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Connecting the Everglades from Marsh to Mangrove: A Conceptual Ecological Model for Lostmans Slough

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Abstract

Restoring freshwater flow to the southern Everglades requires decisions that account for where, when, and in what condition water moves through connected landscapes. Lostmans Slough is situated at the ecotonal interface between the wet prairie and cypress-dominated habitats of Big Cypress and the sawgrass sloughs characteristic of the Everglades. This transitional landscape spans freshwater marl prairie and ridge-and-slough wetlands, a mangrove ecotone, tidal rivers, and nearshore Gulf waters, yet this corridor is not fully represented by existing Everglades conceptual ecological models. We develop a Lostmans-specific conceptual ecological model that links regional water-management actions to hydrologic and water-quality stressors, ecological responses, measurable indicators, and restoration tradeoffs across four ecological zones. We hypothesize that Lostmans Slough functions as a connected but spatially heterogeneous freshwater-to-estuarine corridor. Freshwater delivery is the principal management lever, but ecological outcomes depend on hydrology together with landscape connectivity, fire, coastal forcing, and sea-level rise. Additional freshwater may reduce excessive drying, improve aquatic-refuge persistence and prey production, and moderate coastal salinity. However, benefits may not propagate uniformly and may be accompanied by nutrient loading, prolonged inundation, altered material transport, or effects on other regional flow paths. Because Lostmans-specific monitoring and empirical studies remain limited, the model distinguishes locally supported relationships from regional evidence and working hypotheses. We propose linked indicators spanning hydrology, water quality, periphyton, aquatic prey, vegetation, fire, salinity, and coastal conditions. The framework supports adaptive management by clarifying expected responses, identifying unintended consequences, and directing monitoring toward uncertainties that most influence restoration decisions under changing climatic conditions.

Introduction

Conceptual ecological models provide a structured representation of pathways through which natural processes, management actions and environmental change are expected to affect ecological systems (Gentile et al 2001; Lima et al 2023). Rather than predicting a single outcome, they identify hypothesized causal relationships, measurable indicators, uncertainties, and potential unintended consequences that can guide monitoring and management (Diefenderfer et al 2021). These models are especially relevant to spatially connected ecosystems in which interventions may generate different responses among landscape components and across ecological boundaries.

Located along the western flank of Shark River Slough (SRS) in the southern Everglades, Lostmans Slough occupies a transitional landscape where the freshwater wetlands of Everglades National Park (ENP) and the eastern Big Cypress National Preserve (BCNP) landscape grade into mangrove forests, tidal rivers, and the nearshore Gulf of Mexico (Fig. 1; Davis et al 2005). Because ecological processes and management effects cross these connected but distinct environments, studies and management of Lostmans Slough will benefit from an integrated conceptual ecological model (CEM). For purposes of this CEM, the system is represented as a freshwater-to-estuarine corridor comprising four linked

ecological zones: 1) an upstream freshwater inflow zone; 2) an interior mosaic of marl prairie, ridge-and-slough wetlands, tree islands, and aquatic refugia; 3) a mangrove-dominated coastal ecotone; and 4) the tidal rivers and nearshore waters receiving freshwater discharge from the watershed. Hydrologic processes originating in the freshwater Lostmans Slough headwaters propagate across wetland and estuarine environments, linking hydroperiod, water quality, fire regime, vegetation, aquatic production, salinity, and coastal habitat conditions along a common flow path. By treating Lostmans Slough as a connected but spatially heterogeneous ecohydrological corridor, the proposed model can provide a unified framework for identifying causal linkages, articulating testable hypotheses, selecting indicators appropriate to different landscape zones, and evaluating restoration outcomes and tradeoffs that cannot be adequately addressed through adjacent ecosystem models considered independently.

Prior to extensive drainage and water-management modification via the Central and Southern Florida Project (Davis and Ogden 1994), the ecological character of Lostmans Slough was likely governed primarily by the depth, duration, distribution, and seasonal variability characteristic of two southern Everglades ecosystems; ridge-and-slough and marl prairies. The ridge-and-slough component was historically associated with low-velocity sheet flow, oligotrophic waters, organic soils, sawgrass ridges, open-water sloughs, wet-prairie vegetation, and tree islands (Ogden 2005), while the surrounding marl prairies were characterized by relatively short hydroperiods, annual dry-downs, calcitic periphyton mats, marl-forming processes in a mosaics of wet prairie, sawgrass, tree islands, and tropical hammocks (Davis et al 2005b). Seasonal expansion of surface water connected the interior wetlands with downstream mangrove and estuarine environments. Thus, rather than representing a single homogeneous wetland type, the reference condition for Lostmans Slough is best understood as a spatially connected mosaic maintained by interactions among freshwater flow, seasonal drying, local elevation, soil-forming processes, fire, tidal exchange, and coastal salinity (Davis et al 2005a; Duever 2005; Davis et al 2005b; Ogden 2005).

The hydrologic and ecological connectivity of the greater Everglades ecosystem, including Lostmans Slough, has been altered by the broader reorganization of the south Florida water-management system (McVoy et al 2011). Roads, canals, levees, and associated water-control operations have modified the quantity, timing, distribution, and direction of freshwater movement across the southern Everglades, contributing to shortened hydroperiods and greater drought severity in some locations while producing prolonged inundation or reversals of natural drying patterns in others. Within Lostmans Slough, these alterations can affect hydrologic conditions and ecological processes in the freshwater interior while also modifying freshwater delivery, material transport, and salinity conditions downstream. The effects of these processes interact with fire, invasive species, storms and sea-level rise such that the present condition of Lostmans Slough reflects the cumulative effects of both regional water management and environmental change.

Despite the uncertainty in the hydrological needs of Lostmans Slough, the slough has assumed increased restoration relevance as projects and operational changes seek to improve the hydrologic and ecological connectivity across the central and western Everglades. Within the Comprehensive

Everglades Restoration Plan, Western Everglades Restoration Project (WERP) (US Army Corps of Engineers 2023) has potential to affect Lostmans Slough. Currently underway water management/operational planning associated with Central Everglades Planning Project (CEPP) operations has begun to explore utilizing expected infrastructure identified in WERP. Proposed structural and operational changes associated with these projects may alter the magnitude, timing, distribution, direction, and quality of freshwater delivered to Lostmans Slough and its allocation relative to other regional flow paths (Fig. 1). Evaluating the potential influence of these projects therefore requires an integrated framework capable of tracing potential benefits, risks, and tradeoffs from the freshwater interior to the mangrove ecotone and estuarine receiving waters. Such an integration is particularly important because a hydrologic change that benefits one portion of the corridor may affect conditions elsewhere (Cohen et al 2011). Therefore, a Lostmans-specific CEM provides such a framework by linking regional restoration actions to environmental stressors, ecological responses, measurable indicators, and critical uncertainties.

The objectives of this paper are to develop a CEM that integrates current understanding of Lostmans Slough as a connected but spatially heterogeneous freshwater-to-estuarine ecosystem. Specifically, we aim to (i) synthesize existing conceptual and empirical knowledge across the four linked ecological zones; (ii) identify the principal external drivers and ecosystem stressors affecting the corridor; (iii) articulate testable hypotheses linking freshwater quantity, timing, distribution, direction, and quality to key ecological processes and attributes; and (iv) identify candidate indicators for evaluating ecological responses and supporting monitoring and adaptive management. Because direct empirical evidence from Lostmans Slough remains limited, the model also distinguishes well-supported relationships from those inferred from analogous Everglades landscapes and identifies critical uncertainties and research needs. In doing so, the model provides a framework for evaluating both the anticipated benefits and potential tradeoffs of restoration actions across the interconnected freshwater, mangrove, and estuarine components of the Lostmans Slough corridor.

Methods

Study area and conceptual scope

We treated Lostmans Slough as a freshwater-to-estuarine corridor comprising an upstream freshwater inflow zone, an interior mosaic of marl prairie and ridge-and-slough wetlands, a mangrove-dominated coastal ecotone, and tidal rivers and nearshore receiving waters. These zones provided the spatial framework for organizing drivers, stressors, ecological effects, candidate indicators, and restoration tradeoffs.

Conceptual model development and evidence synthesis

The Lostmans Slough conceptual ecological model was developed through a narrative synthesis of existing Everglades conceptual models, peer-reviewed literature, agency reports, monitoring information, hydrologic-model products, and restoration-planning documents relevant to Lostmans Slough and adjacent landscapes. Sources were identified through reference lists of existing publications and reports, and targeted searches conducted during model development. A formal systematic literature search, predefined search protocol, or quantitative evidence-grading procedure was not used. Therefore, the resulting synthesis should be interpreted as a conceptual integration of currently identified evidence rather than as a comprehensive or systematic review of all potentially relevant literature.

Evidence was organized into a causal hierarchy linking external drivers to ecosystem stressors, ecological effects, and measurable ecological attributes. Cross-cutting stressors were retained where they modified multiple pathways or ecological zones. Where possible, relationships were evaluated qualitatively according to their geographic relevance, ecosystem comparability, study design, temporal coverage, and directness to the proposed causal pathway. Because direct empirical information from Lostmans Slough was limited, the model distinguishes relationships supported by local observations from those transferred from analogous Everglades landscapes or retained as working hypotheses.

Hydrologic data sources

Hydrologic conditions within the upper Lostmans Slough study area were characterized using two complementary spatial datasets, output from the Natural System Regional Simulation Model (NSRSM) and water-level surfaces produced by the Everglades Depth Estimation Network (EDEN). The NSRSM was used to characterize estimated natural-system hydrology, whereas observed data from EDEN was used to characterize hydrologic conditions within the contemporary managed landscape. These datasets were interpreted as complementary reference and contemporary-condition products rather than as directly equivalent observations because they differ in their underlying data, spatial resolution, model structure, and representation of the landscape.

Data from the NSRSM and EDEN were processed independently in their native spatial frameworks. Resampling between the NSRSM computational mesh and the EDEN grid was not performed when calculating the reported summary statistics. Daily ponding depth was defined as the water-surface elevation relative to local ground surface elevation where positive values indicate surface-water inundation. Hydroperiod was calculated as the number of days with ponding depths greater than 0 cm. Annual average ponding depth and annual hydroperiod were calculated based on water year (May to April) by cell. Spatially averaged ponding depth and hydroperiod values were calculated for the indicator region representing the headwaters of Lostmans Slough.

The NSRSM and EDEN metrics were compared descriptively to evaluate differences in the magnitude, temporal variability, and spatial distribution of hydroperiod and ponding depth between estimated natural-system and contemporary managed conditions. Because the datasets differ in model structure, spatial resolution, ground-elevation representation, and period of record, differences were not interpreted

as formal model-to-observation validation or as changes between directly paired grid cells. Instead, the comparison was used to identify broad departures in the hydrologic regime and to provide context for the hydrologic stressor pathways represented in the Lostmans Slough conceptual ecological model.

Statistical analysis

Temporal trends in annual EDEN-derived hydroperiod and ponding depth were evaluated using the Kendall's τ rank-correlation test ('*cor.test*' function in stats R package). Trend tests were applied only to the EDEN time series because the NSRSM sequence represents simulated natural-system responses to the climatic input record and was used as a hydrologic reference rather than as an observed historical trajectory. All statistical operations were performed in R © (Ver 4.1.0, R Foundation for Statistical Computing, Vienna Austria). The critical level of significance was set to $\alpha = 0.05$.

Results and Discussion

External Drivers and Ecological Stressors

The major external drivers affecting Lostmans Slough are regional water-management practices, the construction and operation of water-management and transportation infrastructure, and climatic and coastal forcing (Fig. 2). These drivers generate four interacting stressor pathways: (1) altered freshwater hydrology and connectivity; (2) altered water quality and material transport; (3) altered fire regimes; and (4) changing coastal dynamics and salinity regimes. Connectivity loss and non-native biota operate across these pathways as landscape wide cross-cutting stressors because their effects extend across multiple ecological zones and interact with hydrologic, water-quality, fire, and coastal processes. Since Lostmans Slough extends from freshwater wetlands to coastal receiving waters, the magnitude and ecological expression of these stressors are expected to vary longitudinally and interact across the corridor. Freshwater hydrology functions as a master driver across the freshwater interior, establishing the conditions under which water quality, fire, and connectivity operate. Meanwhile, the coastal ecotone and estuarine zone are exceptions, influenced by both freshwater and marine forcings.

Water Management Practices

The construction of Tamiami Trail and its associated canal in 1928 and the subsequent Central and Southern Florida (C&SF) project in the 1960s reorganized regional hydrology through roads, through canals, levees, impoundments, and water-control structures, including the L-28 and L-29 systems and the S-12 structures (Fig. 3; Light and Dineen 1994; US Army Corps of Engineers and US Department of Interior 2008). These features had major effects on the mosaic of ecosystems within the Lostmans Slough area by significantly reducing the volume and altering the timing and distribution of water as documented by historical aerial imagery (US Army Corps of Engineers and US Department of Interior 2008). Together, these features reduced the continuity of sheet flow, altered the volume, timing,

distribution, and direction of freshwater movement, and changed hydrologic connectivity among WCA-3A, the eastern Big Cypress landscape, Lostmans Slough, and SRS.

The ecological consequences of these changes have varied across the landscape. Restricted freshwater delivery contributed to shortened hydroperiods and greater drought exposure in areas south of Tamiami Trail, whereas the concentration of discharge through water-control structures (e.g. the S-12 structures) redistributed flow in Northwest SRS. Flow redistribution can alter the timing and duration of inundation and may prolong flooding or disrupt seasonal drying where deliveries do not correspond with local rainfall, stage, and recession conditions. In Lostmans Slough, these hydrologic changes may affect dry-season refugia, aquatic prey dynamics, periphyton and marl formation, vegetation mosaics, fire susceptibility, and the downstream freshwater–salinity gradient. They may also alter lateral connectivity among freshwater marshes, sloughs, tree islands, and coastal wetlands, limiting the movement of water, organisms, and materials across the corridor.

More recent restoration projects and operational plans have sought to improve the timing and distribution of water delivered to ENP. The Combined Operational Plan (COP), implemented in late 2020 (Fig. 3), represented an incremental shift toward more operational flexibility and more ecologically responsive operations (US Army Corps of Engineers 2020). Differentiating the impacts of these operational changes from rainfall driven water availability is difficult. Nonetheless, implementation underscores a central issue for water management to Lostmans Slough, operational changes redistribute a finite and dynamically varying water supply among regional flow paths, so benefits within one part of the system may be accompanied by reduced delivery, altered water quality, or other hydrologic tradeoffs elsewhere in the system.

Climate and Coastal Forcing

Climate and coastal processes are external drivers of the Lostmans Slough ecosystem that operate across multiple temporal scales and interact with regional water management (Fig. 2). Seasonal rainfall and evapotranspiration regulate the annual expansion and contraction of surface water, whereas droughts and unusually wet periods alter hydroperiod, recession rates, and the availability of dry-season aquatic refugia (Duever et al 1994; Moses et al 2013). Tropical cyclones and other extreme events impose shorter-duration disturbances through intense rainfall, wind damage, storm surge, saltwater intrusion, sediment deposition, and prolonged coastal inundation. In mangrove forests, hurricanes can alter forest structure through defoliation, stem breakage, and uprooting, while storm-driven sediment deposition can add mineral material and nutrients that influence soil elevation and post-disturbance recovery (Chavez et al 2025). However, storm effects are spatially heterogeneous: evidence from southwestern Florida indicates that severe mangrove mortality can occur where storm surge becomes impounded and saline water drains slowly, demonstrating that elevation and hydrologic connectivity mediate ecological response to coastal disturbance (Lagomasino et al 2021).

At longer timescales, sea-level rise increases the frequency and duration of coastal inundation and promotes the landward movement of marine influence and the marsh–mangrove ecotone. Paleoecological evidence from the Shark River Estuary documents a long-term inland shift of mangroves as marine influence increased, while regional projections indicate that the future persistence and migration of coastal wetlands will depend partly on whether soil accretion can maintain wetland elevation relative to rising water levels (Sklar et al 2021). Increasing salinity and inundation may alter vegetation composition, soil microbial processes, organic-matter accumulation, nutrient availability, and the stability of freshwater and mangrove peat soils (Charles et al 2019; Zhao et al 2020). Experimental and modeling studies in the coastal Everglades further indicate that freshwater inflow and sea-level rise jointly regulate porewater salinity, emphasizing that marine forcing and managed freshwater delivery should not be treated as independent controls on the coastal ecotone (Swain et al 2019; Zhao et al 2020). For Lostmans Slough, these interactions may shift the position and variability of the salinity gradient, influence tidal mixing and residence time, and alter the spatial arrangement of freshwater marsh, brackish wetlands, mangrove forest, and open estuarine water. The ecological consequences of coastal forcing will therefore depend not only on the magnitude of sea-level rise and storm disturbance, but also on local elevation, soil accretion, drainage connectivity, freshwater delivery, and the capacity of vegetation and soils to adjust to changing hydroperiod and salinity conditions. These interacting controls are reflected in the CEM (Fig. 2), which treats ecotone position, peat stability, porewater salinity, elevation change, and drainage connectivity as central uncertainties and candidate indicators.

Altered freshwater hydrology

In the pre-drainage Everglades, the hydrologic regime of Lostmans Slough would have been governed primarily by seasonal rainfall, evapotranspiration, regional surface- and groundwater storage, low-gradient sheet flow and discharge toward the mangrove coast and Gulf of Mexico (Harvey and McCormick 2009; Figs. 4 and 5). Roads, canals, levees, and water-control structures compartmentalized the historically connected system into hydrologically distinct compartments, disrupting the magnitude, timing, duration and direction of freshwater movement through the landscape (Davis and Ogden 1994; Ogden 2005). These modifications reduced regional storage and sheet flow while producing a mosaic of over drained and ponded wetlands. In Lostmans Slough, hydrologic alteration cannot be represented solely as reduced total flow, rather as changes in the magnitude, timing, duration, distribution, and direction of freshwater movement across the headwaters, marl-prairie and ridge-and-slough interior, mangrove ecotone, and downstream estuarine waters.

A useful reference for evaluating the magnitude and spatial patterns of hydrologic restoration across the system is the NSRSM (Said and Brown 2013). Rather than reproducing the actual hydrology of a specific historical period, the NSRSM through simulation provides a glimpse of the pre-drainage Everglades landscape using recent climatic inputs, thereby permitting comparison of natural-system and managed-system hydrology under comparable climatic forcing. In upper Lostmans Slough (Fig. 1), the NSRSM

annual hydroperiod ranged from 301 to 365 days yr^{-1} and average ponding depth ranged from 24 to 49 cm (water year 1966–2016; Fig. 4).

Contemporary monitoring and spatial water-depth estimates provide a complementary characterization of realized hydrologic conditions. The observed annual hydroperiod for the upper Lostmans Slough ranged from 155 to 354 days yr^{-1}, and average ponding depth ranged from 11 to 40 cm between May 1991 and April 2026 (WY 1992–2026) (Fig. 4). Additionally, during this period of record, annual hydroperiod and ponding depth have significantly declined (Kendall; $\tau = -0.34$, p-value < 0.01 and $\tau = -0.28$, p-value < 0.05, respectively). The lowest hydroperiods occurred in upper portion of the Lostmans Slough headwaters, whereas downstream sloughs retained surface water for longer portions of the year (Fig. 5). Independent Restoration, Coordination and Verification (RECOVER) assessments identify low hydroperiods and water depths as continuing concerns in Lostmans Slough, particularly during the late dry season from March through May (RECOVER 2024). This assessment reported no significant difference in hydroperiod or water depth between its baseline and reporting periods for the BCNP Lostmans Slough monitoring location but determined increases in soil-oxidation risk within Lostmans during the reporting period. These results suggest that recent regional hydrologic improvements have not yet produced a clearly detectable improvement in Lostmans Slough, although attribution remains complicated by climatic variability and limited spatial representation of monitoring locations for the region.

Compartmentalization, facilitated by the L-28 and L-29 canal–levee systems, Loop Road, Tamiami Trail, and associated control structures, further modifies hydrologic response by constraining lateral and southward movement and concentrating discharges through discrete structures rather than allowing broadly distributed sheet flow (Fig. 1). Therefore, in the conceptual model, therefore compartmentalization acts both as a direct loss of landscape connectivity and as a mechanism that amplifies hydrologic alteration by producing overdrainage, localized ponding, and spatially abrupt differences in water depth and hydroperiod (Fig. 3). Seasonality of hydrologic conditions has a profound ecological effect. Insufficient or prematurely declining dry-season water levels can increase the frequency and duration of complete dry-downs, reduce the persistence of sloughs, solution holes, and alligator holes as aquatic refugia, and limit recovery time for aquatic-faunal populations (Trexler et al 2005; Rehage et al 2014). Whereas excessive or mistimed delivery may extend inundation into the natural drying period, reverse seasonal recession patterns, reduce prey concentration, and shift vegetation toward communities associated with deeper or more persistent water (Busch et al 1998; Beerens et al 2017). The desired hydrologic condition is therefore not maximum hydroperiod throughout Lostmans, but restoration of an appropriate spatial mosaic of water depths, inundation durations, recession patterns, and flow paths consistent with the ecological character of each landscape zone. The existing Lostmans linkage matrix identifies these relationships as strongly supported mechanistically by the Big Cypress, Southern Marl Prairies, and Ridge and Slough CEMs, while recognizing that Lostmans-specific hydrologic thresholds remain uncertain (Fig. 2).

Hydrologic-model evaluations conducted for the WERP further illustrate the spatial variability of restoration response within Lostmans Slough (US Army Corps of Engineers 2023). The WERP vegetation-community performance measure evaluated marl-prairie suitability at a northern indicator region, near the Lostmans slough headwaters and wet-prairie suitability at a southern indicator region further downstream. Generally, the evaluated alternatives improved modeled marl-prairie suitability at the northern location relative to the future-without-project condition, whereas improved wet-prairie suitability was generally not observed at the southern location. These results indicate that restoration benefits may attenuate with distance from structural modifications, and that increased delivery at the northern boundary cannot be assumed to restore hydrologic conditions uniformly throughout the corridor. Accordingly, evaluation of altered freshwater hydrology should consider not only total inflow or average hydroperiod, but also longitudinal water-depth gradients, flow direction, recession rate, timing of dry-season minima, groundwater contributions, and the propagation of managed flows toward the mangrove ecotone.

Altered water quality and material transport

Hydrologic alteration can modify water quality by changing both the amount of material entering Lostmans Slough and the pathways by which constituents are transported, retained, or transformed. In the ridge-and-slough and marl-prairie interior, managed inflows can transport phosphorus and nitrogen from upstream sources, with nutrient loads being dependent on concentration and discharge and further downstream being modified by uptake and retention processes as water moves through the marsh (Rudnick et al. 1999). Meanwhile ecological exposure also varies with timing, flow direction, residence time and contact with soils, periphyton, and vegetation (Gaiser et al 2005; Noe et al 2010). Distributed sheet flow and longer wetland residence time may promote uptake, sorption, settling, and transformation, whereas concentrated discharge can create localized loading gradients and preferential transport pathways (Fernandez et al. 2025). Thus, altered flow magnitude or routing may change not only total downstream export, but also the spatial distribution of nutrients and organic matter that helps maintain differences among sloughs, ridges, tree islands, and surrounding marshes (Ross et al. 2006; Noe and Childers 2007; Wetzel et al. 2009).

These changes are particularly important because the freshwater Everglades is naturally oligotrophic and its periphyton, soils, and vegetation can respond to relatively small increases in phosphorus supply (Dong et al. 2002; Gaiser et al. 2005; Gaiser 2009). Phosphorus enrichment can alter periphyton composition and density which can interfere with their role in regulating water chemistry, alter organic and calcitic material budgets, and favor a transition toward macrophyte-dominated enriched communities (Noe et al. 2001). These effects may be especially consequential in marl prairies, where calcareous periphyton contributes directly to marl formation and provides an important basal resource for aquatic consumers. Hydrologic alteration can interact with nutrient exposure in several ways: shortened hydroperiod and repeated dry-down can reduce periphyton cover, expose soils and organic material to oxidation, and change soil redox conditions, while deeper or extended inundation can alter

floc composition, nutrient content, respiration, and organic-matter processing (Davis et al. 2005b; Noe and Childers 2007; King and Kominoski 2025). Consequently, restoration of freshwater delivery cannot be evaluated solely as a hydrologic benefit. It must also consider whether the quality, seasonal timing, loading rate, and spatial distribution of delivered water remain compatible with oligotrophic periphyton communities, marl-forming processes, and the existing ridge, slough, and prairie mosaic.

Farther downstream, responses reflect additional processing within the mangrove ecotone and estuary where freshwater inflow interacts with tides, salinity, groundwater exchange, and mangrove-derived organic matter. Flow through the freshwater-to-marine continuum mediates nutrient cycling and wetland productivity with seasonal freshwater input strongly affecting nutrient export from the freshwater landscape to coastal waters (Rivera-Monroy et al. 2011). Freshwater inputs can also shift the position of the estuarine mixing zone, change residence time, and regulate inputs of dissolved organic carbon and other terrestrially derived materials. In the Shark River estuary, dissolved organic-matter dynamics respond over multiple timescales to tides, water level, precipitation, and water-management conditions, while ebb tides can rapidly transfer mangrove soil-derived dissolved organic matter to river channels (Regier and Jaffé 2016). Mangrove wetlands are themselves important material sources where tidal exchange facilitate export of dissolved organic carbon to adjacent coastal waters (Smith et al. 2016; Ho et al. 2017). Accordingly, downstream water-quality responses in Lostmans Slough should not be interpreted as simple dilution or conveyance of upstream water. These responses represent the integrated outcome of freshwater loading, marsh retention and transformation, mangrove production, sediment and porewater exchange, tidal mixing, marine inputs, and variable residence time. Because direct observations along the complete Lostmans flow path remain limited, the relative contributions of these processes, including whether increased freshwater delivery increases nutrient and organic-matter export or instead enhances retention and processing within the wetland corridor, is an explicit uncertainty and testable component of the CEM.

Altered fire regime

Fire is a natural component of the Everglades landscape, but its frequency, seasonality, spatial extent, intensity, and ecological effects are closely regulated by interactions among hydrology, climate, topography, vegetation, and ignition source. Water depth and flow influence fuel moisture and the continuity of burnable vegetation, thereby determining when and where fire can spread (Slocum et al 2003). Consequently, restoration of hydrologic conditions alone cannot be assumed to restore an appropriate fire regime because water and fire are linked through fuel moisture and feedback involving vegetation, fuels, and landscape compartmentalization (Lockwood et al 2003). In Everglades National Park, La Niña conditions during 1948–1999 were associated with reduced dry-season rainfall, lower surface-water levels, increased lightning activity, more fires, and greater area burned, whereas El Niño conditions were associated with greater rainfall and water levels, fewer fires, and less area burned (Beckage et al 2003). These relationships demonstrate that climatic variability can regulate regional fire

activity through changes in rainfall and water level and may amplify or obscure the effects of water-management operations on local fire conditions.

Landscape position and antecedent hydrologic conditions further control the patchiness and intensity of individual fires. Along the elevational gradient at Long Pine Key, prescribed fires were less patchy and more intense in relatively high-elevation plant communities than in lower-elevation, long-hydroperiod prairies (Slocum et al 2003). More recent observations along a marl-prairie-to-pine-rockland gradient similarly indicate that the ecological effects of fire cannot be separated from water depth and elevation. Although systematic shifts in plant composition associated with restoration were not detected, the fire frequencies associated with higher plant richness differed among wet, moderately wet, and dry landscape positions (Schneider et al 2024). These findings suggest that hydrologic alteration can modify the fire regime by changing the timing and extent of seasonal fuel drying, the landscape positions available to burn, and the capacity of wet prairies and sloughs to restrict fire spread. Additionally, climatic drought can amplify or obscure the effects of water management.

Fire behavior and ecological effects also depend on ignition source and the timing of burning relative to seasonal rainfall. In ENP, lightning fires generally occurred near the onset of the wet season, whereas incendiary fires were concentrated earlier, near the end of the dry season. Slocum et al (2007) proposed that these late dry-season incendiary fires encountered drier fuels, burned more intensely, and were more likely to spread into lower-elevation areas that ordinarily constrain fire movement due to increased soil moisture. In contrast, prescribed fires generally occurred after wet-season onset, when increasing fuel moisture may have produced patchier and less-intense burns where wetter regions act as a fire break, constraining the fire (Slocum et al 2007). Contemporary fire records from ENP and BCNP demonstrate interannual variability in burned area, ecosystem-specific differences in fire-return intervals, and a major contribution of prescribed burning to recent fire activity, while wildfire activity remained comparatively stable over the study period (Malone et al. 2025). An altered fire regime should therefore not be represented simply as either more or less of fire, but as a multidimensional change in frequency, seasonality, ignition source, spatial extent, patchiness, and intensity.

Fire can redistribute nutrients among vegetation, soils, periphyton, and surface water and alter microbial nutrient transformations and organic-matter processing. These effects vary with fire intensity, hydrologic setting, antecedent nutrient status, and time since burning. Contrasting effects of prescribed fire on nitrogen cycling, and periphyton nitrogen fixation in low-phosphorus reference and higher-phosphorus restored wetlands indicate that fire does not produce a uniform nutrient-cycling response (Liao and Inglett 2012; Liao et al 2013; Liao and Inglett 2014). The differences may reflect variation in the resistance or recovery of periphyton-mediated nutrient cycling, although the available evidence cannot separate ecological resilience from shorter-term effects of nutrient availability, assemblage composition, or seasonal physiology. Fire can also temporarily increase phosphorus in surface water, periphyton, and vegetation, with responses varying according to antecedent nutrient conditions (Nocentini et al 2022). Increased surface-water phosphorus downstream of a burned, nutrient-enriched wetland further indicates that hydrologic connectivity can extend post-fire effects beyond the burn perimeter (Miao et al

2010). Fire therefore links the nutrient-cycling, water-quality, and soil-stability pathways of the CEM through both local ecosystem response and downstream material transport (Fig. 2).

These biogeochemical responses to fire may subsequently influence vegetation recovery. Following a large fire across the ridge-and-slough landscape of Water Conservation Area 3A, sawgrass regrowth was substantially greater in burned than unburned areas but declined with increasing water depth, whereas cattail regrowth and subsequent expansion were associated with peat-burned areas, pre-existing cattail stands, and phosphorus-enriched soils (Wu et al 2012). Thus, fire effects on vegetation cannot be attributed to nutrient release alone, but instead reflect interactions among fire type, post-fire hydrology, antecedent phosphorus status, and the pre-fire plant community. Together, these studies indicate that fire may temporarily alter nutrient availability, nitrogen transformations, microbial activity, carbon processing, material transport, and vegetation recovery, but they do not support a single generalized post-fire response across the Everglades.

For Lostmans Slough, interpretation of post-fire periphyton, water quality, soil, or vegetation change should therefore account for pre-fire nutrient status, fire intensity, burn type, antecedent and post-fire water depth, reflooding, landscape position, and hydrologic connectivity. Additionally, hydrologic modification may alter fire by changing the seasonal availability, moisture, and spatial continuity of fuels across the marl-prairie and ridge-and-slough interior. Shortened hydroperiods, lower water levels, or unusually early dry-downs could increase the exposure of normally wet landscape positions to fire and reduce the effectiveness of sloughs and long-hydroperiod prairies as barriers to fire spread. Conversely, prolonged inundation or reversals of natural drying patterns could restrict fire in fire-influenced herbaceous communities, alter burn patchiness, and contribute to changes in vegetation and fuel structure. These effects would likely vary with elevation, antecedent water level, time since fire, vegetation composition, fuel accumulation, ignition source, season of burn, and fire weather.

Altered coastal dynamics and salinity regime

The coastal salinity regime of the lower Lostmans Slough and creek is determined by the balance among freshwater inflow, rainfall, evapotranspiration, tidal exchange, coastal water levels, groundwater interactions, and episodic storm surge (Rivera-Monroy et al 2011). Together, these processes regulate the magnitude, duration, timing, variability, and inland extent of saline exposure across the freshwater-marsh, mangrove-ecotone, and estuarine portions of the corridor. Water management can modify this balance by changing the quantity, seasonality, and routing of freshwater reaching the coast, while sea-level rise and storms can increase marine influence and shift the freshwater–saltwater transition inland (Ross et al 2000; Rivera-Monroy et al 2011). Because salinity interacts with water depth, inundation duration, drainage, local elevation, and soil conditions, vegetation responses are unlikely to follow a single salinity threshold (Howard et al 2020; Lagomasino et al 2021). Persistent changes in these interacting conditions may favor replacement of freshwater vegetation by salt-tolerant communities and mangroves, alter the position and structure of the coastal ecotone, or contribute to vegetation loss

where soil elevation and wetland development cannot keep pace with water-level change (Ross et al 2000; Sklar et al 2021; Lamb-Wotton et al 2024).

Freshwater management can influence the coastal salinity regime by changing the hydraulic gradient, timing, and routing of water delivered toward the mangrove ecotone, but its effectiveness depends on the balance between upstream freshwater levels and marine forcing. Along Shark River Slough, the freshwater-to-marine head difference was the principal control on the upstream transport of salinity and phosphorus from the Gulf of Mexico, especially during the dry season (Dessu et al 2018). Freshwater inflow may therefore moderate salinity more effectively when timed to periods of low freshwater head, although continued sea-level rise is expected to increase coastal and estuarine water levels and strengthen marine influence (Zhao et al 2020). Thus, freshwater management may moderate, but not eliminate, increasing marine influence in brackish and freshwater portions of the system.

Freshwater delivery can also affect water quality by shifting salinity gradients, residence time, and the relative influence of freshwater and marine nutrient sources. Seasonal variation in freshwater input strongly regulates nitrogen and phosphorus export through the Everglades mangrove ecotone, while reduced freshwater delivery, compartmentalization, and rising coastal water levels have contributed to landward movement of the mangrove boundary elsewhere in the coastal Everglades (Rivera-Monroy et al 2011). In the oligotrophic Everglades estuaries, low freshwater inflow during the dry season increases residence time and the potential importance of internal biogeochemical processing, while precipitation patterns and canal-water management influence both salinity and the marine supply of phosphorus (Childers et al 2006). A regional ridge-to-reef analysis further showed that relationships between salinity and water-column nutrients are spatially heterogeneous and nonlinear. Total phosphorus increased steeply across the low-salinity portion of the observed gradient, whereas total nitrogen generally declined with increasing salinity, and long-term trends in most measured water-quality indicators varied among freshwater marsh, mangrove-fringe, bay, shelf, and reef environments (Julian et al 2024). These patterns indicate that freshwater delivery should not be interpreted as simple dilution of coastal waters. Instead, management-induced changes in freshwater flow may alter salinity, hydraulic connectivity, residence time, nutrient transport, and biogeochemical processing simultaneously.

Persistent changes in salinity and inundation can alter both the position of the marsh–mangrove ecotone and the capacity of coastal wetlands to maintain vegetation and soil elevation. Ecotone migration alone does not offset subsidence, decomposition, erosion, and sea-level rise (Krauss et al 2014; Cahoon et al 2021). Where vegetation productivity or soil formation cannot maintain elevation, chronic waterlogging and salinization may contribute to vegetation loss and transition toward sparsely vegetated or open-water conditions. Accordingly, ecotone position, vegetation composition, soil-surface elevation, accretion, and peat condition should be evaluated together rather than using mangrove expansion alone as an indicator of coastal response (Smith et al 2013; Feher et al 2024). Tracking the mangrove–marsh boundary has been identified as an indicator of long-term ecosystem trajectory under regional water-management change and sea-level rise, while soil-elevation maintenance is a fundamental component of wetland persistence.

Episodic storms provide a distinct but interacting pathway of coastal change. Storm surge can rapidly expose mangrove soils and vegetation to elevated water levels and saline water, but the ecological effect depends on local elevation, landscape connectivity, and the duration of post-storm ponding. Following Hurricane Irma, extensive mangrove dieback in southwest Florida was associated with low-lying, hydrologically isolated areas where storm-surge water remained ponded, indicating that persistent inundation and restricted drainage were important components of the disturbance rather than wind exposure alone (Lagomasino et al 2021). Thus, freshwater delivery, tidal connectivity, and drainage should not be viewed as interchangeable management mechanisms, additional freshwater may moderate salinity exposure, whereas effective exchange and drainage determine whether water and dissolved constituents are flushed or retained. For the Lostmans mangrove ecotone, coastal condition may therefore reflect interactions among chronic sea-level rise, freshwater delivery, soil-elevation change, storm-surge exposure, and the capacity of low-lying areas to drain following episodic events.

Strategically timed freshwater delivery to Lostmans Slough may reduce the magnitude, duration, or inland extent of saline exposure, but the response will depend on coastal water levels, antecedent hydrologic conditions, flow paths, and exchange with tidal creeks and receiving waters. The potential benefit of freshwater delivery may be limited where poor drainage or hydrologic isolation promotes prolonged ponding, while excessive or poorly routed delivery could also extend inundation where drainage is restricted. Changes in salinity may additionally modify how freshwater-derived nitrogen and organic matter interact with marine or coastal phosphorus sources, potentially producing different water-quality responses along the marsh-to-mangrove-to-estuary continuum. Because direct observations along the Lostmans flow path remain limited, quantitative relationships derived from Shark River Slough, the broader coastal Everglades, and post-storm mangrove studies should be treated as transferred mechanistic evidence rather than as locally validated thresholds.

Cross cutting stressors: connectivity loss and non-native biota

Loss of ecological connectivity and the establishment of non-native biota are cross-cutting stressors because they affect multiple landscape zones and modify the pathways through which hydrologic, water-quality, fire, and coastal changes are expressed. In an unfragmented wetland corridor, seasonal expansion and contraction of surface water connect marshes, sloughs, tree islands, aquatic refugia, mangrove wetlands, and downstream estuarine waters, permitting the movement of organisms, nutrients, organic matter, and energy among habitats (Harvey et al 2017). Roads, canals, levees, and water-control structures have disrupted these linkages by dividing the landscape into hydrologically distinct compartments, restricting lateral and downstream sheet flow, and concentrating movement through canals, culverts, and control structures (Wdowinski et al 2004; Variano et al 2009; Saberski et al 2022). Such alterations can isolate aquatic habitats during seasonal drying, interrupt recolonization following drought or fire, constrain organism movement among foraging and refuge habitats, and reduce the propagation of freshwater and materials toward the mangrove ecotone. Fragmentation can also alter

spatial feedback that maintains patterned wetlands. Zweig et al (2011) determined that altered hydrology and landscape position can interact to degrade wetland pattern, driven by the creation of artificial impoundments, resulting in discontinuities in elevation and fragmentation of ridge vegetation. Connectivity loss is therefore not simply a reduction in connection but a reorganization of when, where, and by what routes water, organisms, fire, and materials move through the landscape.

This distinction between loss of natural connectivity and creation of artificial connectivity is particularly important for non-native biota. The canal network can fragment adjacent wetlands while simultaneously providing persistent aquatic habitat and dispersal pathways for species poorly adapted to the seasonal drying regime of the marsh. Wetland connectivity, hydrologic influence, and habitat complexity are controlling factors for fish assemblage composition. Native fish richness and abundance declined as conditions became increasingly disconnected from adjacent marshes, whereas the contribution of non-native fishes increased and reached nearly half of the assemblage at the most novel end of the sampled gradient (Gandy and Rehage 2017). Canals may also function as drought and thermal refuges and as pathways from which non-native fishes disperse into wetlands during periods of hydrologic connection. Therefore, infrastructure that reduces sheet-flow connectivity can nevertheless increase connectivity for selected non-native organisms, producing a landscape in which native movement is constrained while invasion pathways are maintained or enhanced.

The effects of non-native fish may be amplified where hydrologic alteration reduces the quality or persistence of natural dry-season refugia. In short-hydroperiod karst wetlands of the southern Everglades, many solution holes dried before wet-season reflooding, while those retaining water had low fish survival and were dominated by non-native species, acting as sinks rather than effective sources for native-fish recolonization (Rehage et al 2014). More recently, Flood et al (2025) determined non-native fish invasion can cause persistent changes in aquatic-community composition and shifts in native-consumer diets, trophic niches, basal energy use, and energy fluxes. However, there are complicating factors and uncertainty as the observed changes occurred alongside hydrologic restoration and therefore required analysis of interacting invasion and hydrologic effects. Combined, these studies demonstrate that non-native fishes should not be treated as an ecological pressure independent of water management. Hydroperiod, dry-season refuge persistence, canal proximity, and the timing of marsh–canal reconnection can influence both native faunal recovery and the opportunity for non-native predators or competitors to enter and persist within wetlands.

Non-native plants provide a parallel pathway through which biological invasion can alter ecosystem structure and process. Invasive plants can form dense stands, displace or shade native vegetation, alter habitat structure, and interfere with natural-community recovery. The major invasive plant species that pose a significant risk to the Everglades have been studied and reviewed (Wheeler et al 2016; Sebesta et al 2016; Rodgers et al 2018; Smith 2022; Smith et al 2024). Herbaceous and woody invasive plants have the potential to alter water movement and influence fire conditions, due to fuel load and structure, while aquatic invasive plants can obstruct waterways and reduce the functionality of water control infrastructure. Disturbance may further influence invasion dynamics, for instance fire can stimulate

melaleuca seedling recruitment, although biological control combined with mechanical and chemical treatment has reduced recruitment and the extent of melaleuca-dominated areas in South Florida (Smith et al 2024). Consequently, hydrologic restoration or prescribed fire cannot be assumed to produce native-community recovery where non-native propagules, established infestations, or altered vegetation–fire feedbacks remain influential.

Connectivity restoration should be evaluated by the ecological functions restored rather than by structural removal or increased water movement alone. Reconnecting historical flow paths may improve sheet flow, seasonal access to refugia, recolonization by native aquatic fauna, material transport, and freshwater propagation toward the coast. However, new or strengthened aquatic connections could also facilitate the dispersal of non-native fishes or plants from canals and other source habitats. The objective should therefore be to restore the timing, direction, spatial distribution, and habitat linkages characteristic of the native wetland corridor while limiting artificial pathways that favor non-native species. Because connectivity influences the movement of water, materials, organisms, and disturbance, its loss or restoration can modify hydrologic, water-quality, fire, and coastal pathways rather than acting as an independent stressor.

Ecological effects and causal pathways

Altered hydroperiod and drying dynamics

Changes in the quantity, timing, distribution, connectivity and routing of freshwater alter the seasonal expansion and contraction of aquatic habitat across Lostmans Slough. Premature drying can reduce periphyton persistence, expose soils to oxidation, diminish aquatic refugia, and increase the susceptibility of normally wet habitats to fire. Meanwhile, prolonged or extended inundation can suppress seasonal drying, disrupt prey concentration, and shift vegetation toward communities associated with deeper water (Busch et al 1998; Trexler et al 2005; Davis et al 2005b; Ogden 2005). The ecological response therefore depends on recession rate, seasonal minimum depth, residual habitat distribution, and landscape position rather than annual hydroperiod alone. Restoration should therefore seek to recover a heterogeneous and seasonally dynamic mosaic rather than maximize water depth or hydroperiod uniformly throughout the corridor. However, Lostmans-specific thresholds remain uncertain, and responses are expected to vary with elevation, soil type, vegetation, and position along the freshwater-to-estuarine gradient.

Reduced periphyton production and marl accretion

Altered hydrology and nutrient exposure may reduce periphyton persistence or shift assemblages away from the calcitic periphyton communities characteristic of oligotrophic marl wetlands (Noe et al 2001; Dong et al 2002; Gaiser et al 2005; Gaiser 2009). Because periphyton contributes to nutrient cycling, marl

formation, soil development and aquatic food webs, these changes can propagate microtopography and consumer production (Davis et al 2005b; Gaiser 2009). Reduced marl accretion should therefore be viewed as part of a reinforcing pathway linking hydrologic alteration, nutrient exposure, periphyton change, soil development, and vegetation structure. The magnitude of this response in Lostmans Slough remains uncertain because periphyton production and marl accretion have not been characterized consistently across its hydrologic and geomorphic zones.

Loss of dry-season refugia and reduced aquatic prey production

Seasonal drying ordinarily concentrates aquatic organisms within sloughs, solution holes, alligator holes, and other residual-water habitats, from which populations may recolonize the surrounding marsh after reflooding. Premature or unusually severe drying can reduce refuge persistence, increase mortality, and delay aquatic-community recovery (Trexler et al 2005; Rehage et al 2014). Additionally, climate change can alter the drying and rewetting cycle with delayed onset of the wet season and prolonged dry season potentially affecting the aquatic-community recovery (Obeysekera et al 2015; Flower et al 2017). Fragmentation by roads, canals, levees, and altered flow paths may compound this effect by restricting movement between drying marshes and persistent-water habitats. Some artificial deep-water habitats may retain aquatic organisms during drought, but they can also favor non-native species and may not provide the ecological functions of naturally distributed refugia.

Ecological performance consequently depends on the sequence of wet-season production, gradual recession, prey concentration, and retention of sufficient refugia through the late dry season (Trexler et al 2005; Beerens et al 2017). Evidence from the southwestern coastal Everglades further indicates that the relevant hydrologic sequence may differ among prey taxa. Cocoves et al (2021) correlated exceptional White Ibis nesting with greater crayfish abundance and the continued availability of seasonally drying, short-hydroperiod wetlands near coastal colonies. White Ibis initially relied heavily on freshwater crayfish, particularly *Procambarus alleni*, and shifted toward fish later in the provisioning period as crayfish use declined. These observations suggest that aquatic-prey support for coastal nesting depends not only on dry-season concentration of fishes, but also on antecedent drying, wet-season reflooding, production of crayfish in seasonal wetlands, and the sequential availability of foraging habitats across the marl-prairie and slough landscape (Cocoves et al 2021).

Vegetation shifts, soil instability, and altered fire feedbacks

Changes in hydroperiod, water depth, nutrient availability, salinity, and disturbance can shift vegetation composition and weaken the spatial mosaic of marl prairie, wet prairie, sawgrass ridges, sloughs, tree islands, and coastal wetlands (Busch et al 1998; Davis et al 2005b; Ogden 2005; Zweig et al 2011). Vegetation change can reinforce hydrologic and soil alteration by modifying flow resistance,

evapotranspiration, organic-matter inputs, shading, and fuel structure. Repeated drying exposes organic soils to oxidation and increases their vulnerability to combustion, while severe fire can consume peat, lower soil elevation, and create depressions that experience deeper or more persistent inundation after reflooding (Slocum et al 2003; Wu et al 2012; Nocentini et al 2022). These interactions create feedbacks in which hydrologic alteration changes vegetation and fire exposure, and vegetation change or soil loss subsequently modifies local hydrology, habitat structure, and future fire behavior.

Coastal transgression and altered estuarine productivity

In the lower Lostmans corridor, reduced or seasonally mistimed freshwater delivery can increase the magnitude, duration, or inland extent of saline exposure, while sea-level rise and storm surge strengthen marine influence from the coast (Ross et al 2000; Rivera-Monroy et al 2011; Zhao et al 2020; Sklar et al 2021). Persistent changes in salinity and inundation may promote landward movement of mangroves and other salt-tolerant vegetation into formerly freshwater wetlands. Coastal transgression, however, does not necessarily indicate successful wetland adjustment. Where vegetation production, sediment deposition, and soil accretion are insufficient to maintain elevation relative to rising water levels, salinization and chronic inundation may destabilize peat, reduce vegetation cover, and contribute to conversion toward sparsely vegetated or open-water conditions.

Changes in freshwater inflow can also alter salinity gradients, hydrologic connectivity, residence time, and the transport and processing of nutrients and organic matter, with effects that vary along the freshwater–mangrove–estuarine continuum (Childers et al 2006; Rivera-Monroy et al 2011; Regier and Jaffé 2016; Dessu et al 2018; Julian et al 2024). Consequently, ecological responses to freshwater management may be spatially connected without being uniform or unidirectional. A change that improves hydroperiod or refuge persistence in one portion of Lostmans Slough may alter nutrient transport, inundation, salinity, or productivity elsewhere. Evaluation of restoration outcomes therefore requires integration across landscape zones and explicit consideration of hydrologic benefit, water-quality risk, coastal forcing, and regional water-distribution tradeoffs.

Spatial integration and restoration tradeoffs

Ecological responses to restoration in Lostmans Slough must be interpreted across a connected landscape in which water, dissolved and particulate materials, organisms, and disturbances move among freshwater and coastal environments (Fig. 6). Because these linkages operate across different spatial and temporal scales, a hydrologic change can produce beneficial, neutral, or adverse responses depending on where and when the response is evaluated. Spatial integration therefore requires attention not only to average system condition, but also to the distribution of water and ecological outcomes among landscape zones, the propagation of effects along the corridor, and the possibility that benefits in one location may coincide with risks elsewhere.

Interactions among the four ecological zones

The four ecological zones of Lostmans Slough are linked sequentially but do not respond uniformly to changes in freshwater delivery (Fig. 6). Conditions established in the upstream inflow zone influence the quantity, timing, direction, and quality of water entering the marl-prairie and ridge-and-slough interior. Within the interior wetlands, water and transported materials may be retained, transformed, redistributed, or released downstream through interactions with periphyton, vegetation, floc, and soils. The resulting discharge then influences freshwater head, salinity, residence time, nutrient processing, and habitat conditions within the mangrove ecotone and estuarine receiving waters. Tides, storm surge, groundwater exchange, and marine-derived materials can also propagate influence inland, making connectivity across the corridor bidirectional rather than exclusively downstream.

Ecological outcomes consequently depend on both connectivity and landscape position. Greater upstream delivery may improve hydroperiod, refuge persistence, and aquatic production without producing an equivalent response farther downstream if water is retained, redirected, or attenuated before reaching the coast. Conversely, changes that appear modest in the freshwater interior may alter salinity or material transport within the coastal ecotone when they occur during the dry season or coincide with elevated coastal water levels. Additionally, mobile consumers (e.g. birds) may integrate conditions across multiple zones, hydrologic settings, or regions. Restoration performance should therefore be evaluated using linked indicators across the four zones rather than assuming that an improvement at an upstream monitoring location represents recovery of the entire Lostmans corridor.

Hydrologic benefit versus water-quality risk

Increasing freshwater delivery may reduce excessive drying, improve seasonal connectivity, support dry-season refugia, and moderate saline intrusion. However, the same delivery can increase the load or alter the distribution of phosphorus, nitrogen, dissolved organic matter, suspended material, major ions, or other constituents entering oligotrophic wetlands. Ecological response depends on the concentration and composition of source water together with discharge volume, timing, flow path, residence time, and contact with periphyton, vegetation, and soils. Hydrologic restoration and water-quality protection should therefore be evaluated as interacting objectives rather than treating additional freshwater as an unqualified ecological benefit.

This tradeoff is likely to vary spatially and seasonally. Distributed sheet flow and greater wetland contact may promote retention and transformation, whereas concentrated discharge can create preferential transport pathways and localized exposure near inflow points. Materials retained within the freshwater marsh may subsequently be recycled or mobilized during drying, fire, reflooding, or high-flow events, and material reaching the mangrove ecotone may be further transformed through tidal and porewater exchange. Evaluation should therefore consider loading rate, source-water chemistry, flow distribution, and downstream export in addition to water-column concentrations. The relevant management question

is not simply whether more water can reach Lostmans Slough, but whether water of suitable quality can be delivered at ecologically appropriate times and distributed without transferring unacceptable risk among zones.

Tradeoffs among Lostmans, Shark River Slough, and other flow paths

Lostmans Slough is embedded within a regional water-management system in which operational decisions distribute a finite and climatically variable water supply among competing flow paths. Increasing delivery toward Lostmans may improve conditions in its headwaters and interior wetlands, but the response will depend on conveyance, landscape storage, structural controls, and the amount of water that ultimately propagates toward the mangrove ecotone. As part of the WERP planning effort, modeled improvements were stronger in a northern marl-prairie indicator region than at a more southerly wet-prairie location, indicating that benefits near a point of intervention cannot be assumed to extend uniformly throughout the corridor.

Redistribution of water toward Lostmans must also be considered relative to potential changes in Shark River Slough and other regional pathways (Fig. 6). The appropriate comparison is not simply which flow path receives a greater volume or what water could be siphoned to Lostmans, but how alternative distributions affect hydroperiod, recession, nutrient exposure, landscape connectivity, coastal freshwater head, and ecological attributes across the broader southern Everglades. In some circumstances, operational changes may provide complementary benefits by improving spatial distribution and reducing damaging extremes. In others, a benefit to one flow path may involve reduced delivery or a shifted timing of delivery elsewhere. The CEM does not resolve these allocation decisions, but it provides a structure for making the ecological consequences and uncertainties of alternative distributions explicit.

Climate change, sea-level rise, and shifting restoration baselines

Climate change complicates restoration because the climatic and coastal conditions under which historical ecosystem patterns developed are not stationary. Changes in rainfall seasonality, evapotranspiration, drought, extreme precipitation, tropical cyclones, and sea level may alter the amount of water available for management, the amount needed downstream, and the ecological response to a given operational schedule. At the coast, sea-level rise can increase marine influence, reduce freshwater-to-marine head differences, extend salinity exposure, and shift the mangrove ecotone inland. Freshwater management may moderate some of these effects, particularly during seasonally dry conditions, but cannot independently offset continued sea-level rise or guarantee wetland persistence where soil elevation and accretion do not keep pace with coastal water levels.

Restoration targets should therefore retain the historical or natural-system condition as an ecological reference without assuming that every historical spatial boundary can be maintained indefinitely. A shifting baseline does not eliminate the need for directional objectives. Instead, it emphasizes maintaining processes that support ecosystem resistance and adaptive capacity, including appropriate freshwater delivery, seasonal recession, oligotrophic conditions, soil formation, hydrologic connectivity, and opportunities for the landward adjustment of coastal wetlands. Evaluation should distinguish between management outcomes that remain actionable, such as flow timing, distribution, and water quality, and changes increasingly controlled by external forcing. This framing allows monitoring results to inform adaptation without redefining ecological degradation as restoration success merely because environmental conditions have changed.

Together, these tradeoffs indicate that restoration success in Lostmans Slough cannot be represented by a single flow target, hydroperiod metric, or ecological endpoint. A robust evaluation should determine whether management restores an appropriate spatial and seasonal distribution of freshwater, maintains water quality compatible with oligotrophic wetlands, supports ecological connectivity and dry-season refugia, and moderates coastal salinity without creating excessive inundation or transferring risk to adjacent flow paths. The CEM therefore provides a framework for comparing alternatives across locations, seasons, ecological attributes, and plausible future conditions rather than identifying a universally optimal quantity of freshwater delivery.

Monitoring, uncertainty, and adaptive management

The Lostmans Slough CEM is intended to provide a testable representation of ecological relationships rather than a complete or static description of the system. Monitoring is therefore needed not only to document environmental conditions, but also to evaluate whether the hypothesized pathways linking water management, hydrology, water quality, fire, connectivity, salinity, and ecological response are supported across the freshwater-to-estuarine corridor. Because direct observations within Lostmans Slough remain spatially and temporally limited, monitoring priorities should emphasize variables that distinguish among plausible mechanisms, detect the propagation or attenuation of restoration effects among ecological zones, and support revision of the model as new evidence becomes available.

Candidate indicators by ecological zone

Candidate indicators should correspond to both management inputs and ecological responses and should be distributed across the four ecological zones (Fig. 6 and Table 1). No single indicator is sufficient to represent restoration performance. Rather they should be interpreted as linked sets representing hydrologic exposure, ecological process, and biological response rather than as isolated measures of condition. Improvement in a single metric, such as hydroperiod, does not provide a holistic ecological view that demonstrates appropriate recession, compatible source-water quality, downstream flow propagation, or ecological response.

Table 1

Candidate hydrologic, water-quality, process, and ecological indicators for the four ecological zones of the Lostmans Slough freshwater-to-estuarine corridor. Indicators are intended to be interpreted as linked measures of exposure, ecosystem process, and ecological response rather than as independent measures of restoration performance.

Ecological zone	Hydrologic or physical indicators	Water-quality or process indicators	Ecological indicators
Upstream freshwater inflow	Inflow volume, timing, direction, water depth, hydroperiod	Nutrient concentrations and loads, conductivity, major ions, suspended material	Periphyton condition, vegetation boundaries
Marl prairie and ridge-and-slough interior	Hydroperiod, recession rate, dry-season minimum depth, refuge persistence, connectivity	Periphyton production, nutrient exposure, soil oxidation, marl-forming inputs	Aquatic-faunal abundance, prey concentration, vegetation pattern, fire extent
Mangrove ecotone	Freshwater head, inundation, drainage, porewater salinity	Nutrient processing, dissolved organic matter, accretion and elevation change	Ecotone position, mangrove condition, peat stability, coastal wading-bird nesting effort and prey use
Estuarine and nearshore waters	Salinity distribution and variability, residence time, freshwater discharge	Nutrient and organic-matter export, mixing and processing	Primary or secondary production, prey resources, habitat condition

Evidence strength and transferability

The evidence supporting the CEM varies in spatial relevance and inferential strength. Most relationships are supported by monitoring, hydrologic modeling, or restoration assessments conducted in systems immediately adjacent to Lostmans Slough. Many relationships are transferred from the southern marl prairies, ridge-and-slough, Shark River Slough, coastal Everglades mangroves, and regional canal systems. These sources provide mechanistic support where comparable hydrologic, geomorphic, or ecological conditions occur, but they do not establish Lostmans-specific response magnitudes or thresholds. Evidence should therefore be evaluated according to its geographic proximity, ecosystem comparability, study design, temporal coverage, and directness with respect to the proposed causal relationship. These distinctions are used qualitatively rather than as a formal evidence-grading system.

As part of the CEM development, evidence was identified through a narrative process rather than a formal systematic search and screening protocol. Therefore, relevant studies or alternative interpretations may have been missed. While thorough, the assembled literature should not be considered comprehensive. This limitation reinforces the intended role of the CEM as a revisable organizing hypothesis rather than a definitive evidence assessment.

Critical uncertainties and alternative hypotheses

Direct empirical information from Lostmans Slough remains limited, particularly for processes linking upstream freshwater delivery to ecological responses across the interior wetlands, mangrove ecotone, and estuarine receiving waters. Consequently, many relationships in the CEM are working hypotheses derived from established understanding of the Greater Everglades and evidence from analogous landscapes, including the Big Cypress region, Shark River Slough, and Taylor Slough. Although these systems provide a strong mechanistic basis for the proposed pathways, differences in hydrologic setting, landscape structure, water quality, coastal connectivity, and management history may affect how strongly those relationships apply within Lostmans Slough. Understanding these uncertainties is especially important because competing mechanisms or alternative hypotheses may imply different restoration responses.

For example, increased freshwater delivery at the upstream boundary may propagate through the complete corridor, or its effects may attenuate due to landscape storage, evapotranspiration, groundwater exchange, structural barriers, or preferential routing toward other flow paths. Likewise, increased flow may elevate constituent loading and localized exposure, or it may enhance distributed wetland contact, retention, and biogeochemical transformation. These alternatives cannot be resolved using inflow volume or water-column concentration alone. Evaluating them requires spatially distributed measurements of flow, constituent loads, residence time, hydrologic connectivity, and ecological change along the freshwater-to-estuarine gradient.

Ecological responses may also arise from interacting rather than singular causes. Reduced aquatic-prey availability could reflect insufficient wet-season production, premature loss of dry-season refugia, disrupted recession patterns, habitat fragmentation, effects of non-native consumers, or interactions among these processes. Vegetation change could result from altered hydroperiod, nutrient exposure, fire, salinity, or feedbacks among vegetation, soils, and hydrology. At the coast, freshwater delivery may moderate salinity, but its effectiveness may decline as sea level rises or where restricted drainage and tidal connectivity constrain water exchange. Framing these explanations as alternative hypotheses allows monitoring to test the proposed causal pathways rather than merely associate ecological condition with changes in freshwater delivery.

Aquatic-prey and consumer-response dynamic provides a specific example of this uncertainty. Cocoves et al (2021) documented a dramatic increase in coastal White Ibis nesting with greater crayfish abundance and availability of seasonally drying freshwater foraging habitat. However, this inference was based on prey use comparison during two contrasting breeding seasons, different colonies sampled between years and spatially limited crayfish sampling. The relative contributions of antecedent drying, wet-season flooding, crayfish production, recession-driven habitat availability, fish production, and regional movement of breeding birds therefore remain unresolved. Concurrent monitoring of these processes is needed before the observed association is treated as a predictive relationship for prey-consumer dynamics within Lostmans Slough.

Application to adaptive management

Within an adaptive-management framework, the CEM can be used to translate restoration actions into predicted changes in hydrologic and water-quality exposure, ecological processes, and measurable response. Before an operational or structural change, the model can identify the zones and indicators expected to respond, the anticipated direction and timing of change, and possible unintended effects elsewhere in the corridor. Monitoring can then determine whether the predicted sequence occurred and whether responses propagated among zones as expected. Results that depart from predictions provide information for revising causal relationships, modifying monitoring priorities, or adjusting the timing and distribution of freshwater delivery.

Adaptive management should evaluate restoration outcomes across multiple hydrologic conditions rather than relying on a single pre- and post-project comparison. Droughts, wet periods, fires, storms, and rising coastal water levels may amplify, suppress, or reverse the apparent response to management. Repeated evaluation across these conditions can help distinguish operational effects from climatic variability and determine whether management remains effective as the restoration baseline changes. The CEM therefore serves as both an organizing hypothesis and a revisable decision framework, not as a fixed endpoint.

Conclusions

We hypothesize that Lostmans Slough functions as a connected but spatially heterogeneous freshwater-to-estuarine corridor (Fig. 6). Its ecological character emerges from interactions among upstream freshwater delivery, seasonal drying, marl-prairie and ridge-and-slough processes, mangrove and coastal dynamics, and the movement of water, materials, and organisms among these environments. Evaluating Lostmans as a single homogeneous wetland or as an isolated component of the broader Everglades would therefore obscure the longitudinal linkages and spatial differences that govern ecological response.

Freshwater delivery is the primary management lever for influencing the condition of the corridor, but ecological benefit cannot be inferred from water volume alone. Outcomes depend on the magnitude, timing, duration, distribution, direction, and quality of delivery, as well as antecedent water levels, landscape connectivity, fire, tidal exchange, storms, and sea-level rise. Additional freshwater may reduce excessive drying, improve refuge persistence, and moderate coastal salinity, yet benefits may attenuate downstream or be accompanied by nutrient exposure, prolonged inundation, altered material transport, or changes in adjacent regional flow paths. Restoration should therefore seek an ecologically appropriate spatial and seasonal distribution of water rather than maximum delivery or hydroperiod throughout the system.

The Lostmans Slough CEM (Fig. 2) provides a framework for converting these relationships into testable hypotheses, linked indicators, and explicit restoration tradeoffs. Its principal contribution is not the

identification of a single optimal hydrologic condition, but the integration of freshwater, wetland, mangrove, and estuarine responses within a common causal and spatial framework. By distinguishing established relationships from transferred evidence and unresolved hypotheses, the model can guide monitoring, support comparison of management alternatives, and be revised as Lostmans-specific evidence accumulates. This application will be essential for evaluating whether regional restoration actions improve ecological function across the complete corridor while remaining responsive to climatic variability, sea-level rise, and changing restoration baselines.

Declarations

Conflict of Interest Statement

The authors declare that they have no conflict of interest

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Author Contributions:

PJ conceived the study, conducted the hydrologic analysis, developed figures, and drafted the manuscript. LK and ERS contributed to manuscript revision. All authors reviewed and approved the final manuscript.

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Data availability statement

The generalized Lostmans Slough spatial representation and editable source files for Figs. 2 and 6 are available through Figshare at https://doi.org/10.6084/m9.figshare.33350532 (Julian 2026). Hydrologic information derived from NSRSM and EDEN was obtained from the respective source datasets described in the Methods and is not redistributed in the Figshare repository.

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Figures

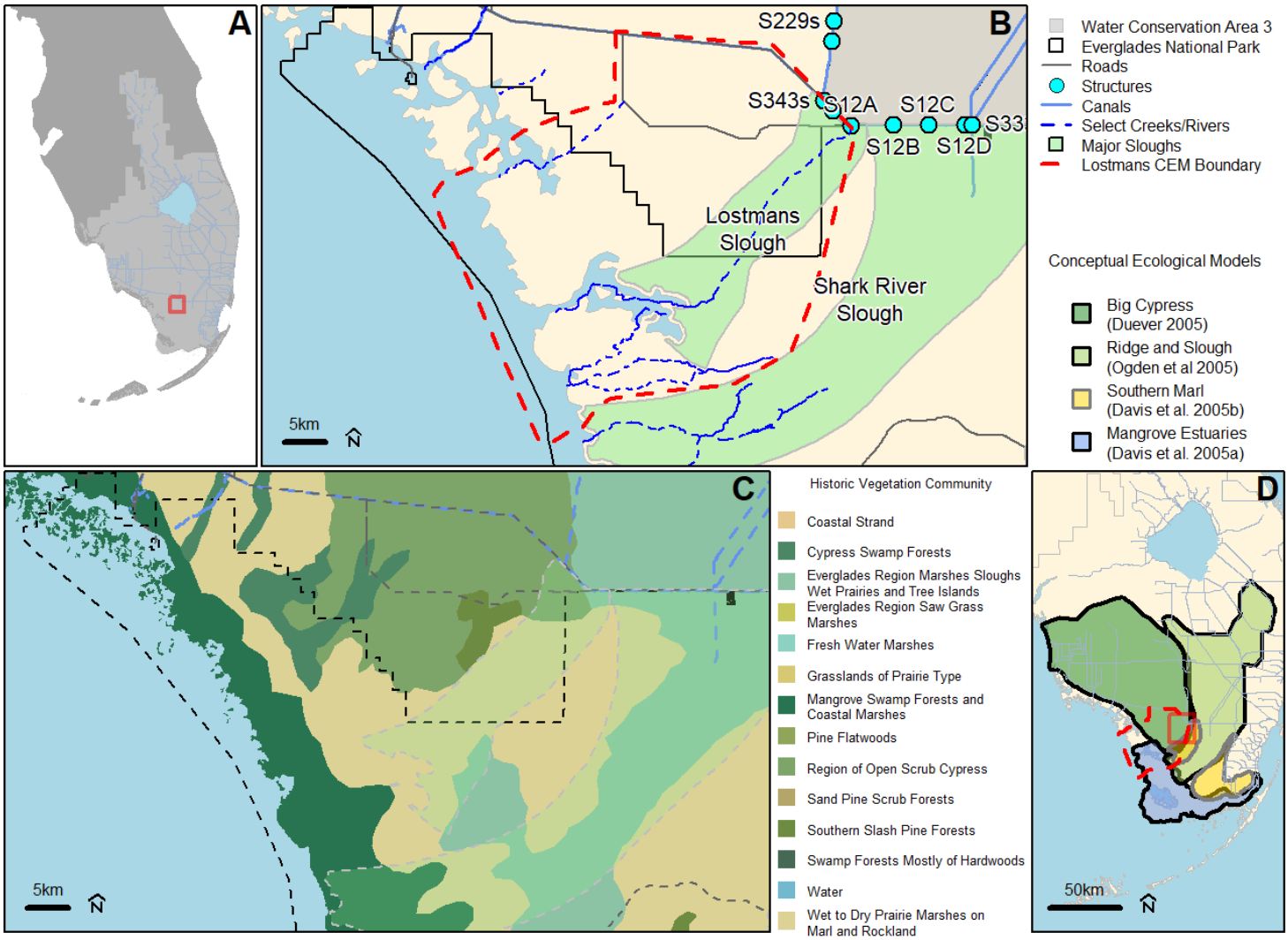


Figure 1

Spatial and ecological context of the Lostmans Slough study area in southern Florida. (A) Regional location of the study area within South Florida; the red box indicates the extent shown in panels B and C. (B) Major landscape and water-management features surrounding Lostmans Slough. (C) Historical vegetation communities within and surrounding Lostmans Slough. (D) Geographic extents of existing conceptual ecological models for Big Cypress, Ridge and Slough, Southern Marl Prairies, and Mangrove Estuaries in relation to the Lostmans Slough study area.

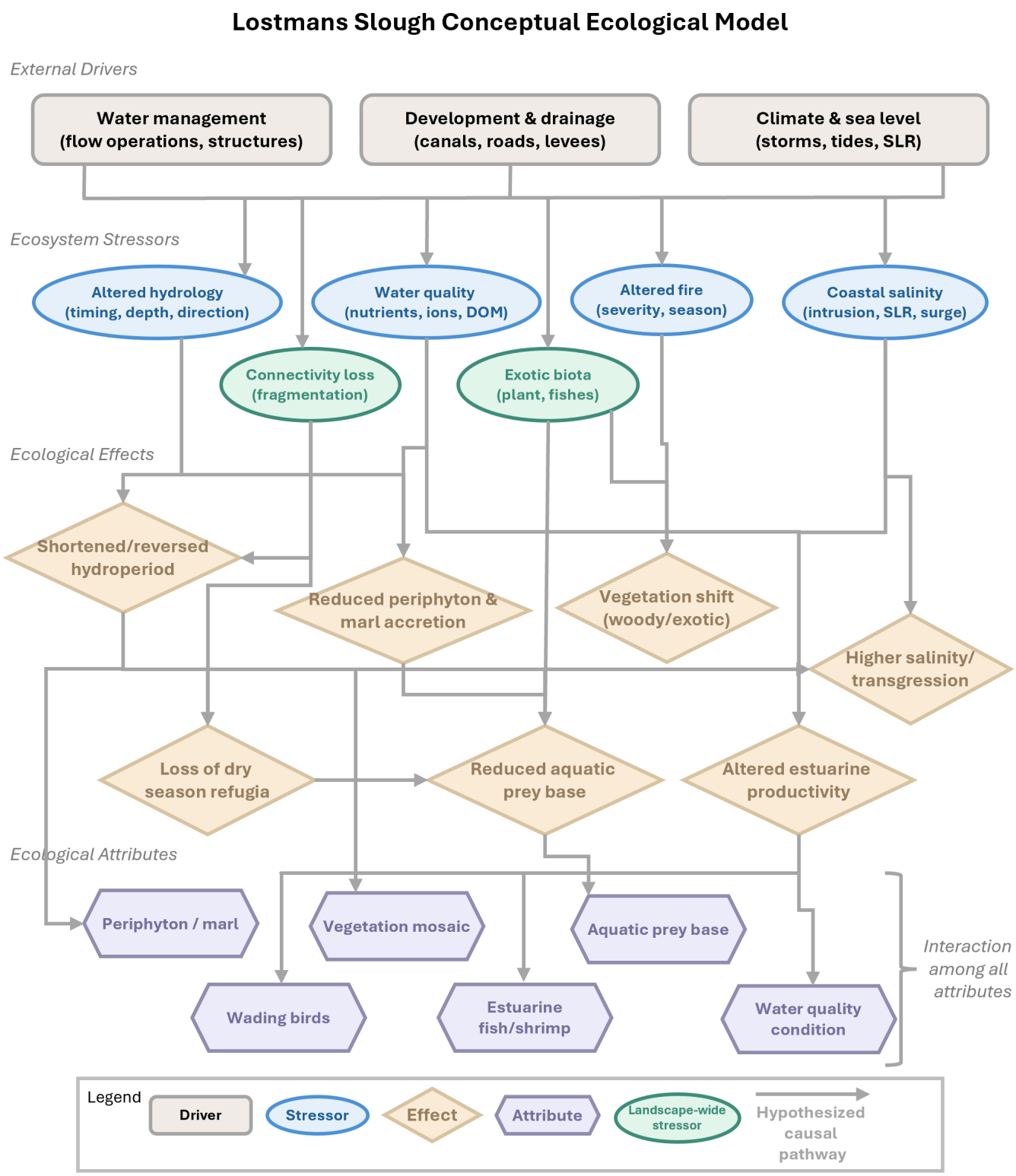


Figure 2

Lostmans Slough conceptual ecological model linking external drivers and cross-cutting landscape stressors to ecosystem stressors, ecological effects, and ecological attributes across the freshwater-to-estuarine corridor. Solid gray arrows represent hypothesized causal pathways, and dashed purple arrows represent feedbacks among ecological attributes. Pathways indicate expected directions of influence but not equivalent relationship strength or evidentiary confidence.

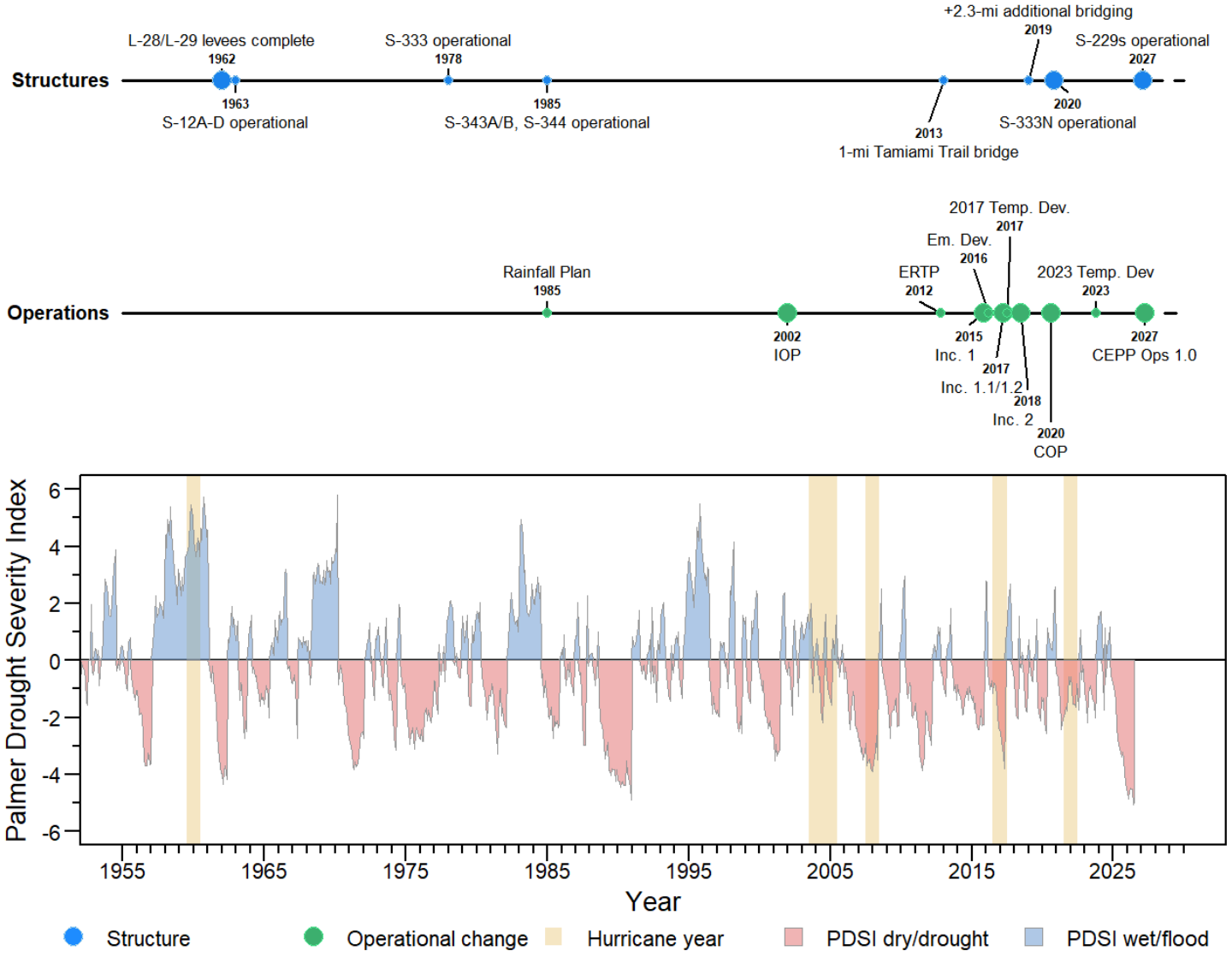


Figure 3

Timeline of major structural modifications and operational changes affecting hydrologic management in the study area, shown in relation to regional wet and dry conditions. Structural milestones, including completion or operation of levees, water-control structures, and Tamiami Trail bridging, are shown in blue; operational changes are shown in green. Regional hydroclimatic conditions are represented by the Palmer Drought Severity Index (PDSI) for Florida Division 5, with positive values indicating wetter conditions or flooding and negative values indicating drier conditions or drought. Yellow shading identifies hurricane years relevant to the timeline. Events through 2023 represent historical milestones, whereas the S-229 structures and Central Everglades Planning Project (CEPP) Operations 1.0 entries for 2027 represent anticipated milestones. Em. = Emergency; Temp. = Temporary; Dev = Deviation; Inc. = Increment; mi = mile(s); IOP = Interim Operations Plan; ERTP = Everglades Restoration Transition Plan; COP = Combined Operational Plan

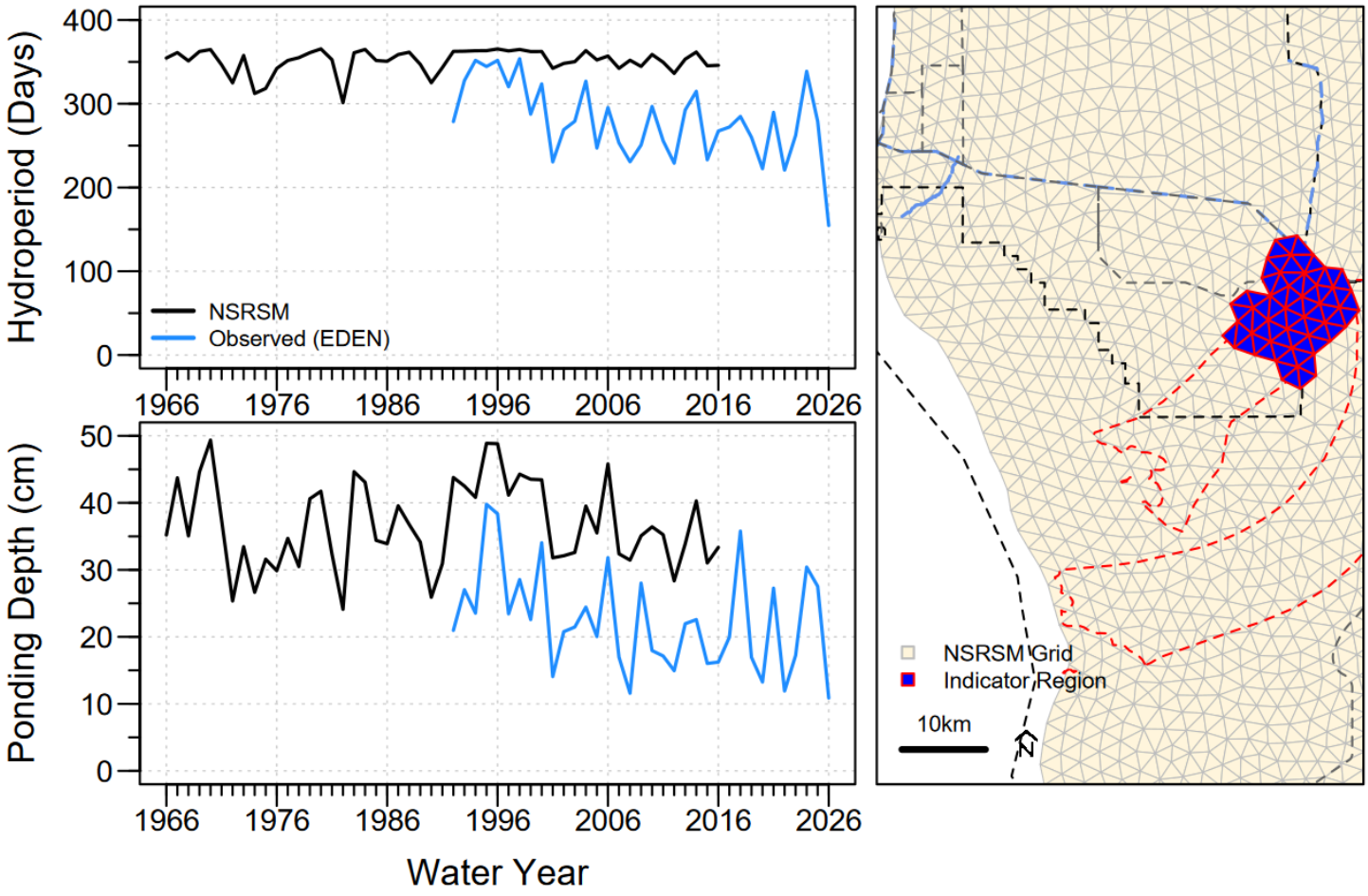


Figure 4

Natural System Regional Simulation Model (NSRSM) and Everglades Depth Estimation Network (EDEN) annual hydroperiod (top) and ponding depth (bottom) time series for the Lostmans Slough headwaters region.

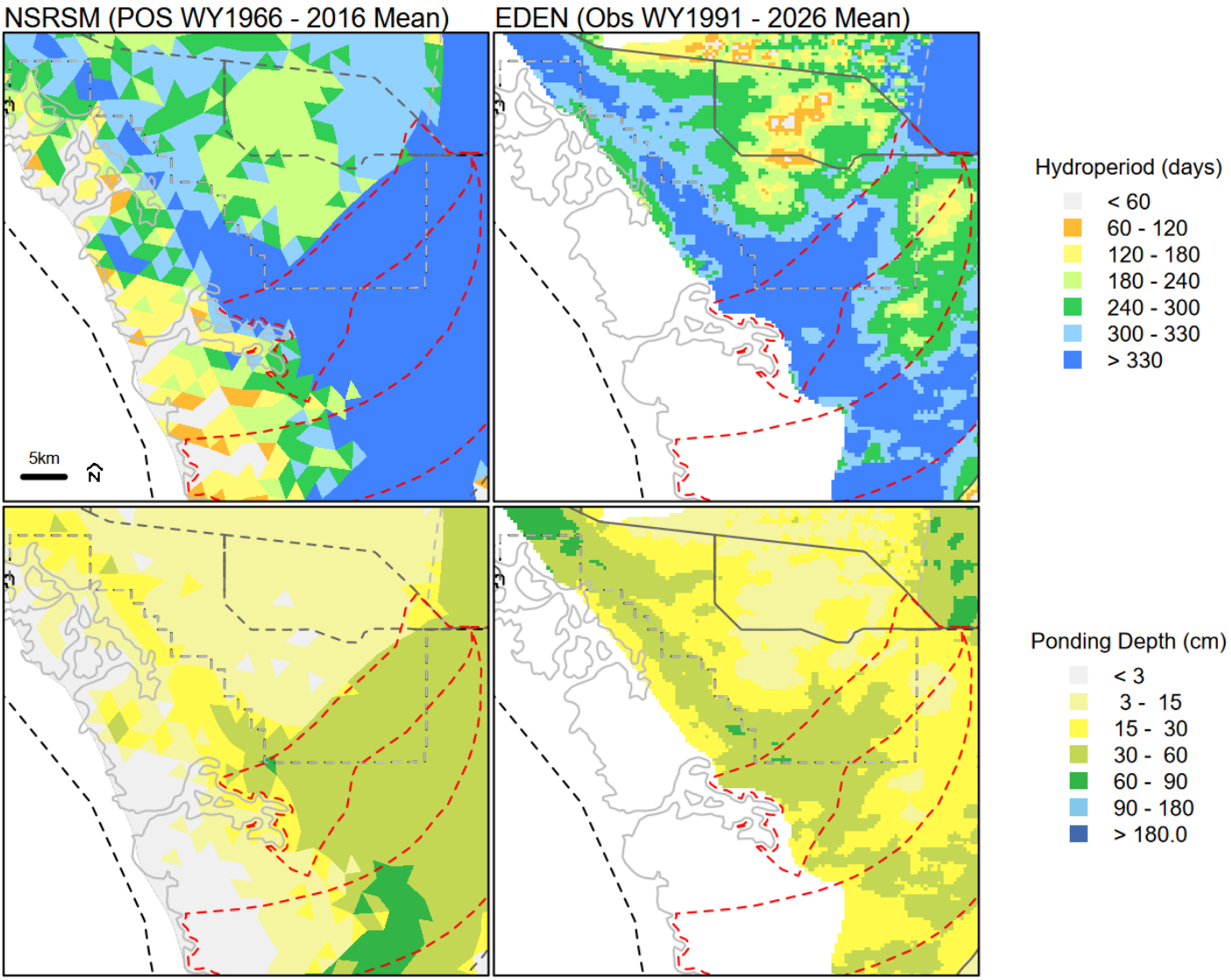


Figure 5

Natural System Regional Simulation Model (NSRSM) and Everglades Depth Estimation Network (EDEN) hydroperiod and ponding depth spatial distribution for the Lostmans slough headwaters region.

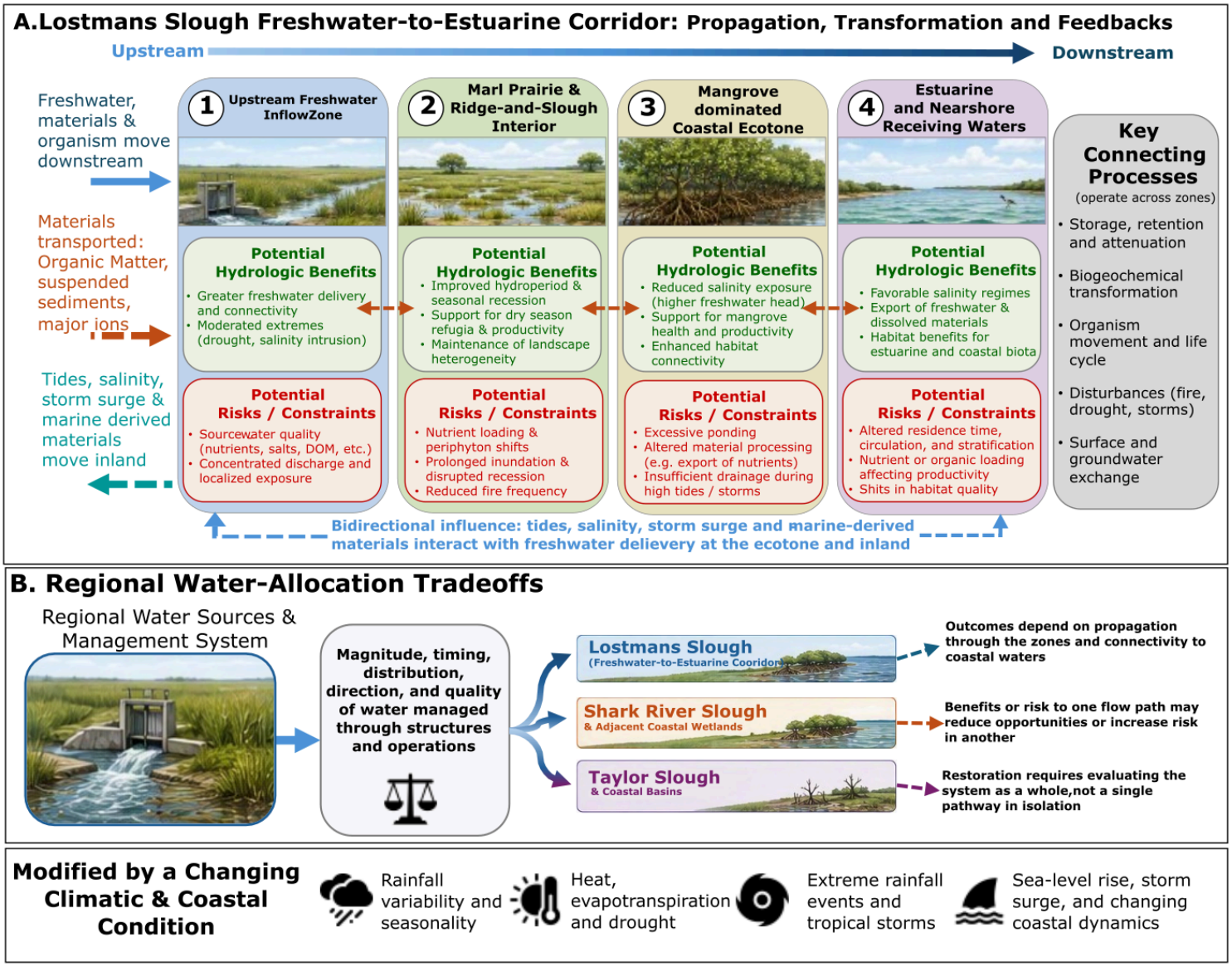


Figure 6

Spatial integration and restoration tradeoffs across the Lostmans Slough freshwater-to-estuarine corridor. Freshwater-management decisions affect the magnitude, timing, distribution, direction, and quality of water entering Lostmans Slough and its allocation relative to Shark River Slough and other regional flow paths. Within Lostmans Slough, water and transported materials are retained, transformed, and redistributed as they move through upstream freshwater wetlands, the marl-prairie and ridge-and-slough interior, the mangrove ecotone, and estuarine receiving waters. Potential benefits and risks vary among zones and are modified by climate variability, storms, sea-level rise, and marine forcing. Arrows represent conceptual pathways rather than quantified flows; dashed pathways identify relationships that remain uncertain or have not been validated directly within Lostmans Slough.