearing habitats (Dudley and Platania 2007; Widmer et al. 2010). Further, the parameters in our model are fit to observed data from 1993-2019 and are thus driven by the relationships between flow and geomorphology present during that period. Habitat restoration projects or natural geomorphic changes that increase connectivity between the main channel and floodplain habitats at lower discharge levels could alter these relationships in the future and may reduce the amount of discretionary water needed to be added to spring high flows to have meaningful impacts on RGSM populations. As such, the empirical model underlying our simulations (Walsworth and Budy 2020, 2021) should be updated regularly to include newly observed data. Additionally, for tractability of our simulations, we only examined the effect of adding discretionary water evenly to flows across the months of May and June in this analysis. Users can readily examine other delivery timing approaches during spring (e.g., spread supplemental flows across fewer days to achieve a higher peak) using this modeling approach.

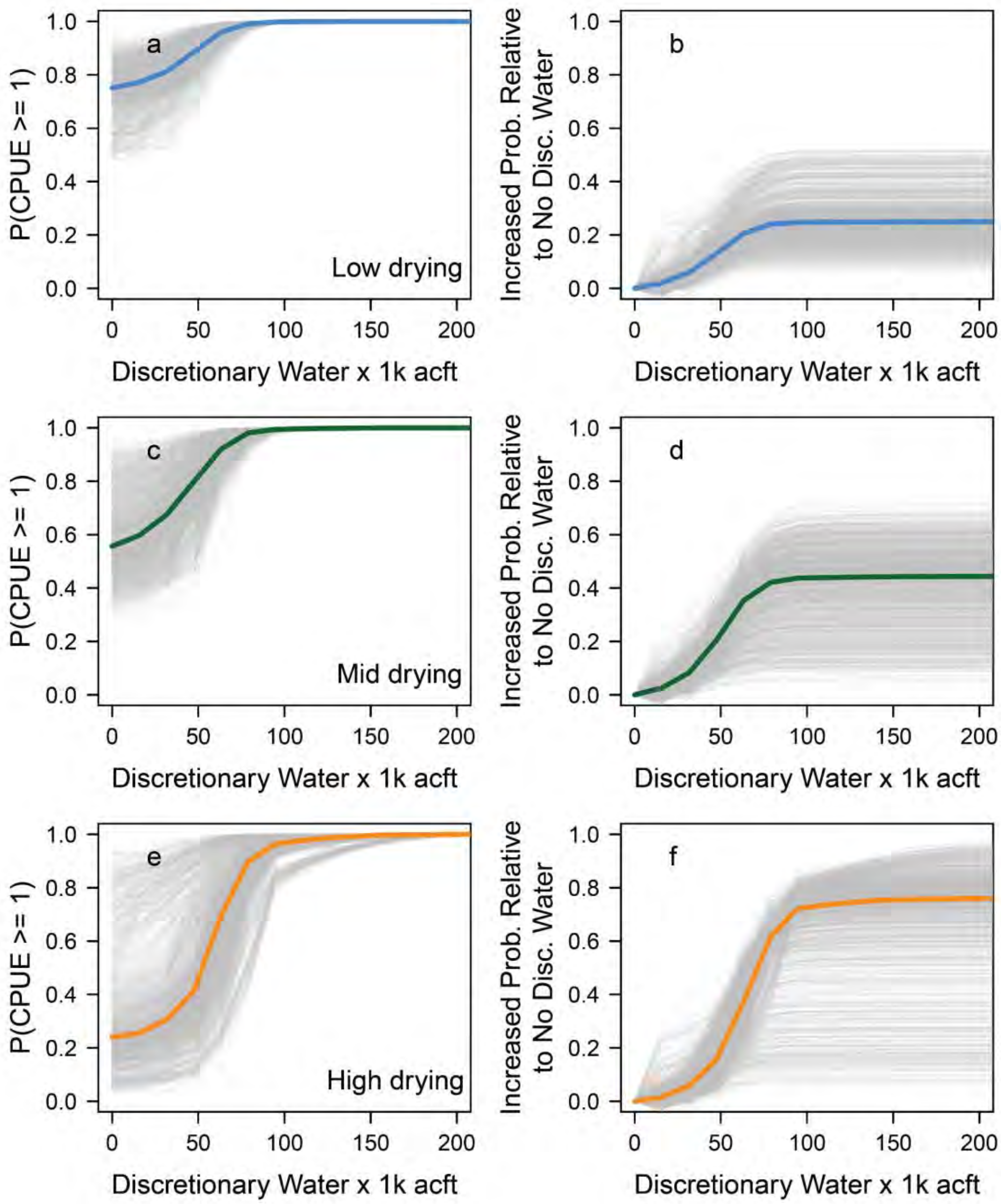

Figure 12. (Left column) Simulated probabilities of achieving a target October RGSM CPUE of 1 RGSM per 100m^2 across a range of discretionary water amounts added to May and June flows. Simulations were run for low flow years when the (a) 10th percentile of expected summer dying occurs, (c) the median expected summer drying occurs, and (e) when the 90th percentile summer dying occurs. (Right column) Increased probabilities of achieving the CPUE target relative to adding no discretionary water for (b) low, (d) median, and (f) high drying scenarios. Light grey lines indicate the relationships for individual randomized hydrographs, while thick colored lines indicate the median values all stochastic simulations.

Case Study: 2021 forecast hydrograph

As an example of how the model can be used to inform management for a specific hydrograph, stakeholders submitted 51 alternative flow management strategies to be applied to the forecast Middle Rio Grande hydrograph during 2021 (Figs. 3, 4; Supp. Figs. S1, S2; Table 3). Not surprisingly, all management strategies performed better under the 50% flow exceedance scenario (Figs. 13-15) than the 70% flow exceedance scenario (Supp. Figs. S15-S17), as there is simply more water in the system regardless of management compared to the 70% flow exceedance scenario. Generally, the differences in performance within management strategies but across drying scenarios were greater than those across strategies but within drying scenarios, particularly when comparing expected RGSM densities in the high drying scenario against the median or low drying scenarios. For both the 50% and 70% exceedance scenarios, nearly all water management scenarios are predicted to have substantially reduced densities of RGSM per $100m^2$ when summer drying is specified at the 90^{th} percentile for the forecast flow conditions (Fig. 13, Supp. Fig. S15), and thus have low probability of meeting management targets (Figs. 14, 15, Supp. Figs. S16, S17). However, for the 50% exceedance forecast, the strategy *ISC.6* (number 46 on Figs. 3,4) performs well regardless of the severity of summer drying (Figs. 13, 14, 15). This strategy stores water during spring high flows and releases them throughout the summer, maintaining summer flows at 425 cfs. In the 70% exceedance scenario, strategy *ISC.6* also performs well, though is more strongly impacted by drying severity as summer flows are maintained at only 100cfs in this scenario (Supp. Figs. S15, S16, S17). By maintaining substantial flows throughout the summer, this strategy is expected to result in minimal channel drying in the 50% exceedance scenario, even at the upper predicted drying severity (Fig. 2). The variation in drying extent for a given summer low flow at the Central Gage is driven by many factors, including but not limited to interannual geomorphic changes, downstream water management decisions, and summer precipitation patterns. However, as summer minimum flows increase, the effect these other factors have on drying extent is reduced, as there is enough water in the channel to maintain continuous flow.

For the 50% exceedance scenario, the *ISC.6* strategy (ID# 46) consistently performed better than other strategies (Fig. 16). The next best tier of strategies included *30K_May_June_Plus* (ID# 37)*, 30K_VDry* (ID# 33), and *20K_March_to_Oct* (ID# 25). Each of these top performing strategies supplemented flows throughout the summer low flow period (Figs. 3,4). All of them except *ISC.6* also supplemented spring high flows. The performance of the different strategies relative to each other does not change dramatically between the 50% and 70% exceedance scenarios (Fig. 16, Supp. Fig. S18). The *ISC.6* strategy still performs best relative to other strategies examined, though its expected performance in medium and high drying scenarios declined relative to the 50% exceedance scenario. However, the relative difference in rank performance among strategies was much smaller for the 70% exceedance scenario than the 50% exceedance scenario. The *30K_May_June_Plus* (ID# 37) strategy also performs highly under the 70% exceedance scenario, having the second highest median rank performance. These results support the idea that in low flow years (such as the forecast for 2021), supplementing flows during summer low flow periods may provide greater benefits than strategies increasing spring flows, particularly when limited volumes of water are added or shifted to spring high flow months.

The simulation model can also be used to examine reach-specific probabilities of meeting management targets. Across each of the alternative flow management strategies submitted, the Angostura reach consistently had the lowest probability of meeting a management target of 1 RGSM per $100m^2$, followed by the Isleta reach, with the San Acacia reach having the greatest probability of meeting the target across all strategies (Fig. 17). Only strategy *ISC.6* (which maintained summer flows at 425 cfs) was predicted to have a probability greater than 0.75 of meeting the management target in all reaches across all drying severity scenarios.

The relative performance of example alternative strategies submitted for the 2021 forecast hydrograph highlights the importance of limiting drying during summer low flow periods in this low water year. The decidedly best performing strategy (*ISC.6*) supplemented flows throughout the summer to maintain relatively high flows and thus limit channel drying. All other strategies experienced substantial declines in their expected probabilities of meeting RGSM density targets in the high drying scenario. However, if summer drying can be limited, meeting the sustainable population target of 1 RGSM per 100m^2 is much more likely, though not guaranteed. The poor performance of strategies focusing only on spring high flows is likely due to the limited volumes of water being added or shifted across time in the submitted strategies. As our generalized simulations above highlight, very large volumes of water need to be added during low water years for the supplementation of spring flow to have a meaningful impact on expected probabilities of meeting RGSM management goals. The volumes of supplemental water examined in this example are unlikely to substantially increase the availability of the low velocity off-channel habitats that spring high flow supplementation is aiming to produce. While this analysis was not intended to provide specific management advice, the results are consistent with our generalized strategies analysis that, in low water years, managing flows to reduce the severity of summer drying is more beneficial than supplementing spring high flows.

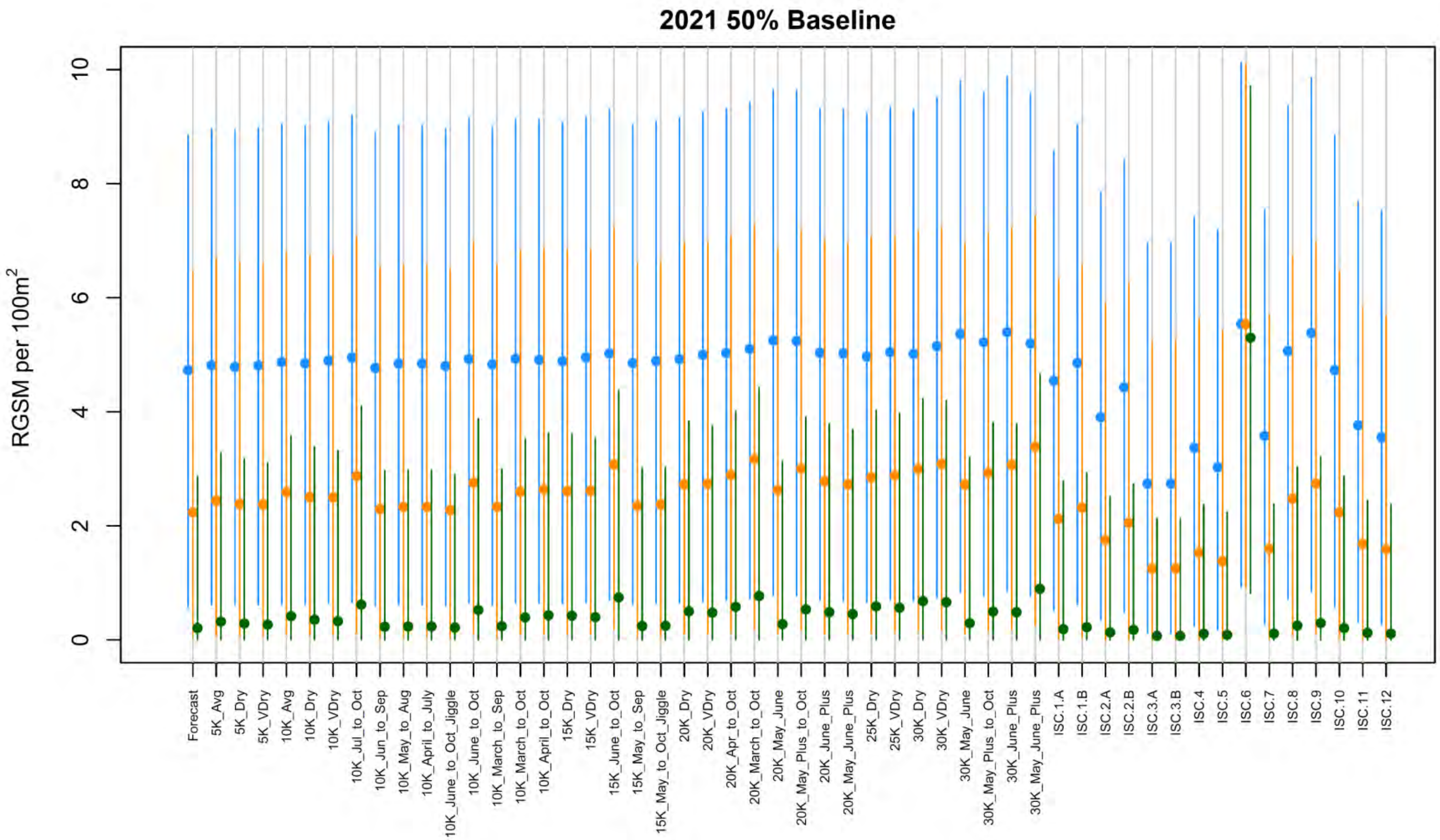

Figure 13. Predicted October RGSM CPUE in the MRG under alternative water management strategies for the 50% exceedance forecast for 2021. Points indicate the median CPUE estimates, while vertical bars indicate the 95% simulation intervals. Blue points indicate predicted CPUE under 10th percentile river drying given forecast summer discharge, orange indicates expected CPUE under median expected drying extent, and green indicates expected CPUE under 90th percentile drying given summer discharge.

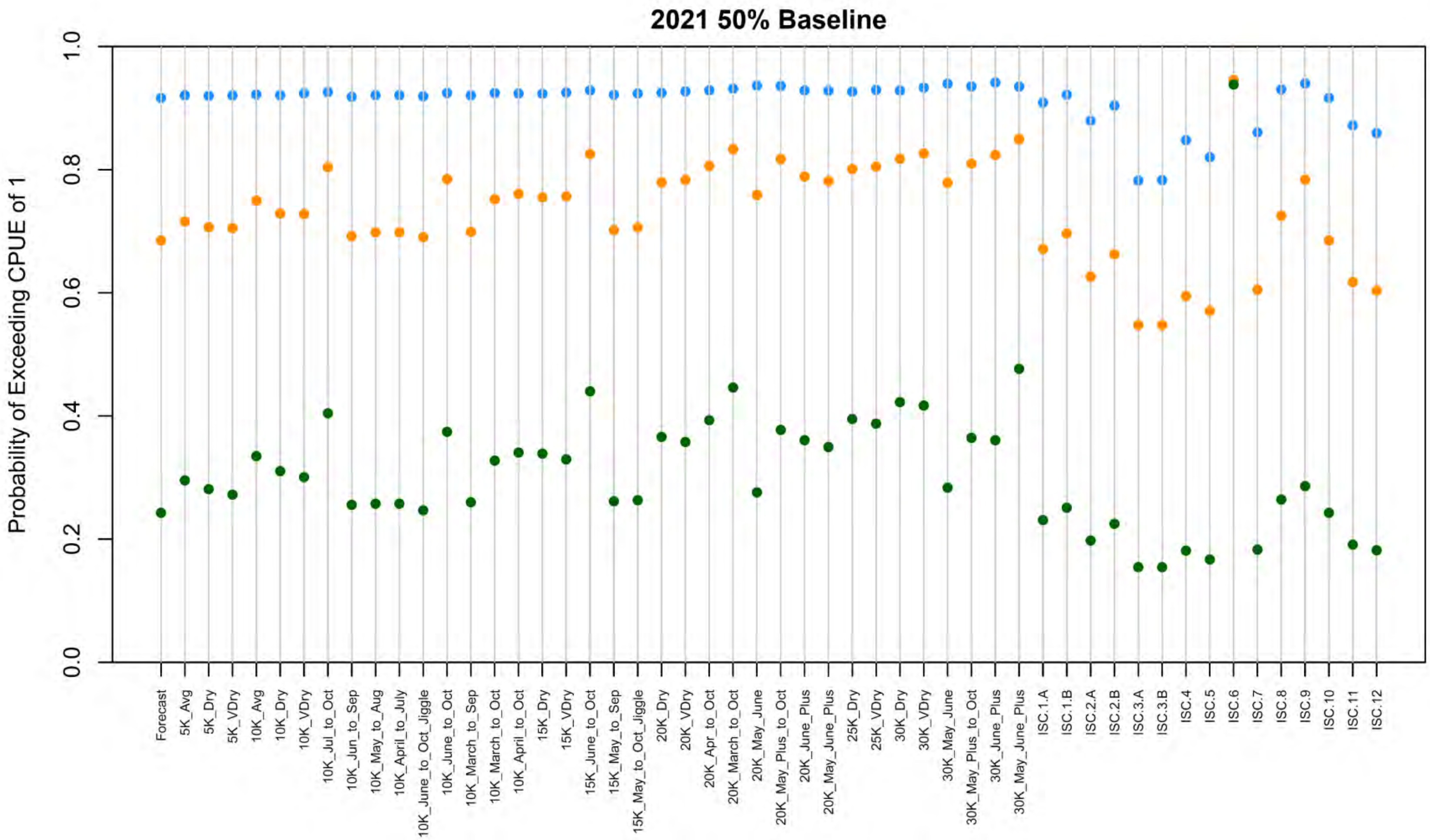

Figure 14. Predicted probability of October RGSM CPUE exceeding the management target of 1 RGSM per 100m^2 under different alternative water management strategies applied to the 50% exceedance forecast for 2021. Blue points indicate the probability of exceeding the management target under 10th percentile (lower than expected) river drying given forecast summer discharge, orange indicates indicate the probability of exceeding the management target under median expected drying extent, and green indicates indicate the probability of exceeding the management target under 90th percentile (higher than expected) drying given summer discharge.

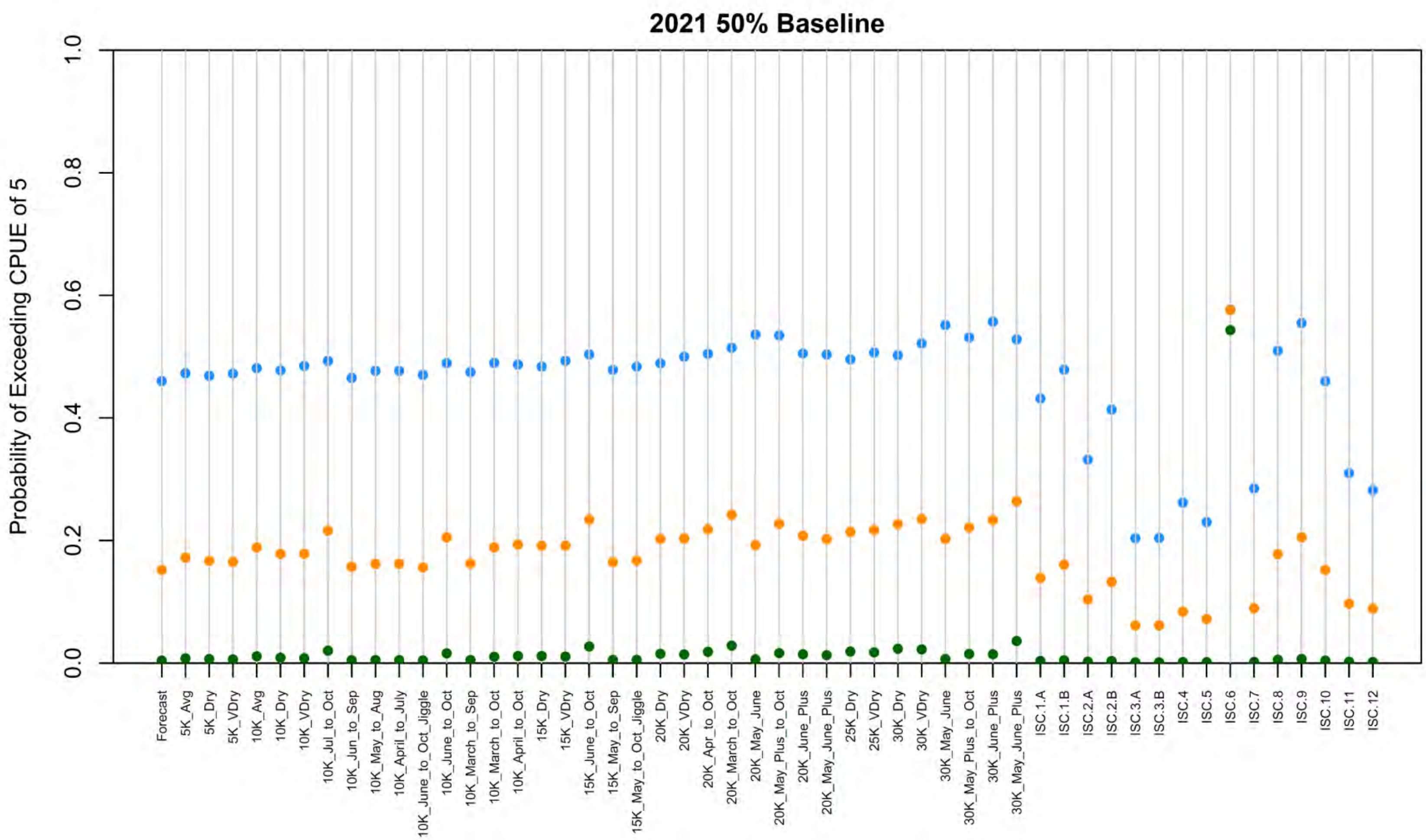

Figure 15. Predicted probability of October RGSM CPUE exceeding the down-listing target of 5 RGSM per 100m^2 under different alternative water management strategies applied to the 50% exceedance forecast for 2021. Blue points indicate the probability of exceeding the down-listing target under 10th percentile (lower than expected) river drying given forecast summer discharge, orange indicates indicate the probability of exceeding the down-listing target under median expected drying extent, and green indicates indicate the probability of exceeding the down-listing target under 90th percentile (higher than expected) drying given summer discharge.

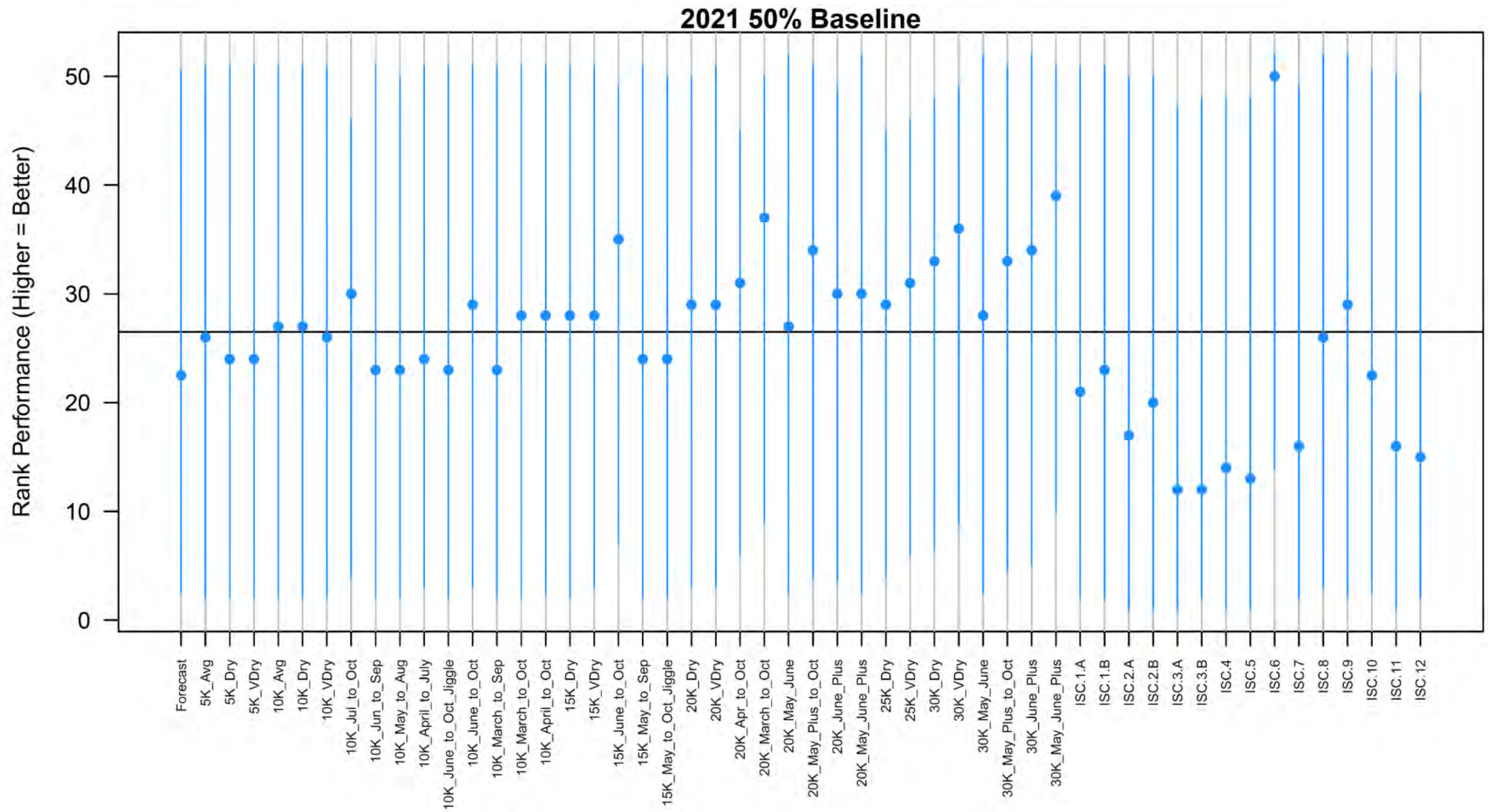

Figure 16. Rank performance of alternative water management strategies applied to the 50% exceedance forecast hydrograph for 2021. Points indicate the median rank performance of a strategy across all simulations, while the vertical bars indicate the 95% simulation interval of rank performance.

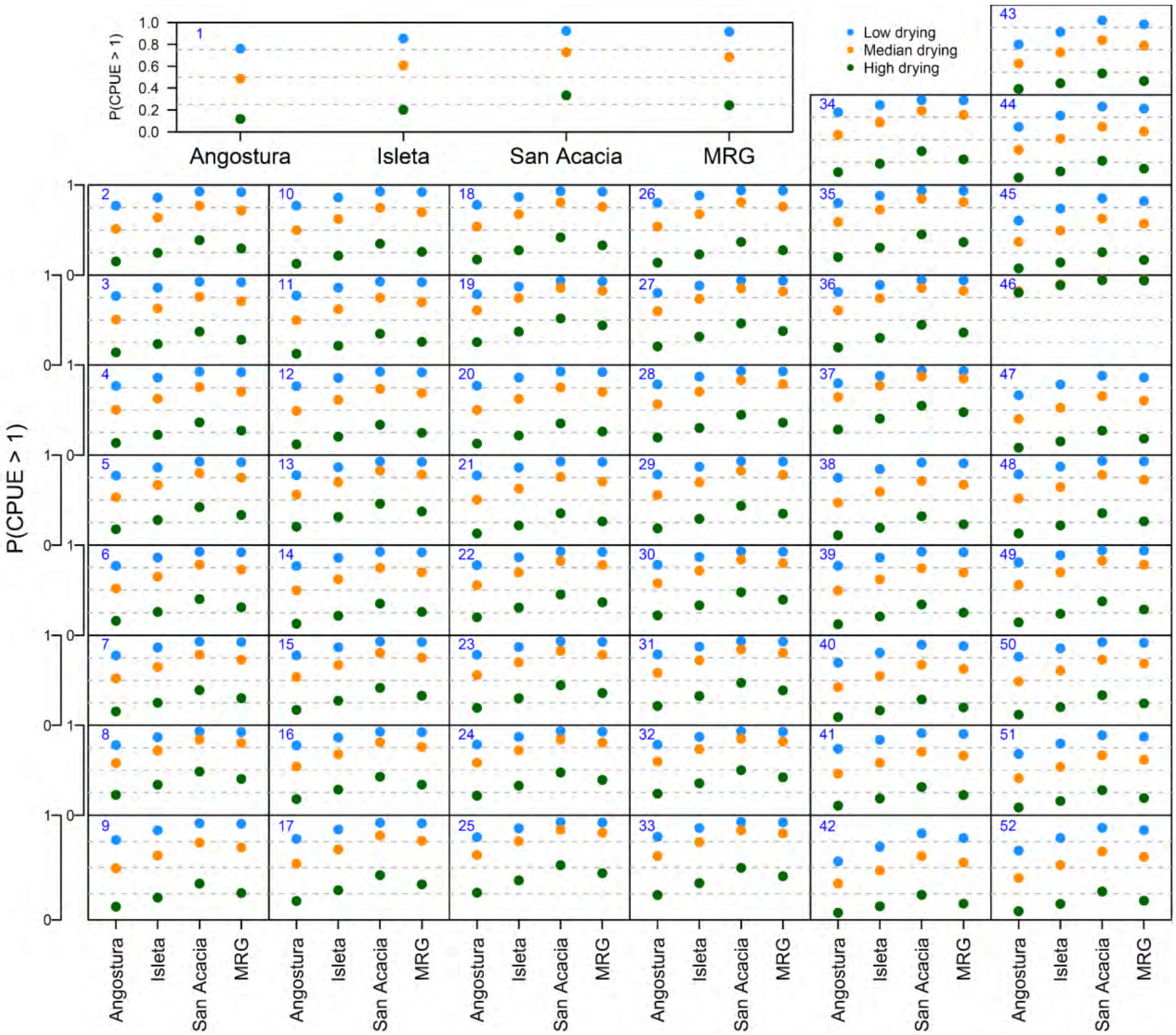

Figure 17. Reach-specific probabilities of meeting management target of 1 RGSM per 100m^2 for each alternative flow management strategy submitted for the 2021 forecast hydrograph (50% exceedance scenario). Blue points indicate probability of meeting management targets in low drying scenarios, orange points indicate probability of meeting management targets in median drying scenarios, and green dots indicate probability of meeting management targets in high drying scenarios. Numbers in upper left corner of each panel indicate the strategy ID number indicated in Table 3.

Conclusions

Decision making for natural resource management is a continual challenge, as ecosystems are highly complex, can be non-stationary, and generally involve great uncertainty regarding the relationships driving ecological changes (Walters 1986; Allen et al. 2011). Simulation models based on empirical relationships provide a means to rapidly assess the expected performance of multiple competing hypothetical management strategies and inform managers which strategy is most likely to provide desired results given what is currently known about the system and given management options available or potentially available in the future (Sainsbury et al. 2011; Smith et al. 2013). Simulation models can be used to generate short-term, tactical advice, such as our case study examining alternative approaches to managing the 2021 forecast hydrograph, as well as to explore alternative long-term, strategic management plans, such as our single-year and multi-year analyses of randomized hydrographs. Critically, alternative management approaches that may currently be infeasible due to available infrastructure or policy constraints can be examined in simulations, as has been done herein, thus informing whether long-term infrastructure development or policy changes may be worthwhile pursuits. Our simulation analyses identify three major results regarding managing flows to meet RGSM management targets; limiting summer drying extent is critical to meeting management targets in low water years, supplementing only spring high flow periods has limited benefits unless large volumes of water can be added, and the ability to manage water across multiple years greatly improves management success rates. Importantly, it should be recognized that the management targets examined herein are likely not representative of a fully recovered population that would no longer require conservation interventions, and that much larger-scale actions than those considered here would be necessary to achieve full recovery.

The importance of flow conditions to RGSM population dynamics has long been understood (Bestgen and Platania 1991; Dudley and Platania 2007), though the relative benefit of large spring high flows as opposed to higher summer minimum flows has been difficult to tease apart (Walsworth and Budy 2020, 2021). High spring flows can connect the main channel to the floodplain and off-channel habitats which are considered critical low velocity rearing habitats that both provide productive growing conditions (Pease et al. 2006; Medley and Shirey 2013; Valdez et al. 2019), as well as limit downstream transport of eggs and developing larvae (Dudley and Platania 2007; Widmer et al. 2010). Extensive channel drying in the summer can lead to stranding of RGSM in isolated pools (Archdeacon 2016; Archdeacon and Reale 2020), which will eventually desiccate unless flows resume due to monsoon rains or increased water releases through dams and diversions. However, years with large spring high flows typically also have greater summer flow minima, challenging our ability to determine which season's flows are most critical to the RGSM population (Walsworth and Budy 2020, 2021). Yet, our simulation analyses reveal that limiting the extent of channel drying that occurs during summer months was more beneficial for meeting management targets than increasing spring high flows during low water years. For the 2021 forecast hydrograph case study, scenarios with extensive summer drying had low probabilities of meeting management targets for nearly all management strategies explored, while the same management strategies with less drying were predicted to much higher chances of meeting these targets. Indeed, the top performing strategy supplemented flows throughout the summer, limiting expected channel drying even in the high drying scenarios. In the multi-year simulation analysis, 15 of the top 20 alternative flow management strategies included supplementing flows during summer in low water years. While some of the factors driving interannual variation in the extent of drying during summer low flow conditions are not immediately controllable (e.g., frequency and intensity of monsoon rains, geomorphic changes), reduced water withdrawals or larger releases from upstream reservoirs at strategic times could maintain greater flows in the channel and reduce the extent of channel drying in the MRG. Our drying threshold analysis indicates that the probability of achieving CPUE targets declines rapidly with small increases in either the spatial extent of drying or the duration of drying conditions (or both). Conversely, this also indicates that management actions able to reduce either drying extent or duration even modestly may have substantial conservation benefits for the RGSM. These results can inform manager and stakeholder decisions as they determine how to balance the needs of off-stream water users and the MRG ecosystem. Importantly, while drying in the MRG has occurred during low water years over the past century (Miller 1961), it should be expected that low water years will become increasingly prevalent as winter snowpack is reduced with changing precipitation patterns and evaporation and transpiration rates increase with increasing temperatures (Hurd and Coonrod 2012). Thus, the challenges of limiting summer flows will only become increasingly important and determining management approaches that can reduce the extent of channel drying during low flow periods will be critical to the persistence and conservation of the RGSM in the MRG.

Spring high flows connecting the main channel of the MRG to the floodplain and low velocity off-channel habitats provide important rearing habitats for larval and juvenile RGSM (Pease et al. 2006; Medley and Shirey 2013; Valdez et al. 2019). Additionally, these low velocity habitats available when flows reach the floodplain retain pelagic larvae within reaches of the MRG, limiting displacement and loss into downstream reaches or Elephant Butte Reservoir (Dudley and Platania 2007; Widmer et al. 2010). However, spring high flow events that are insufficient to reach the floodplain can increase downstream displacement of larvae and do not provide the extensive low velocity off-channel habitats required for production of large year cohorts. Thus, increasing flows in during spring high flow months should be expected to have limited benefits for the RGSM population until discharges sufficient to overflow banks and create off-channel habitats are achieved. Our analyses support this effect, as adding discretionary water to spring high flow periods during low water years had minimal impact until very large volumes of water were available, particularly in high summer drying scenarios. Currently, managers have approximately 15,000 AF of discretionary water available for supplementing flows to benefit RGSM throughout the year. Our results indicate that using these flows during spring high flow periods in low water years is unlikely to have substantial benefits RGSM populations. However, in years during which the addition of relatively small amounts of water would be sufficient to inundate floodplain habitats, the current discretionary water amounts may increase the availability and persistence of off-channel rearing habitats. Indeed, those strategies incorporating the supplementation of spring high flows were most beneficial in medium water years. Still, our generalized single year analyses suggest that, in low water years when management has the greatest impact, using smaller (<30,000 AF) amounts of discretionary water to supplement summer low flows is generally more beneficial than supplementing spring high flows. This finding likely represents a tradeoff between limiting extensive mortality events due to summer drying versus slightly increasing recruitment success when small volumes of discretionary water are added to spring high flow periods. Unless additional floodplain inundation is extensive, reducing mortality due to summer channel drying is likely to have a more substantial impact on the population. Similarly, small increases in recruitment become a moot point if extensive drying drives high mortality rates that following summer. We caution that these results should not be interpreted as indicating that summer low flow conditions are more important than spring high flow conditions for RGSM populations, but rather that the ability to meaningfully impact summer low flow conditions in low water years is greater than the ability to meaningfully impact spring high flows with the lower volumes of discretionary water explored in this analysis. Further, while the higher volumes of discretionary water availability examined here are currently not realistic, the results of these analyses are informative regarding the relative scale of flow manipulation that may be required to achieve meaningful impacts on the RGSM population.

One approach that may be able to mitigate the effect of low water years on RGSM population dynamics is to store water during high water years and use it to supplement flows during subsequent low or medium water years. In our multi-year simulation analyses, those strategies which moved water across years consistently and substantially outperformed those strategies only managing flows within a single year. In low water years, managers' ability to move flows among different months or seasons is more limited, as there is less water to store for later release, yet it is precisely these low water years in which management decisions are most important to RGSM productivity and survival. By storing water during high flow periods in high water years and releasing it in low water years, across-year management can either increase rearing habitat availability in spring high flow months or maintain habitat availability and connectivity during summer low flow months. These actions may be able to dampen the negative population effects of low water years on RGSM populations, increasing the probability that management targets are met. Additionally, storing water during high water years for conservation actions during low water years may reduce conflicts over how water is used during low water years. Stored water could provide supplemental water for RGSM management while not impacting the ability of off-stream water users to use native flows. While adopting multi-year management approaches may face substantial logistical, legal, and social hurdles, the consistent superior performance of approaches moving water from high water years to low water years may warrant the start of discussions among stakeholders and policymakers about whether multi-year management is something they wish to pursue.

When considering the results presented here, it is important to recognize that not all the alternative flow management strategies examined would be legally or logistically possible to implement currently. For example, the Rio Grande Compact prohibits the storage of native water in years when the combined storage of Caballo and Elephant Butte reservoirs is less than 400,000 AF. While our simulation model does not explicitly account for the constraints presented by standing water agreements, users can account for these requirements in when designing the alternative hydrographs they wish to compare for specific forecast hydrographs. Additionally, the ability to examine strategies which are not currently feasible or legal in a simulation framework can inform managers and stakeholders whether there are policy or infrastructure changes that may be worth discussing to benefit RGSM conservation.

The model underlying the simulations is based on empirical relationships between observed hydrologic conditions and RGSM densities (Walsworth and Budy 2020, 2021). These results are informed by the data observed in the river from 1993-2019 and are thus limited by the range of conditions experienced during that time. By extrapolating to novel conditions, our expectations of how the RGSM population will respond becomes increasingly uncertain. However, the relative performance of different the different flow management strategies is representative of how we would expect the system to respond given historic observations and dynamics. As such, these results will be most useful when interpreted in a relative fashion. Specifically, examining which water management strategy (or strategies) performs better than the other strategies across many simulations is more appropriate than concentrating on the exact predicted probabilities of meeting management targets for each strategy - a concept true for most population viability analyses.

While we base our conclusions on simulations of the dynamics of a complex natural population, the ability of the underlying model to reproduce historic RGSM catch rates within the three reaches of the MRG (Walsworth and Budy 2020, 2021) suggests that the broad patterns identified in the modeling are robust to most of the mechanistic uncertainty that remains. Given the great reduction in range and abundance of RGSM and their short life histories (Pflieger 1980; Bestgen and Platania 1991), it is critical that effective management strategies are identified quickly. The simulation models examined herein provide a valuable starting point for informing water management discussions in both the short- and long-term. Using the simulation model (potentially in conjunction with alternative mechanistic models) in an adaptive management framework (Walters 1986), wherein simulations are used to compare broad management strategies, can inform water management and help prioritize adaptive management experiments. Critically, each of the underlying empirical model, simulation model, and management actions should be regularly updated as more data are collected. Such an approach can provide a path forward informed by our best understanding of the conditions driving observed RGSM population dynamics.

Acknowledgements

This work was funded by the U.S. Bureau of Reclamation Upper Colorado Basin - Albuquerque Area Office and the U.S. Geological Survey – Utah Cooperative Fish and Wildlife Research Unit (in-kind). We thank Ashlee Rudolph and Mark McKinstry for project logistical support. We thank Steve Platania, Robert Dudley, and American Southwest Ichthyological Researchers for collecting and providing the Rio Grande Silvery Minnow catch data used in the model underlying these simulations. We thank Ashlee Rudolph, Joel Lusk, Jennifer Bachus, Eric Gonzalez, Caroline Donnelly, Rich Valdez, Kevin McDonnell, Charles Yackulic, Thomas Archdeacon, Mickey Porter, and all attendees of the January 2021 simulation model workshop for their valuable feedback on the simulation model structure and interface. We thank the Department of Watershed Sciences and the Ecology Center at Utah State University for administrative assistance. No new animal data were collected as part of this study

Code Availability

Simulation model code for comparing alternative management strategies is available in Appendix A.

References

Allen, C.R., Fontaine, J.J., Pope, K.L. and Garmestani, A.S. 2011. Adaptive management for a turbulent future. *Journal of Environmental Management*, 92(5): 1339-1345.

Archdeacon, T.P. 2016. Reduction in spring flow threatens Rio Grande Silvery Minnow: trends in abundance during river intermittency. *Transactions of the American Fisheries Society,* 145:754–765.

Archdeacon, T.P. and Reale, J.K. 2020. No quarter: Lack of refuge during flow intermittency results in catastrophic mortality of an imperiled minnow. *Freshwater Biology,* 65(12): 2108-2123.

Archdeacon, T.P., Diver-Franssen, T.A., Bertrand, N.G. and Grant, J.D. 2020. Drought results in recruitment failure of Rio Grande silvery minnow (Hybognathus amarus), an imperiled, pelagic broadcast-spawning minnow. *Environmental Biology of Fishes,* 103(9): 1033-1044.

Blythe, T.L., and Schmidt, J.C. 2018. Estimating the natural flow regime of rivers with long- standing development: The Northern branch of the Rio Grande. *Water Resources Research,* 54: 1212–1236.

Bestgen, K.R., and Platania, S.P. 1990. Extirpation of Notropis simus simus (Cope) and Notropis orca (Pisces: Cyprinidae) from the Rio Grande in New Mexico, with notes on their life history. *Occasional Papers the Museum of Southwestern Biology,* 6: 1–8.

Bestgen, K.R. and Platania, S.P. 1991. Status and conservation of the Rio Grande silvery minnow, *Hybognathus amarus*. *Southwestern Naturalist,* 36(2): 225-232.

Boroughs, C. 2013. User manual for the Upper Rio Grande Water Operations Model (URGWOM).Version 5.0.2. https://w3.spa.usace.army.mil/urgwom/documentation/URGWOM_UserManual_v5-0-2_Sept-2013_Final.pdf

Chen, W. and Olden, J.D. 2017. Designing flows to resolve human and environmental water needs in a dam-regulated river. *Nature Communications,* 8(1): 1-10.

Dudley, R. K., and Platania, S.P. 2007. Flow regulation and fragmentation imperil pelagic-spawning riverine fishes. *Ecological Applications*, 17: 2074–2086.

Dudley, R.K., Platania, S.P. and White, G.C. 2018. Rio Grande Silvery Minnow population monitoring during 2017. Report to the US Bureau of Reclamation, Albuquerque, New Mexico, USA.

Evans, M.C., Tulloch, A.I., Law, E.A., Raiter, K.G., Possingham, H.P. and Wilson, K.A. 2015. Clear consideration of costs, condition and conservation benefits yields better planning outcomes. *Biological Conservation*, 191: 716-727.

Göthe, E., Degerman, E., Sandin, L., Segersten, J., Tamario, C., and Mckie, B.G. 2019. Flow restoration and the impacts of multiple stressors on fish communities in regulated rivers. *Journal of Applied Ecology*, 56: 1687-1702.

Hurd, B.H. and Coonrod, J. 2012. Hydro-economic consequences of climate change in the upper Rio Grande. *Climate Research*, 53(2): 103-118.

Junk, W.J., Bayley, P.B. and Sparks, R.E. 1989. The flood pulse concept in river-floodplain systems. *Canadian Special Publication in Fisheries and Aquatic Sciences*, 106(1): 110-127.

Makar, P. W. and J. Aubuchon. 2012. Channel Changes on the Middle Rio Grande. Pages 2556-2569 in E. D. Loucks (Ed), World Environmental and Water Resources Congress 2012: Crossing Boundaries, American Society of Civil Engineers.

McKenna, C. 2019. 2019 RiverEyes Monitoring Report. Prepared for U.S. Bureau of Reclamation, Albuquerque Area Office. Prepared by GeoSystems Analysis, Inc., under Sub-Contract with AJAC Enterprises. Albuquerque, NM.

Medley, C.N. and Shirey, P.D. 2013. Review and reinterpretation of Rio Grande Silvery Minnow reproductive ecology using egg biology, life history, hydrology, and geomorphology information. *Ecohydrology*, 6(3): 491-505.

Miller, R.R. 1961. Man and the changing fish fauna of the American Southwest. *Papers of the Michigan Academy of Science, Arts, and Letters*, 46: 365-404.

Mills, K.E., Pershing, A.J., Sheehan, T.F. and Mountain, D. 2013. Climate and ecosystem linkages explain widespread declines in North American Atlantic salmon populations. *Global Change Biology*, 19(10): 3046-3061.

Minckley, W.L., and Deacon, J.E. 1991. Battle against extinction: native fish management in the American West. University of Arizona Press, Tucson, Arizona, USA.

Naiman, R.J., Latterell, J.J., Pettit, N.E. and Olden, J.D. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience*, 340(9-10): 629-643.

Olden, J.D. and Poff, N.L. 2005. Long-term trends of native and non-native fish faunas in the American Southwest. *Animal Biodiversity Conservation*, 28(1): 75-89.

Pease, A.A., Justine Davis, J., Edwards, M.S. and Turner, T.F. 2006. Habitat and resource use by larval and juvenile fishes in an arid-land river (Rio Grande, New Mexico). *Freshwater Biology*, 51(3): 475-486.

Pennock, C.A., Budy, P., Macfarlane, W.W., Breen, M.J., Jimenez, J., and Schmidt, J.C. 2021 Native fish need a natural flow regime. *Fisheries*, doi: 10.1002/fsh.10703

Pflieger, W.L. 1980. Hybognathus nuchalis Agassiz, central silvery minnow. Atlas of North American Freshwater Fishes, 867.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. 1997. The natural flow regime. *BioScience*, 47(11): 769-784.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Sainsbury, K.J., Punt, A.E. and Smith, A.D., 2000. Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, 57(3): 731-741.

Smith, D.R., McGowan, C.P., Daily, J.P., Nichols, J.D., Sweka, J.A. and Lyons, J.E., 2013. Evaluating a multispecies adaptive management framework: must uncertainty impede effective decision-making? *Journal of Applied Ecology*, 50(6): 1431-1440.

Swanson, B.J., Meyer, G.A. and Coonrod, J.E. 2011. Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reductions and engineering: magnitude and uncertainty of change from air photo measurements. *Earth Surface Processes and Landforms*, 36(7): 885-900.

Tonkin, J.D., Olden, J.D., Merritt, D.M., Reynolds, L.V., Rogosch, J.S. and Lytle, D.A., 2020. Designing flow regimes to support entire river ecosystems. *Frontiers in Ecology and the Environment*, 19: 326-333.

Treviño-Robinson, D. 1959. The ichthyofauna of the Lower Rio Grande, Texas and Mexico. *Copeia*, 1959:253–256.

U.S. Fish and Wildlife Service. 2016. Final Biological and Conference Opinion for Bureau of Reclamation, Bureau of Indian Affairs and Non-Federal Water Management and Maintenance Activities on the Middle Rio Grande, New Mexico. Albuquerque, NM. December 2, 2016. pp. 1-192.

Valdez, R.A., Haggerty, G.M., Richard, K. and Klobucar, D. 2019. Managed spring runoff to improve nursery floodplain habitat for endangered Rio Grande Silvery Minnow. *Ecohydrology*, 12(7): e2134.

Walsh, J.C, Connors, K., Hertz, E., Kehoe, L., Martin, T.G., Connors, B., Bradford, M.J., Freshwater, C., Frid, A., Halverson, J., Moore, J.W., Price, M.H.H., and Reynolds, J.D. 2020. Prioritizing conservation actions for Pacific salmon in Canada. *Journal of Applied Ecology*, 57(9): 1688-1699.

Walsworth TE and Budy P. 2021. An empirically based simulation model to inform flow management for endangered species conservation. *Canadian Journal of Fisheries and Aquatic Sciences*, 78: 1770-1781.

Walsworth TE and Budy P. 2020. Hydrologic controls on abundance and distribution of the endangered Rio Grande Silvery Minnow in the Middle Rio Grande. Final report to the U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Basin Region, Albuquerque Area Office. https://webapps.usgs.gov/MRGESCP/documents/hydrologic-controls-on-abundance-and-distribution-of-the-endangered-rio-grande-silvery-minnow-in-the-middle-rio-grande

Walsworth, T.E. and Schindler, D.E. 2016. Long time horizon for adaptive management to reveal predation effects in a salmon fishery. *Ecological Applications*, 26(8): 2695-2707.

Walsworth, T.E., Schindler, D.E., Colton, M.A., Webster, M.S., Palumbi, S.R., Mumby, P.J., Essington, T.E. and Pinsky, M.L. 2019. Management for network diversity speeds evolutionary adaptation to climate change. *Nature Climate Change*, 9(8): 632-636.

Walters, C.J. 1986. Adaptive management of renewable resources. Macmillan Publishers Ltd. Basingstoke, UK.

Walters, C., Korman, J., Stevens, L.E. and Gold, B. 2000. Ecosystem modeling for evaluation of adaptive management policies in the Grand Canyon. *Ecology and Society*, 4(2): 1

Walters, C.J. and Hilborn, R. 1978. Ecological optimization and adaptive management. *Annual Review of Ecology and Systematics*, 9(1): 157-188.

Widmer, A.M., Fluder III, J.J., Kehmeier, J.W., Medley, C.N. and Valdez, R.A. 2012. Drift and retention of pelagic spawning minnow eggs in a regulated river. *River Research and Applications*, 28(2): 192-203.

Supplemental Materials

Supplemental Figures File: Figures for additional simulated scenarios, including the 70% exceedance forecast for 2021, and additional combinations of storage availability, proportional management, and discretionary water availability for the generalized hydrograph analyses.

Appendix A: A ZIP file containing the simulation model code, parameter files, scenario input files, and a getting started document for comparing alternative management strategies against a baseline hydrograph.

Supplemental Figures: Examining the effectiveness of alternative water management strategies to support Rio Grande Silvery Minnow conservation within and across years

Timothy E. Walsworth[1,2] and Phaedra Budy[3,1]

[1] *Department of Watershed Sciences, Utah State University, Logan, UT*

[2] *The Ecology Center, Utah State University, Logan, UT*

[3] *U.S. Geological Survey Utah Cooperative Fish and Wildlife Research Unit, Utah State University, Logan, UT*

Alternative Hydrographs for the 2021 Forecast 70% Exceedance Scenario

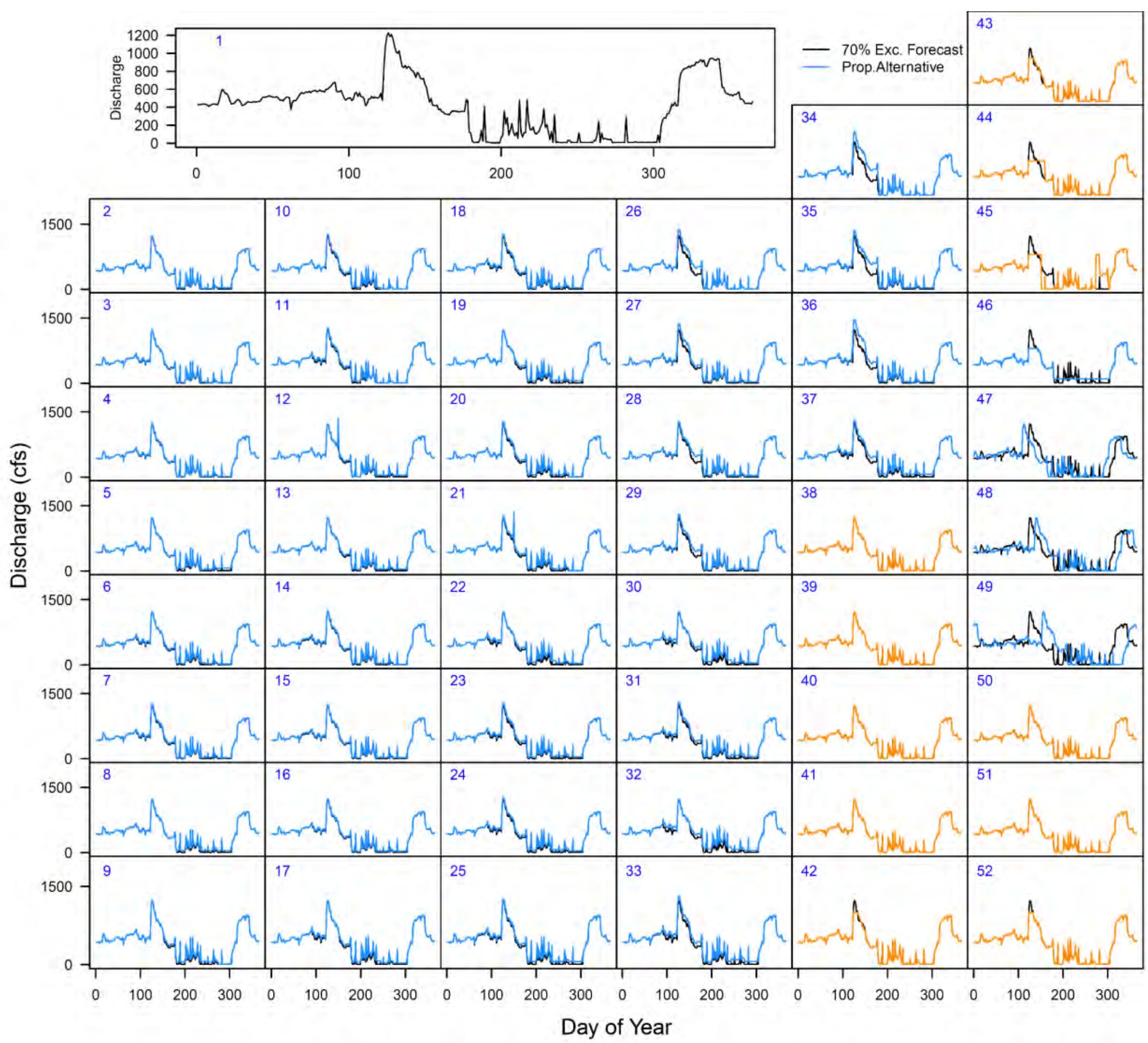

Figure S1. Forecast 2021 hydrograph for the 70% exceedance scenario (top panel with blue number 1 in top left), as well as the hydrographs proposed for exploration as alternative management actions submitted by stakeholders following the winter 2021 workshop. Each alternative hydrograph is identified by the blue number at the top left of each panel, whose descriptions can be found in Table 3. The blue lines represent the alternative hydrographs proposed while the black line represents the forecast hydrograph. Alternative hydrographs shown in orange were developed for the 50% hydrograph and likely do not achieve the same goals when enacted upon the 70% hydrograph.

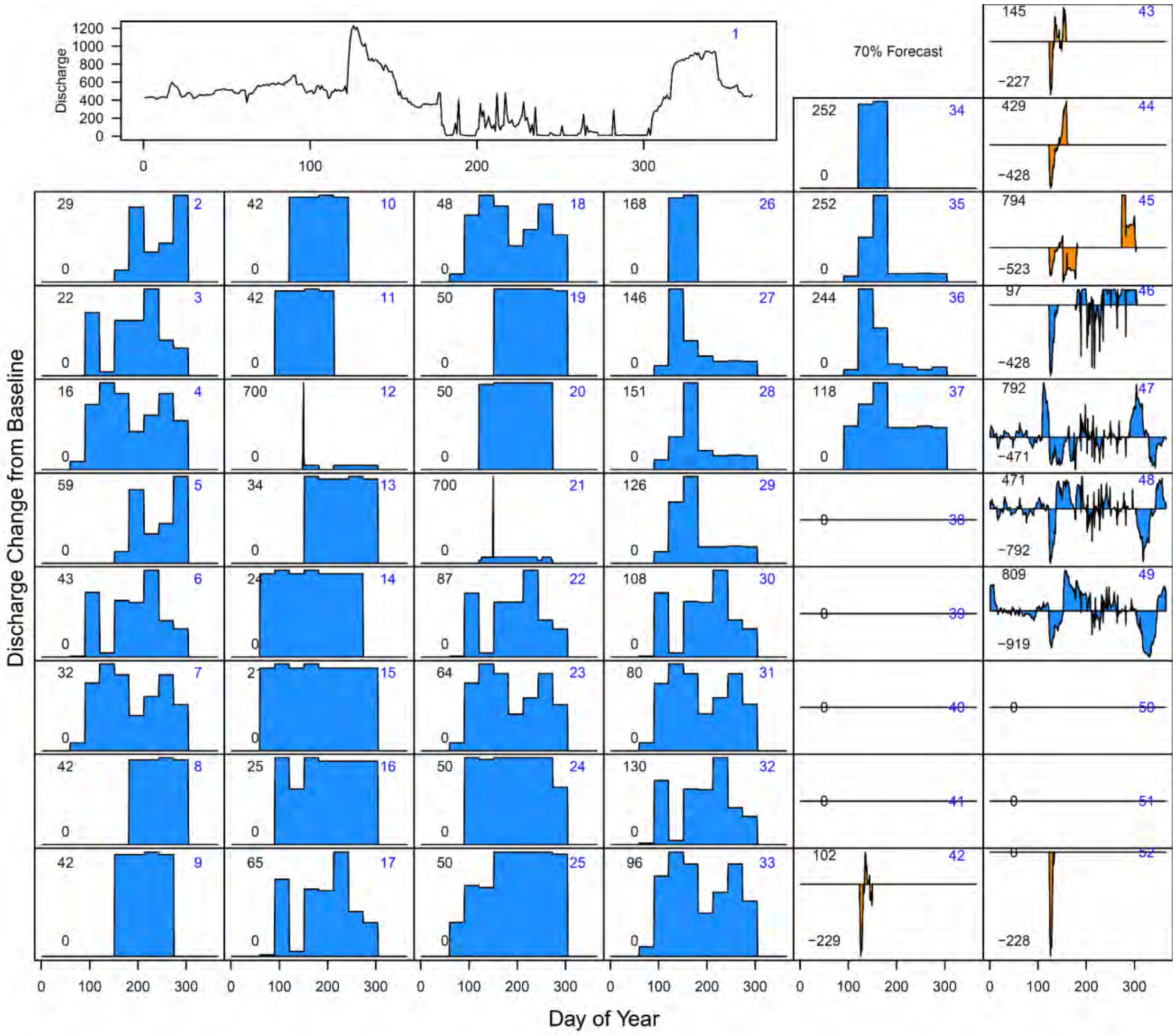

Figure S2. Forecast 2021 hydrograph for the 70% exceedance scenario (top panel with blue number 1 in top right), as well as deviations from the forecast for the different management actions submitted by stakeholders following the winter 2021 workshop. Each alternative hydrograph is identified by the blue number at the top right of each panel. The maximum and minimum deviations are indicated in black numbers on the left side of each panel. Deviations shown in orange were developed for the 50% hydrograph and likely do not achieve the same goals when enacted upon the 70% hydrograph. Blue numbers in the top right of each panel indicate the strategy ID number in Table 3 of the main document.

Single Year Generalized Strategy Simulations

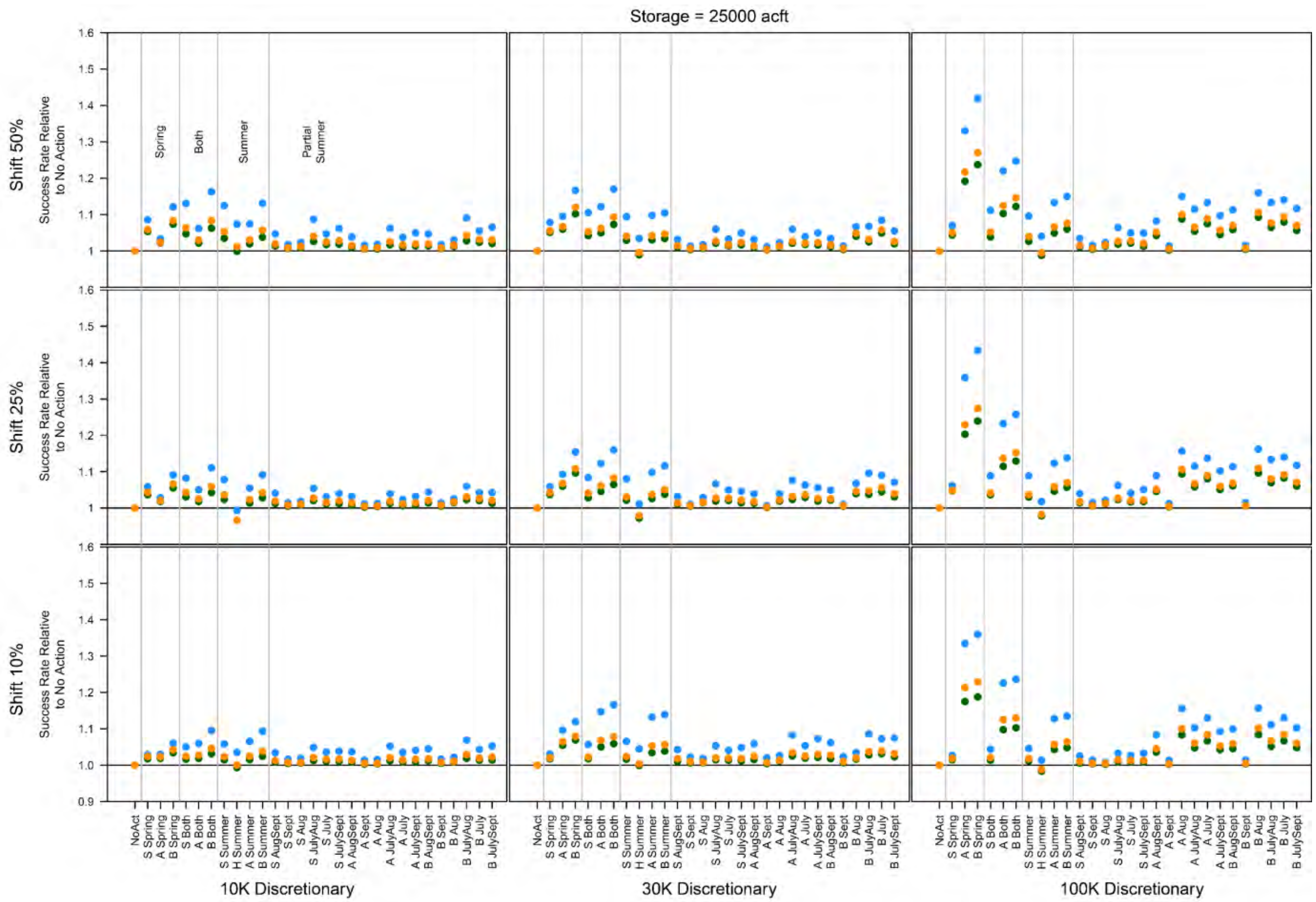

Figure S3. Success rates of alternative water management strategies relative to no action across different discretionary water availability (columns) and proportional management (rows) scenarios when 25,000 acft of temporary storage is available. Blue points represent relative performance in low water years, orange points represent medium water years, and green points represent high water years. Values of 1 indicate that the alternative management strategy does not improve the probability of successfully meeting management targets compared to taking no action. A value of 1.05 indicates that the probability of success for a management strategy is 5% greater than that of the no action strategy.

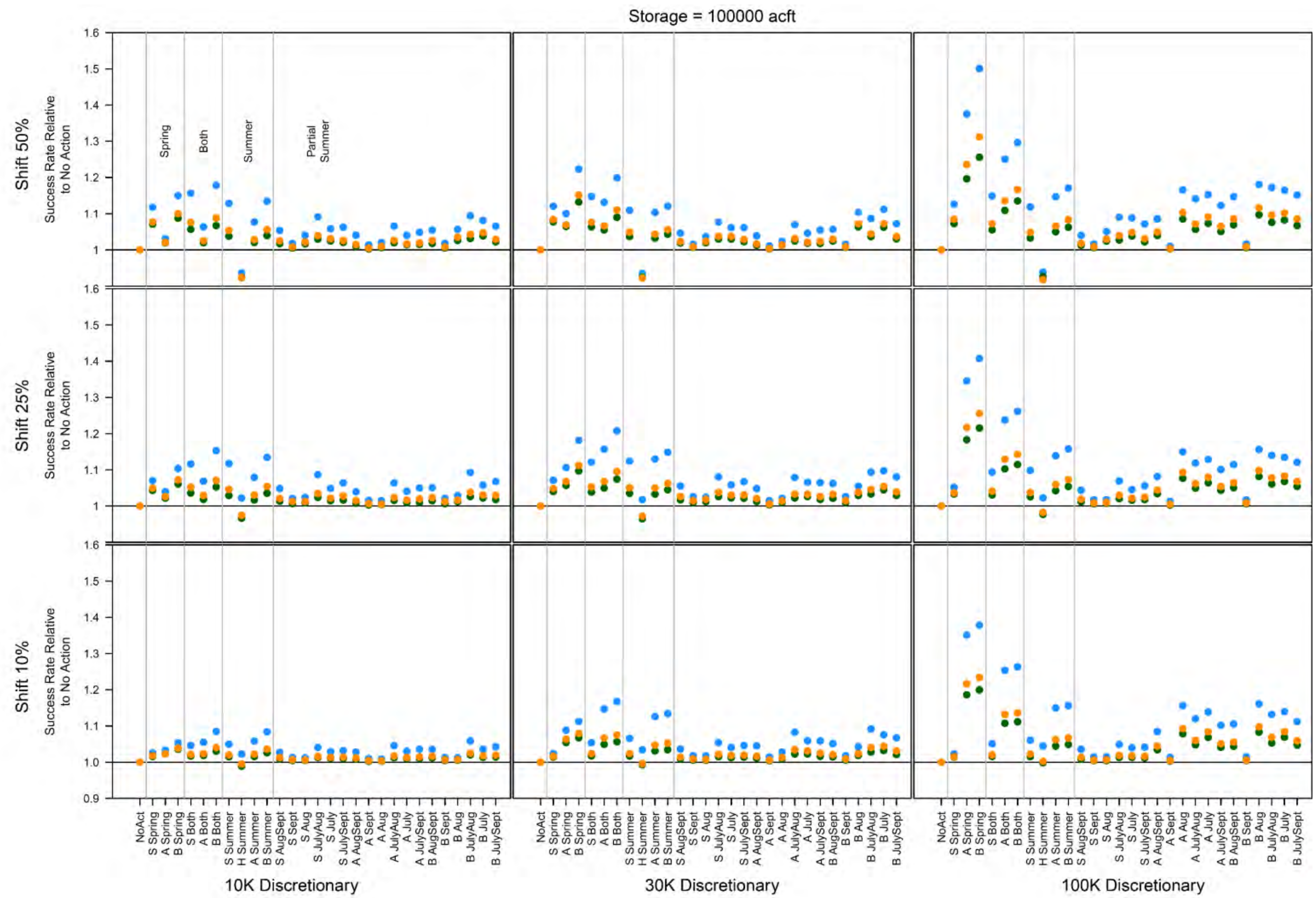

Figure S4. Success rates of alternative water management strategies relative to no action across different discretionary water availability (columns) and proportional management (rows) scenarios when 100,000 acft of temporary storage is available. Blue points represent relative performance in low water years, orange points represent medium water years, and green points represent high water years. Values of 1 indicate that the alternative management strategy does not improve the probability of successfully meeting management targets compared to taking no action. A value of 1.05 indicates that the probability of success for a management strategy is 5% greater than that of the no action strategy.

Multi-year Generalized Strategy Simulations

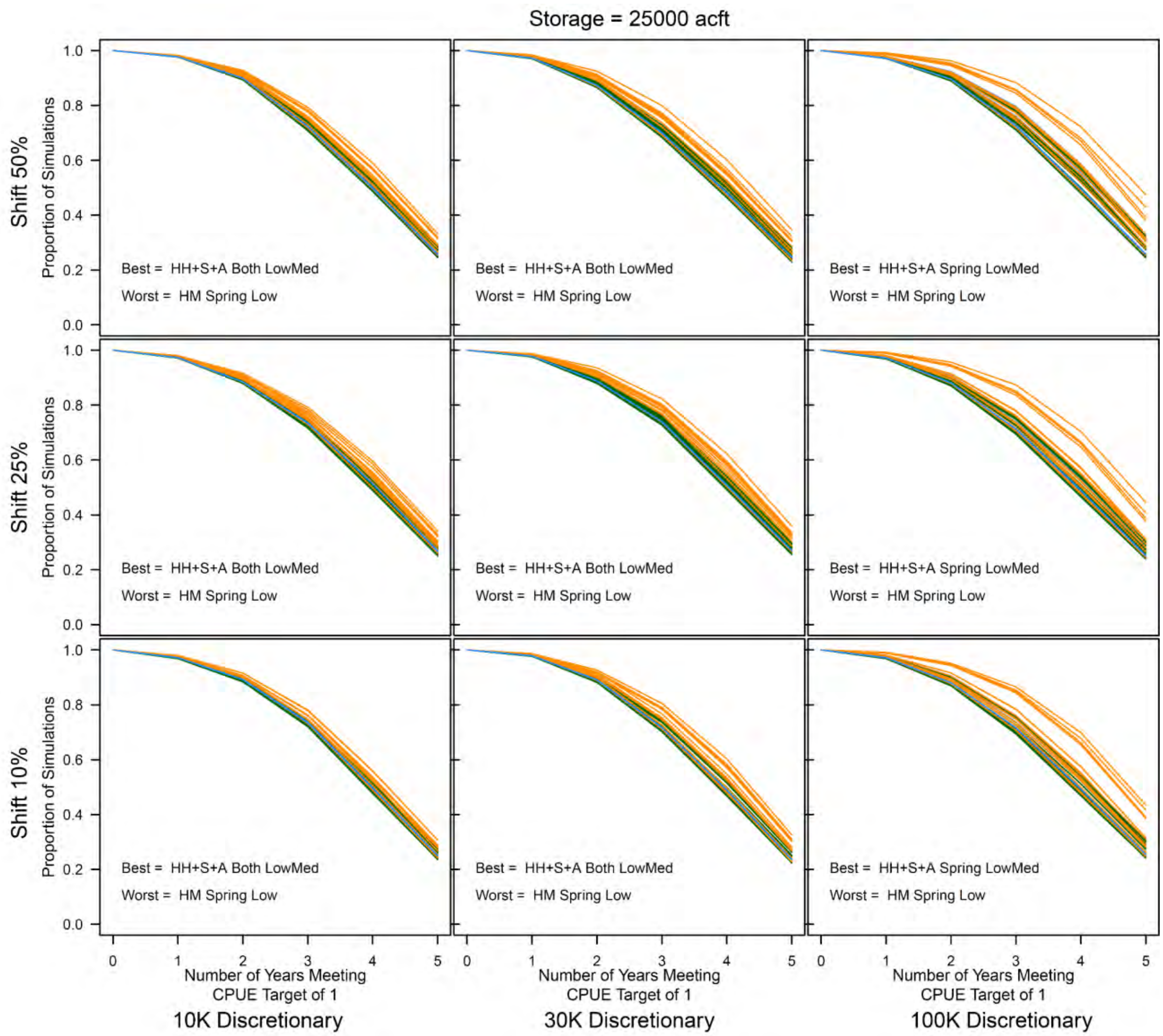

Figure S5. Proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per $100m^2$ successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 25,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

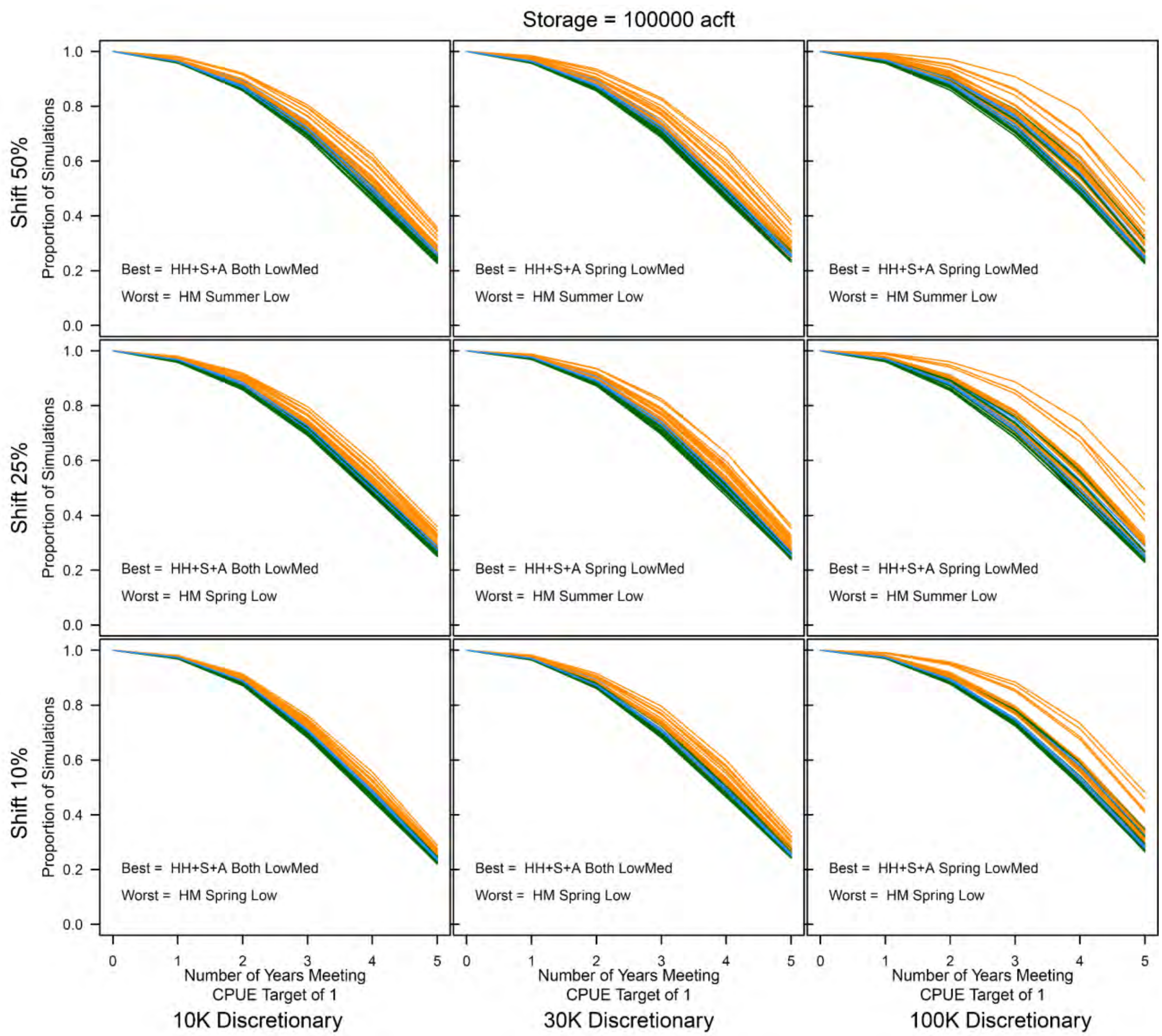

Figure S6. Proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per 100m^2 successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 100,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

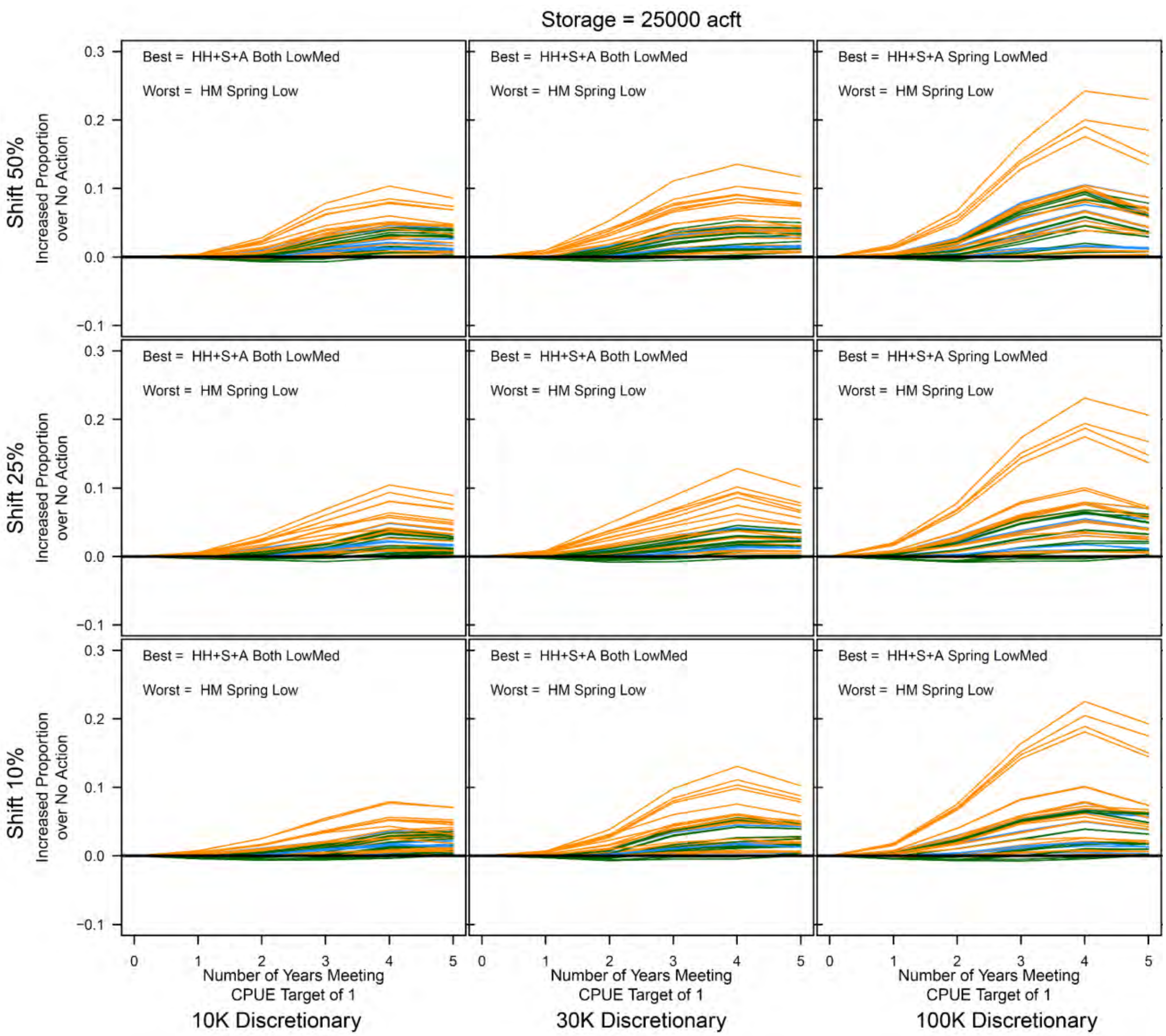

Figure S7. Change in the proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per 100m^2 successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 25,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

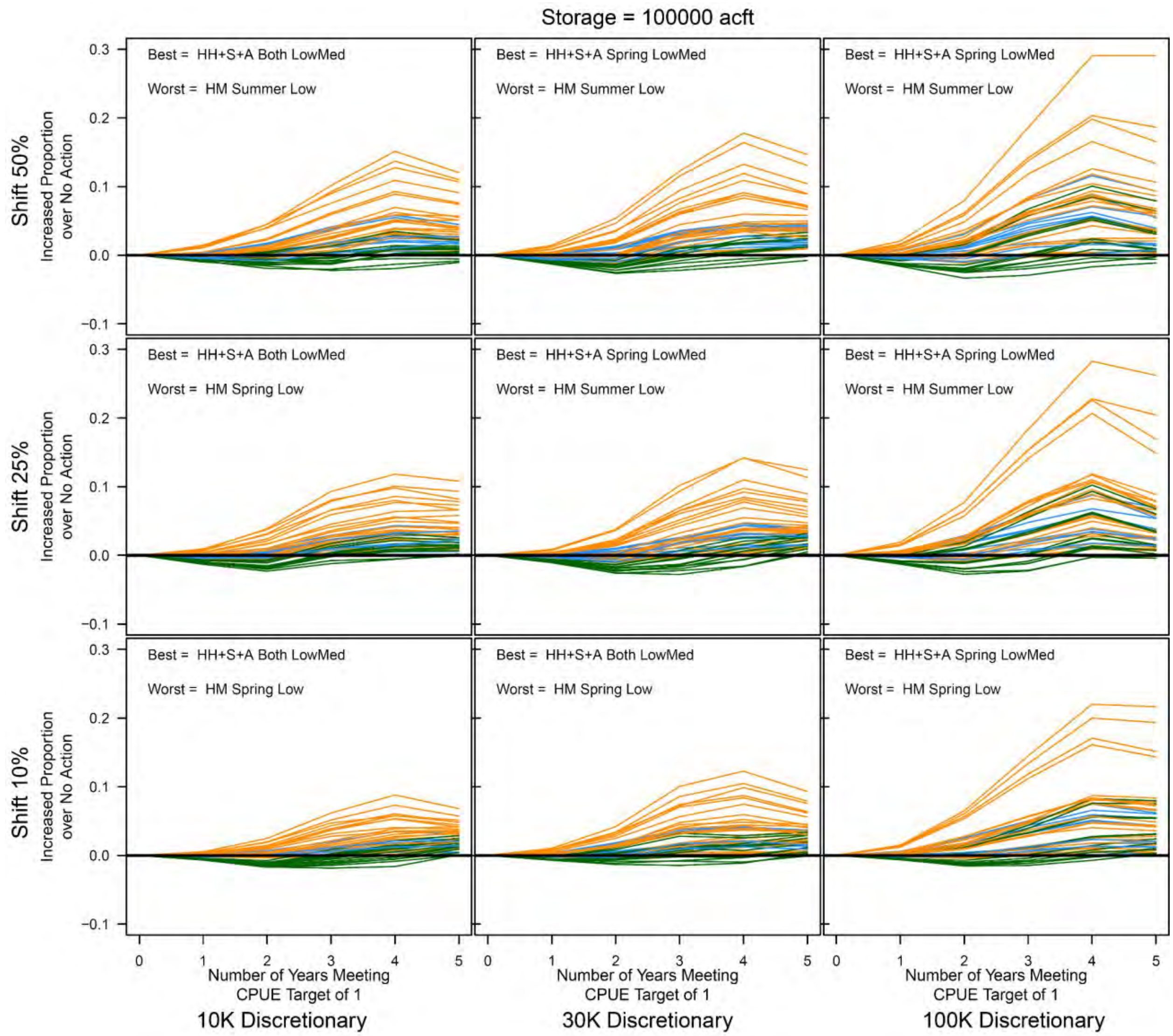

Figure S8. Change in the proportion of simulations in which at least a given number of years have the management goal of 1 RGSM per $100m^2$ successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 100,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

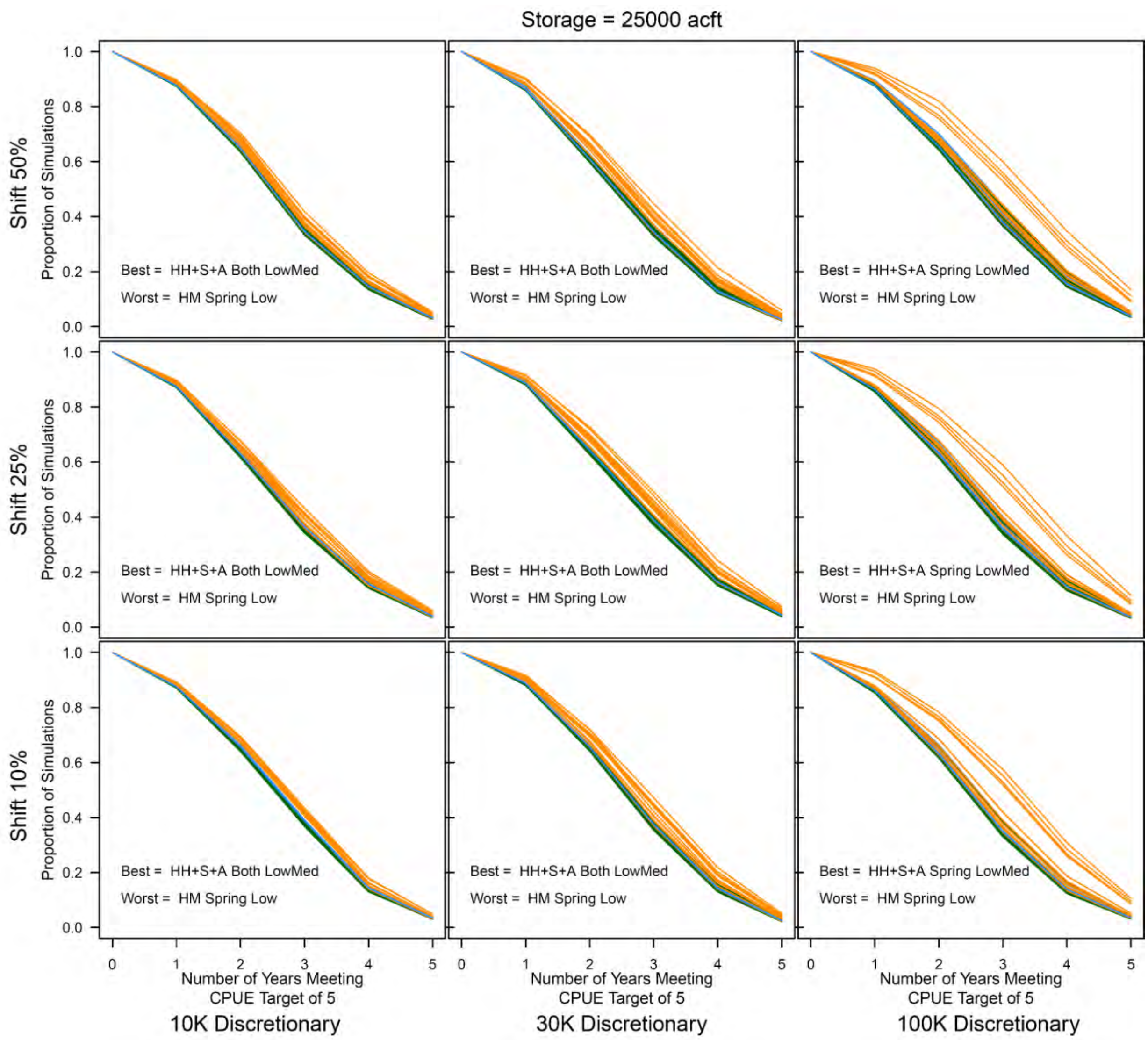

Figure S9. Proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per 100m^2 successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 25,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

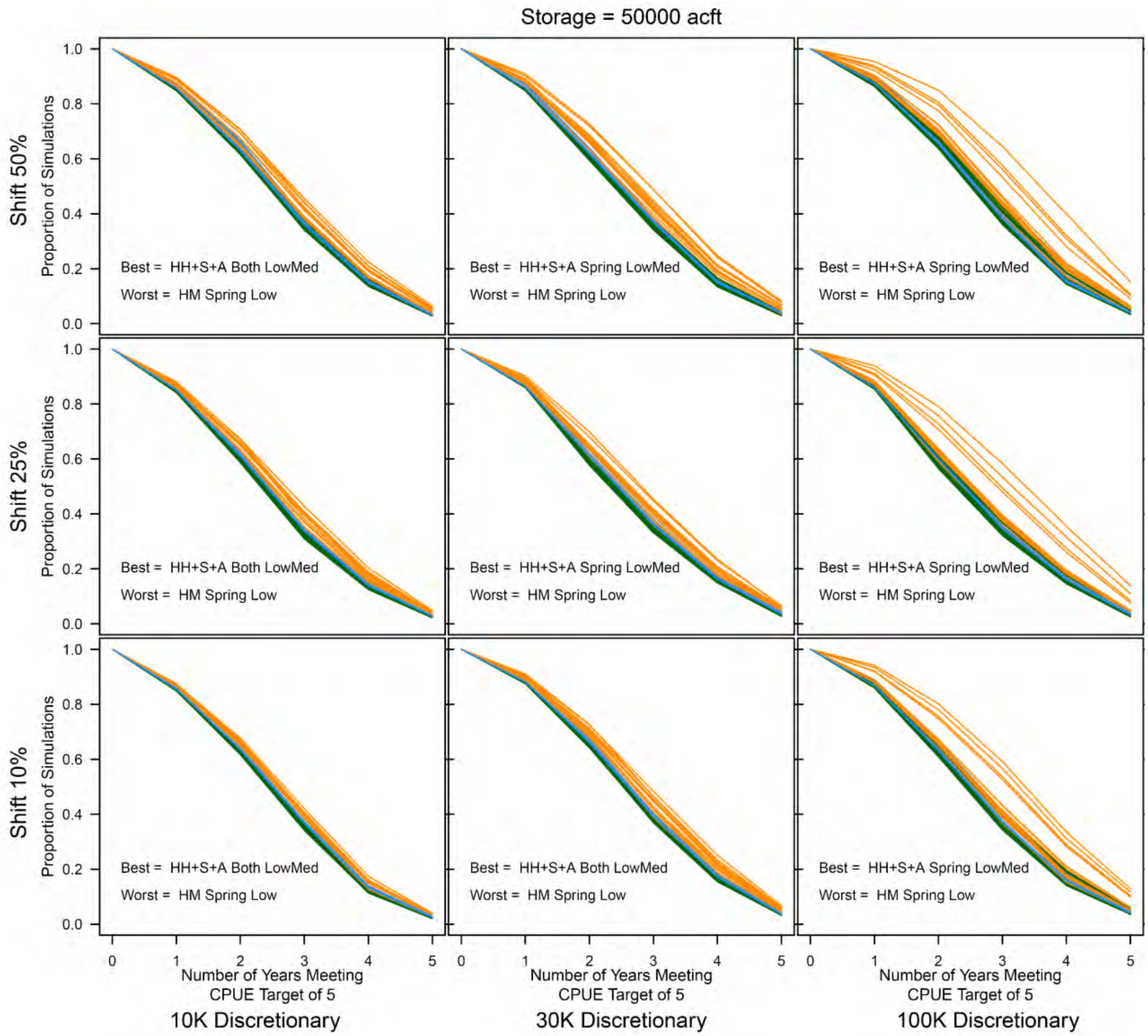

Figure S10. Proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per 100m^2 successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 50,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

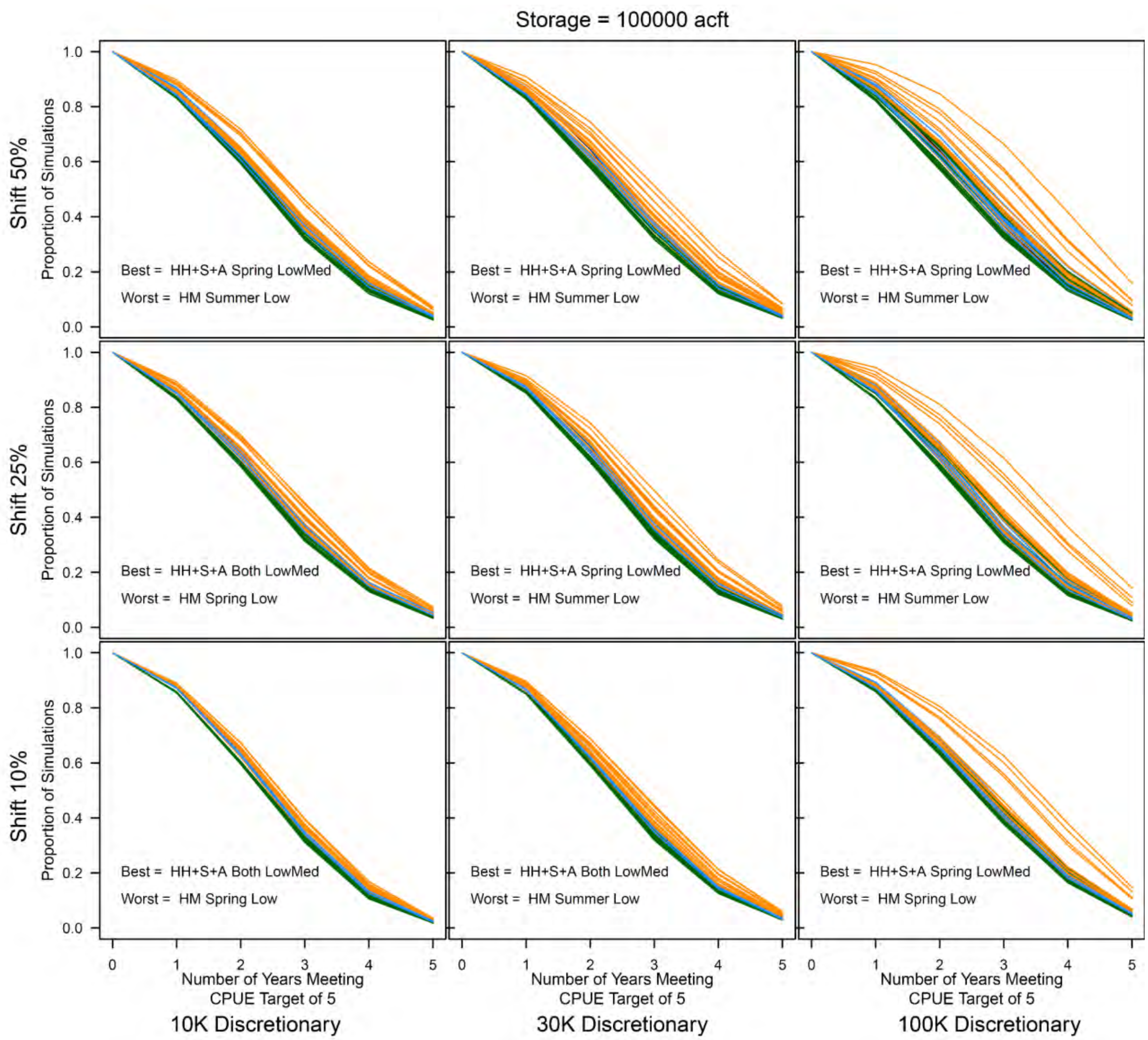

Figure S11. Proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per 100m^2 successfully met by different management strategies across different proportional management (rows) and discretionary water availability scenarios (columns) when 100,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

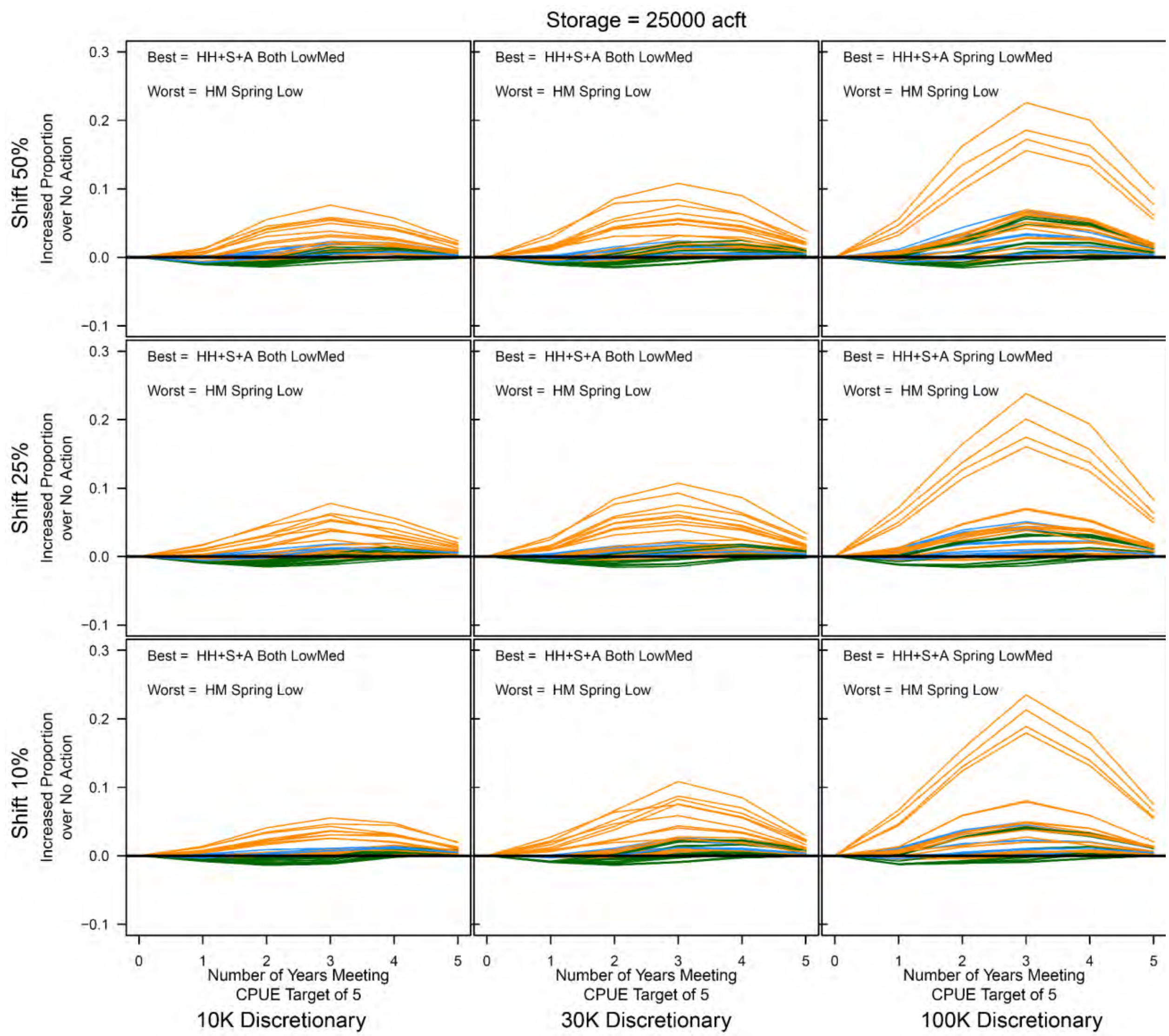

Figure S12. Change in the proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per 100m^2 successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 25,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

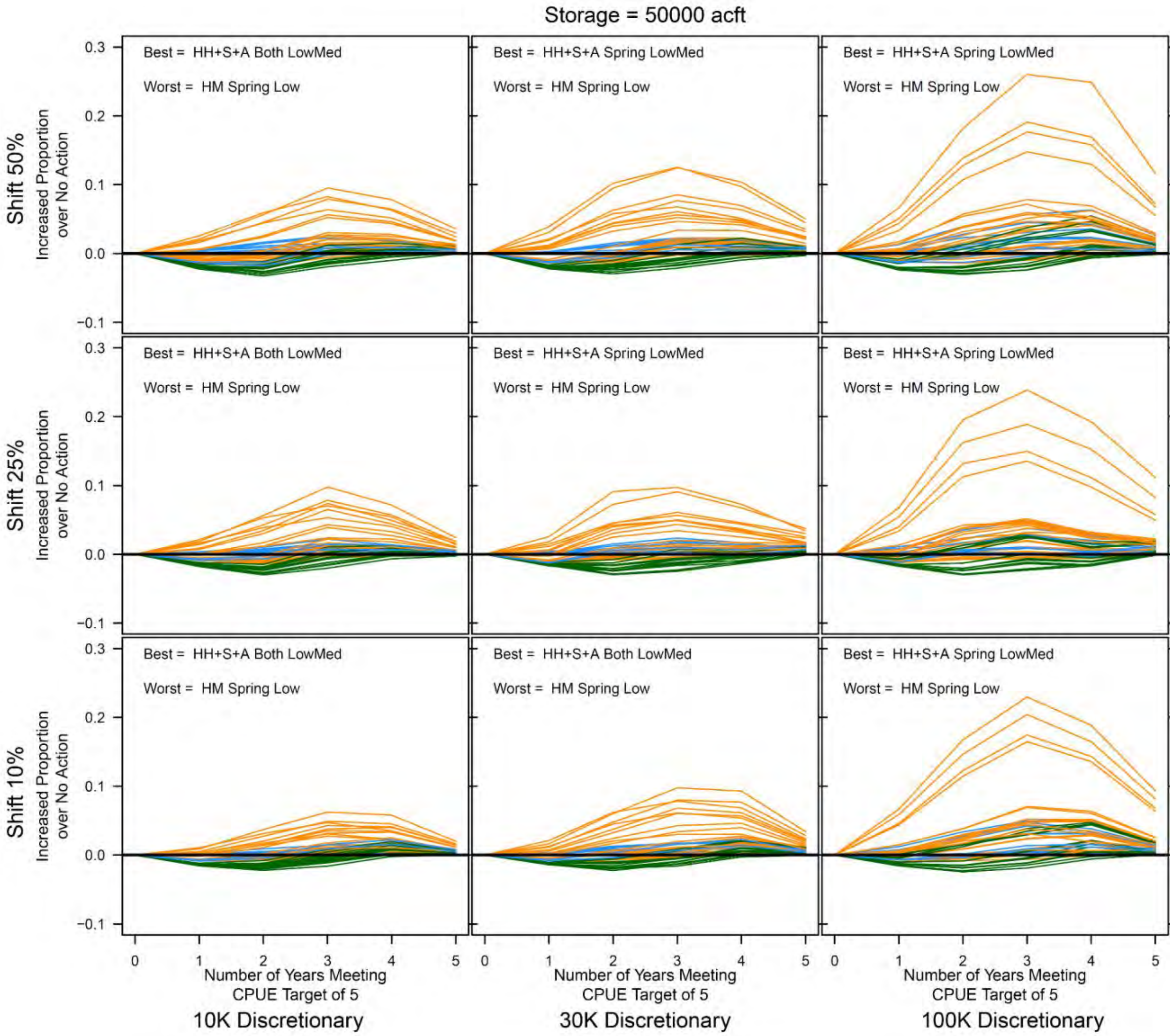

Figure S13. Change in the proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per 100m^2 successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 50,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

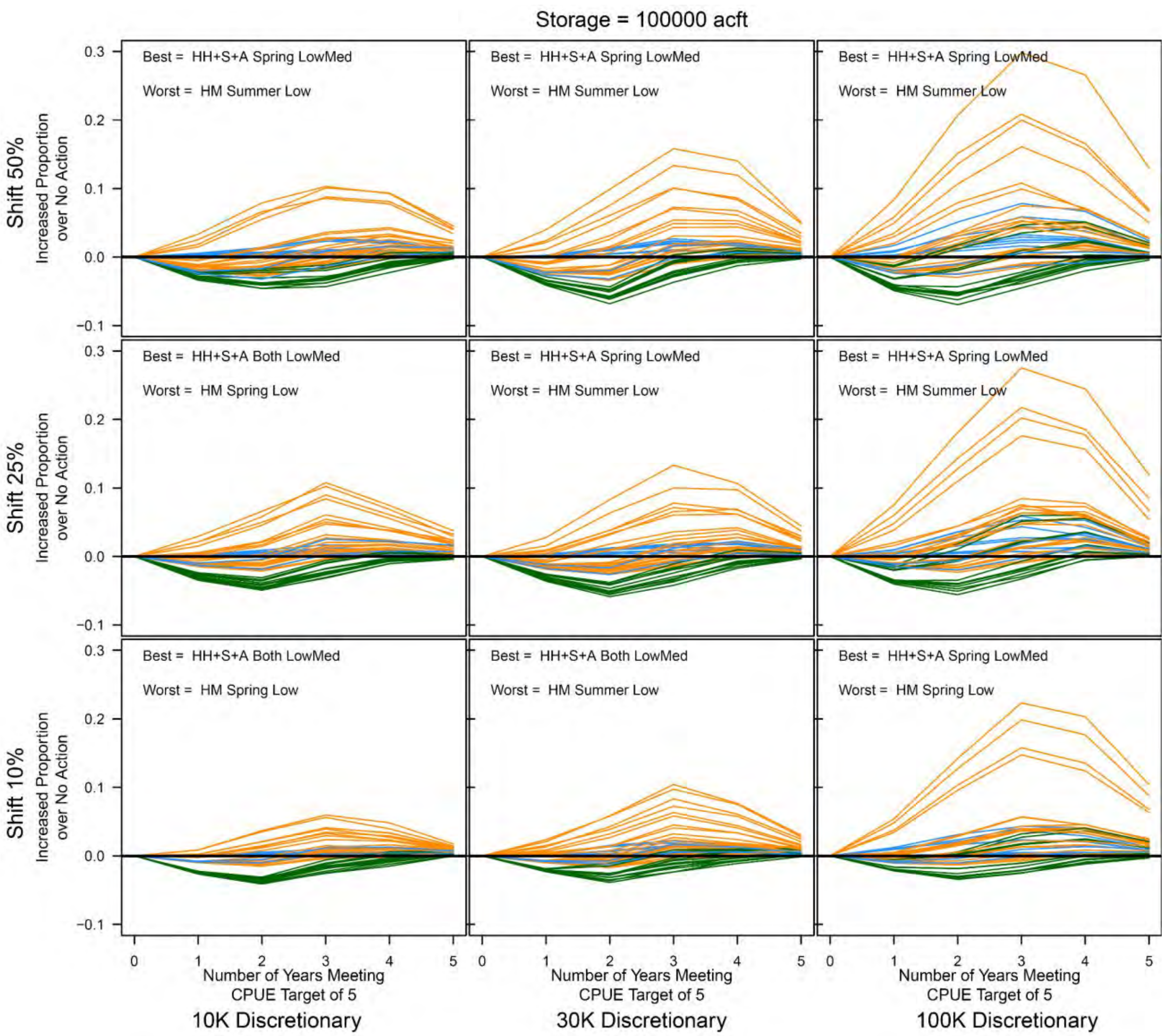

Figure S14. Change in the proportion of simulations in which at least a given number of years have the management goal of 5 RGSM per $100m^2$ successfully met by different management strategies relative to the "No Action" strategy across different proportional management (rows) and discretionary water availability scenarios (columns) when 100,000 acft of storage is available. Each line represents a unique management strategy, with orange lines indicating those in which water is stored in high water years for use in lower water years, green indicating those in which water is stored in both high and medium water years for use in low water years, blue indicating those in which water is moved or added, but only within a single year, and black indicating no action. The best and worst performing strategies are identified within each panel.

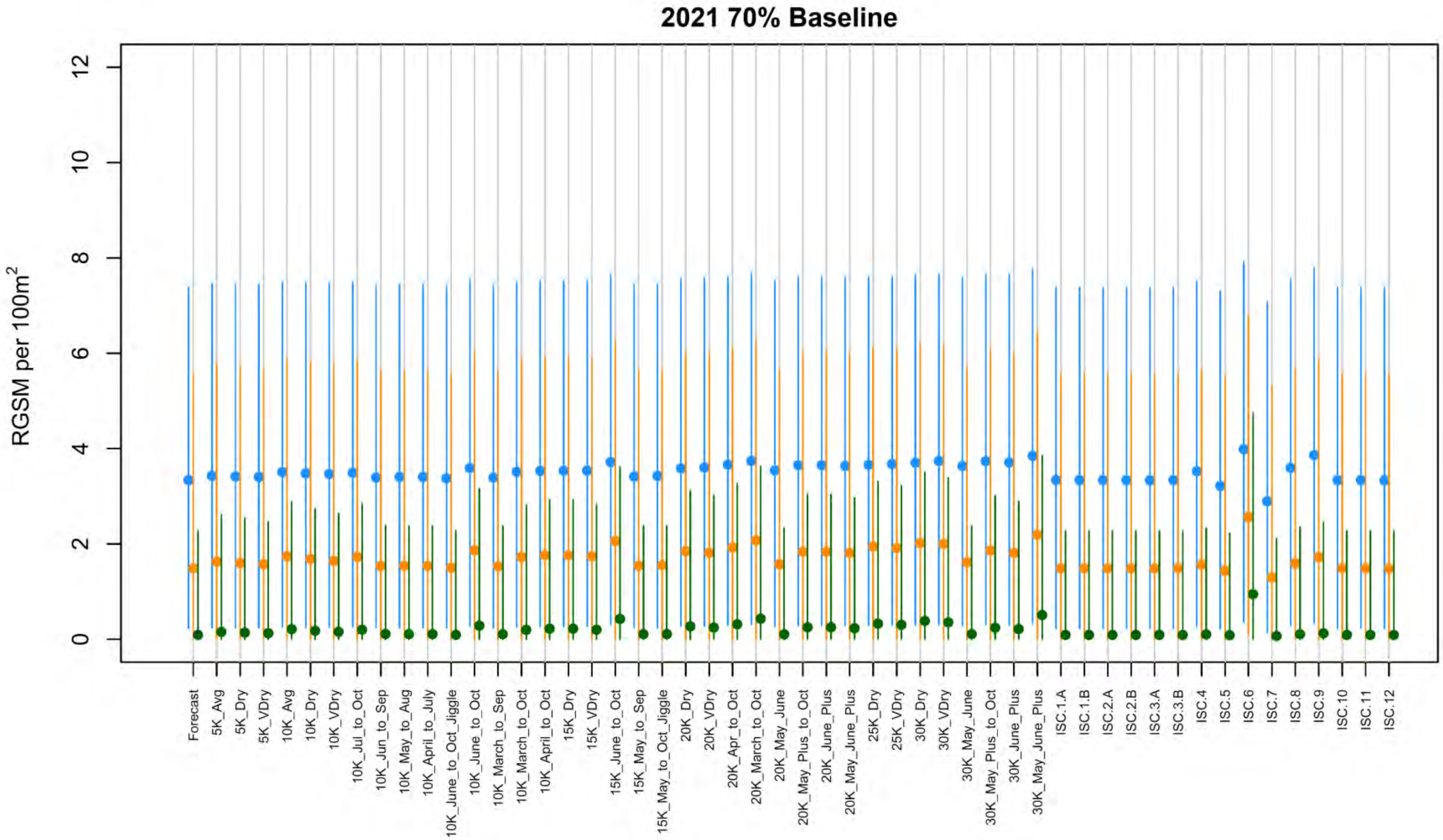

Figure S15. Predicted October RGSM CPUE in the MRG under alternative water management strategies for the 70% exceedance scenario. Points indicate the median CPUE estimates, while vertical bars indicate the 95% simulation intervals. Blue points indicate predicted CPUE under 10^{th} percentile river drying given forecast summer discharge, orange indicates expected CPUE under median expected drying extent, and green indicates expected CPUE under 90^{th} percentile drying given summer discharge.

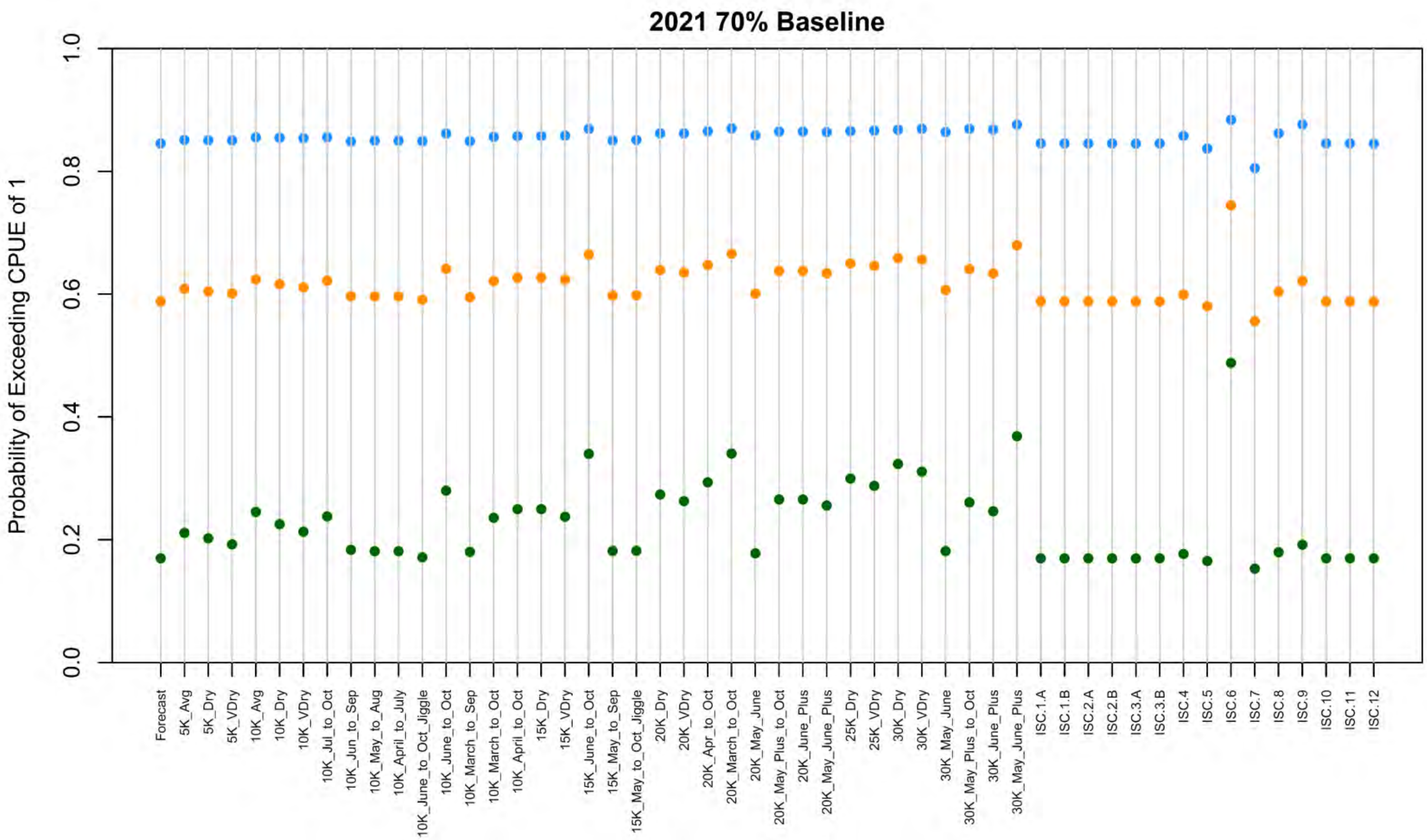

Figure S16. Predicted probability of October RGSM CPUE exceeding the management target of 1 RGSM per 100m^2 under different alternative water management strategies applied to the 50% exceedance forecast for 2021. Blue points indicate the probability of exceeding the management target under 10th percentile (lower than expected) river drying given forecast summer discharge, orange indicates indicate the probability of exceeding the management target under median expected drying extent, and green indicates indicate the probability of exceeding the management target under 90th percentile (higher than expected) drying given summer discharge.

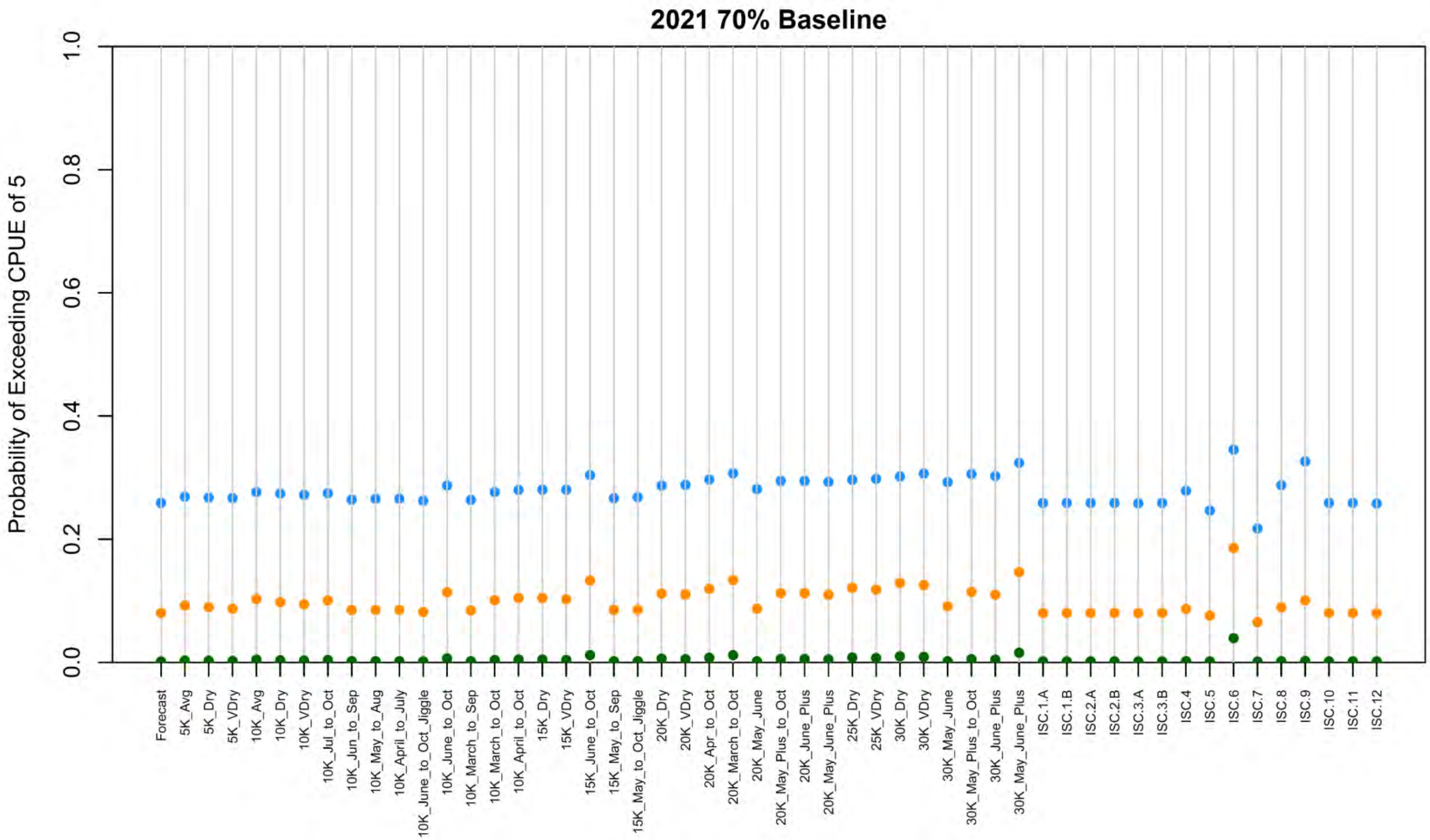

Figure S17. Predicted probability of October RGSM CPUE exceeding the down-listing target of 5 RGSM per $100m^2$ under different alternative water management strategies applied to the 50% exceedance forecast for 2021. Blue points indicate the probability of exceeding the down-listing target under 10^{th} percentile (lower than expected) river drying given forecast summer discharge, orange indicates indicate the probability of exceeding the down-listing target under median expected drying extent, and green indicates indicate the probability of exceeding the down-listing target under 90^{th} percentile (higher than expected) drying given summer discharge.

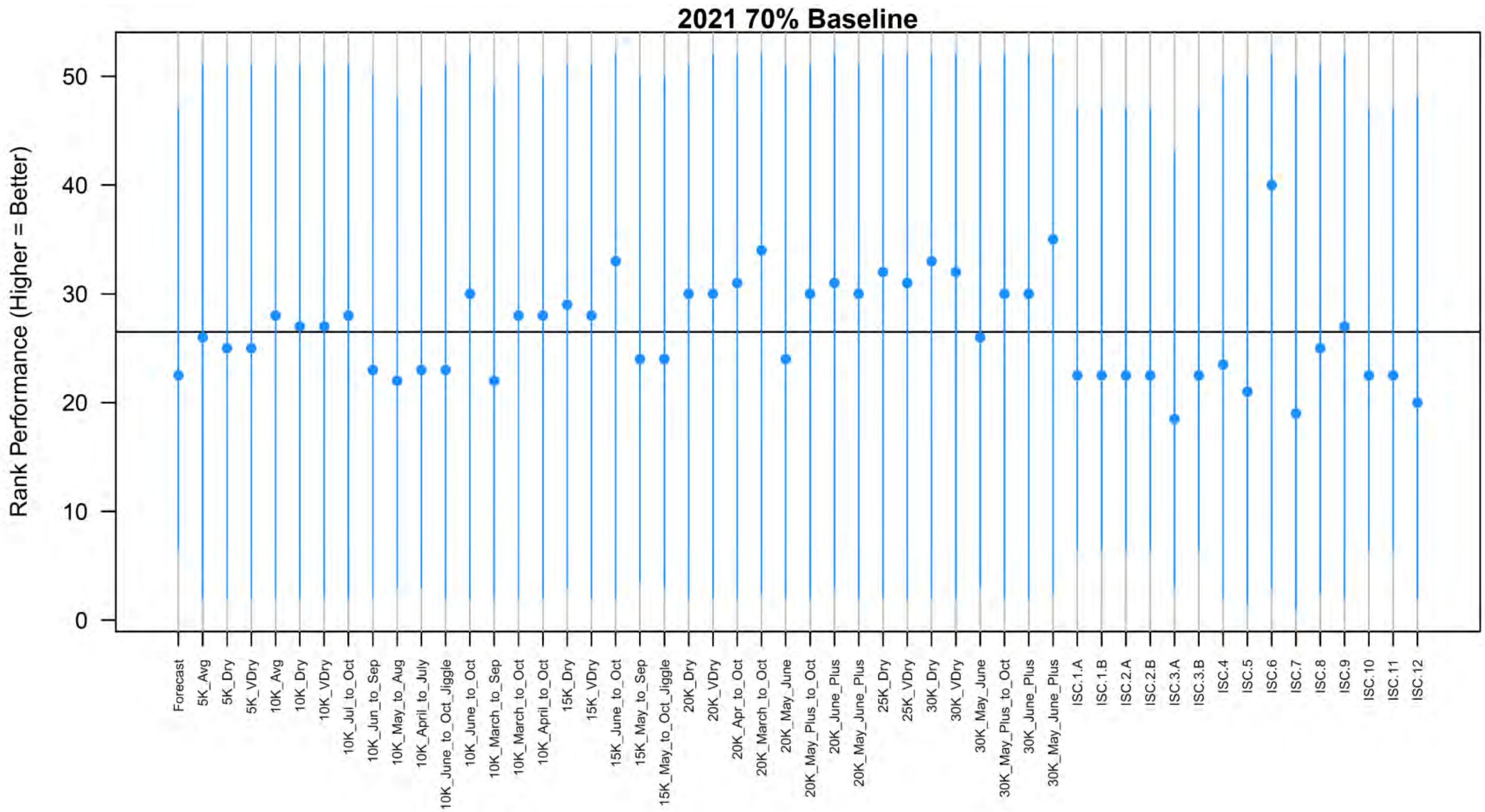

Figure S18. Rank performance of alternative water management strategies applied to the 50% exceedance forecast hydrograph for 2021.Points indicate the median rank performance of a strategy across all simulations, while the vertical bars indicate the 95% simulation interval of rank performance.