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A hydro-economic model of South Florida water resources system

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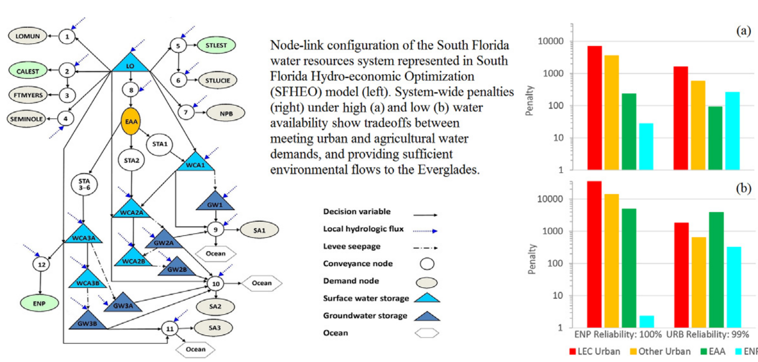
HIGHLIGHTS

- South Florida's water management tradeoffs are examined using a hydro-economic approach
- Maintaining high reliability of flows to the Everglades creates occasional urban and agricultural water shortage
- System-wide tradeoffs are more pronounced under scenarios of reduced water availability
- High reliability of urban water demands is possible under reduced water availability but agricultural losses are likely

GRAPHICAL ABSTRACT



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ABSTRACT

South Florida's water infrastructure and ecosystems are under pressure from socio-economic growth. Understanding the region's water resources management tradeoffs is essential for developing effective adaptation strategies to cope with emerging challenges such as climate change and sea level rise, which are expected to affect many other regions in the future. We describe a network-based hydro-economic optimization model of the system to investigate the tradeoffs, incorporating the economic value of water in urban and agricultural sectors and economic damages due to urban flooding while also accounting for water supply to sustain fragile ecosystems such as the Everglades and coastal estuaries. Results illustrate that maintaining high reliability of urban water supply under scenarios of reduced water availability (i.e., drier climate conditions) may trigger economic losses to the Everglades Agricultural Area, which will likely become more vulnerable as competition over scarce water resources increases. More pronounced economic losses are expected in urban and agricultural areas when flows to the Everglades are prioritized. Flow targets for coastal estuaries are occasionally exceeded under optimal flow allocations to various demand nodes, indicating that additional storage may be needed to maintain the environmental integrity of the estuarine ecosystems. Wetter climate conditions, on the other hand, generally lead to increased flows throughout the system with positive effects on meeting water demands, although flood

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mitigation efforts will necessitate additional releases to the estuaries. Strengths and limitations of the hydro-economic model are discussed.

1. Introduction

South Florida has one of the world's largest water infrastructure systems consisting of canals, levees and flood control structures to manage water resources under extreme conditions (e.g., floods and droughts), allowing human settlement in low-lying wetlands and coastal strips (SFWMD, 2010). The juxtaposition of human development and fragile ecosystems, including coastal estuaries, mangroves, and Everglades National Park (ENP), has caused complex sustainability concerns associated with competing, economically driven water demands. Maintaining the ecological integrity of natural environments in the face of growing water demands, climate change, land use change, sea level rise, and saltwater intrusion into coastal aquifers creates system-wide tradeoffs. For example, releasing surface water to reduce the risk of urban flooding affects the ability to meet water delivery targets along the lower east coast (LEC). Likewise, maintaining coastal ecosystem services in ENP by meeting environmental flow targets may decrease water availability for agricultural and urban uses.

The South Florida Water Management District (SFWMD) uses a number of simulation and optimization models with varying levels of complexity to inform regional planning and management. A prime example is the South Florida Water Management Model (SFWMM; SFWMD, 2010), which simulates the physical processes governing the availability and flow of water in the highly managed system at the scale of 2-mile by 2-mile grid cells (~5.18 km^2). The Natural System Model (NSM; VanZee, 1999) and Natural System Regional Simulation Model (NSRSM; Said and Brown, 2011) help examine pre-development hydrologic conditions of the Everglades system, providing a basis to evaluate the impacts of current water resources management plans. Furthermore, the Regional Simulation Model (RSM) facilitates analysis of optimal system operations under different climatic scenarios (SFWMD, 2005), while the REservoir Sizing and OPerations Screening (RESOPS) model, a higher level systems model compared to RSM, assists with rapid preliminary analysis and screening of alternative storage configurations and operation rules (SFWMD, 2009).

In this paper, we apply an economics-driven modeling approach, known as hydro-economic optimization (HEO), to investigate South Florida's water resources management tradeoffs. Hydro-economic optimization models are solution-oriented tools that represent the economic value of scarce water resources (Heinz et al. 2007; Harou et al., 2009; Mirchi et al., 2010). The approach has been widely applied in water resources planning and management to analyze trade-offs and interactions among different stakeholder groups that share surface water and groundwater resources, and to guide policies for operating water infrastructure (e.g., Lund and Ferreira, 1996; Watkins and Moser, 2006; Ward and Pulido-Velázquez, 2008; Maneta et al., 2009). Although hydro-economic models most frequently have been used to inform management decisions under conditions of water scarcity (Jenkins et al., 2004; Marques et al., 2005; Pulido-Velázquez et al., 2006; Ward and Pulido-Velázquez, 2008; Maneta et al., 2009), they are also useful for regions where economic performance is highly dependent on managing flood risk (e.g., Needham et al., 2000).

Watkins Jr. et al. (2004) developed the South Florida Systems Analysis Model (SFSAM) as a network optimization model to support the Central and Southern Florida Project Comprehensive Review Study (USACE/SFWMD, 1999). The model was applied to the screening of storage alternatives for improving environmental quality and urban and agricultural water supply reliability affected by the Central and Southern Florida Project. SFSAM was a generalized network flow model made of arcs and nodes with corresponding penalty functions that express system operation targets (e.g., flow and storage) and capacity constraints. The model represented key functions of the water resources system, including water supply for population centers, the Everglades Agricultural Area (EAA), and environmental nodes (e.g., ENP), providing insights about water supply reliability and the capacity of the system to cope with potential water shortages during droughts (Watkins Jr. et al., 2004). The model was formulated with the objective of minimizing system-wide penalties associated with deviating from specified performance targets. However, due to unavailability of economic information, penalty functions were developed in terms of relative, ordinal penalty values as opposed to reflecting cardinal economic value of water in different use sectors.

The South Florida Hydro-Economic Optimization model (SFHEO) presented herein was developed as part of the South Florida Water, Sustainability, and Climate project (SFWSC; Lanier and Sukop, 2016), which provided an opportunity to adopt an interdisciplinary approach to improve SFSAM. The SFHEO model (Mirchi et al., 2015) is a linear-programming model developed using the General Algebraic Modeling System (GAMS) version 23.3.3 (Rosenthal, 2008). It advances SFSAM in a number of important ways. First, SFHEO updates the South Florida water resources network representation to better capture hydrologic interconnectedness of the system in the EAA and stormwater treatment areas (STA) that control the flow of nutrient-rich agricultural runoff into fragile downstream aquatic habitats (Chen et al., 2015). Second, SFHEO accounts for the economic value of water in sectors where economic-based penalty functions have been developed, including urban areas and the EAA. The hydro-economic modeling framework also allows for accounting of the economic value of water at environmental nodes, although this capability has not been included in the current version of SFHEO because the corresponding ecological-economic relationships are still under development. Third, the model incorporates economic damages associated with urban flooding, based on statistical relationships between groundwater table variation and property damages as estimated from flood insurance claims (Czajkowski et al., 2018). The following sections describe the hydro-economic setting and modeling framework, as well as present example analysis results under variable climate conditions as a plausible scenario of system change.

2. Hydro-economic setting

The Kissimmee River Valley (KRV) forms the headwaters of Lake Okeechobee (LO) and the Everglades (Fig. 1). Once a wide floodplain with a meandering river, the KRV is now largely dedicated to cattle ranching and citrus production, containing over 400,000 cattle and approximately 9.5 million citrus trees (USDA, 2015, 2017). The KRV also contains approximately 45,000 ha under irrigation, resulting in over 870,000 m^3 per day in freshwater withdrawals (USDA, 2012). High nutrient loads in approximately1.2 billion $m^3\ yr^{-1}$ of surface water discharges from the KRV have contributed to eutrophication in LO (SFWMD, 2016). Restoration efforts over the last 18 years, valued at close to $1 billion (SFWMD, 2016), have focused on returning the river's natural meandering course and connection with the surrounding floodplain. Recent efforts to reduce discharge and nutrients flowing to LO have resulted in the establishment of a program to compensate private landowners who agree to temporarily store water on their property (Lynch and Shabman, 2011). The expected value of these contracts is approximately $43 million over a 10-year period, establishing more than 1600 ha of new reservoir area in the KRV.