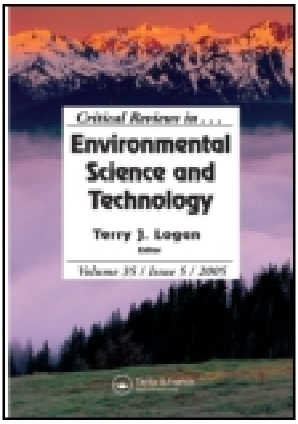

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Integrated Ecological Modeling and Decision Analysis Within the Everglades Landscape

H. Carl Fitz [a] , Gregory A. Kiker [b] & J. B. Kim [b c]

[a] Soil & Water Science Department, Fort Lauderdale Research & Education Center, IFAS, University of Florida, Davie, FL, USA

[b] Department of Agricultural and Biological Engineering, IFAS, University of Florida, Gainesville, FL, USA

[c] Environmental Laboratory, Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, MS, USA

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Integrated Ecological Modeling and Decision Analysis Within the Everglades Landscape

H. CARL FITZ,[1] GREGORY A. KIKER,[2] and J. B. KIM[2,3]

[1]*Soil & Water Science Department, Fort Lauderdale Research & Education Center, IFAS, University of Florida, Davie, FL, USA*

[2]*Department of Agricultural and Biological Engineering, IFAS, University of Florida, Gainesville, FL, USA*

[3]*Environmental Laboratory, Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, MS, USA*

Planning for complex ecosystem restoration projects involves integrating ecological modeling with analysis of performance trade-offs among restoration alternatives. The authors used the Everglades Landscape Model and Multi-Criteria Decision Analysis to explore the effect of simulated ecosystem performance, risk preferences, and criteria weights on the ranking of three alternatives to restoring overland sheet flow in the Everglades. The ecological model outputs included both hydrologic and water quality criteria. Results were scored in the decision analysis framework, highlighting the trade-offs between hydrologic restoration and water quality constraints. Given equal weighting of performance measures, the alternative with more homogenous sheet flow was preferred over other alternatives, despite evidence of some localized eutrophication risk.

KEYWORDS: decision analysis, Everglades, hydrology, integrated model, phosphorus, restoration, sheet flow

INTRODUCTION

Simulation models are explicit abstractions of reality that can help organize or synthesize scientists' understanding of the ecology of a system, and this understanding may be applied to evaluating scenarios of future ecosystem

Address correspondence to H. Carl Fitz, Soil and Water Science Department, Fort Lauderdale Research & Education Center, UF/IFAS, 3205 College Ave., Davie, FL 33314, USA. E-mail: cfitz@ufl.edu

changes. Canham et al. (2004) described the design and application of numerous ecological models, reflecting the wide range in modeling approaches to address different questions. Some ecological models employ agents that represent individual animals, with interacting behaviors that result in a variety of realistic, emergent system-level patterns. Other types of ecological models simulate the cascading interactions among ecosystem processes such as nutrient uptake and plant growth in the system. Here, we give an overview of a model framework that is general enough to address such integrated ecosystem processes within large spatial domains at decadal time scales. In development of this framework, we focused on the integration of biogeochemical and physical properties of soils with the landscape drivers of hydrology, water quality, and disturbances within a variety of landscape types. For this paper, we show how model results can be further interpreted within a decision analysis framework to aid in understanding the relative benefits of specific components of a restoration plan.

Review of Concepts

Everglades Restoration Planning

The Everglades region of South Florida, USA, is a system of neotropical estuaries, wetlands, and uplands interspersed among agricultural and urban land uses. Water historically flowed from the north into and through the Everglades largely as overland sheet flow. During the 20th century, an elaborate water management infrastructure was built to improve regional flood control and water supply for urban and agricultural development, with some environmental considerations (Light and Dineen, 1994). Significantly, this network of canals, levees, and water control structures also fragmented the once-continuous Everglades wetlands into a series of large impoundments, or Water Conservation Areas (WCAs). Everglades National Park is south of these WCAs, while Big Cypress National Preserve is to the west (Figure 1). Agricultural land uses dominate the area just north of the Everglades, while extensive urban land uses predominate along the eastern boundary of the Everglades.

The altered distribution and timing of flows in a fragmented Everglades watershed degraded the mosaic of Everglades habitats (Davis and Ogden, 1994), and ultimately a plan to restore the Everglades was developed by federal and state agencies (U.S. Army Corps of Engineers and South Florida Water Management District, 1999). The Comprehensive Everglades Restoration Plan (CERP) is being implemented to address the future of South Florida's ecology—while also enhancing urban and agricultural water supply for the regional population.

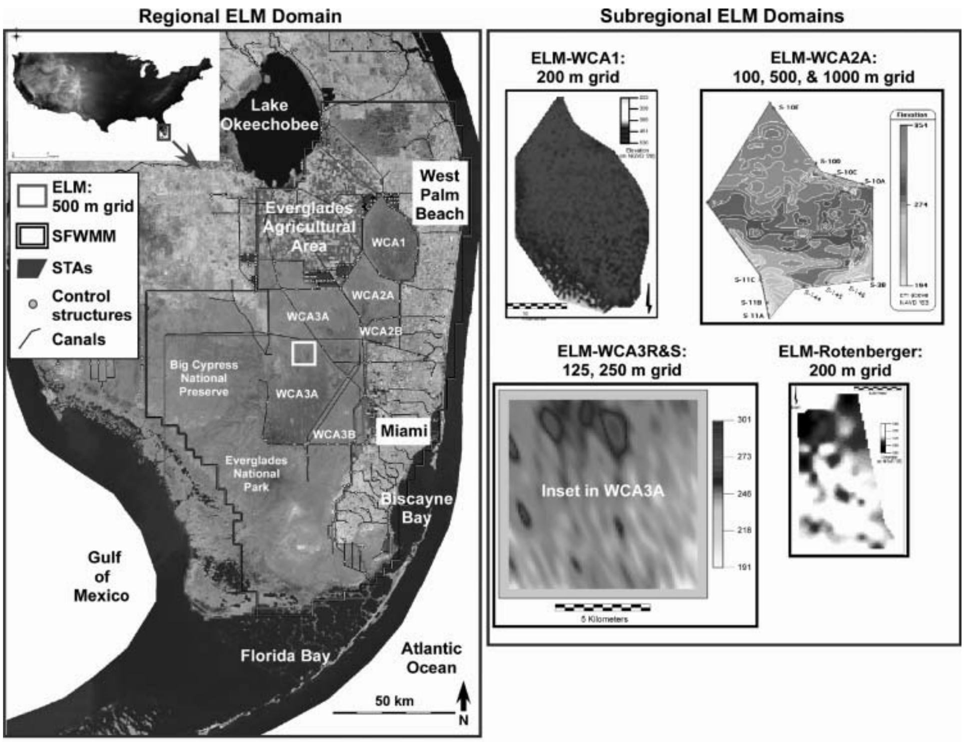

FIGURE 1. The SFWMM domain, and the regional and subregional domains of the ELM applications in South Florida, USA. WCA = Water Conservation Area.

While much of the focus of the CERP is on improved water management and increased Everglades water flows, water quality degradation in the system imposes constraints. As a result of runoff from the agricultural and urban developments, many of the managed Everglades inflows carry higher nutrient loads into the historically oligotrophic system. Because of the significant ecosystem impacts due to these P inputs (see review in Noe et al., 2001), a series of wetlands is being constructed (Stormwater Treatment Areas [STAs]) along the northern periphery of the Everglades to filter excess phosphorus (P) from waters that flow into the Everglades. In parallel with on-farm Best Management Practices initiated in the mid-1990s, the first operational constructed wetlands reduced total phosphorus (TP) concentrations well below the interim target of 50 ug·L^{-1} (Chimney et al., 2000; Nungesser et al., 2001). To reach the threshold TP target of 10 ug·L^{-1} (Florida Department of Environmental Protection, 2000), other P removal mechanisms will likely be added. The likely trade-offs between reducing P loads while increasing Everglades water inflows will be fundamental to CERP planning in the coming decades (Sklar et al., 2005).

Models for Everglades Restoration Planning

In planning for Everglades restoration, predictive simulation models are one of the suite of methods being used to evaluate the relative benefits of management alternatives. The primary model used in the original CERP planning was the South Florida Water Management Model (SFWMM), which simulates rule-based water management and the resultant water levels in the South Florida urban/agricultural and natural systems (Figure 1), from Lake Okeechobee to the southern Everglades (Tarboton et al., 1999). In further evaluating and refining individual CERP projects, hydrologic output from this model continues to be used to predict the relative benefits of alternative scenarios of water management toward system restoration.

In addition to that hydrologic model, ecological and water quality simulation tools were used in the original CERP planning to explore potential ecological dynamics under altered water management. Several Spatially Explicit Species Index models and individual (agent) based models (DeAngelis et al., 1998) estimated the responses of animal species to different water depths among management scenarios. Walker (see Kadlec and Walker 1999) applied a water quality model of the STAs to estimate P loads into the Everglades marshes, and the Everglades Water Quality Model (EWQM; Raghunathan et al., 2001) evaluated the resulting P fate and transport within the Everglades. Both of those water quality models calculated a simple net loss of TP from the surface water column, aggregating the multiple processes involved in P biogeochemistry via a net settling rate parameter. While the EWQM was discontinued, significant refinements were subsequently made to the other ecological and water quality simulation tools.

A variety of other models have been developed to help address hydroecological uncertainties within the Everglades marshes. For example, Larsen and colleagues developed fine (local) scale models (Larsen et al., 2007; Larsen et al., 2009) to evaluate hypotheses of the water flow regimes needed to restore the anisotropically patterned peatlands of the ridge and slough habitats of the Everglades. A next-generation water management model (Regional Simulation Model; Lal et al., 2005) is starting to be applied by the South Florida Water Management District to selected areas of South Florida. Moreover, a new, process-based water quality model (Jawitz et al., 2008) is being integrated with the Regional Simulation Model for Everglades-wide water quality applications.

Presently, the Everglades Landscape Model is the only available simulation tool for evaluating water quality across the regional landscape. While the ELM fully integrates many of the components of an ecosystem (see subsequent subsections), here we restricted the analysis to linking the hydrologic and water quality results of the ELM with a Multi-Criteria Decision Analysis (MCDA) framework/software to provide a systematic approach to analyzing simulated alternatives associated with a relatively simple restoration plan.

ELM Model Description

The documentation of the first publicly released ELM version (Fitz and Trimble, 2006) was reviewed and accepted for CERP applications by an independent panel (Mitsch et al., 2007). Subsequent improvements to the present ELM (version 2.8) were also fully documented, with the Open Source code, data, and documentation being available http://ecolandmod.ifas.ufl.edu, which should be consulted for a hierarchy of detailed information on all aspects of the model and its assumptions. A brief overview of the model is provided here.

Model Goals

The ELM is a regional-scale, integrated ecological assessment tool designed to help scientists understand and predict the relative responses of the Everglades landscape to different water management scenarios. In simulating changes to habitat distributions, the ELM dynamically integrates hydrology, water quality, soils, periphyton, and vegetation. The model has been used as a research tool to understand the dynamics of the Everglades, enabling hypothesis formulation and extrapolation of field scale research to larger spatial and temporal domains. This is a critical, ongoing application of the model. However, one of the primary objectives of this simulation project is to evaluate the relative ecological benefits of alternative management scenarios.

Integrated Ecosystem Processes

The landscape modeling framework is intended to be flexible and applicable to a range of scales and ecosystems. In synthesizing the dynamic ecosystem interactions across a heterogeneous spatial domain, the model becomes a hypothesis of the physical, chemical, and biological dynamic interactions that are important to the function and structure of a simplified conceptual ecosystem (Figure 2). The feedbacks among hydrology, nutrients, soils, and plants form the basis of the ELM. In this interactive system, the physical hydrology of wetlands and uplands is a principal driver of ecosystem dynamics (e.g., Band, 1993; Mitsch and Gosselink, 2000). Interacting with these hydrologic dynamics are the nutrient transformations and transport: as the physical and chemical dynamics interact with the biological communities, the cumulative system dynamics define different ecosystem states under different conditions. As shown in previous results (Fitz et al., 2004), the integrated model effectively simulated the feedbacks among general ecosystem processes, including the resulting patterns of soil properties and vegetative succession at the landscape scale.

Spatial Modeling Environment

Consisting entirely of Open Source software, the ELM uses the high-level modeling environment of the Spatial Modeling Environment (SME [version 2];

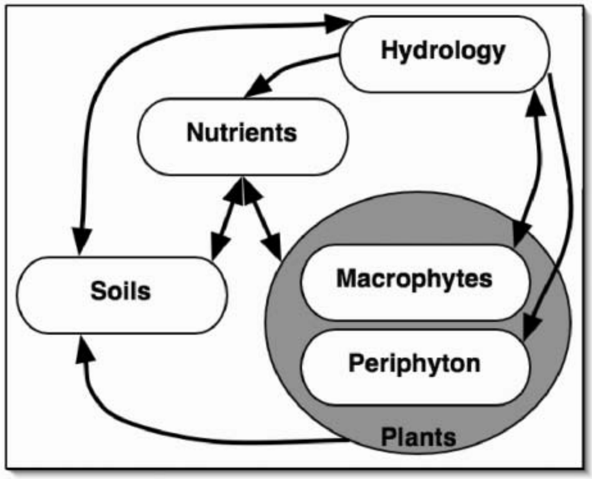

FIGURE 2. Dynamic interactions among primary hydroecological modules of a simple conceptual ecosystem of the Everglades, representing the fundamental feedbacks found in the unit model of the ELM.

Maxwell and Costanza, 1995). The SME (Figure 3) is a comprehensive toolkit for spatial ecological models, with hierarchical C language modules that perform tasks such as linking spatial map (GIS) data with ecological algorithms, spatial interpolations of input data, and flexible management of input/output. Raster cell surface and groundwater flows in the horizontal dimension are solved using a finite difference, Alternating Direction Explicit technique, providing for propagation of water and water-borne constituents (e.g., chloride, phosphorus) across space. Vertical integration of surface and groundwater flows are calculated within the groundwater module, using an iterative mass balance approach that evaluates storage potentials following overland and groundwater flows.

Rivers and canal/levees are represented by a set of linked vector objects that interact with a linked set of raster landscape cells. This vector-based flow allows for rapid flux of water and dissolved constituents over long distances, relative to the slower overland flow among grid cells. Within each vector (e.g., canal) reach segment, water and dissolved constituents are distributed homogeneously along the entire segment, with an iterative routine allowing exchange among the linked grid cells.

General Ecosystem Model

The vertical solutions of the landscape simulation are calculated in modules of a generic unit ecosystem model. An overall goal was to develop a model structure that was generalized enough to make intercomparisons of different ecosystems with one unit model. We avoided structure- or process-specific details that may vary among distinct ecosystems, such as upland forests vs.

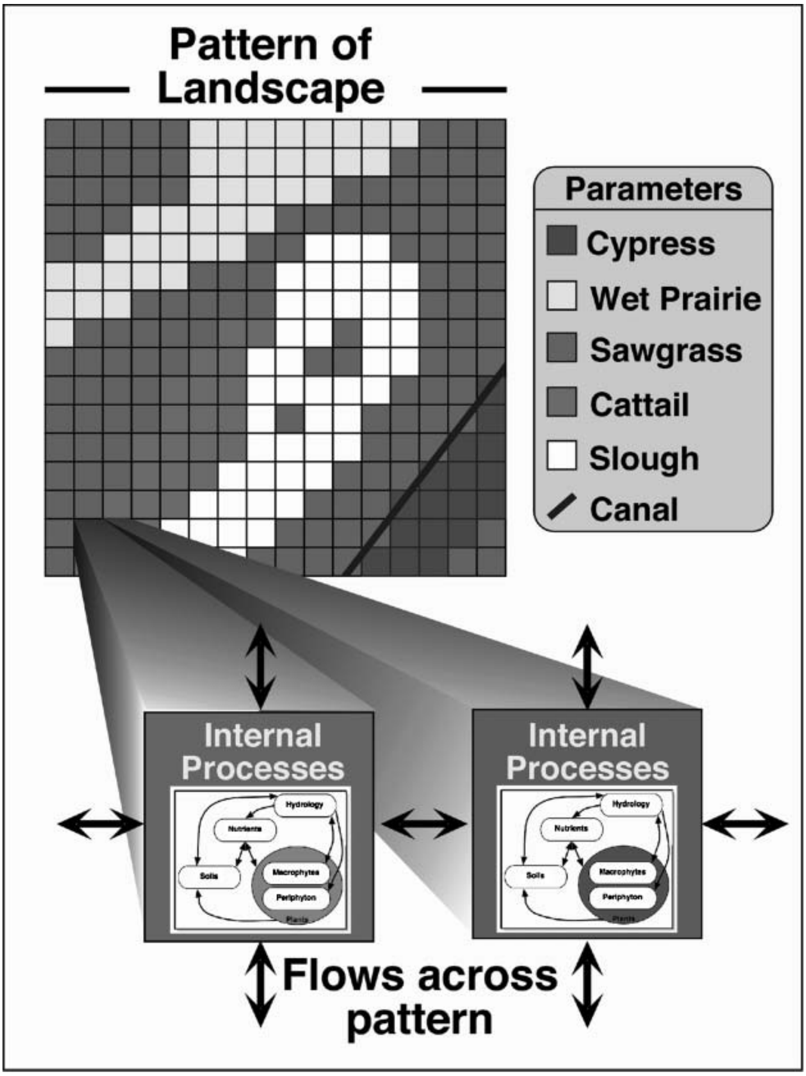

FIGURE 3. The Spatial Modeling Environment conceptualization of how the unit model of general ecosystem dynamics is applied across the spatial grid of a hypothetical landscape comprising five unique habitat types.

gramminoid wetlands. Instead, we strived to characterize the commonalities in ecosystem processes, keeping the ecosystem model simple and general (Fitz et al., 1996).

The unit model is comprised of linked modules for different ecosystem components, including water, phosphorus, chloride, periphyton, macrophytes, flocculent detritus, and soils (Figure 4). In its spatially distributed application, user-selected modules are executed for each grid cell within a landscape. The grid cells are assigned an initial habitat type, with different

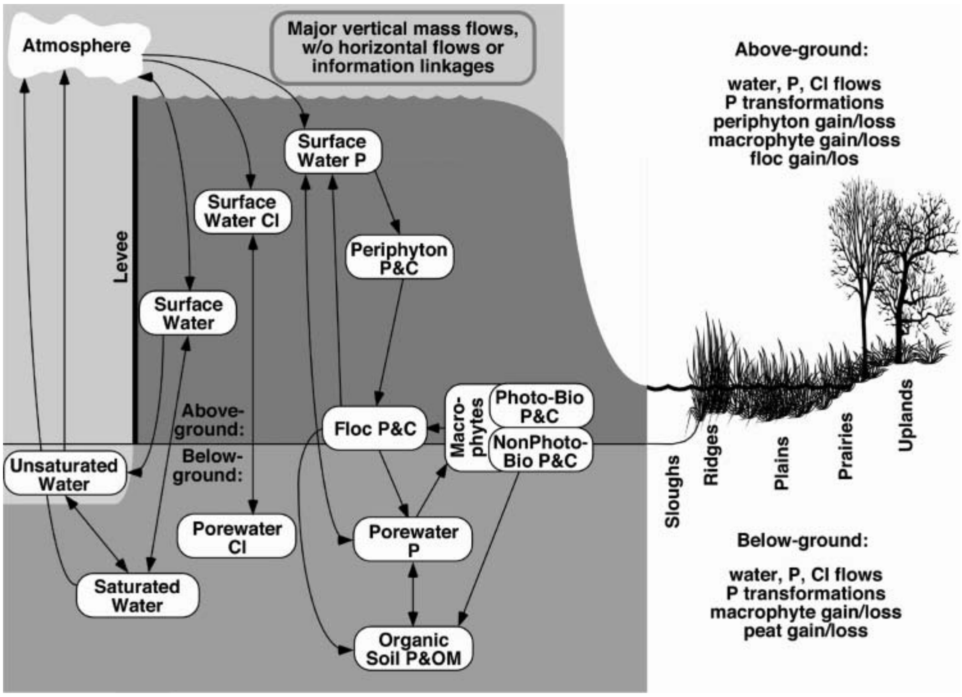

FIGURE 4. Conceptual unit model of vertical solutions of ecosystem processes. Model state variables are in oval boxes, linked by the major flow pathways among those variables. P = Phosphorus; Cl = Chloride; C = Carbon; OM = Organic Matter; Photo-Bio = Photosynthetic biomass of macrophytes; NonPhoto-Bio = Nonphotosynthetic biomass of macrophytes; Floc = Flocculent detritus layer on/above soil.

habitats potentially having unique parameter values that define processes such as nutrient uptake kinetics or surface roughness for overland flows. Thus, the pattern of habitats in the landscape can influence material fluxes among cells in the landscape, and the within-cell ecosystem dynamics can lead to ecosystem changes and succession that alters the landscape pattern. Within the spatial modeling framework, the model provides an integrated synthesis of ecosystem processes over large time and space domains, for use in better understanding and evaluating ecosystems across heterogeneous landscapes.

Adaptive Management and Decision Analysis

As a response to complex challenges in ecosystem evaluations, adaptive management (National Research Council [NRC], 2004; Walters and Holling, 1990) has been used (at least in principle) by many resource management agencies. Recent Everglades management plans have laid out a conceptual framework for adaptive management at the project scale (NRC, 2003b, 2008). In order to successfully manage the wide range of ecosystem, hydrological and socioeconomic information, MCDA provides one approach to create iterative, transparent and ultimately reproducible decisions (Keeney and Raiffa, 1976, Hammond et al., 1999, Clemen and Riley 2000, Figueira et al., 2005). The primary purpose of MCDA methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis that attempts to overcome the potential pitfalls of unstructured individual or group decision making. A detailed analysis of the theoretical foundations of these decision methodologies along with their associated advantages and disadvantages is presented in Belton and Steward (2002), while a review of MCDA applications in various environmental projects is presented by Kiker et al. (2005).

DECOMP Restoration Project

One CERP restoration project will decompartmentalize the flows between WCA-3A, WCA-3B, and Everglades National Park (Figure 1). Planned in different phases, ultimately most of the levee infrastructure that impounds the southern portions of those WCAs will be removed, along with numerous other planned features in order to restore more homogenous sheet overland surface water flow across a large portion of the Everglades marshes.

One of the first components to be evaluated in this WCA-3 Decompartmentalization and Sheetflow Enhancement Project (referred to as the DECOMP project) is to backfill or plug portions of the Miami Canal (Figure 5). Outflows from this canal presently convey water either to the urban regions to the east, or further south along the L-67A canal within the WCA depending on the time-varying management operations. While there are no continuous levees along the sides of the Miami Canal within the WCA, the presence of the canal in the marsh interrupts the overland sheet flow of water, and leads to increased rates of drainage of upslope areas due to short-circuiting of normally slower, downslope overland flows within the marshes. This overdrainage led to numerous fires over multiple decades, some of which have burned intensely enough to oxidize the peat (i.e., muck fires).

Modification to the Miami Canal is merely an initial step toward removing barriers to flow in the central Everglades: relatively little direct ecological benefit is expected from this component alone. However, the combined infrastructure and operational changes planned for the DECOMP project should have significant ecological benefits. Indeed, the long-term effects of DECOMP implementation is fundamentally important to meeting the overall goals of CERP. The Miami Canal model experiments described here thus do not involve the majority of planned changes under DECOMP, with expectations of relatively subtle hydroecological effects under different management scenarios.

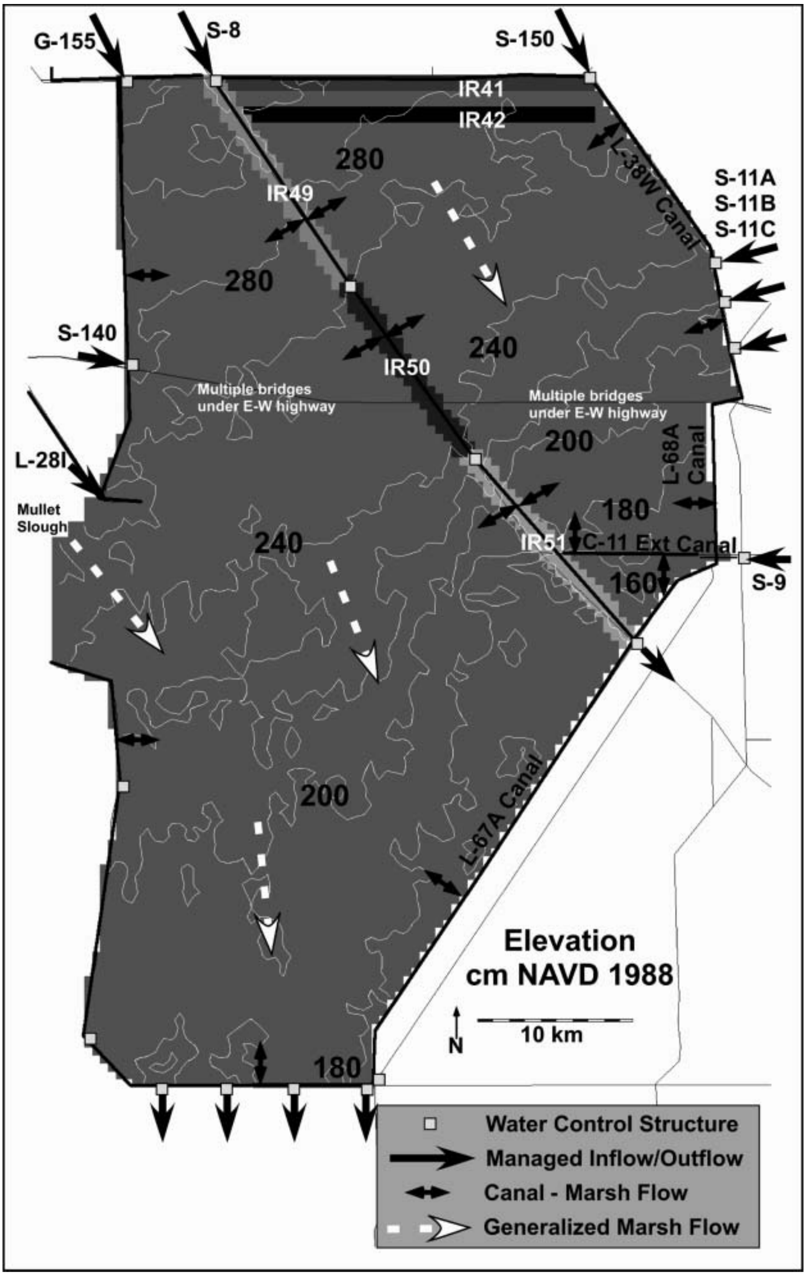

FIGURE 5. Map of WCA-3A showing land elevation contours, selected Indicator Regions (IR), canals/levees, major structures, and most flows into, within, and out of the region (for the Base scenario). Names are shown for all managed inflow structures. IR 49–51 encompass the Miami Canal. The east-west highway (Interstate 75) has borrow canals along both sides, with multiple small bridges to allow water flows under the road barrier.

METHODS

Model Performance Testing

The ELM has been implemented at a range of scales (see Figure 1) depending on the specific project objectives. Using spatial data at different scales, the same code was used to investigate hypotheses involving decadal to century time frames, in smaller subregions with model grid resolutions ranging from 1 ha to 1 km^2. For this manuscript, we used the regional (10,394 km^2) ELM v2.8 application at 0.25 km^2 grid resolution, and a multidecadal time domain.

While a variety of new capabilities were encoded into ELM v2.8, the dynamic algorithms remained the same as those in ELM v2.5 (Fitz, 2009). The principal change to the regional ELM v2.8 was increasing grid resolution from 1 km^2 to 0.25 km^2, by resampling most of the 1.0 km^2 spatial input maps. The exception was the initial condition map of land surface elevation, for which we generated a new 0.25 km^2 interpolation of the best available elevation survey data. Details of those data processing methods are found in Fitz (2009).

Prior to applying a model to evaluate management scenarios, it is important to communicate how reliably the model meets its objectives. An evaluation of the model performance in history-matching is a fundamental component of that communication. The methods of evaluating and improving the performance of a distributed, integrated ecological model are wide ranging, involving both analytic tools and science-based judgments. Fitz and Trimble (2006) detailed the methods that were used to calibrate and validate ELM v2.5, which were reviewed and accepted by Mitsch et al. (2007); we employed those same methods and 1981–2000 historical data to assess the hydroecological performance of ELM v2.8 (Fitz, 2009).

Simulation of Restoration Alternatives

For our model experiments, all flows in the marsh and canals were calculated by the ELM algorithms, but managed water control structure flows were input from daily output flow (point) data of a future base simulation of the SFWMM v5.5. That simulation was referred to as the Lake Okeechobee Regulation Schedule 2007 (LORS07), and had objectives that were independent of any future DECOMP project plans.

The LORS07 involved a variety of assumptions regarding future water management practices, including that most managed inflows into the greater Everglades marshes were from STAs. For all ELM simulations of LORS07 and associated alternative scenarios, we assumed that all daily water inflows into the model domain from STAs had a temporally constant TP concentration of 20 ug l^{-1}, which is approximately the long term mean concentration in outflows from the most effective STAs to date (Pietro et al., 2009). Note that a relatively small number of Everglades inflows were not routed through

STAs, including all flows via L-28I and S-140, and periodic storm events during which STAs were bypassed due to flooding. For the LORS07, the climate drivers of the SFWMM and ELM were the observed rainfall and potential ET data from 1965–2000. When running a future simulation such as LORS07, model outputs are assumed to represent how the system would respond to a repetition of the historical 36-year climate drivers, but under future management plans.

We compared hydroecological Performance Measures amongst the base run and two scenario alternatives. The three ELM simulations were the following:

- Base: LORS07, with all managed water control structure flows from SFWMM output data; SFWMM output was also used for daily stage boundary condition data (along the ELM domain periphery).
- Plugs: modified LORS07, in which managed flows into the Miami Canal (via S-8) were diverted to a new spreader canal along the northern boundary of WCA-3A; three plugs were placed into the Miami Canal at the location of three existing structures, blocking all downslope flows within the canal at those three points.
- Fill: modified LORS07, in which managed flows into the Miami Canal (via S-8) were diverted to a new spreader canal along the northern boundary of WCA-3A; the Miami Canal was completely removed from WCA-3A, assuming that the canal was completely filled with soils/sediments.

It is important to note that no changes to the timing nor the magnitudes of water control structure flow data were made in the ELM simulations. Our evaluations of this portion of the project are example model experiments, and are not part of any formal DECOMP project evaluation process to be undertaken in the future. Under more formal evaluations of these types of scenarios, managed water control structure flows from multiple SFWMM simulations would be used, as managed flows would likely change among scenarios.

Performance Measures

Performance Measures were formulated to quantitatively compare one simulation run relative to another. While a variety of model output variables could be compared, we limited the Performance Measures to three concerns based on past research:

- Total Ecosystem P Accumulation: the area of marsh in the WCA3-A basin with mean (36 year) accumulation rates exceeding 50 mg P m^2 yr^{-1}. This was the approximate threshold above which there is a reasonable possibility of eutrophication impact to the ecosystem over decadal time scales (RECOVER, 2007).

- Sheet Flow Skewness: the uniformity of sheet flow associated with the mean (36-yr) surface water flow velocities in the WCA-3A basin. The skewness of velocities across the basin discerned the relative magnitude of discontinuities in sheet flows at that basin scale. It was recognized that differences in flow velocity occur between sawgrass ridges interspersed with deeper-water sloughs (e.g., Larsen et al., 2007); these differential ridge and slough characteristics are generally at scales on the order of 100–200 m or less, and were not simulated in our 500 m grid scale model application.
- Muck Fire Index Days: the annual mean number of days that the unsaturated zone extended deeper than 15 cm below the land surface, and had unsaturated soil moisture of less than 50%. This was evaluated in a set of model grid cells encompassing local areas where change was considered likely due to changes in known flow pathways. These sets of grid cells, termed Indicator Regions, were along the Miami Canal and immediately downstream of the spreader canal inflows (see Figure 5).

To reiterate, relative to the Base simulation, we sought to determine if the model Performance Measures were able to quantify whether any scenario resulted in: (a) enhanced, more homogenous, sheet flow, while (b) not leading to phosphorus eutrophication nor excessive drying in the marsh ecosystem, employing a MCDA tool to guide that process.

Decision Analysis Methods

The MCDA alternative rankings were calculated in a similar methodology to recent ecological risk analysis studies (Kiker et al., 2008). The three primary performance measures or decision criteria (Sheet Flow, P accumulation, and Fire Index) were combined using a simple additive utility function (Keeney and Raiffa, 1976):

$$\mathrm{U} = \sum_i w_i \, u(x_i)$$

where U is the overall utility of a specific alternative, i is the total number of criteria, w_i represented the weight for each criterion i (with $\Sigma_\mathrm{i}\ w_i = 1$), and u is a utility function for each performance measure (criterion) value x_i, (described in more detail subsequently). Within specific decision criteria, a single utility function, $u_i(x_i)$ was used to reflect the decision maker's utility (u_i) toward a criteria value (x_i) generated by ELM for a particular alternative. We constructed a set of varying utility functions to explore the sensitivity of alternative rankings by decision makers. Research has shown that decision-makers are often risk averse because they want to achieve their objectives with more certainty (e.g., Eeckhoudt et al., 2000; Peters and Marmorek, 2001). Therefore, less variance in system performance is usually preferred to more variance.

The utility function describes human satisfaction on a 0 to 1 scale (0 being minimal utility and 1 maximal utility) against decision criteria values. For simplicity, a constant risk attitude function, $u_i(x_i) = a\text{-}b(e^{-cx})$, where $u_i(x_i)$ represents the degree of preference concerning criteria value x_i, a and b are constants to scale each u_i from zero to one (worst to best) respectively and c, called risk tolerance, is positive for increasing utility functions and negative for decreasing utility functions when b is positive (Keeney and Raiffa, 1976, Kirkwood, 1997, Kiker et al., 2008). Furthermore, the greater the risk aversion, the greater c becomes in absolute value. For each criterion utility function, we used a different utility function because each criterion has different lowest and highest values. For each decision criteria, we developed utility curves showing three basic shapes named *Viewpoint A*, *Neutral Viewpoint,* and *Viewpoint B* (Figure 6). These shapes approximated different utility responses based on differing risk viewpoints and were used to test different value judgments toward the ELM-simulated performance measures.

Viewpoint A assigns large marginal utility increases as the criteria level moves away from the worst-case criteria value toward the best-case criteria value. We assumed an exponential function in which $x_i = 0.75x_{i,\mathrm{b}} + 0.25x_{i,\mathrm{w}}$ is indifferent to a 50:50 lottery between the best value $x_{i,\mathrm{b}}$ and the worst value $x_{i,\mathrm{w}}$. At the midpoint between worst and best case, the marginal utility reaches 0.75. The change in marginal utility diminishes rapidly as the criteria levels approach the best case level.

The Neutral Viewpoint provides a linear relationship between the least acceptable criteria value (utility = 0) and the most acceptable criteria value (utility = 1.0). Thus, this viewpoint assigns the same marginal utility increase

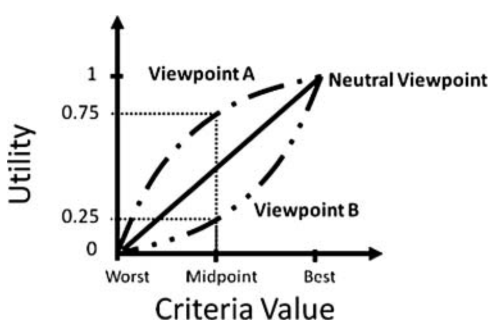

FIGURE 6. Utility scores of three hypothetical attitudes toward risk and ecosystem Performance Measure (Criteria Value).

to all criteria levels from the worst case toward the best case and is also described as a risk neutral function.

Viewpoint B assigns small marginal utility increases as the criteria level moves away from the worst-case criteria value toward the best-case criteria value. At the midpoint between worst and best case, the marginal utility reaches 0.25 in which $x_i = 0.25x_{i,\mathrm{b}} + 0.75x_{i,\mathrm{w}}$ is indifferent to a 50:50 lottery between the best value $x_{i,b}$ and the worst value $x_{i,\mathrm{w}}$.

For simplicity, each major decision criteria x_i (Total Ecosystem P Accumulation, Sheet Flow Skewness, and Mean Muck Fire Index Days) was given an equal weight (w_i; 33.33%) in the utility calculations. As the Mean Muck Fire Index Days was further divided into five spatial areas, these subareas were equally weighted within the utility calculations. Smaller values for each performance criteria are preferred over larger values. As such, the most preferred alternative would have the lowest levels of phosphorus accumulation, variation in flow velocity (skewness), and fire days. A sensitivity analysis was used to explore whether changes in the criteria weights or subarea weights had any effect on utility rankings of the alternatives. All decision analysis calculations were performed with the Criterium DecisionPlus software (InfoHarvest, 2003).

RESULTS

Model Performance

Statistics

The full complement of statistical and graphical comparisons for the present ELM v2.8 were provided by Fitz (2009), and are only briefly summarized here. The ELM v2.8 showed very good hydroecological performance in matching (1981–2000) historical observations with simulated data. In predicting water stage, the median (across 82 monitoring stations, Figure 7) Nash-Sutcliffe Efficiency statistic was 0.61 and the median bias was 0 cm (for comparisons of daily observed and simulated stage data). The conservative chloride tracer was an indicator of how well the gradients of surface water flows were simulated compared to observed data: the median (across 78 stations, Figure 8) seasonal (using bins of data available within each wet and dry season) bias was 6 mg l^{-1} in the marsh and 13 mg l^{-1} in canals, with a median relative bias (i.e., bias/mean) across all stations of 10% in the marshes, and 11% in canals. The simulated and observed phosphorus concentrations were very closely related, with a seasonal median bias (across 78 stations, Figure 9) of 0 ug l^{-1} in both the marsh and the canal stations.

Landscape Patterns

A variety of general spatial gradient and pattern trends can be summarized from the maps of the 20-year mean values of the above water quality

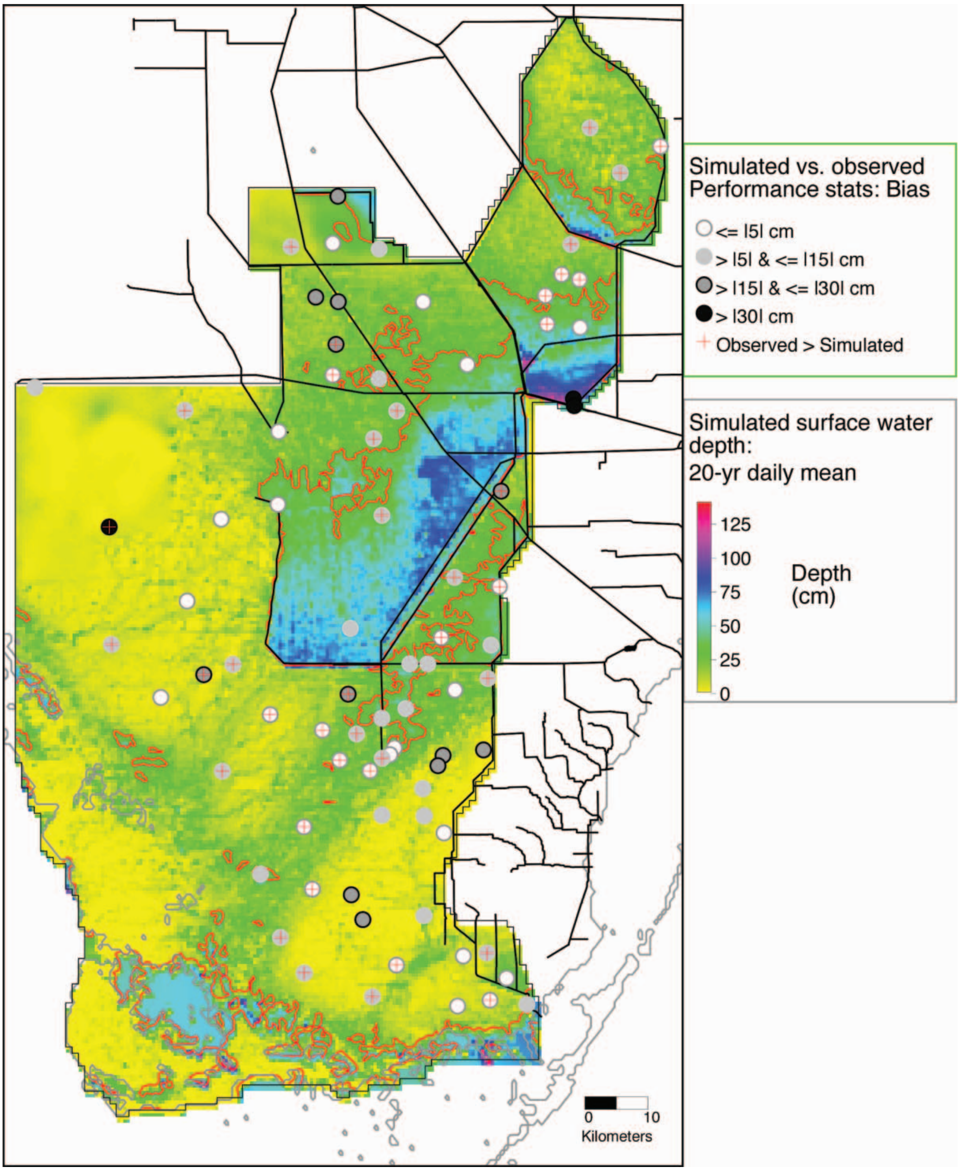

FIGURE 7. Map of statistical bias in model predictions of observed water stage elevations in marsh locations from 1981–2000. Background map is the simulated mean daily surface water depth above land surface elevation in the marsh from 1981–2000; the red contour line is the 30 cm depth isoline. (This figure is available in color online.)

variables. The patterns of surface water P eutrophication (Figure 9) followed broadly similar trends to those of the chloride tracer concentrations (Figure 8). Managed flows of (water and) P and chloride constituents into the model domain (i.e., the Everglades) were either introduced directly into the

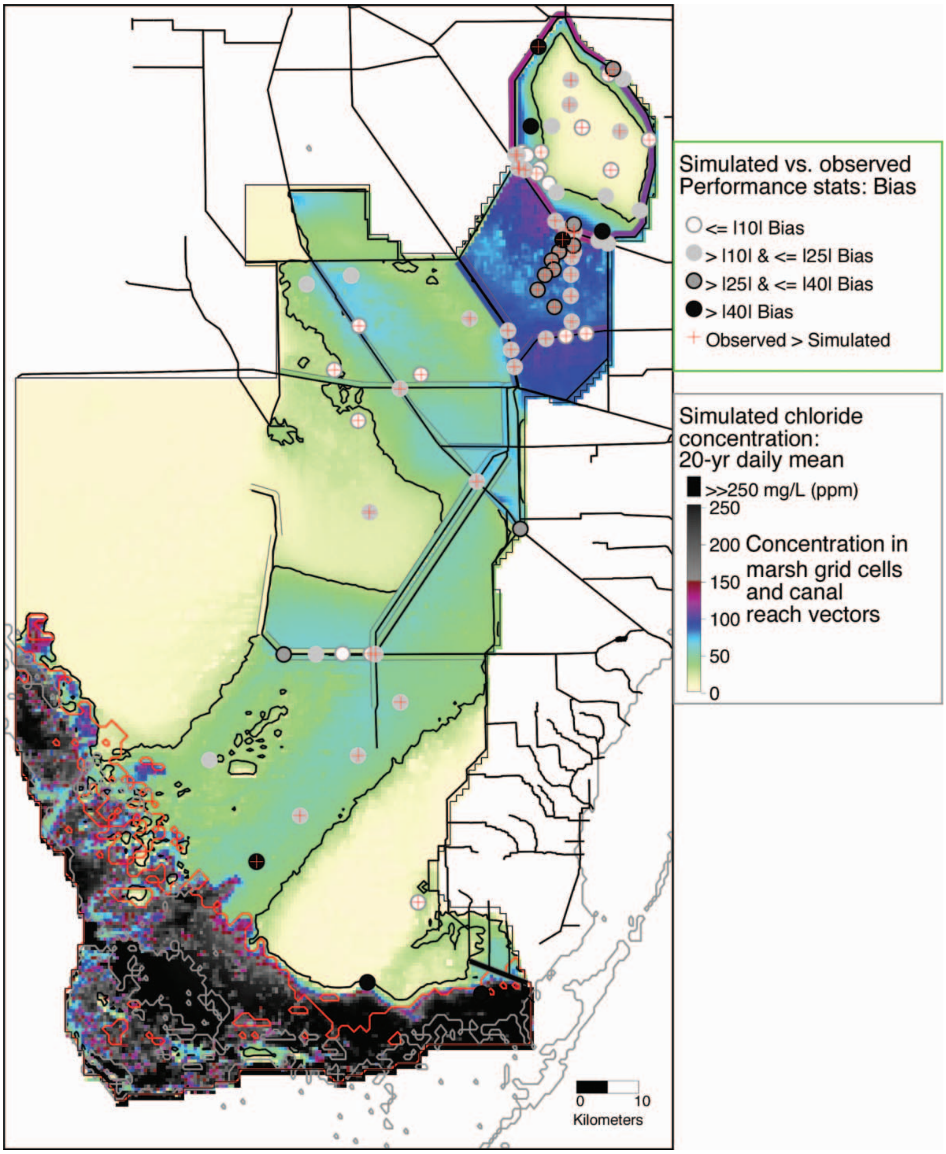

FIGURE 8. Map of statistical bias in model predictions of observed surface water chloride concentrations in marsh and canal locations from 1981–2000. Background map is the simulated mean daily surface water chloride concentrations in the marsh and canals from 1981–2000; the black contour line is the 30 mg l^{-1} isoline. The red contour line is the (1995) extent of mangrove habitats. Canal widths are exaggerated in order to display concentration colors, with the location offset relative to any existing levee. (This figure is available in color online.)

downstream marsh at a point, or introduced into a canal reach with subsequent canal-to-marsh exchange along an extended distance. The multikilometer ring of elevated chloride and TP along the interior perimeter of WCA-1 (location shown in Figure 1) was due to the canal-marsh exchanges

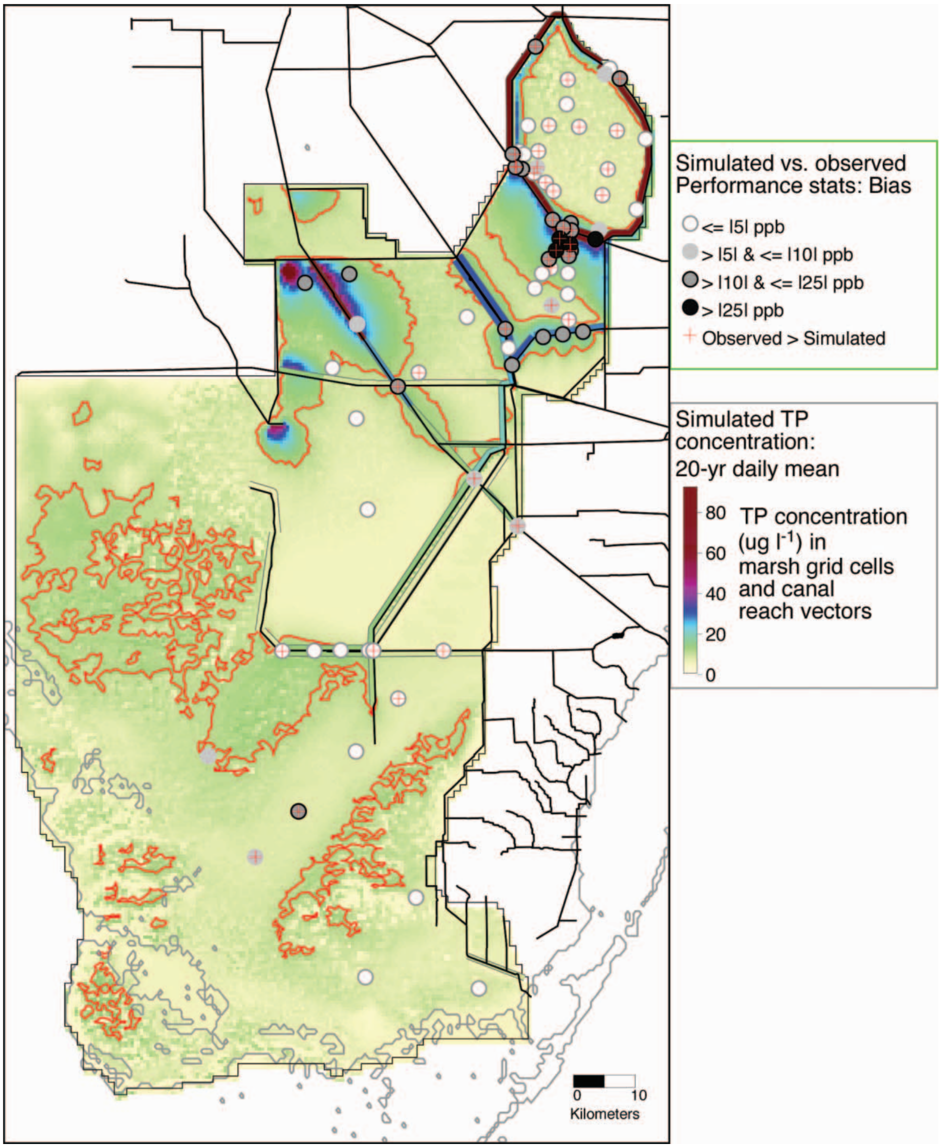

FIGURE 9. Map of statistical bias in model predictions of observed surface water total phosphorus concentrations in marsh and canal locations from 1981–2000. Background map is the simulated mean daily surface water total phosphorus concentrations in the marsh and canals from 1981–2000; the red contour line is the 10 ug l^{-1} isoline. Canal widths are exaggerated in order to display concentration colors, with the location offset relative to any existing levee. (This figure is available in color online.)

along a continuous canal within that basin, whereas an example of a local point release was apparent from the L-28I inflow in the northern part of the levee gap in western central WCA-3A. High concentrations of P and chloride were evident in pronounced north–south gradients in northeast WCA-2A.

This P gradient in particular has been the focus of a wide variety of research and monitoring projects to better understand P dynamics in the Everglades ecosystem (e.g., DeBusk et al., 2001; McCormick and O'Dell, 1996; Newman et al., 2004; Reddy et al., 1993).

Managed inflows and canal-marsh exchanges for WCA-3A are relatively complex (Figure 5), and the gradient pattern of P and chloride were closely tied to the canal network within the basin. The S-8 inflows into the Miami Canal led to overbank flows into the marsh with relatively high concentrations of P in the northern areas, and to a lesser extent the inflows from S-150 and the S11 structures propagated P concentrations above 10 ug l^{-1} into the marsh along the L-68W canal along the eastern border of the basin (Figure 9). The chloride distributions (Figure 8) reflected south–southeast direction of flows from northern WCA-3A, then either along the L-67A canal to the southwest, or into WCA-3B via subsurface flows and one managed flow structure. Releases through water control structures at the southern border of WCA-3A produced elevated chloride concentrations through Everglades National Park (ENP) to the southwest, into the estuarine salinities of mangrove habitats and the Gulf of Mexico. Note that by the time the water was introduced into the ENP, P concentrations above 10 ug l^{-1} were limited to relatively short-distance gradients near the inflow areas.

Comparison of Restoration Alternatives

General

Whereas we ran the full regional simulation within the greater Everglades domain, we restricted our analyses to include only the WCA-3A basin, in which we found virtually all among-simulation differences. For the Base, Plugs, and Fill alternatives, the (36-year) mean P mass loading into the entire WCA3-A basin's area ranged from 63.4 to 65.1 mt P yr^{-1} (metric tons yr^{-1}, including atmospheric deposition). The mean ecosystem P accumulation rate (including atmospheric deposition) for the entire basin area ranged from 32.1 to 32.9 mg P m^{-2} yr^{-1} among the three simulations, with the standard deviations essentially equal to the means (reflecting large spatial variation). For comparison to these rates, the model inputs of atmospheric deposition averaged approximately 25 mg P m^{-2} yr^{-1} across the basin. Mean basin-wide surface flow velocities ranged from 113 to 135 m d^{-1} among alternatives, with the associated Coefficient of Variation (standard deviation/mean) varying from 0.48–0.53. The basin-wide water levels were also generally similar, as reflected in the Muck Fire Index (with a basin-wide mean ranging from 5.3–5.9 days) and other metrics that showed little variation among alternatives. Thus from this highly aggregated perspective, there was little difference among the simulated alternatives.

Performance Measures

Although water levels were generally similar among alternatives, the Muck Fire Index indicated moderate variation among the simulations in some spatial Indicator Regions (Table 1). Directly downstream of new inflows, the Plugs and Fill alternatives had marginally decreased dry-down extents, with mean Muck Fire Indices that were on the order of 2–3 days shorter than that of the Base alternative. That relationship to the Base alternative held true in Indicator Regions along the Miami Canal, with as much as a 2-week difference along the southern segment of the Miami Canal (Plugs vs. Base, Indicator Region 51).

Evaluating the distributions of surface water flow velocities, substantial differences were found among alternatives. Compared to the Fill alternative, both the Base and Plugs runs exhibited noticeably higher velocities in the vicinity of the southernmost reach of the Miami Canal (landscape maps, Figure 10). Those departures from homogenous landscape sheet flow were reflected in the basin-wide Sheet Flow Skewness Performance Measure. The Base and Plugs runs had Sheet Flow Skewness values of 1.11–1.14, compared to 0.86 associated with velocities in the Fill alternative. The presence of an open channel substantially modified flow distributions in this relatively deep-water marsh area of the southern Miami Canal, not only when the reach was involved in managed structure to structure flow (Base), but also in the case in which the reach was isolated from any direct management (Plugs). Particularly due to the vicinity of (and partial connection to) other substantial nearby canal and canal-marsh flows near the eastern border of the WCA (canals L-68A, L-67A, and C-11 extension), this local area around the southern Miami Canal was important to maintain homogenous downslope sheetflow.

The differences in skewness of velocity distributions were further verified by examining simple linear regression of each alternative's velocities to those of the Base run: The velocities in the Plugs run were very similar to those in the Base ($R^2 = .95$; Figure 10), whereas the Fill run departed substantially from the Base run ($R^2 = .55$). It was apparent that the Fill alternative resulted in the most homogenous sheet flow in the WCA-3A region.

TABLE 1. Mean Muck Fire Index in five indicator regions (IR41, 42, 49–50; see Figure 5) for the three model runs

	IR 41	IR 42	IR 49	IR 50	IR 51
Base	7.6	13.6	9.2	15.5	18.7
Plugs	5.9	11.0	7.8	12.2	5.2
Fill	6.0	11.6	8.6	15.4	8.4

Note. Units are annual mean number of days.

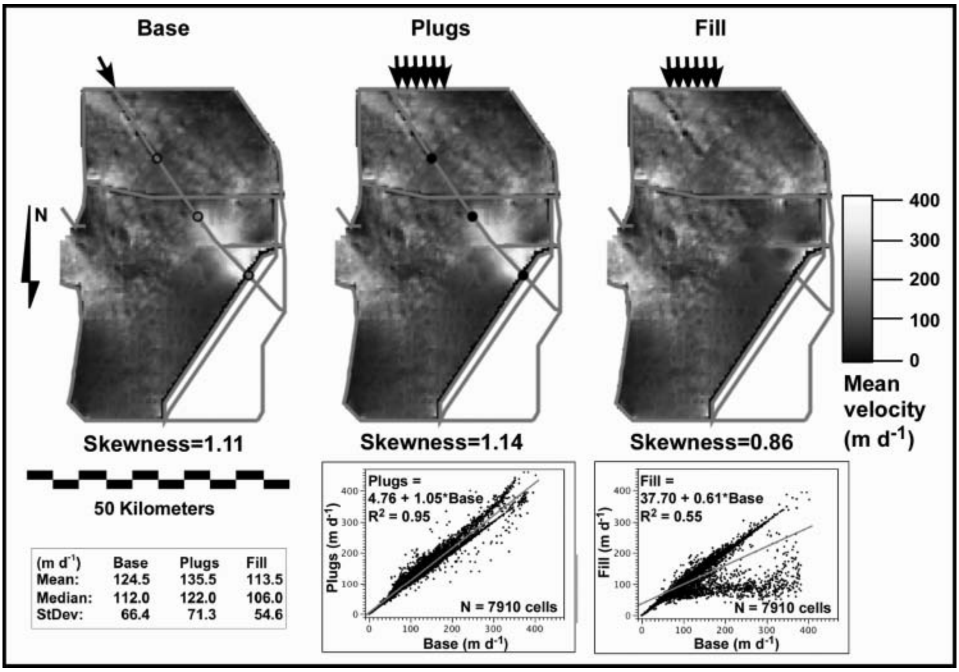

FIGURE 10. Spatial distribution of the 36-year mean surface water flow velocity magnitudes, with summary statistic of skewness of those distributions across the WCA-3A basin for the three alternative scenarios (Base, Plugs, Fill). The redistribution of managed S-8 structure inflows are depicted by the arrows. Open circles represent operating water control structures, closed circles are plugs. Summary statistics of flow velocities are shown in the table. The bottom graphs show simple linear regressions of velocities of each alternative by the Base (including all grid cell data points).

The change in inflow distribution from the Base to both the Fill and Plugs alternatives led to increases in Total Ecosystem P Accumulation in the marshes adjacent to the receiving spreader canal along the northern boundary of WCA-3A. Compared to the Base run, the Plugs and Fill alternatives respectively had 1,200 and 1,300 ha (12 and 13 km^2) more marsh area exceeding 50 mg P m^{-2} yr^{-1} accumulation (Figure 11). In the Base run, the nutrient loads into the Miami Canal were often distributed rapidly down the canal system, either exiting the basin through downstream structures, or further distributed downstream by canal-to-marsh exchanges along the canal network distributed within the basin. The use of the short spreader canal, which was implemented to further hydrate and induce flows into the northern basin, resulted in more localized nutrient loads to marshes in the Plugs and Fill alternatives.

However, downstream of the Miami Canal area, there was little P accumulation difference among the alternatives. Within the area immediately adjacent to the L-67A Canal (Figure 5), accumulation varied between

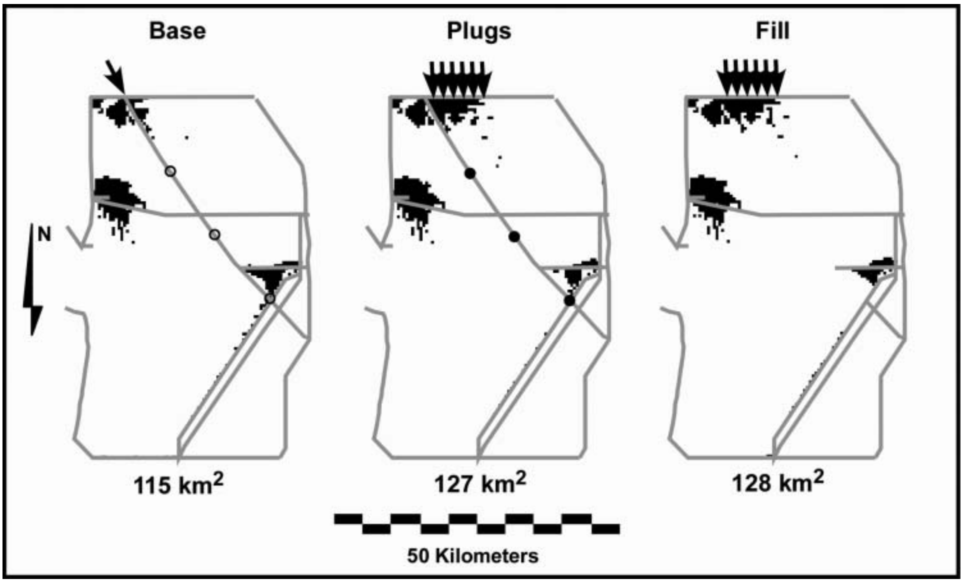

FIGURE 11. For the three alternative scenarios (Base, Plugs, Fill), the spatial distribution and total area of mean P accumulation rates that were >50 mg m^{-2} yr^{-1} within WCA-3A.

33–36 mg P m^{-2} yr^{-1} in the three simulations, while all alternatives had 25 mg P m^{-2} yr^{-1} accumulated in ENP marshes immediately downstream of WCA-3A outflows.

Multi-Criteria Decision Analysis

Decision analysis results showed distinct trade-offs between Total Ecosystem P Accumulation and Sheet Flow Skewness criteria (Figure 12). The Fill alternative scored maximum utility in Sheet Flow Skewness but minimally with Total Ecosystem P Accumulation, while the Base option scored minimally with Sheet Flow Skewness but maximally with Total Ecosystem P Accumulation. The Mean Muck Fire Index Days criteria contributed the most utility score to the Plugs alternative, which by itself would lead toward selection of the Plugs alternative. However, the Plugs alternative scored lowest in the other two criteria, and thus its overall decision score was lowest, regardless of which of the three risk viewpoints were considered. Given the ELM results, the risk viewpoint did not change the overall alternative rankings, but it did have a noteworthy effect on the relative contributions of each criterion to the decision score. Viewpoint A tended toward higher decision scores because it rapidly increased the scores when progressing from low to intermediate criteria values, compared to other Viewpoints (B and C) that did not assign such immediate benefits to small changes at the low criteria values.

Given the closeness of the decision scores for the Base and Fill alternatives, their rankings were effectively tied. A 4% or less change in criteria

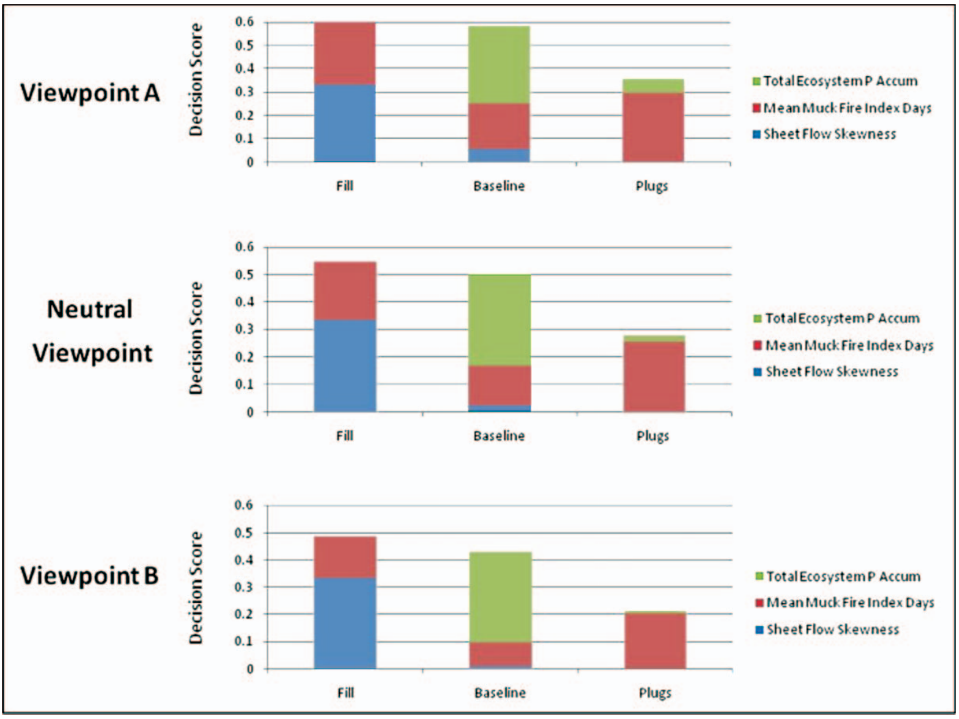

FIGURE 12. Decision score for each alternative based on risk viewpoint. (This figure is available in color online.)

weighting was needed to change the top ranking from the Fill alternative to the Base alternative (assuming all other weights were held constant in their ratios with one another) for Sheet Flow Skewness and the Total Ecosystem P Accumulation (Table 2). The Mean Muck Fire Index Days criteria was not as sensitive: changes of –6.1% could change the ranking from the Fill alternative to the Base alternative for Viewpoint A, while a weight change of –27.8% was required for the same ranking change using risk Viewpoint B. Given that criteria weights derived from swing weights surveys can vary significantly even within a single institution (Kiker et al., 2008), the decision

TABLE 2. Amount of weight change for selected decision criteria to change the top ranking from the Fill alternative to the Base alternative

Alternative	Total ecosystem P accumulation (33.33%)	Sheet flow skewness (33.33%)	Mean muck fire index (33.33%)
Viewpoint A	1.2%	−1.5%	−6.1%
Neutral viewpoint	3.0%	−3.6%	−18.7%
Viewpoint B	3.5%	−4.0%	−27.8%

Note. Original criteria weights listed in parentheses.

scores should be seen as a first, iterative step toward potential refinement of criteria (Performance Measure) definitions and utility valuations.

SUMMARY AND CONCLUSIONS

For these model experiments, the distributions of sheet flow in the landscape were used to differentiate among management alternatives. As discussed by NRC (2003a), restoring homogenous sheet flow is thought to represent an important component of restoring the original ridge and slough pattern of Everglades habitats. However, we have an incomplete understanding of the magnitude and timing of flows needed for such habitat restoration. In response, considerable research efforts have been made to quantify the magnitude of desirable flows (Bazante et al., 2006; Harvey et al., 2009; Larsen et al., 2007; Larsen et al., 2009; Leonard et al., 2006). As restoration targets for water flow—and others—Performance Measure become more fully developed, simulation tools of complex water management and hydroecological dynamics can be applied to help decision makers understand the relative benefits among restoration alternatives.

Multiple Models

There are a wide array of variables and interactions to consider in restoration planning for the broad mosaic of Everglades ecosystems, which are largely driven by a complex water management infrastructure. The SFWMM remains the accepted tool to simulate managed hydrology in South Florida, and planners link hydrologic Performance Measures from that model to anticipated ecological benefits, as outlined in (nonquantitative) Conceptual Ecological Models such as those for the Ridge and Slough and Total System of the greater Everglades (Ogden, 2005; Ogden et al., 2005).

For analysis of ecological Performance Measures such as water quality in CERP planning, the ELM v2.5 was accepted by an independent peer review panel, and subsequently by the CERP's Interagency Modeling Center. The statistical metrics of the ELM v2.8 model skill in matching observations of stage, flows (chloride), and phosphorus water quality were all improvements over the previous version, and we therefore considered the updated model to be suitable for evaluating such landscape hydroecological dynamics across multiple decades.

Because most of the ELM hydrologic dynamics are independent of the SFWMM, it is therefore desirable to ensure that the two models have reasonably consistent results. Reviewed in detail by Fitz (2009), comparisons of water budgets, maps of mean hydroperiods and water depths, and statistical metrics indicated a useful degree of consistency, considering differences in spatial scales and model objectives. For example, when comparing simulated to observed data for the water stage monitoring locations within the Everglades domain, the median Nash-Sutcliffe Efficiency of the ELM v2.8 and SFWMM v5.5 was 0.61 and 0.67, respectively, with both models exhibiting a median bias of 0.0.

While the ELM is the only tool presently available for regional Everglades water quality and related ecological assessment, the EWQM was successfully used in initial development of CERP plans. Raghunathan et al. (2001) presented evidence that the model was reasonably well calibrated relative to its objectives, referring to a South Florida Water Management District report which showed that (during the 1979–1989 simulation period) the mean observed versus predicted phosphorus concentrations within Everglades basins differed by 6–23 ug l^{-1}, whereas one basin (WCA-1) exhibited differences >100 ug l^{-1}. As a tool for making relative comparisons of project alternatives within most Everglades basins, the model was judged acceptable for CERP planning purposes. However, refinement of the model was discontinued, and it is no longer available.

Decision makers need to understand how reliably the models meet their objectives, and under what conditions the models are applicable (i.e., their application niche). While not presented here, a wide range of procedures have been used to evaluate model/data sensitivities as part of the analysis of uncertainties of the ELM (Fitz and Trimble, 2006), including the influence of uncertain processes such as dispersive flux of constituents in surface water flows. Beyond those analyses, it is fundamentally important to communicate a model's simulation performance relative to past observations (i.e., history matching skill) under a wide range of conditions. For this paper, we briefly summarized the useful level of ELM performance in matching observations of principal ecosystem variables (related to hydrology and water quality), encompassing extreme floods and droughts during two decades, and habitats ranging from long-hydroperiod marshes to uplands/short-hydroperiod wetlands. Other statistics, detailed time series graphics, spatial analyses, and budget comparisons for the present model were presented in the Model Performance Chapter 6 of Fitz (2009), including the performance assessment methods of evaluating not only the principal Performance Measure variables, but ensuring that other ecosystem rates and stocks have realistic values throughout the multitude of interactions within this fully integrated ecosystem model.

Alternative Selection

For the MCDA, we weighted each criteria (Performance Measure) equally, which could be modified after further consideration by stakeholders. For example, the Muck Fire Index indicated that the Plugs alternative had somewhat higher utility than other alternatives regarding the relative extent of severe marsh drydowns. However, there was a limited spatial region considered by that index, and the small relative differences among alternatives may not have ecological significance. It could be appropriate to assign a lower weight to this particular Performance Measure. (Regardless, the Plugs alternative scored lower than the Base and Fill alternatives in the other two Performance Measures). Perhaps most importantly, a high priority has been given to restoring sheet flow in the DECOMP and overall CERP projects. Given that restoration goal, it appears that a higher weight could be assigned to the Sheet Flow Skewness Performance Measure. Irrespective of weighting, the Fill alternative, with the highest utility of Sheet Flow Skewness in these model experiments, would provide the greatest sheet flow restoration benefits over the long term.

The trade-off associated with the selection of the Fill alternative is the associated increased area of likely Ecosystem P Accumulation (and thus low utility) relative to the Base condition. This is an example of a case in which it would be useful to conduct consensus-building workshops to determine the most appropriate criteria weights relative to overall restoration goals. If stakeholders determined that the anticipated level of P eutrophication was unacceptable, other planning avenues could be explored. For example, if STA efficiency was improved, eutrophication concerns would be reduced.

Using elements of MCDA and problem structuring in combination with ecological modeling and monitoring results, a transparent framework allowed us to combine different sources of decision-relevant information. In addition, for demonstration purposes different stakeholder attitudes and values were represented at rudimentary levels within this process. While the decision criteria and restoration alternatives considered in this research were not exhaustive, they were chosen to illustrate some of the basic trade-offs facing restoration planners and managers. Trade-off analysis allows decision makers to visualize the relative degree of satisfaction attached to each performance measure (criterion) and which alternatives satisfy conflicting objectives (Yoe, 2002). This analysis also allows decision makers to employ dominance relationships that screen out an alternative if its performance in every criterion is seen to be inferior to another alternative. Thus, the set of possible alternatives can be reduced before advancing on to elicit the weight-judgment process.

Beyond the models and data themselves, it is important to use a systematic method to select a preferred management alternative, and explore the sensitivity of the ranking method. For illustration purposes, we provided a simplified sensitivity analysis of the effects of criteria weights and utility functions on the ranking of preferred alternatives. By adjusting the criteria weights, users can determine how the prioritization can be changed or can explore the robustness of a preferred alternative (i.e., if the preferred alternative is the optimal solution for a wide range of input weights). Additionally, the sensitivity analysis can be conducted with respect to the uncertainties on assessment of criteria. When the model results or assessments are uncertain, the measurement metrics can be adjusted to analyze the effect of various measurements on the decision.

The objective for using MCDA is to improve understanding among the decision participants in a way that facilitates decision making toward risk attitudes, multiple criteria, and potentially conflicting interests. In this context, MCDA approaches should not be used with the mindset that it will single out the correct or even optimal decision. Rather, MCDA can help to visualize some of the trade-offs among multiple, conflicting criteria and can be used further to quantify the effect that uncertainties can have on alternative rankings and decisions. When used in a group decision process, MCDA can provide methods for participatory decision making where stakeholder values are elicited and explicitly incorporated into the decision process.

Given that the Everglades restoration is a significant and iterative exercise in complex problem resolution, sets of integrated modeling and decision tools are an important element in decision process. This example application of ELM indicated that the hydrologic benefits of a restoration alternative were associated with some degree of detrimental water quality characteristics; the MCDA provided a means by which to further evaluate those potential trade-offs in restoration planning.

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