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Upstream water management and its role in estuary health, evaluation of freshwater management and subtropical estuary function

Paul Julian

pjulian@evergladesfoundation.org

The Everglades Foundation https://orcid.org/0000-0002-7617-1354

Leah Reidenbach

Sanibel-Captiva Conservation Foundation

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Abstract

In highly modified and managed systems the balance of freshwater inputs discharged to estuarine systems are important to maintain salinity balances and thus estuarine function. However, the availability of freshwater is highly dependent on upstream water management to provide flood protection whilst meeting freshwater demand for people and the environment. In South Florida, water is managed by a water control plan with Lake Okeechobee at the center. Currently, water levels within the lake are managed based on the Lake Okeechobee Regulation Schedule of 2008. The new regulation schedule, Lake Okeechobee System Operating Manual (LOSOM), updates water management rules while attempting to balance the needs of downstream systems; salinity and water quality in the Caloosahatchee and Saint Lucie (northern) estuaries; and more water for the southern Everglades. This study evaluates LOSOM relative to ecologically significant performance measures for the northern estuaries. Overall the proposed regulation schedule is expected to provide a more sustainable flow regime to the estuaries by reducing stressful and damaging discharge events. Moreover, new management rules combined with new infrastructure are expected to reduce low discharge events to the Caloosahatchee estuary and reduce stress on key indicator species such as *Vallisneria americana* during the wet season. This regulation schedule provides improved conditions for the estuaries, but Lake Okeechobee carries the burden. Future restoration and water management strategies are needed to maintain the benefits afforded to the estuaries while at the same time reducing the stress and damage to Lake Okeechobee to develop a more sustainable and resilient system.

Introduction

Many of the changes in estuarine ecosystem function including physical, biogeochemical, and biological attributes are due to changes to the balance of freshwater inputs and water from the marine end member (Sklar and Browder 1998; Buzzelli et al. 2014; Tibby et al. 2022). Changes to hydrologic flows can affect sediment, nutrient, and dissolved organic matter transport, water depth, salinity regimes, and turbidity conditions within the coastal environment (Lee et al. 2006; Chen and Doering 2016; Milbrandt et al. 2016; Moncada et al. 2021). Moreover, altered freshwater discharges to estuarine environments can substantively affect the composition, distribution, abundance, and status of ecologically valuable benthic communities such as oyster beds and seagrass meadows (Volety et al. 2009; Herbert et al. 2011; Santos and Lirman 2012; Buzzelli et al. 2015).

Freshwater demand and upstream water management decisions can have profound implications for coastal ecosystems and estuaries (Sklar and Browder 1998; Alber 2002; Newton et al. 2020; Stein et al. 2021). Freshwater discharges to the Caloosahatchee River and St. Lucie River estuaries (CRE and SLE, respectively) on the west and east coast of Florida (Fig. 1) have been impacted by both urban and agricultural development in their watersheds. Regulated discharges through the Central and Southern Florida (C&SF) project canal system from Lake Okeechobee are an additional major contributing factor. In general, these alterations have resulted in unnaturally high discharges in the wet season (May – Oct) and low discharges in the dry season (Nov – Apr). The lack of freshwater inflow to the Caloosahatchee during the dry season can be particularly severe (Doering and Chamberlain 1999). These unnatural patterns of freshwater inflow to the estuaries cause stress and mortality of estuarine benthic indicator species such as submerged aquatic vegetation (SAV) and oysters which provide essential habitat to estuarine species (Doering et al. 2002).

Located upstream of both the CRE and SLE, Lake Okeechobee is a major feature of the C&SF project in which water management is balanced between federal (USACE) and local (SFWMD) entities. Since the construction of the C&SF project, there have been several authorized Lake regulation schedules to accommodate changes in infrastructure and other demands (Tarabih and Arias 2021; Julian and Welch 2022). Several regulation schedules were implemented prior to the 1990s, however, in 1991 a regulation schedule called Run 25 was implemented to reduce high-volume discharges to the estuaries and changes to areas in Lake Okeechobee without affecting water users. Run 25 was replaced by the Water Supply and Environment (WSE) schedule in 2000 which expanded the zone in which water levels were maintained. The goals of WSE were to decrease water discharges to the estuaries, decrease the frequency of high-stage flooding in Lake Okeechobee, and meet water users' demands. Due to a combination of potential shortcomings in the WSE schedule, the onset of severe climatic factors (extreme drought and multiple hurricanes), and concerns for public safety related to the integrity of the surrounding levee, the 2008 Lake Okeechobee Regulation Schedule (LORS08) was adopted. This regulation schedule was designed to prevent high lake stages and identified several additional seasonal and operational bands to dictate water management decisions.

With the near completion of several large restoration (storage infrastructure) projects downstream of the lake, as well as improvements to the integrity of the Herbert Hoover Dike system surrounding this waterbody, the latest iteration of a regulation schedule and water control plan was recently developed and called the Lake Okeechobee System Operating Manual (LOSOM). The goal of LOSOM is to incorporate flexibility in water management to better balance congressionally authorized project purposes including flood control, water supply, navigation and recreation, and preservation of fish and wildlife. Given the additional flexibility afforded by new infrastructure projects around the lake and in the Greater Everglades ecosystem, it is expected that the preferred alternative will result in lake water levels deeper than baseline conditions (Julian and Welch 2022), thereby affecting discharges to downstream systems like the Northern Everglades Estuaries. The objective of this study is to compare the modeled preferred alternative of the new Lake Okeechobee regulation schedule to baseline conditions for the northern estuaries (Caloosahatchee and St. Lucie). Due to how water is managed upstream in the current regulation schedule (LORS08), it is expected that regulatory discharges to the Northern Estuaries will vary between baseline and preferred alternative conditions.

At the time of this study, the final LOSOM modeling has been completed and a draft water control plan has been developed. The potential effects of LOSOM on the system will be evaluated using the final model results and will be published in an Environmental Impact Statement (EIS). While this study was conducted before the completion of the final EIS and water control plan, the modeling gives an approximation of how the system will behave given the regulatory discharge recommendations and operational rules used in the modeling. It is expected that the final EIS and the record of the decision will be finalized sometime in mid-2023.

Methods

Study Area

Lake Okeechobee is a large (~ 1,730 km^2) shallow (~ 2.7 m) lake at the center of the Kissimmee-Okeechobee-Everglades ecosystem and the C&SF Project (Fig. 1). The lake is surrounded by an earthen dike constructed in the early 1900s for flood protection and water management purposes. The lake serves as a major source of water to other parts of the Kissimmee-Okeechobee-Everglades system including the Caloosahatchee River Estuary (CRE)/C-43 canal (west), St. Lucie River Estuary (SLE)/C-44 (east), Lake Worth Lagoon (LWL; southeast) and the Water Conservation Areas (WCAs)/Everglades ecosystem (south) (Steinman and Rosen 2000; Havens and James 2005). Water levels within Lake Okeechobee are influenced by the subtropical climate of south Florida combined with the multi-purpose water management of the Lake for regulatory, water supply, and flood protection purposes (Qiu and Wan 2013).

The Caloosahatchee River and its estuary are located on the lower west coast of Florida, USA (Fig. 1). The historic Caloosahatchee River was originally a shallow, meandering river with its headwaters located approximately 100 km inland at Lake Hicpochee and tidally influences approximately 70 km upstream. To accommodate navigation, flood control, and land reclamation needs the river was straightened and extended eastward and connected to Lake Okeechobee in the late 1800s essentially converting the river to a canal, resulting in the C-43 canal designation. In the early 1900s, three lock-and-dam structures were constructed to control flow and stage elevation along the river. Of the three lock-and-dam structures installed, the final downstream structure identified as the S-79 regulates discharge from the canal to the estuary (Doering and Chamberlain 1999; Barnes 2005; Julian and Osborne 2018).

The St. Lucie River and its estuary are located on the lower east coast of Florida, USA (Fig. 1). Historically the St. Lucie River and its estuary was a freshwater system only occasionally exposed to the coastal ocean through ephemeral passes in the barrier islands. As part of the extensive hydrological modifications that have shaped the modern Everglades ecosystems, the St. Lucie inlet was permanently opened in the late 1800s to provide a connection between the estuary and the Atlantic Ocean. In the early 1900s the C-44 canal was completed linking the southern fork of St. Lucie estuary with Lake Okeechobee, with S-80 regulating freshwater discharges to the St. Lucie River. Meanwhile, the C-23, C-24 and Ten Mile Creek discharge to the northern fork of the St. Lucie River via the S-48, S-49 and Gordy Road weir. Much like other regions in southern Florida, the St. Lucie river watershed has been highly modified to accommodate agriculture and coastal development resulting in significantly altered natural sloughs and wetlands. Due to the modified hydrology and altered watershed, connections to and drainages from the watershed and Lake Okeechobee have led to extreme freshwater inflows via the S-80 structure resulting in altered salinity regimes, phytoplankton blooms, and benthic flora and fauna impacts (Buzzelli et al. 2015).

Data Source

Scenario modeling was conducted using the Regional Simulation Model – Basins (RSM-BN). The RSM model uses existing climatology in a link-node framework to simulate hydrologic conditions by using a Hydrologic Simulation Engine (Chin et al. 2005) combined with a Management Simulation Engine (Bras et al. 2019). The RSM model has a 52-year simulation period of record from 1 January 1965 to 31 December 2016. For purposes of restoration planning, the RSM model uses observed climatology across the SFWMD boundary as input to simulate water management changes. Therefore, over the 52-year simulation period, the model includes extreme events such as prolonged drought, hurricanes, tropical storms, and prolonged periods of high and low rainfall. The RSM is a robust simulation tool that has been used in project planning efforts for several projects including the Central Everglades Planning Project, Lake Okeechobee Watershed Restoration Project, Western Everglades Restoration Project, Everglades Restoration Transition Plan, and Combined Operational Plan (South Florida Water Management District 2020).

In this evaluation, three alternatives were considered, including two baseline conditions and the final preferred alternative (proposed regulation schedule). The first baseline condition is the existing condition baseline for 2019 (ECB19) and represents existing infrastructure, conditions, and operations in place during 2019 with LORS08 as the regulation schedule guiding water management for the lake. The second baseline condition is no-action 2025 (NA25f) representing the additional operational flexibility that downstream infrastructure and improved levee integrity would provide in 2025 if LORS08 was still guiding water management decisions. In NA25f additional infrastructure includes the completion of capital projects and foundational Comprehensive Everglades Restoration Plan (CERP) projects including the rehabilitation of the HHD, C-44 reservoir and stormwater treatment area (downstream of the eastern outlet), C-43 reservoir (downstream of the western outlet), and the A-2 stormwater treatment area (downstream of southern outlets). The final alternative is the preferred alternative 2025 (PA25) and represents the completed infrastructure outlined above for the NA25f alternative with water management being guided by the new LOSOM regulation schedule.

Data Analysis

To compare differences in regulatory releases from Lake Okeechobee between the baseline and preferred alternatives, annual total regulatory releases for each major outlet using the Kruskal-Wallis rank sum test and a post-hoc Dunn's test of multiple comparisons (*"dunn.test"* function in the "dunn.test" R-package; Dinno 2015). Major outlets include the Caloosahatchee River (S-77; CR), St. Lucie River (S-308; SLR), Lake Worth Lagoon (S-271; LWL), and Everglades (S-351 & S-354; WCAs).

The Northern Estuaries Salinity Envelope Performance Measure was used to evaluate changes to freshwater discharges to the Caloosahatchee and St. Lucie estuaries. This performance measure provides a biological and ecological evaluation and assessment of salinity regimes across baselines and the preferred alternative conditions. At the core of the performance measure, experimental and field-based studies, peer-reviewed literature, technical literature, and long-term monitoring data were used to set salinity ranges around conditions of optimum, stressful, and damaging effects for specific indicator species (RECOVER 2020). The CH3D hydrodynamic model (Sun et al. 2016) was used to simulate salinity, from which 14-day average salinity outputs were derived and formed the basis of the relationship between discharge and salinity for the Caloosahatchee and St. Lucie estuaries. Based on resulting salinities throughout each estuary and the potential physiological or ecological impact on indicator species, four discharge envelopes or categories were considered low, optimum, stressful, and damaging (Table 1). Each flow envelope threshold differs between estuaries due to differences in estuary geomorphology, hydrology, and ecology (RECOVER 2020).

Table 1

Low, optimum, stress, and damaging discharge envelopes in giga-liters per day ($x10^9$ L day^{-1}) for the Caloosahatchee and St Lucie Estuaries.

Estuary	Low	Optimum	Stress	Damaging	Extreme
Caloosahatchee Estuary	< 1.83	1.83–5.14	5.14–6.36	> 6.36	> 15.90
St. Lucie Estuary	< 0.37	0.37–3.43	3.43–4.16	> 4.16	> 9.79

[1] Original discharge envelopes developed in units of ft^3sec^{-1} (Caloosahatchee: < 750, 750–2100, 2100–2600, > 2600, > 6500; St. Lucie: < 150, 150–1400, 1400–1700, > 1700, > 4000)

The Northern Estuaries Salinity Envelope Performance Measure uses 14-day moving average discharges to count discharge events in the low, optimum, stress, and damaging flow events within a given 14-day period during the period of simulation. Additionally, for stress and damaging flow categories discharge volumes were parsed between the watershed and Lake Okeechobee (i.e. regulatory) sources. For the Caloosahatchee River estuary, simulated discharge values for S-79 were evaluated across the different baselines and preferred alternatives (Fig. 1). For the St. Lucie river estuary, simulated discharge values for S-80, S-48, S-49, and Ten Mile Creek were evaluated across the different baselines and preferred alternatives (Fig. 1). To compare differences between the baseline and preferred alternatives, discharge category event counts were compared using Chi-squared analysis. Currently, no salinity envelope performance measure has been developed for the Lake Worth Lagoon.

To further evaluate the change of freshwater flow to the Caloosahatchee River estuary between the baseline and preferred alternatives, a salinity time series model (Qiu and Wan 2013) was used to simulate salinity conditions at locations in the upper estuary (Fig. 1). These modeled salinity values were then used to assess the stress on *Vallisneria americana* (tape grass), an indicator species in the Caloosahatchee River estuary. Modeled salinities were used to calculate the *Vallisneria* Stress Index (VSI) consistent with Eq. 1 and (Douglass et al. 2020). The VSI is a logistic curve that increases from near zero at salinities < 3 (no stress) to near 1 at salinities of 18 (high stress). Annual average wet (May – October) and dry (November – April) season VSI values were compared across preferred alternative and baseline conditions separately using the Kruskal-Wallis rank sum test and a post-hoc Dunn's test of multiple comparisons to test the seasonal differences across alternatives.

$$VSI = \frac{1}{1+e^{-0.5\times(Salinity-10)}}$$ Eq 1

Non-parametric statistics were used to evaluate the data for this study due to the nature of the data (i.e. modeled hydrology and salinity) and the data did not conform to any parametric statistical assumptions. All plots were generated in base R and tables were formatted using the "flextable" R-package (Gohel 2021). All statistical operations were performed using R (Ver 4.0.4, R Foundation for Statistical Computing, Vienna, Austria). Unless otherwise stated, all statistical operations were performed using the base R library. The critical level of significance was set at $\alpha = 0.05$.

Results

Regulatory Discharges

Regulatory discharges varied between alternatives, including the two baseline conditions for each outlet, some more so than others. Generally, annual average discharges in the preferred alternative were reduced for the northern estuaries (CR and SLR) and LWL relative to both baseline conditions (Table 2). Discharges in the preferred alternative for SLR and LWL were significantly lower relative to the baseline conditions ($\chi^2 = 29.8$; df = 3; ρ-value < 0.01 and $\chi^2 = 51.1$; df = 3; ρ-value < 0.01, respectively; Fig. 2). Relative to the no-action alternative, average annual discharges were reduced by 40% and 81% (average percent difference) for SLR and LWL, respectively (Table 2). Meanwhile, regulatory discharges to the WCAs in the preferred alternative were significantly higher relative to the baseline conditions ($\chi^2 = 54.6$; df = 3; ρ-value < 0.01; Fig. 2), and relative to the no-action alternative discharges were increased by > 200% (Table 2). However, regulatory discharges to the CR in the preferred alternative were not significantly different than the two baseline conditions ($\chi^2 = 0.06$; df = 3; ρ-value = 0.97; Fig. 2) despite a slight (4%) decrease in discharges in the preferred alternative relative to the no-action alternative (Table 2).

Table 2
– Summary statistics of annual regulatory discharges from Lake Okeechobee to the Caloosahatchee River (S-77), St. Lucie River (S-308), Water Conservation Areas (S-351 and S-352) and Lake Worth Lagoon (S-271) for existing condition baseline (ECB19), no-action baseline (NA25f), and preferred alternative (PA25) observed during the period of simulation.

Discharge (x10[illegible] L Yr^{-1})						
Region	Alt [1]	Mean	Standard Deviation	Median	Minimum	Maximum
Caloosahatchee River (CR)	ECB19	629.1	706.0	386.1	0.0	3025.3
	NA25f	645.2	722.5	440.4	0.0	3161.4
	PA25	618.1	698.9	315.2	0.0	2620.0
St. Lucie River (SL)	ECB19	282.6	326.6	168.2	0.0	1428.1
	NA25f	229.6	299.4	119.8	0.0	1367.8
	PA25	138.6	300.5	0.0	0.0	1250.2
Water Conservation Areas (WCAs)	ECB19	74.5	73.5	49.8	0.0	342.4
	NA25f	74.2	64.6	55.8	0.0	281.5
	PA25	253.8	148.6	265.8	0.0	651.6
Lake Worth Lagoon (LWL)	ECB19	70.0	44.9	72.9	0.0	150.6
	NA25f	72.5	46.6	75.3	0.0	153.3
	PA25	13.9	13.9	9.1	0.0	61.7

[1] ECB19 = existing condition baseline; NA25f = no action baseline; PA25 = preferred alternative

Estuary Salinity Envelope

Due to the differences in regulatory discharges to the northern estuaries, the distribution of discharges to the estuaries varied between the preferred alternative, and both baseline conditions (Fig S1). This difference is also reflected in the distribution and counts of 14-day events in the various discharge envelope categories for the CRE and SLE systems. The count of 14-day discharge events for the CRE was significantly different between baseline conditions and preferred alternatives for most discharge envelope categories (Table 3). Generally for the CRE, discharge events in the low, stress, and damaging from Lake Okeechobee categories of the preferred alternative were less than both baseline conditions (Table 3 and Fig. 3). Meanwhile, optimal flow events were significantly greater in the preferred alternative relative to the baseline conditions (Table 3 and Fig. 3). Extreme discharge events from the basin and Lake Okeechobee as well as basin-derived stressful flow events were not significantly different between baseline conditions and preferred alternatives (Table 3). In the SLE, the count of 14-day discharge events in the optimum flow envelope did not significantly change between baseline conditions and the preferred alternative, however, low discharge events significantly increased and lake-derived stress and damaging discharges decreased (Table 3 and Fig. 3). Basin-derived stressful events significantly increased between baseline conditions and the preferred alternative for the SLE and extreme discharge events were not significantly different between baseline conditions and the preferred alternative (Table 3).

Table 3
Caloosahatchee and St. Lucie estuary discharge envelope 14-day event count for each discharge category with chi-square statistical results comparing baseline and preferred alternative during the 52-year simulation period of record.

					ECB19 vs PA25		NA25f vs PA25	
Estuary	Discharge Envelope Cateogry	ECB19 [2]	NA25f [2]	PA25 [2]	χ^2	ρ-value	χ^2	ρ-value
CRE [1]	Low	663	556	455	38.70	*< 0.01*	10.09	*< 0.01*
	Optimum	469	588	765	71.00	*< 0.01*	23.16	*< 0.01*
	Stress (Basin)	157	119	139	1.09	0.30	1.55	0.21
	Stress (LOK)	184	183	66	55.70	*< 0.01*	54.98	*< 0.01*
	Damaging (Basin)	228	172	181	5.40	*< 0.05*	0.23	0.63
	Damaging (LOK)	198	187	81	49.06	*< 0.01*	41.93	*< 0.01*
	Extreme (Basin)	15	12	11	0.62	0.43	0.04	0.83
	Extreme (LOK)	51	45	61	0.89	0.34	2.42	0.12
SLE [1]	Low	109	107	183	18.75	*< 0.01*	19.92	*< 0.01*
	Optimum	831	865	912	3.76	0.05	1.24	0.26
	Stress (Basin)	190	210	283	18.29	*< 0.01*	10.81	*< 0.01*
	Stress (LOK)	164	145	30	92.56	*< 0.01*	75.57	*< 0.01*
	Damaging (Basin)	432	429	453	0.50	0.48	0.65	0.42
	Damaging (LOK)	159	140	38	74.32	*< 0.01*	58.45	*< 0.01*
	Extreme (Basin)	123	113	125	0.02	0.90	0.61	0.44
	Extreme (LOK)	56	49	39	3.04	0.08	1.14	0.29

[1] CRE = Caloosahatchee River Estuary; SLE = St. Lucie River Estuary

[2] ECB19 = existing condition baseline; NA25f = no action baseline; PA25 = preferred alternative

Vallisneria Stress Index

The effects of freshwater inflow on predicted salinities varied across the different alternatives and upper estuarine locations (Table 4 and Fig S2). Generally, the mean period of simulation salinity values was greatest for the ECB19 baseline condition across all estuary locations (Fig S2) and irrespective of the season (Table 4). Moreover, the distribution of salinity values in the upper portion of the estuary (i.e. BR31, Val-I75, Bird-IS and FortMyers) were relatively similar, with some expectations (Table 4).

Table 4
– Period of simulation mean and maximum simulated salinity and the percent of salinity < 10, 10–15, and ≥ 15 during the period of simulation for each alternative and site in the upper estuary.

				% < 10		**% 10–15**		**% ≥ 15**	
Site	Alternative [1]	Mean Salinity [2]	Maximum Salinity [2]	Wet	Dry	Wet	Dry	Wet	Dry
BR31	ECB19	3.4	15.7	46.0	38.5	3.1	10.6	1.3	0.5
	NA25f	1.5	15.5	49.3	48.4	0.8	1.1	0.3	0.1
	PA25	1.1	15.5	49.4	48.7	0.8	1.0	0.2	0.0
Val-I75	ECB19	3.8	16.3	45.7	37.9	3.0	9.7	1.7	2.0
	NA25f	2.2	16.0	49.3	48.3	0.7	1.0	0.4	0.3
	PA25	1.9	16.0	49.4	48.6	0.7	1.0	0.3	0.0
Bird-IS	ECB19	4.0	17.5	45.2	37.2	3.0	7.3	2.2	5.1
	NA25f	1.9	17.3	49.2	48.3	0.6	0.8	0.5	0.5
	PA25	1.4	17.3	49.3	48.6	0.6	0.8	0.4	0.2
FtMyers	ECB19	6.7	22.6	42.0	25.6	3.0	11.6	5.3	12.5
	NA25f	4.6	22.3	46.6	40.4	2.7	7.8	1.2	1.4
	PA25	4.3	22.3	47.8	44.9	1.5	3.6	1.1	1.1

[1] ECB19 = existing condition baseline; NA25f = no action baseline; PA25 = preferred alternative

[2] Period of Simulation Statistics

Variability in VSI was high across all simulated sites with daily and seasonally averaged values ranging from zero to one (Fig S3). Similar to simulated salinity conditions, VSI values were greatest in the ECB19 baseline condition with dry season values being greater than wet season values (Fig. 4 and Fig S3). There were significant differences in VSI across the preferred alternative and baseline conditions for dry and wet seasons across sites (Table 5 and S1). During the wet season, VSI values did not significantly differ between the NA25f baseline and PA25 preferred alternative (Fig. 4). However, during the dry season, VSI values at BR31, Bird-IS, and FtMyers were significantly lower in the preferred alternative relative to both NA25f and ECB19 baseline conditions (Fig. 4). Dry season VSI values at Val-75 did not significantly differ between the NA25f baseline conditions and the PA25 preferred alternative, presumably due to variability in (simulated) salinity at this site in the PA25 alternative (Fig. 4).

Table 5
– Seasonal median *Vallisneria* stress index and Kruskal-Wallis rank sum test results comparing *Vallisneria* stress index between alternatives for each site and season.

Site	Season	Median VSI	χ^2	ρ-value
BR31	Wet	0.016	34.67	*< 0.01*
	Dry	0.026	31.29	*< 0.01*
Val-I75	Wet	0.021	29.00	*< 0.01*
	Dry	0.036	22.95	*< 0.01*
Bird-IS	Wet	0.023	34.79	*< 0.01*
	Dry	0.041	31.10	*< 0.01*
FtMyers	Wet	0.102	23.50	*< 0.01*
	Dry	0.231	20.49	*< 0.01*

Discussion

Water management should take into account the needs and uses of water within the watershed and downstream. These needs and uses could vary from human needs such as water supply for consumption (i.e., drinking water, agricultural irrigation, etc.), flood protection, and recreation to ecological needs such as balancing water levels in lakes and wetlands and maintaining a salinity balance in downstream estuaries (Obeysekera et al. 2011). In South Florida, Lake Okeechobee is managed through a water control plan/regulation schedule which dictates water level and regulatory discharges to downstream tributaries throughout the year. As water management priorities and infrastructure capabilities have changed over the years, regulation schedules have also changed (Julian and Welch 2022). As such, the timing, distribution, and volume of water released from the lake to its tributaries have also varied (Julian and Osborne 2018; Tarabih and Arias 2021) with notable changes to the salinity balance in the northern estuaries (Doering 1996; Doering and Chamberlain 1999; Barnes 2005; Sime 2005).

As expected, the preferred alternative will alter the distribution of water from the Lake to its tributaries relative to both baseline conditions (Fig. 2 and Table 2). Under the LORS08 schedule (i.e. ECB19 and NA25f), most of the water is sent to the northern estuaries, and discharge to the south is significantly restricted due to a combination of downstream water quality and infrastructure restrictions (Fig. 2). While infrastructure changes provide the means to manage water differently, discharge guidance is where the rubber meets the road as demonstrated by the relative change in annual average regulatory discharge between the NA25f baseline and the PA25 preferred alternative (Fig. 2). Under LORS08 (ECB19 and NA25f) the majority (~ 2/3rd) of the regulatory discharges were to the CR while the remaining was distributed between SLR, LWL, and WCAs (Fig. 2, Fig S4, and Table 2). In the preferred alternative (PA25), regulatory discharges remain relatively the same (slight decreases relative to NA25f) while discharges from SL and LWL were redistributed to the WCAs (Fig. 2, Fig S4, and Table 2) where it will provide benefits to the Everglades ecosystem. These changes to regulatory discharges to the northern estuaries can significantly alter the salinity balance within the northern estuaries.

The Northern Estuaries (CRE and SLE) are highly altered systems situated in a water management infrastructure dependent on operations balanced between the weather and human demands (i.e. flood protection, health and safety, navigation, water supply, etc.)(Barnes 2005; Sime 2005). Either from the context of restoration activities (i.e., Comprehensive Everglades Restoration Project) or water management (i.e., Lake Okeechobee System Operating Manual), a sustainable salinity balance is needed to facilitate proper ecological function. This balance is dictated by freshwater deliveries where too low of flows can cause higher than average salinity or hypersaline conditions while too many freshwater discharges can depress salinity resulting in stress or damage to estuarine functions (Ji et al. 2007; Sun et al. 2016). As such, discharge conditions for the baseline alternatives (ECB19 and NA25f) are either too low on the low end or too high on the high end for CRE and SLE (Fig. 3). The preferred alternative (PA25) was developed to target discharges in the optimal flow range for estuary health by reducing high and low, stressful, and damaging discharges by adjusting the timing and distribution of discharges from Lake Okeecobee (LOK) and leveraging restoration infrastructure. While regulatory discharges from LOK did not significantly change between alternatives for the CR (Fig. 2), how and when the discharges were performed allowed for the system to attenuate discharges and achieve a more balanced flow regime. The improvement in optimal discharges to the SLE did not change much between baselines and the preferred alternative (~ 5%; Table 3), but the reduction in stress and damaging discharges were redistributed to the lower end of the hydrograph allowing for a more manageable discharge regime facilitated by the operation of the C-44 reservoir (Fig. 3). While discharge volumes did not change significantly between baseline conditions and the preferred alternatives for the CRE, the combined effect of the C-43 reservoir and changes to operational rules helped modulate discharges to the estuary reducing stress and damaging discharge while improving optimal conditions. This change in discharge regime for the preferred alternative is a combined result of water management rules (when and where) and restoration infrastructure (how) such as the C-43 reservoir for the CRE (Julian and Welch 2022).

With little to no change in regulatory discharge volume to the CRE but the vastly improved estuary salinity envelope counts (Fig. 3) and reduced stress conditions during the wet season for *Vallisneria* (Fig. 4) between baseline conditions and the preferred alternative, storage features such as the C-43 reservoir can provide a significant ecological lift to estuarine systems. Additional storage could provide more flexibility and improved estuarine conditions with respect to basin/watershed-derived discharges and extreme discharge by providing storage capacity and provide supplemental base flows to the estuary during periods of low run-off. The change to salinity envelope counts for the SLE is just as dramatic as the CRE, especially with respect to stress and damaging discharges from Lake Okeechobee

(Fig. 3), but the C-44 reservoir was included in the baseline and preferred alternatives. This does not negate the need for additional storage to curb basin/watershed stress and damaging or extreme discharge events since LOSOM only addresses Lake derived discharge. The combined effect of sustainable water management decisions and restoration infrastructure can provide flexibility to water management decisions, balance freshwater discharges and ensure a resilient estuary.

Climate combined with water management dictate conditions in the downstream estuary. In South Florida, due to the subtropical climate, there are distinct wet and dry seasons with episodic deviations from the average in the form of droughts and tropical activity (Obeysekera et al. 2007). Salinity patterns in the estuary also vary spatially and seasonally driven by freshwater either from watershed runoff or regulatory discharges from LOK (Fig S2). These conditions can have significant effects on benthic communities throughout the estuary. Benthic communities such as SAV have several different mechanisms to aid in recovery post-disturbance/stress (Douglass et al. 2020). For *Vallisneria*, recovery is a combination of a sufficient seed bank, recruitment success, grazing pressure, and balanced salinity conditions (Kraemer et al. 1999; Doering et al. 2002; Hauxwell et al. 2004; Moore et al. 2010; Boustany et al. 2010). Presumably, the most important driver of *Vallisneria* recovery, assuming a sufficient seed bank is established, is the balance of salinity conditions (Frazer et al. 2006; Boustany et al. 2010). As suggested by the VSI the preferred alternative, especially in the dry season, is much lower promoting less stressful salinity conditions for *Vallisneria* in the upper estuary (Table 4 and Fig. 4 and S2). This reduction in stress is a combination of changes to how and when the water is delivered to the estuary facilitated by better freshwater management afforded by the C-43 reservoir. The reservoir is a deep reservoir that allows for the reduction of high-flow events and supplemental freshwater flows in the dry season to maintain salinities in the estuary (Julian and Osborne 2018).

While the VSI index is specific to salinity stress on *Vallisneria* and salinity conditions in the upper estuary, given how freshwater is delivered to the estuary in the preferred alternative, benthic indicator species such as other SAV species and oysters are expected to have similar responses in reduced stress and damaging conditions (Fig. 3). Something not accounted for in the VSI or salinity metrics is the delivery of color or colored dissolved organic matter (CDOM) typically associated with freshwater discharges (Chen et al. 2015; Chen and Doering 2016). In the CRE, light attenuation is predominately regulated by CDOM in the upper estuary and turbidity in the more marine segments (Chen and Doering 2016). Therefore changes to freshwater discharges will ultimately affect the transport of CDOM to the upper estuary. Generally, in the preferred alternative (PA25), discharges are shifted to lower daily discharge values relative to NA25 (Fig S1) potentially indicating that the CDOM pressure will not dramatically increase in the upper estuary and not limit the growth of *Vallisneria* from a light requirement perspective.

In the complex water management regime of south Florida, the northern estuaries and the Caloosahatchee specifically are often thought of as the release valve of the system. While the physical capacity of the CR and its estuary can move significant volumes of water from Lake Okeechobee, ecologically high-volume freshwater discharges can significantly impact the health and function of the ecosystem (Buzzelli et al. 2014, 2015). Under CERP, critical project components combined with water management strategies aim to create or maintain critical hydrologic characteristics conducive to supporting the health and diversity of the estuarine ecosystem (RECOVER 2020). The revised Lake Okeechobee Regulation Schedule (i.e. LOSOM; this study) is a major shift in how freshwater discharges are managed to the Northern Estuaries by providing more sustainable discharge conditions and hopefully developing more ecologically resilient estuaries.

While this regulation schedule does overall improve conditions for the estuaries relative to past regulation schedules, upstream Lake Okeechobee carries the burden with more frequent high water level events and potentially stressed ecology (Julian and Welch 2022). Future restoration and water management strategies are needed to maintain the benefits afforded to the estuaries while at the same time reducing the stress and damage to Lake Okeechobee. Another factor not considered in the planning effort or this analysis is future climate conditions over the next decade or more. How water is managed in the future in light of climate change will be the largest determinant of near-term health across the entire system but Lake Okeechobee especially. Given the changing climate, future management and restoration efforts must build adaptability and flexibility into how water is managed across the system with an eye on the health of the ecosystem whilst at the same time providing robust water supply and flood protection. The revised plan does acknowledge the potential effects of extreme conditions and includes an optional operational strategy to be used to provide a recovery period for the lake and to some extent the estuaries. However, these modest, optional, and infrequent (at best) operational changes are unlikely to replace the long-term need for additional watershed storage. Therefore future efforts are needed to focus on water storage and treatment within the greater Everglades ecosystem to improve water quantity and quality conditions along with improved distribution and timing.

Declarations

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Conflict of Interest

The author(s) declare that they have no conflict of interest

References

1. Alber M (2002) A conceptual model of estuarine freshwater inflow management. Estuaries 25:1246–1261. https://doi.org/10.1007/BF02692222

2. Barnes T (2005) Caloosahatchee Estuary conceptual ecological model. Wetlands 25:884. https://doi.org/10.1007/BF03173126
3. Boustany RG, Michot TC, Moss RF (2010) Effects of salinity and light on biomass and growth of Vallisneria americana from Lower St. Johns River, FL, USA. Wetlands Ecol Manage 18:203–217. https://doi.org/10.1007/s11273-009-9160-8
4. Bras RL, Ponce VM, Sheer D (2019) Peer review of the Regional Simulation Model. South Florida Water Management District, West Palm Beach, FL
5. Buzzelli C, Doering PH, Wan Y, et al (2014) Modeling ecosystem processes with variable freshwater inflow to the Caloosahatchee River Estuary, southwest Florida. I. Model development. Estuarine, Coastal and Shelf Science 151:256–271. https://doi.org/10.1016/j.ecss.2014.08.028
6. Buzzelli C, Gorman P, Doering P, et al (2015) The application of oyster and seagrass models to evaluate alternative inflow scenarios related to Everglades restoration. Ecological Modelling 297:154–170. https://doi.org/10.1016/j.ecolmodel.2014.10.029
7. Chen Z, Doering PH (2016) Variation of light attenuation and the relative contribution of water quality constituents in the Caloosahatchee River Estuary. Florida Scientist 17
8. Chen Z, Doering PH, Ashton M, Orlando BA (2015) Mixing Behavior of Colored Dissolved Organic Matter and Its Potential Ecological Implication in the Caloosahatchee River Estuary, Florida. Estuaries and Coasts 38:1706–1718. https://doi.org/10.1007/s12237-014-9916-0
9. Chin DA, Dracup JA, Jones NL, et al (2005) Peer Review of the Regional Simulation Model. South Florida Water Management District, West Palm Beach, FL
10. Dinno A (2015) Dunn's test of multiple comparisons using rank sums. CRAN R-Project
11. Doering PH (1996) Temporal variability of water quality in the st. Lucie Estuary, South Florida. J Am Water Resources Assoc 32:1293–1306. https://doi.org/10.1111/j.1752-1688.1996.tb03498.x
12. Doering PH, Chamberlain RH (1999) Water Quality and Source of Freshwater Discharge to the Caloosahatchee Estuary, Florida1. JAWRA Journal of the American Water Resources Association 35:793–806. https://doi.org/10.1111/j.1752-1688.1999.tb04175.x
13. Doering PH, Chamberlain RH, Haunert DE (2002) Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee estuary, Florida. Estuaries 25:1343–1354. https://doi.org/10.1007/BF02692229
14. Douglass JG, Chamberlain RH, Wan Y, Doering PH (2020) Submerged Vegetation Responses to Climate Variation and Altered Hydrology in a Subtropical Estuary: Interpreting 33 Years of Change. Estuaries and Coasts 43:1406–1424. https://doi.org/10.1007/s12237-020-00721-4
15. Frazer TK, Notestein SK, Jacoby CA, et al (2006) Effects of storm-induced salinity changes on submersed aquatic vegetation in Kings Bay, Florida. Estuaries and Coasts: J ERF 29:943–953. https://doi.org/10.1007/BF02798655
16. Gohel D (2021) flextable: Functions for Tabular Reporting

17. Hauxwell J, Frazer T, Osenberg C (2004) Grazing by manatees excludes both new and established Wild Celery transplants: Implications for restoration in Kings Bay, FL, USA. Journal of Aquatic Plant Management 42:49–53
18. Havens KE, James RT (2005) The Phosphorus Mass Balance of Lake Okeechobee, Florida: Implications for Eutrophication Management. Lake and Reservoir Management 21:139–148. https://doi.org/10.1080/07438140509354423
19. Herbert DA, Perry WB, Cosby BJ, Fourqurean JW (2011) Projected Reorganization of Florida Bay Seagrass Communities in Response to the Increased Freshwater Inflow of Everglades Restoration. Estuaries and Coasts 34:973–992. https://doi.org/10.1007/s12237-011-9388-4
20. Ji Z-G, Hu G, Shen J, Wan Y (2007) Three-dimensional modeling of hydrodynamic processes in the St. Lucie Estuary. Estuarine, Coastal and Shelf Science 73:188–200. https://doi.org/10.1016/j.ecss.2006.12.016
21. Julian P, Osborne TZ (2018) From lake to estuary, the tale of two waters: A study of aquatic continuum biogeochemistry. Environment Monitoring and Assessment 190:1–24. https://doi.org/10.1007/s10661-017-6455-8
22. Julian P, Welch Z (2022) Understanding the ups and downs, application of hydrologic restoration measures for a large Subtropical Lake. Lake and Reservoir Management 38:304–317. https://doi.org/10.21203/rs.3.rs-1739423/v2
23. Kraemer GP, Chamberlain RH, Doering PH, et al (1999) Physiological responses of transplants of the freshwater angiosperm Vallisneria americana along a salinity gradient in the Caloosahatchee Estuary (Southwestern Florida). Estuaries 22:138–148. https://doi.org/10.2307/1352934
24. Lee SY, Dunn RJK, Young RA, et al (2006) Impact of urbanization on coastal wetland structure and function. Austral Ecol 31:149–163. https://doi.org/10.1111/j.1442-9993.2006.01581.x
25. Milbrandt EC, Bartleson RD, Martignette AJ, et al (2016) Evaluating light attenuation and low salinity in the lower Caloosahatchee Estuary with the River, Estuary, and Coastal Observing Network (RECON). Florida Scientist 16
26. Moncada AM, Melesse AM, Vithanage J, Price RM (2021) Long-Term Assessment of Surface Water Quality in a Highly Managed Estuary Basin. International Journal of Environmental Research and Public Health 18:9417. https://doi.org/10.3390/ijerph18179417
27. Moore KA, Shields EC, Jarvis JC (2010) The Role of Habitat and Herbivory on the Restoration of Tidal Freshwater Submerged Aquatic Vegetation Populations. Restoration Ecology 18:596–604. https://doi.org/10.1111/j.1526-100X.2010.00699.x
28. Newton A, Icely J, Cristina S, et al (2020) Anthropogenic, Direct Pressures on Coastal Wetlands. Frontiers in Ecology and Evolution 8:
29. Obeysekera J, Irizarry M, Park J, et al (2011) Climate change and its implications for water resources management in south Florida. Stoch Environ Res Risk Assess 25:495–516. https://doi.org/10.1007/s00477-010-0418-8

30. Obeysekera J, Trimble P, Neidrauer C, Cadavid L (2007) Consideration of Climate Variability in Water Resources Planning & Operations – South Florida's Experience. https://doi.org/10.1061/40927(243)70
31. Qiu C, Wan Y (2013) Time series modeling and prediction of salinity in the Caloosahatchee River Estuary. Water Resources Research 49:5804–5816. https://doi.org/10.1002/wrcr.20415
32. RECOVER (2020) Northern Estuaries Performance Measure: Salinity Envelope. US Army Corp of Engineers, Jacksonville, FL
33. Santos RO, Lirman D (2012) Using habitat suitability models to predict changes in seagrass distribution caused by water management practices. Can J Fish Aquat Sci 69:1380–1388. https://doi.org/10.1139/f2012-018
34. Sime P (2005) St. Lucie Estuary and Indian River Lagoon conceptual ecological model. Wetlands 25:898. https://doi.org/10.1672/0277-5212(2005)025[0898:SLEAIR]2.0.CO;2
35. Sklar FH, Browder JA (1998) Coastal Environmental Impacts Brought About by Alterations to Freshwater Flow in the Gulf of Mexico. Environmental Management 22:547–562. https://doi.org/10.1007/s002679900127
36. South Florida Water Management District (2020) Technical Document to support the Central Everglades Planning Project: Everglades Agricultural Area Reservoir Water Reservation. South Florida Water Management District, West Palm Beach, FL
37. Stein ED, Gee EM, Adams JB, et al (2021) Advancing the Science of Environmental Flow Management for Protection of Temporarily Closed Estuaries and Coastal Lagoons. Water 13:595. https://doi.org/10.3390/w13050595
38. Steinman AD, Rosen BH (2000) Lotic–lentic linkages associated with Lake Okeechobee, Florida. Journal of the North American Benthological Society 19:733–741. https://doi.org/10.2307/1468130
39. Sun D, Wan Y, Qiu C (2016) Three dimensional model evaluation of physical alterations of the Caloosahatchee River and Estuary: Impact on salt transport. Estuarine, Coastal and Shelf Science 173:16–25. https://doi.org/10.1016/j.ecss.2016.02.018
40. Tarabih OM, Arias ME (2021) Hydrological and Water Quality Trends through the Lens of Historical Operation Schedules in Lake Okeechobee. Journal of Water Resources Planning and Management 147:04021034. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001395
41. Tibby J, Haynes D, Gibbs M, et al (2022) The terminal lakes of the Murray River, Australia, were predominantly fresh before large-scale upstream water abstraction: Evidence from sedimentary diatoms and hydrodynamical modelling. Science of The Total Environment 835:155225. https://doi.org/10.1016/j.scitotenv.2022.155225
42. Volety AK, Savarese M, Tolley SG, et al (2009) Eastern oysters (Crassostrea virginica) as an indicator for restoration of Everglades Ecosystems. Ecological Indicators 9:S120–S136. https://doi.org/10.1016/j.ecolind.2008.06.005

Figures

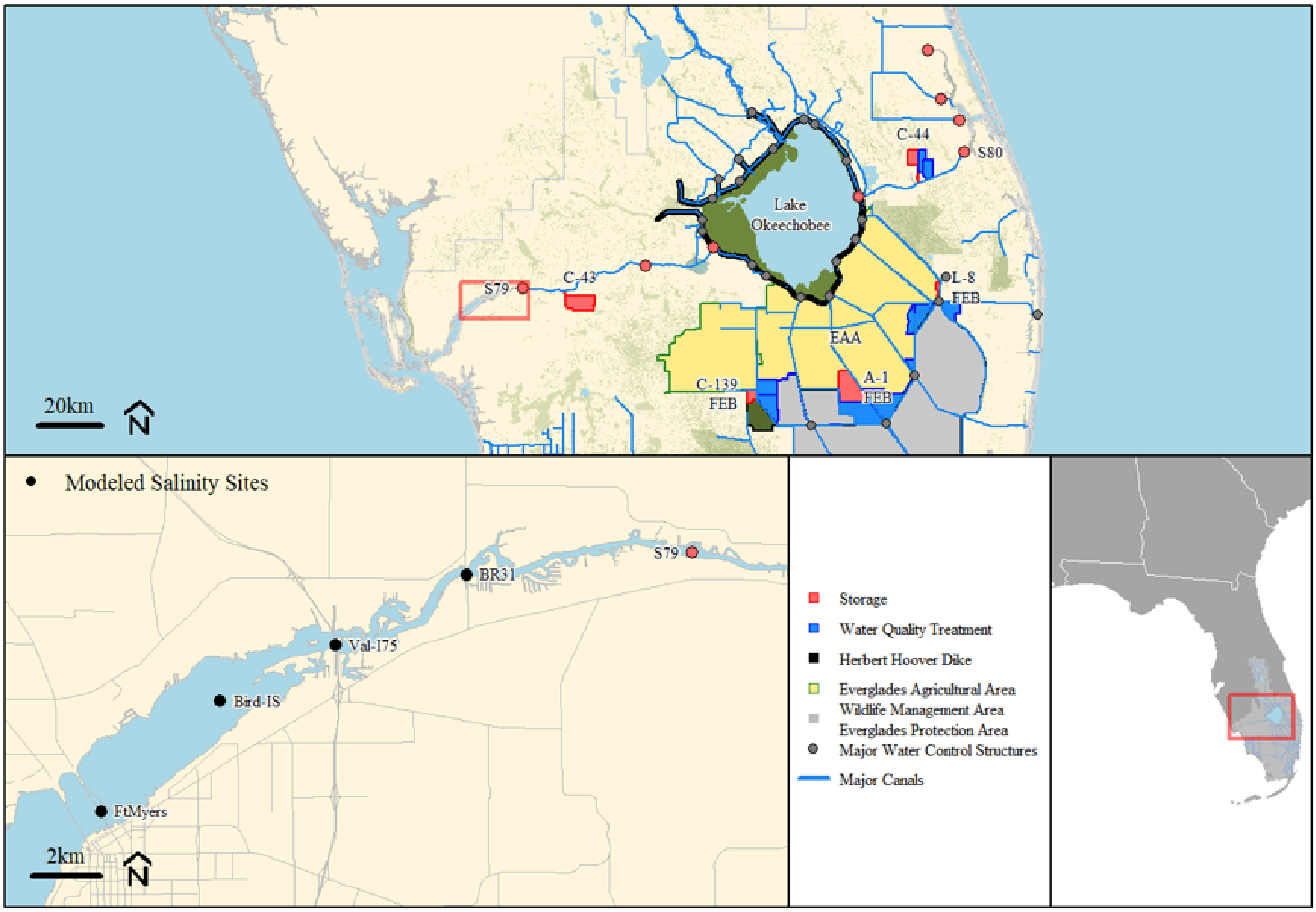

Figure 1

Top: Overview of south-central Florida with storage, water quality, and major infrastructure identified specific to features in the Lake Okeechobee System Operation Manual Planning effort. Bottom left: Caloosahatchee River upper estuary modeled salinity monitoring locations.

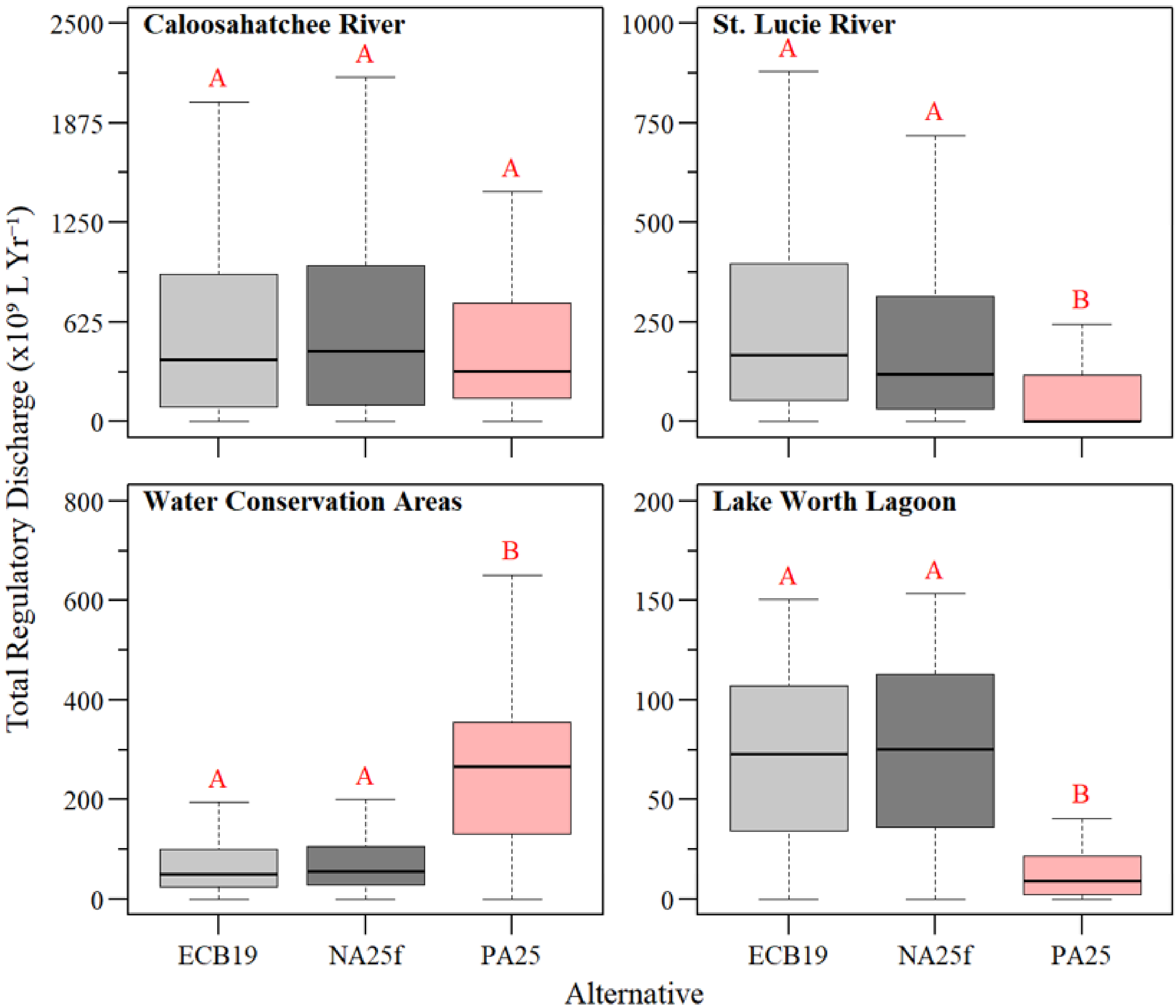

Figure 2

Boxplot of annual regulatory discharges from Lake Okeechobee to the Caloosahatchee River (S-77), St. Lucie River (S-308), Water Conservation Areas (S-351 and S-352) and Lake Worth Lagoon (S-271) for existing condition baseline (ECB19), no-action baseline (NA25f), and preferred alternative (PA25) observed during the period of simulation. The letters above boxplots indicate pairwise comparisons between alternatives using Dunn's test of multiple comparisons.

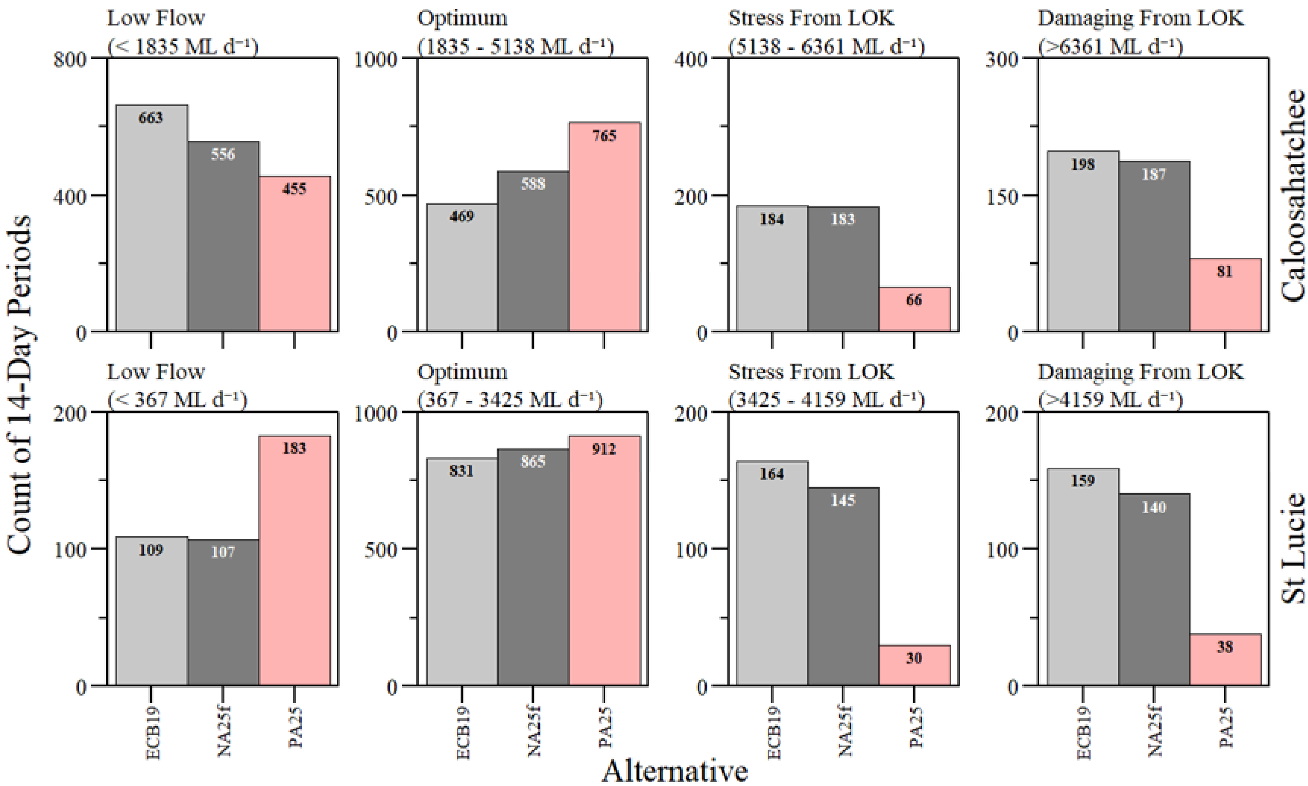

Figure 3

Caloosahatchee (S-79; top) and St. Lucie (S-80; bottom) estuary discharge envelope 14-day event count for low, optimum, stress from Lake Okeechobee (LOK) and Damaging from LOK during the 52-year simulation period of record across the baseline conditions and preferred alternative. Alternatives include the existing condition baseline (ECB19) no-action baseline (NA25f), and preferred alternative (PA25).

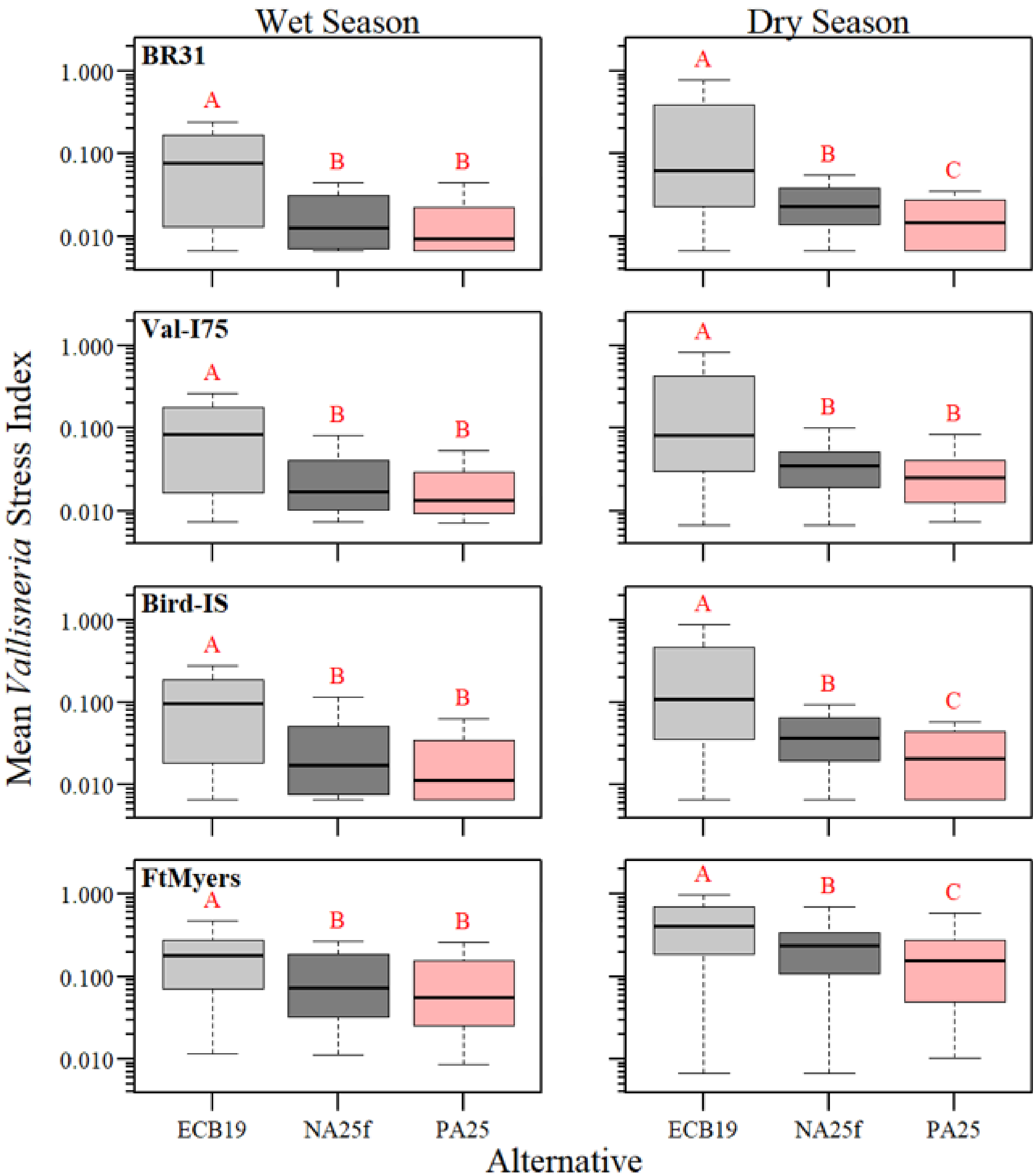

Figure 4

Boxplot of seasonal (wet and dry season) mean *Vallisneria*Stress Index for existing condition baseline (ECB19), no-action baseline (NA25f), and preferred alternative (PA25) observed during the period of simulation at salinity simulation sites (Fig 1) in the upper Caloosahatchee River Estuary. The letters above boxplots indicate pairwise comparisons between alternatives using Dunn's test of multiple comparisons.

Supplementary Files

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