Understanding the ups and downs: application of hydrologic restoration measures for a large subtropical lake

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ABSTRACT
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Hydrologic regimes in shallow lakes strongly influence the system’s function and ecology. Changes in water levels can have nonlinear, disproportionate effects in these low-gradient systems. High water levels can submerge upper elevation littoral areas, degrade benthic habitats, and redistribute sediments and nutrients throughout the lake. When water levels are low, wetland littoral areas are dried out, prompting shifts in plant communities. Lake Okeechobee, a large shallow lake, is a diverse and complex ecosystem managed for multiple purposes. Currently, water levels within the lake are managed based on the Lake Okeechobee Regulation Schedule of 2008, which is being replaced as restoration projects now are complete. 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 estuaries; and more water for the southern Everglades. This study evaluates LOSOM relative to ecologically significant performance measures for the lake. Overall, the proposed regulation schedule is expected to cause deeper average lake levels, increased occurrence of damaging high-stage events, and reduced frequency of low-stage events. While decreases in the severity and frequency of low stages will be beneficial, increases in high stages may affect the long-term ecology of the system. As lake management shifts to optimize restoration efforts around and downstream of Lake Okeechobee, restoration projects upstream of the lake become critical to building and improving resilience in this central South Florida ecosystem.

Water management and regional flood control projects can have significant influences on the hydrology and ecology of lakes, reservoirs, and downstream ecosystems (Havens 2002, Richter et al. 2003, Suen and Eheart 2006). Lakes and reservoirs provide similar ecosystem benefits but differ in the functioning of basic physical, chemical, and biological processes. A primary driver of these differences is linked to hydrology and water level fluctuations (Tundisi 2018), both of which can be dramatically altered through water management practices. For example, the alteration of river flow regimes associated with dam operation has been identified as one of the leading factors influencing aquatic animals within reservoirs and downstream systems (Pringle et al. 2000). Modern water management has to balance both the human needs, such as water supply and flood protection, and the ecological needs of a functioning ecosystem that better benefits society (von Korff et al. 2012, Cosgrove and Loucks 2015).

Lake Okeechobee (Florida, United States) is a large, shallow, subtropical lake that has been extensively studied, both as a major component of the regional (Central and Southern Florida [C&SF]) flood-control project and in terms of its importance to water supply, but primarily due to its being plagued by non-point source nutrient inputs over the last century. Before the construction of the south rim of the Herbert Hoover Dike (HHD) in the 1930s, Lake Okeechobee was unconstrained and in wet periods covered more than 2000 km². However, the present-day hydrology of Lake Okeechobee is entirely novel; the
HHD encloses the majority of the lake, and water levels are kept approximately 0.6–1.5 m lower than historically, controlled by water control structures at several major outlets (Fig. 1; Steinman and Rosen 2000, Havens 2002). Water levels in the lake are regulated by a Water Control Plan developed by the US Army Corps of Engineers (USACE) in cooperation with the South Florida Water Management (SFWMD). This plan includes regulatory (flood control) discharges, water supply deliveries to permitted users, and deliveries (ecological water supply) for water quality protection in downstream ecosystems (Steinman et al. 2002). When lake stages are high (>4.6 m National Geodetic Vertical Datum of 1929 [NGVD29]), water reaches the foot of the levee and begins to function as a reservoir as floodwaters are contained within the perimeter of the levee. This results in flooding the vast majority of the littoral wetland footprint and increasing the depth of water over shallow marshes (Fig. 1). When stages are low (<3.7 m NGVD29), much of the littoral marsh is dry and hydrologically disconnected from other portions of the lake (Havens and Gawlik 2005). The spatial extent and composition of the littoral zone in Lake Okeechobee are largely determined by the lake stage and are affected by climatic conditions, weather events, and the water control plan that is in place. As such, hydrologic restoration goals were developed roughly 20 yr ago to guide water management decisions for this regionally critical waterbody (Havens 2002).

**Ecological conceptual models**

There are several ecologically distinct regions of Lake Okeechobee, driven by spatial heterogeneity...
of hydrologic, biogeochemical, and biotic characters, so two conceptual models were developed to summarize the effects of hydrologic variation within the lake. Spatially the lake can be broken into three distinct zones: limnetic/pelagic, nearshore, and littoral. The central limnetic region is the deepest portion of the lake (mean water depth of 2.7 m; Steinman and Rosen 2000), with predominantly turbid, nutrient-rich water resulting primarily from sediment suspension processes (Havens et al. 2007). This region is devoid of vascular plants, and low-light adapted phytoplankton are the dominant primary producers. Changes in lake stage do have the potential to influence turbidity and water column phosphorus concentration in this region to some extent (Maceina 1993, Havens and Walker 2002, Havens and Gawlik 2005), but water management and restoration efforts will have the greatest effect on the nearshore and littoral zones, where small changes can have profound ecological effects due to nutrient transport and bathymetric gradients (Havens and Gawlik 2005).

The nearshore conceptual model accounts for a shallow nearshore region adjacent to the limnetic zone where ecological conditions are sensitive to changes in lake stage (Havens 2002). This region is the middle ground between the relatively “deeper” limnetic zone and the higher littoral shelf within the lake. Generally, when stages exceed 4.6 m NGVD29, wind-driven currents can transport sediment and nutrient-rich water to the nearshore environment, thereby affecting light attenuation characteristics with algal biomass and nonliving seston (Havens 2002). However, this threshold may vary spatially across the lake; for example, the southern littoral zone may be more sensitive relative to 4.0–4.3 m NGVD29 (Maceina 1993, Havens and Walker 2002). The attenuation of light reaching the benthos at higher water levels can cause reductions and/or loss of submerged aquatic vegetation (SAV), which can further increase turbidity and nutrient release, creating positive feedback loops. Alternatively, when stages are below 4.6 m NGVD29, transport of nutrients and sediment to the nearshore zone is reduced by bathymetric features, including rocky shoals in the southern portion of the lake (Rivero et al. 2020), resulting in improved light penetration, facilitating the persistence of SAV and its self-sustaining feedback loops as well (Havens et al. 2004).

The littoral zone itself is a large (~400 km²) wetland mosaic that supports a diverse array of habitat types, from moist-soil flats of beak rushes (Rhynchospora spp.) and sand cordgrass (Spartina bakerii) at high elevations, to permanently flooded fringes of giant bulrush (Schoenoplectus californicus), Egyptian paspalidium (Paspalidium geminatum), and maidencane (Panicum hemitomon), grading to floating aquatic vegetation to SAV at roughly 1.5 m downslope (Havens and Gawlik 2005, Johnson et al. 2007). When lake stages are low (<3.3 m NGVD29), all but the fringing bulrush zone, SAV, and interior bays are close to dried-out conditions, with any flooded portions within the marshes hydrologically isolated from the nearshore and limnetic areas. However, when lake stages are very high (>5.2 m NGVD29), sediment and nutrients can be carried by the lake’s large fetch and transported into the littoral zone, causing enriched phosphorus (P) conditions and facilitating the spread of nutrient tolerant species such as cattails (Typha spp.) and other nuisance or invasive plants (Johnson et al. 2007). Increased total-P inputs also influence periphyton communities, shifting the dominance to more eutrophic species, resulting in a cascade of effects that can shift basal foodweb structure in this zone (Carrick and Steinman 2001, Rodusky et al. 2001, Rodusky 2010). High water levels also affect the density and spatial extent of emergent aquatic vegetation (EAV) at the outer edges of the littoral zone, reduce coverage of woody species within the higher marshes, and generally shift littoral communities upslope. If high water levels persist for long enough, this results in the loss of EAV and SAV coverage, reducing the spatial extent of the littoral ecosystem (Johnson et al. 2007).

Preferred lake water level fluctuations for the current configuration of the lake have been identified as an average high level at the end of the wet season of approximately 4.6 m NGVD29 and a low at the end of the dry season of approximately 3.6 m NGVD29 to support a healthy ecology (i.e., littoral vegetation, SAV, fishery; RECOVER 2020). Due to drainage in the lake’s watershed, the high level is exceeded during pronounced wet events, and the low level is exceeded.
during severe dry events, due to reduced base flow and high evaporation rates. Management of lake water levels through water control plans or regulation schedules can anticipate but not control these events; thus, there are frequent variations from optimal lake levels.

**Regulation schedules old and new**

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 (Fig. 2; Julian and Osborne 2018, Tarabih and Arias 2021). During the 1970s, levee improvements were made so that Lake Okeechobee could safely handle water levels between 4.7 and 5.3 m. In 1978, the regulation schedule was changed in response to federal US Fish and Wildlife consultation to maintain water levels between 4.7 and 5.6 m. In 1991, a regulation schedule called Run 25 was implemented to reduce high-volume discharges to the estuaries and changes in the littoral zone without affecting water users by maintaining lake levels between 4.8 and 5.1 m. Run 25 was then replaced by the Water Supply and Environment (WSE) schedule in 2000, which allowed for lower and higher lake stages, by maintaining water levels between 4.1 and 5.6 m. The goals of WSE were to decrease water discharges into the estuaries, decrease the frequency of littoral zone flooding, and also meet water users’ demands by allowing water levels to drop to lower than in antecedent schedules. Additionally, WSE was the first instance of a proactive decision tree guide that incorporated current lake conditions combined with short- and long-term inflow predictions. 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 lake level exceedances above 5.2 m, kept the lake below 4.9 m most of the time (Gray 2017), and identified several additional seasonal and operational bands to dictate water management decisions (Fig. 2).

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 was recently developed: 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. The objective of this study is to compare the modeled preferred alternative of the new Lake Okeechobee regulation schedule to baseline conditions, using the similar methods Havens (2002) developed to establish and evaluate restoration goals for the lake through stage-based metrics. Since the ecology of the lake is tightly linked to hydrodynamics, the implementation of this new, generally wetter regulation schedule may have predictable effects on this well-studied littoral ecosystem.

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 decision will be finalized sometime in mid 2023.

**Study site**

Lake Okeechobee (27°N, 81°W) is a large (1803 km²), shallow (mean depth 2.7 m), subtropical lake in south Florida (Fig. 1; Aumen 1995).
The lake can be divided broadly into 3 regions: (1) littoral, (2) nearshore, and (3) limnetic zones. The shallow nearshore and littoral region comprises one-third of the total surface area of the lake and contains a diverse plant community of emergent and submerged aquatic vegetation communities. The limnetic zone or open water region of the lake makes up the remaining two-thirds of the surface area. This limnetic portion in the central, north, and east has predominately

Figure 2. Lake Okeechobee Regulation Schedules and timeline from the early 1970s to 2022. Each zone or management band corresponds to prescribed management actions to change water levels within the lake by managing inflow and outflow discharges.
flocculent mud sediments (Fisher et al. 2001), which are a persistent source of turbidity and nutrients in the lake (Phlips et al. 1993, Harris et al. 2007, James et al. 2008). Peat sediments are found in the southern and western portions of the lake, while sand, rock, and peat are present around the periphery of the mud zone.

Materials and methods

Data source

Scenario modeling was conducted using the Regional Simulation Model—Basins (RSM-BN). The RSM 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 yr 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 yr 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 (SFWMD 2020).

In this evaluation, 3 alternatives were considered, including 2 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 were 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 just outlined for the NA25f alternative with water management being guided by the new LOSOM regulation schedule.

Data analysis

To evaluate the change in water management specific to Lake Okeechobee, and consistent with Havens (2002), 5 hydrology-based ecological performance measures were used to analyze the hydro-pattern associated with alternative plans. Lake stage performance measures (PMs 1–4; Table 1) scores were assigned based on the number of exceedance events per decade (Table 2). The fifth performance measure used to evaluate

| Performance measure | Description |
|---------------------|-------------|
| 1 Extreme-high lake stage (>5.18 m NGVD29/>17 Ft NGVD29) | This performance measure indicates the frequency of events that result in wind and wave damage to shoreline plant communities and transport phosphorus-rich water into oligotrophic interior regions of the littoral zone. |
| 2 Moderate-high lake stage (>4.88 m NGVD29/>16 Ft NGVD29) | This performance measure indicates the frequency of prolonged (>90 consecutive days) events that limit light penetration to the lake bottom, causing a loss of benthic plants and algae, and transport phosphorus-rich water to the nearshore zone. |
| 3 Moderate-low lake stage (<3.35 m NGVD29/<11 Ft NGVD) | This performance measure indicates the frequency of prolonged (>90 consecutive days) events that substantially reduce the littoral zone area as habitat for aquatic biota and promote exotic plant expansion. |
| 4 Extreme-low lake stage (<3.05 m NGVD29/<10 Ft NGVD) | This performance measure indicates the frequency of events that result in the loss of the littoral zone as habitat for aquatic biota and promote exotic plant expansion. |
| 5 Spring recession rate | This performance measure indicates the number of years with recession rate between −0.02 and 0.02 m/week (−0.05 to 0.05 ft/week) for more than a quarter of the spring/snail kite nesting period (1 Mar–15 Jun). |
The occurrence and duration of particular stage events varied between the different alternatives including the 2 baseline conditions. Under the ECB19 condition, there were relatively high occurrences of extreme-low and moderate-low water level recession/accession rates was modified from an overall seasonal range of stage decline (Havens 2002) to a more specific metric developed by the US Fish and Wildlife Service, regarding peak nesting season requirements of the endangered Everglade snail kite (*Rostrhamus sociabilis plumbeus*). This PM evaluates rates of water level change during the 1 March to 15 June nesting period (PM5; Table 1) and has higher scores corresponding to a greater number of events that met recession/ascension targets (Table 2). Lake stage performance measures were based on consecutive days above or below each respective threshold. Lake recession/accession rates were calculated on a moving 7 d stage difference throughout the entire period of simulation. Each individual performance measure was scored based on average events per decade:

\[
\text{total events} = (10 \text{ yrs}) / (52 \text{ weeks / yr})
\]

(1)

(see scores, Table 2). This method of scoring assumed that the severity of effects increase in a nonlinear manner as events become more frequent. Consistent with Havens (2002), the overall weighted score for each alternative (i) is calculated using equation 2:

\[
S_i = \frac{(PM1\times5) + (PM2\times5) + (PM3\times4) + (PM4\times4) + (PM5\times3)}{21}
\]

(2)

where \(S_i\) range from 0 (severe stress/damaging conditions) to 1.0 (healthy/optimal conditions), and the PM terms correspond to the previously defined performance measures (Table 1).

Performance measures related to high lake stage (PMs 1 and 2) were further analyzed with survival regressions to estimate and compare the probability of those occurrences within a given year. Performance measure 2 represented the probability that moderate-high (4.9 m NGVD29; Table 1) stage events lasting greater than 90 d (3 months) would occur, while PM 1 represented the probability of extreme-high (5.2 m NGVD29) stage events within a given year. The Kaplan–Meier (KM) method was used to estimate survival, or the probability of a PM-related event not occurring. In this case, it is the probability of moderate-high events >90 d or consecutive extreme-high events not occurring. The “survfit” function in the “survival” R-package was used (Therneau 2020). Survival curves were compared using a log-rank test ("survdiff" function in the “survival” R-package). Additionally, Cox proportional hazards regression was applied to the same data to evaluate the occurrence of moderate-high events >90 d or consecutive extreme-high events happening and to estimate the hazard ratio between NA25f and PA25 modeling alternatives. To test the proportional hazards assumption of the cox regressions, the “cox.zph” function was applied to each model.

Annual maximum stage was estimated for each model alternative during the period of simulation. Return frequency of extreme- and moderate-high stage events was estimated using the L-moment Log Pearson type III (LP3) distribution (Griffis and Stedinger 2009, Hosking 2019). To compare the return frequencies between alternatives, bootstrapping was conducted to sample 90% of the data for 500 replications. Pairwise comparison of the bootstrapped return intervals for extreme- and moderate-high stage events was compared using Dunn’s test of multiple comparisons (Dinno 2015).

### Results

#### Performance measure score

The occurrence and duration of particular stage events varied between the different alternatives including the 2 baseline conditions. Under the ECB19 condition, there were relatively high occurrences of extreme-low and moderate-low

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**Table 2.** Lake Okeechobee stage-based performance measure (PM) scores adapted from Havens (2002) for each performance measure presented in Table 1.

| Performance measures | Events per decade | Score |
|----------------------|-------------------|-------|
| PM 1–4               | 0                 | 1.0   |
|                      | 1                 | 0.8   |
|                      | 2                 | 0.7   |
|                      | 3                 | 0.5   |
|                      | 4                 | 0.4   |
|                      | 5                 | 0.2   |
| ≥6                   | 0                 | 0.0   |
| PM 5                 | 10                | 1.0   |
|                      | 9                 | 0.8   |
|                      | 8                 | 0.6   |
|                      | 7                 | 0.4   |
|                      | 6                 | 0.1   |
| ≤5                   | 0                 | 0.0   |

Nonlinear score curves are presented in Fig. S1.
stage events during the period of simulation (12 and 10 events, respectively; Fig. 3). This event count corresponds to an average of 2.3 and 1.9 events per decade for extreme-low and moderate-low stage events, respectively (Table 3). Extreme- and moderate-high stage events were less frequent during ECB19, with only 3 events for each category (Fig. 3) during the period of simulation (0.6 events per decade; Table 3). Ideal spring recession occurred on average as 6.7 events per decade during the period of simulation (35 events). The overall score for this alternative was 0.73 out of a possible 1.0 (Fig. 4).

Under the NA25f condition, extreme-low and moderate-low events were reduced relative to ECB19 with 10 and 8 events during the period of simulation (Fig. 3). This corresponds to an average of 1.9 and 1.5 per decade for extreme-low and moderate-low events, respectively (Table 3). Extreme- and moderate-high events only shifted slightly, with 4 and 2 events observed during the

| Alternative | Extreme-high stage | Moderate-high stage | Moderate-low stage | Extreme-low stage | Spring recession rate |
|-------------|-------------------|---------------------|-------------------|------------------|---------------------|
| ECB19       | 0.6               | 0.6                 | 1.9               | 2.3              | 6.7                 |
| NA25f       | 0.8               | 0.4                 | 1.5               | 1.9              | 7.3                 |
| PA25        | 1.9               | 3.1                 | 1.5               | 2.3              | 5.6                 |

In the PA25 condition, extreme- and moderate-high stage events increased substantially relative to both baseline conditions, with 10 and 16 events observed during the period of simulation (average of 1.9 and 3.1 events per decade, respectively; Fig. 3 and Table 3). Moderate- and extreme-low stage events were relatively similar to baseline conditions, with 8 and 12 events observed during the period of simulation (average of 1.5 and 2.1 events per decade, respectively; Table 3). Ideal spring recession rates occurred on average as 5.6 events per decade during the period of simulation (29 events). The overall score for the PA25 alternative was 0.55 out of a possible 1.0, indicating significant ecological stress (Fig. 4). The biggest discrepancy was the nearly doubling or tripling of...
Survival and hazard analysis

Consecutive extreme-high stage event survival curves (Fig. 5) were not significantly different between the 3 alternatives ($\chi^2 = 3.9; \ df = 2; \ P = 0.14$), despite the PA25 having more observed events (Table 3). During the 52 yr stimulation period of record, the survival probability of consecutive extreme-high stage events for ECB19, NA25f, and PA25 was 88.5%, 81.1%, and 0%, respectively. These survival probabilities indicate that PA25 has a higher probability of extreme-high stage events occurring. The extreme-high stage events relative to baseline conditions (either ECB19 or NA25f).

Figure 4. Lake stage-based weighted ecological performance measure scores for existing condition baseline (ECB19), no-action baseline (NA25f), and preferred alternative (PA25) observed during the period of simulation. Overall weighted score range from 0.0 (severe stress/damaging conditions) to 1.0 (healthy/optimal conditions).

Figure 5. Survival probability curve of extreme-high stage events and moderate-high stage events greater than 90 d for each alternative during the 52 yr simulated period of record.
event hazard ratio was 2.25 but was not statistically significant \((z = 1.35, P = 0.18)\).

Moderate-high stage event survival curves (Fig. 5) were significantly different between the 3 alternatives \((\chi^2 = 14.1; df = 2; P < 0.01)\). During the 52 yr stimulation period of record, the survival probability of a moderate-high stage event greater than 90 d for ECB19, NA25f, and PA25 was 88.5%, 93.4%, and 0%, respectively. These survival probabilities indicate that PA25 has a higher probability of moderate-high stage events >90 d occurring. The hazard ratio based on Cox proportional regression of moderate-high stage events for >90 d was 7.0 \((z = 2.6, P < 0.01)\), suggesting that with the PA25 alternative it is 7 times more likely that moderate-high stage events for >90 d will occur relative to NA25f.

**Return interval**

The estimated return interval for extreme-high stages varied from 5.5 to 27.4 yr during the 52 yr period of simulation and was significantly different across all alternatives \((\chi^2 = 1219.1, df = 2, P < 0.01;\) Fig. 6). The return interval for the PA25 condition (5.5 yr) was significantly lower than for the ECB19 (27.4 yr; \(z\)-score = 34.8, \(P < 0.01\)) and NA25f (17.3 yr; \(z\)-score = 20.0, \(P < 0.01\)). Moreover, there was a significant difference between baseline conditions \((z\)-score = 14.8, \(P < 0.01\)). The estimated return interval for moderate-high stages varied from 2.5 to 4.1 yr during the simulation period, with significant differences between both baseline conditions and PA25 \((\chi^2 = 999.7, df = 2, P < 0.01;\) Fig. 6).

**Discussion**

Processes in the littoral and nearshore zone are crucial for the overall conditions and stability of lake ecosystems (Burks et al. 2006, Jeppesen et al. 2014). As observed in Lake Okeechobee (Havens et al. 2004) and elsewhere (Keto et al. 2008), changes in water levels can greatly affect biota in the littoral and nearshore zones. For example, SAV coverage (vascular and nonvascular species) has varied from as little as 9.0 km² to more than 240 km² in a roughly 20 yr period on the lake. This 2 decade period included record low water levels and multiple hurricane events (Welch et al. 2021). Similarly, the size of the emergent littoral marsh has waxed and waned over the same period in response to changes in water levels.

Changes in water levels are an important factor affecting the functioning of lake and wetland ecosystems (Coops et al. 2003, Burks et al. 2006, Beklioglu et al. 2007, Jeppesen et al. 2014). Water levels and depth regulate the hydrodynamics, light attenuation, nutrient transport, littoral zone vegetation dynamics, limnetic zone algae dynamics, and other lake processes (Havens and Gawlik 2005, Johnson et al. 2007, James et al. 2008, Mjelde et al. 2013, Bakker and Hilt 2016). The 5 performance measures used in this study (Table 1 and Fig. 4) and in Havens (2002) address how water level and its seasonal variation affect the intrinsic ecological and societal values of Lake Okeechobee. The variable weighting of performance measures to indicate an overall level of stress and/or benefit reflects that not all hydrological events have similar effects. As discussed earlier, extreme or prolonged high water levels can affect numerous ecosystem attributes across the lake (Steinman et al. 2001, Havens and Gawlik 2005, Havens and Steinman 2015),
some of which may require periods of low water to offset the effects (e.g., extirpated SAV beds, loss of woody species), or, at the very least, long return intervals between these stressful events. Meanwhile, low lake levels also cause harm to the lake (and reliant downstream resources), but the effects are generally isolated to the littoral and nearshore zones. Additionally, infrequent low lake stages can be beneficial in oxidizing organic detritus, facilitating fire management, and promoting seed germination and SAV expansions or recovery. Low water levels have also been implemented to counter plant community impacts resulting from extreme-high events (Havens et al. 2001).

Under both baseline conditions, water levels were relatively low and rarely exceeded extreme- and moderate-high water level thresholds, and more often exceeded low stage thresholds (Table 3 and Fig. S3), with overall weighted scores suggesting potential stressed conditions (Fig. 4). Meanwhile, the preferred alternative (PA25) showed more frequent extreme- and moderate-high water levels, primarily through limiting discharges across a broader range of lake stages than under baseline conditions. This operational strategy makes conservative releases under most conditions, which permits water levels to fluctuate considerably, rather than targeting specific lake stages, which would require considerable fluctuations in discharge. However, prioritizing release rates over lake stage targets makes it harder to provide optimal water levels for lake ecology (Table 3, Figs. 3 and 4). The weighted score for PA25 suggests significantly stressed conditions from a hydrologic standpoint, which are primarily driven by high lake stage events (Fig. 5), an obvious effect of discharge constraints. Moreover, the expected return period of moderate and high stage events in PA25 is significantly reduced from both baseline conditions, suggesting less recovery time between events. This could lead to less favorable antecedent ecological conditions at the onset of impacts, and possible increases in overall effects as a result (Fig. 6).

Ideally, return intervals between stressful or damaging events would be long enough to allow for recovery of affected resources, for example, degraded SAV beds, to recover root and shoot biomass, or for fish populations to have a strong spawn and recruitment year. The duration required of a recovery period can vary depending on the affected attribute and other circumstances (i.e., extent and duration of high/low events, climatic variability, light attenuation, nutrient load, other disturbances). The recovery of aquatic plants, for example, is a complex interaction of abiotic factors and species growth requirements (Bornette and Puijalon 2011), and is often the first critical step to any subsequent faunal recoveries. After a regional drought that followed a period of prolonged high lake stage, Havens et al. (2004) characterized SAV community succession (based on vascular plant assemblages and biomass) on the lake as having a recovery period of 2 to 3 yr even when extremely low water levels occur, which was consistent with other studies (Scheffer and van Nes 2007). When return intervals of stressful or damaging high water events are too short, or if periods of low water and recovery do not occur between them, relatively short-term impacts can stretch into multiyear, threshold events, even causing long-term population crashes for higher level fauna (Havens et al. 2005, Fletcher et al. 2021, Essian et al. 2022). While PA25 is not intended to serve as a restoration project, but rather as a means to better balance water between Lake Okeechobee and downstream systems, this regulation schedule will affect the ecological function of the lake, especially in wetter climatic conditions. As proposed, the regulation schedule has the potential to reduce the resilience of lake ecological communities from baseline conditions, arguably moving away from the goals of CERP for Lake Okeechobee (Havens 2002).

In the complex water management regime of south Florida, Lake Okeechobee is easily and often necessarily thought of as a natural reservoir. While the lake does hold significant volumes of water, it is more than a waterbody encircled by a levee; it is a complex, novel ecosystem that can support abundant fisheries and prolific avian fauna (Johnson et al. 2007), despite the enormity of change endured over the last century and more. As envisioned in the CERP, water levels were expected to be managed up to 4.6 m NGVD29 with improved conditions from a
hydrologic standpoint, providing benefits afforded to water quality and biological components of the ecosystem (Havens 2002). However, the revised Lake Okeechobee regulation schedule (i.e., LOSOM; this study) and future restoration projects (Lake Okeechobee Watershed Restoration Plan; USACE 2022) are expected to cause higher water levels and with greater frequency, potentially reducing earlier conceived improvements and benefits of CERP for the lake. The change to water levels and duration is partly due to utilizing the full range of the improved infrastructure (i.e., Herbert Hoover Dike), but there is a lack of large-scale storage north of Lake Okeechobee. In the case of the Lake Okeechobee Watershed Restoration Plan, the storage capacity of the current plan has been dramatically reduced by removing a key wetland restoration and storage feature and relying on aquifer storage and recovery to shoulder the water storage burden.

While climate conditions over the next decade will be the largest determinant of near-term lake health, this proposed regulation schedule has the potential to significantly affect the ecology of the lake, particularly through increased frequency of stressful events. In light of climate change, future restoration and management efforts must build flexibility and adaptability into how water is managed across the board to ensure a healthy ecology, robust water supply and requisite flood control. Furthermore, while the lake is taking the brunt of the effects, LOSOM is expected to improve conditions to the downstream systems including the northern estuaries (Caloosahatchee, Saint Lucie and Lake Worth Lagoon) and southern Everglades. Acknowledging potential effects of high water to the lake, LOSOM does include an optional operational strategy to occasionally lower lake stages for factors such as SAV, woody species, and soil oxidation. However, these modest, optional, and infrequent (at best) operational changes are unlikely to replace the long-term need for additional watershed storage. While not perfect as indicated, LOSOM was a compromise solution among the various interests across the system. As management of Lake Okeechobee and implementation of existing restoration projects move forward, more restoration projects are needed to improve water quantity and quality conditions that will benefit limnetic and near-shore environments, in turn building resilience in aquatic vegetation communities, fisheries, avian fauna, and other wildlife on the lake.

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Conflict of interest statement

The authors declare that they have no conflict of interest.

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