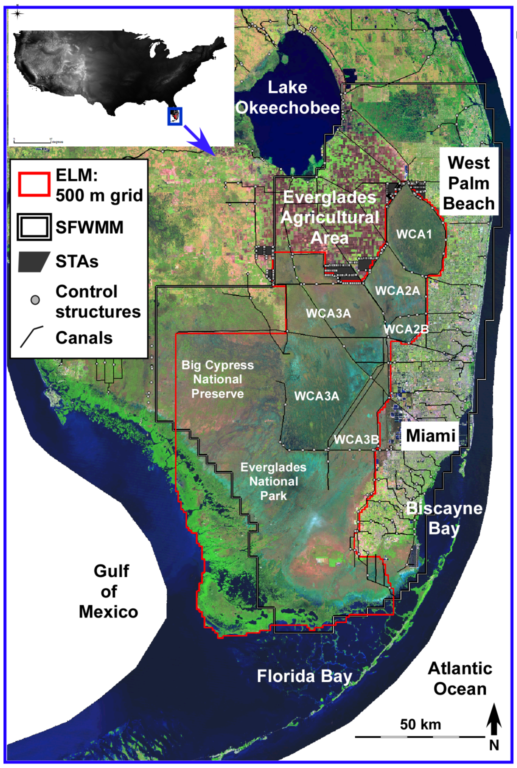
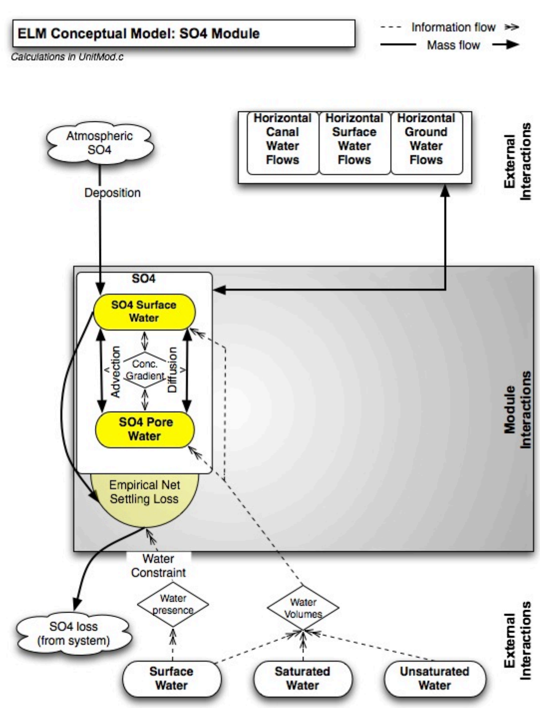
Everglades Landscape Sulfate Dynamics: Final Summary Evaluation of CERP ASR Alternatives





http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR

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Introduction

The Regional Aquifer Storage and Recovery (ASR) Study that was undertaken as a part of the Comprehensive Everglades Restoration Plan (CERP) is evaluating the risks and benefits of 200 ASR wells located around the perimeter of Lake Okeechobee. ASR is a water management technology that involves pumping excess surface water into underground storage aquifers and retrieving (recovering) this water during periods when water supplies are low. The CERP plan included a total of 333 ASR wells (many not located in proximity to the Lake), each with a capacity of 5 million gallons per day. The Regional ASR Study was intended to characterize the engineering and ecological feasibility of installing and operating 333 ASR wells in South Florida, with this ecological modeling report being specific to the subset of 200 wells in proximity of the Lake.

Study planners recognize that water recovered from ASR wells might differ significantly in quality such that adverse impacts might occur. Since sulfate is known to be present in the storage aquifer at concentrations well above surface water concentrations, and sulfate plays an important role in the bioavailability of mercury in the surface water environment, the effect of ASR-derived sulfate discharges on the environment is of specific interest to South Florida ecologists. In partial support of the overall Regional ASR Study ecological assessment, the regional Everglades Landscape Model (ELM v2.8.6, see map figure on title page) was applied to evaluate the relative differences in landscape sulfate distributions among several ASR Study Alternatives. Other collaborations and analyses will explore the implications of these sulfate distributions on mercury methylation risks.

This report summarizes the ELM sulfate module applications for the ASR Study, and serves as a framework to guide an interested reader to more detailed model documentation and results that are contained on EcoLandMod web pages at:

http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/

As outlined below, that web site contains comprehensive model documentation, ASR Study-specific model configurations and assumptions, and ASR Study-specific model Performance Measure/Indicator outputs.

Sulfate module development

A new sulfate module was added to the ELM simulation framework (new ELM v2.8.6), then tested and calibrated in 20-year simulations across the greater Everglades region (including the Water Conservation Areas and much of Everglades National Park and Big Cypress National Preserve). The only code changes from v2.8.4 to v2.8.6 are the addition of the sulfate (SO_4) module. The only (v2.8.4 - v2.8.6) data changes were the additions of sulfate boundary conditions, a net settling rate map, and observed data for use in calibrating the model performance in matching observed sulfate concentrations in surface waters. The 128-page documentation report for the development and calibration/testing of ELM v2.8.6 is available at: http://ecolandmod.ifas.ufl.edu/publications/index.html#ELM286 .

Sulfate performance

The sulfate module is driven by a first order, net settling rate equation, and the model-data calibration resulted in an overall median predictive bias of 0 and -2 mg L^{-1} in 78 marsh and canal sites, respectively (Figure 1). The statistical and graphical assessments of model performance were consistent with other ELM-simulated water quality variables, and the sulfate module was acceptable for applications to evaluate future scenarios of multi-decadal sulfate dynamics across the greater Everglades region.

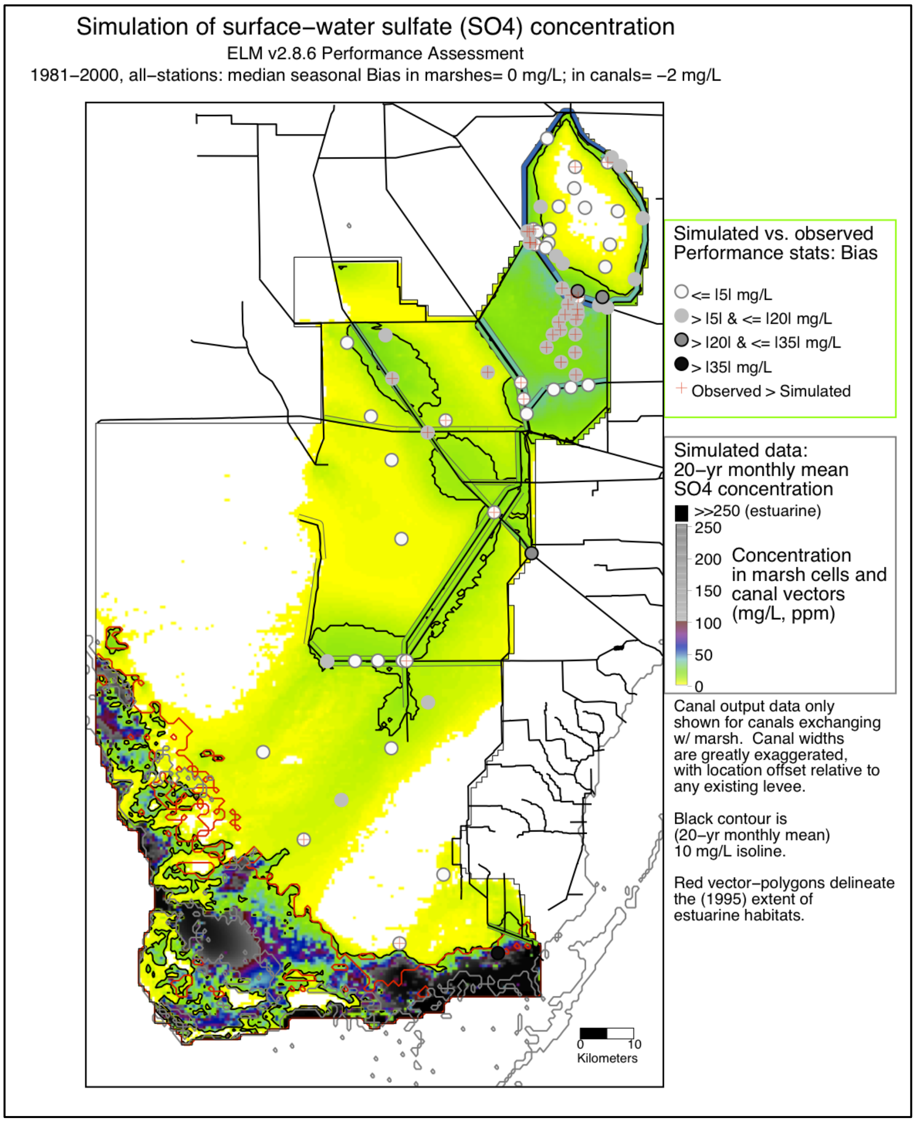

Figure 1. Map of seasonal bias in model predictions of observed surface water sulfate concentrations in marsh and canal locations. Background map is the simulated mean monthly SO4 concentration during 1981-2000. See Model Documentation report for detailed statistics.

ASR sulfate application: assumptions

Common data

ELM input data that are common to all baseline and Project Alternatives include input parameters and maps of initial conditions (http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/index.html#DataCommon). Due to constraints from other ASR Study modeling and the availability of historical water quality data, the period of ELM simulation for all ASR Study runs encompassed January 1974 through April 2000 (instead of January 1965 through December 2000). Compared to the ELM v2.8.4 applications, the only new map data were initial condition maps of surface- and unsaturated- water depths that were specific to the new 1974 initialization date, and the new sulfate settling rate map (which of course was the same as that used in the historical calibration run).

Boundary conditions

The driving variables of these Everglades landscape modeling evaluations were the boundary conditions associated with several ASR Alternatives. Alternative ASR_ALT2C assumes 200 Upper Floridan ASR wells placed around the perimeter of the Lake. In this alternative, the sulfate concentration in the recovered water discharged to the Lake was conservatively assumed to be equal to the background groundwater sulfate concentration, as measured or estimated for each ASR well. Alternative ASR_ALT2V also assumes 200 Upper Floridan ASR wells placed around the perimeter of the Lake. However, in this alternative, the sulfate concentration in the recovered water discharged to the Lake was assumed to vary linearly during the recovery period, ranging between the surface water sulfate concentration (approximately 30 mg L^{-1}) to the background groundwater sulfate concentration as measured or estimated for each ASR well (200 to 350 mg L^{-1}). Alternative ASR_ALT4V likewise assumes 200 wells with 48 Upper Floridan wells, 120 Avon Park Producing Zone wells, and 48 Boulder Zone wells. In this alternative, the sulfate concentration in the recovered water discharged to the Lake was assumed to vary linearly over the recovery period between the above surface water sulfate concentration to the background groundwater sulfate concentration as measured or estimated for the geologic unit for each recovery well. The Upper Floridan estimated sulfate concentrations vary from 200 to 350 mg L^{-1} depending upon location; the Avon Park Producing Zone has estimated sulfate concentrations that range from 350 to 550 mg L^{-1}.

For the simulated water management in our ASR Study evaluations, the SFWMM v5.4 hydrologic simulations of the 2050 future base (2050B2) and the updated CERP plan (CERP0) served as drivers of all managed water flows for all ELM simulations (http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/index.html#RunTable). The 2050B2 was a general baseline, with no CERP features operating. The baseline used to evaluate ASR Study Alternatives was the CERP0 without any additional ASR wells (ASR_BASE). The same CERP0 SFWMM output was also used for the three ASR Alternatives.

While the ASR_BASE and all ASR Alternatives shared the same CERP0 hydrologic flows (i.e., no effect of additional ASR on water management), the ASR_BASE and Alternatives differed in Everglades sulfate loads due to varying availability of ASR-derived sulfate sources under different ASR configurations/operations. A variety of methods were used to develop sulfate concentrations for ELM boundary conditions (http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/index.html#DataSpecific). The ASR Alternatives routed ASR-derived sulfate through Lake Okeechobee, then into the Everglades Stormwater Treatment Areas (STAs), which then flowed into the Water Conservation Areas (WCAs) in the greater Everglades domain of ELM. The Lake Okeechobee Environment Model (LOEM), a new Simple Model of STAs, and other quantitative tools were used to establish boundary-condition sulfate loads to the Everglades, with the ELM simulating the downstream landscape patterns of sulfate availability over decadal time scales in the greater Everglades.

ASR inflows and outflows to Lake Okeechobee were estimated using a modified version 5.71 of the LOOPs[1] model for simulating Lake Okeechobee operations. The ASR flows from the LOOPs model were used as boundary conditions for the LOEM simulation of ASR impacts to Lake water quality. Because the simulation period for the LOEM (2000-2009) did not overlap with the ELM simulation period (1965-2000), linear regression equations were developed to predict Lake sulfate concentrations for simulated ASR recovery periods that preceded 2000. The independent factors used in the regression equations were the running duration of ASR discharge and daily difference in lake stage between the ASR alternative and the baseline condition.

In developing Project-specific boundary conditions for ELM, the Lake concentrations were of particular interest because the Lake was the sole recipient of ASR recovery water, and the Lake was a variable source of water and

[1] Neidrauer, C., Cadavid, L., Trimble, P., and Obeysekera, J. (2006) A Spreadsheet-based Screening Model for Evaluating Alternative Water Management Strategies for Lake Okeechobee, Florida. Operating Reservoirs in Changing Conditions: pp. 354-363. doi: 10.1061/40875(212)35

sulfate loading to STAs - and subsequently to the Everglades. In these ASR Study simulations, LOEM-simulated daily mean Lake sulfate concentrations varied from long-term means of approximately 30 (ASR_BASE) to 50 (ASR_ALT2C) mg L^{-1}, while Everglades Agricultural Area (EAA) source waters were assumed to be constant and near 50 mg L^{-1} for all simulations.

Depending on daily flows quantified by SFWMM outputs, the calculated inflows to STAs were a spatially- and temporally- varying mixture of Lake outflows plus runoff from the EAA. To different degrees, the ASR Alternatives all increased the sulfate loading from Lake Okeechobee to the STAs - relative to the ASR_BASE. From *Lake sources only*, the annual mean STA inflow loads were 16, 25, 19, and 17 thousand metric tons for the ASR_BASE, ASR_ALT2C, ASR_ALT2V, and ASR_ALT4V, respectively. However, the annual mean surface water sulfate load (i.e., excluding atmospheric inputs) to the downstream WCAs was more than 5x that of the Lake-only (ASR-influenced) inflow loads to the STAs. Thus, while ASR variations had meaningful effects on Lake-derived loads to STAs and WCAs, on average the EAA sulfate loads to STAs and the Everglades were dominant.

Performance Measures & Indicators

While Lake (and thus ASR-derived) sulfate may not be the dominant source of sulfate to the Everglades when considering broad overall loading summaries, those contributions may be important when considering spatial and temporal components of the Everglades responses. The ELM sulfate Performance Measures and Performance Indicators (http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/index.html#PIs) were developed to quantitatively answer questions regarding such spatio-temporal characteristics. *Specifically, do the variations in Everglades sulfate inflow-loads amongst the ASR_BASE and the ASR Alternatives lead to meaningful variations in downstream Everglades marsh sulfate dynamics?*

Two map-based Performance Measures involving long-term temporal means provided useful information on the downstream Everglades patterns of sulfate responses to different ASR configurations/operations: the mean Period Of Simulation (POS) sulfate concentrations in marsh surface waters, and the mean POS sulfate reduction rate (i.e., loss from the surface water). Both of these Performance Measures measured the total area of marsh that exceeded specific numeric criteria (of either simulated sulfate concentration or reduction rate), and compared those areal "habitat units" between each Alternative relative to the ASR_BASE.

To supplement those Performance Measures, six Performance Indicators were used to evaluate high/low/intermediate temporal pulses in sulfate inflows that were associated with ASR operational "stress periods". Like the above Performance Measures, these map-based Performance Indicators summed the marsh area that exceeded (a specific, same as POS) surface water sulfate concentration criteria. But instead of a POS mean, the Performance Indicators employed the 30-day mean sulfate concentrations during specific periods of known high, low, and intermediate magnitudes of ASR operations and/or Lake outflows, as calculated at the end of a wet season and at the end of a dry season during three different years. In this suite of six Performance Measures, a particular dry season that has high Lake outflows and/or ASR operations (e.g., May 1974) likely has higher sulfate loads to the Everglades, and thus that snapshot in time may provide an "Indicator" that best distinguishes among ASR Alternatives under high-sulfate loading conditions. *Note that because these are 1-month "snapshots" during multi-decadal simulations, they are considered to be "Indicators", to be judiciously used in conjunction with other information that considers long-term system responses*.

ASR sulfate application: Results

In applying 2 Performance Measures and 6 Performance Indicators to compare each of the 3 ASR Alternatives to the ASR_BASE baseline, there are 6 sets of Performance Measure difference-map sets, and 18 sets of Performance Indicator difference-map sets. All Performance Measure and Performance Indicator (quantitative) graphics are found at http://ecolandmod.ifas.ufl.edu/projects/ELMreg500mASR/index.html#ResultsAlts. Note that, while these metrics were chosen for their relative simplicity in addressing a complex spatio-temporal question, a simpler summary perspective is available in the below "Summary of Performance Measure & Indicator maps" sub-heading.

Example Performance Measure map

As an example, some of the largest Alternative vs. Base differences may be seen in the sulfate reduction Performance Measure that compares the ASR_ALT2C and the ASR_BASE (Figure 2). In this example, it is clear that, relative to the ASR_BASE, the ASR_ALT2C resulted in meaningful increases (15,875 ha) in total marsh area that exceeded the 15 g m^{-2} y^{-1} sulfate reduction rate criteria, with differences generally found within the northwest and western Water Conservation Area 3-A marshes downstream of inflow structures: the (within-figure) labels show that ASR_ALT2C had 281,950 ha of marsh exceeding 15 g m^{-2} y^{-1} (map on right, Figure 2), while the ASR_BASE had 266,075 ha of marsh exceeding that criteria (map on left, Figure 2). Moreover, when the two maps are directly compared via cell-to-cell subtraction (map in middle, Figure 2), there were 11,300 ha of marsh that had rates that were 5 g m^{-2} y^{-1} greater in ASR_ALT2C relative to the ASR_BASE. This distinction can be important: the area of direct cell-cell differences (middle) almost always differs from the comparisons of total areas in the base vs. alternative. Note that one simulation may significantly re-distribute inflows of waters containing high sulfate concentrations, thus leading to significant cell-cell differences, even when the total landscape area of high sulfate concentrations may be similar between the two simulations.

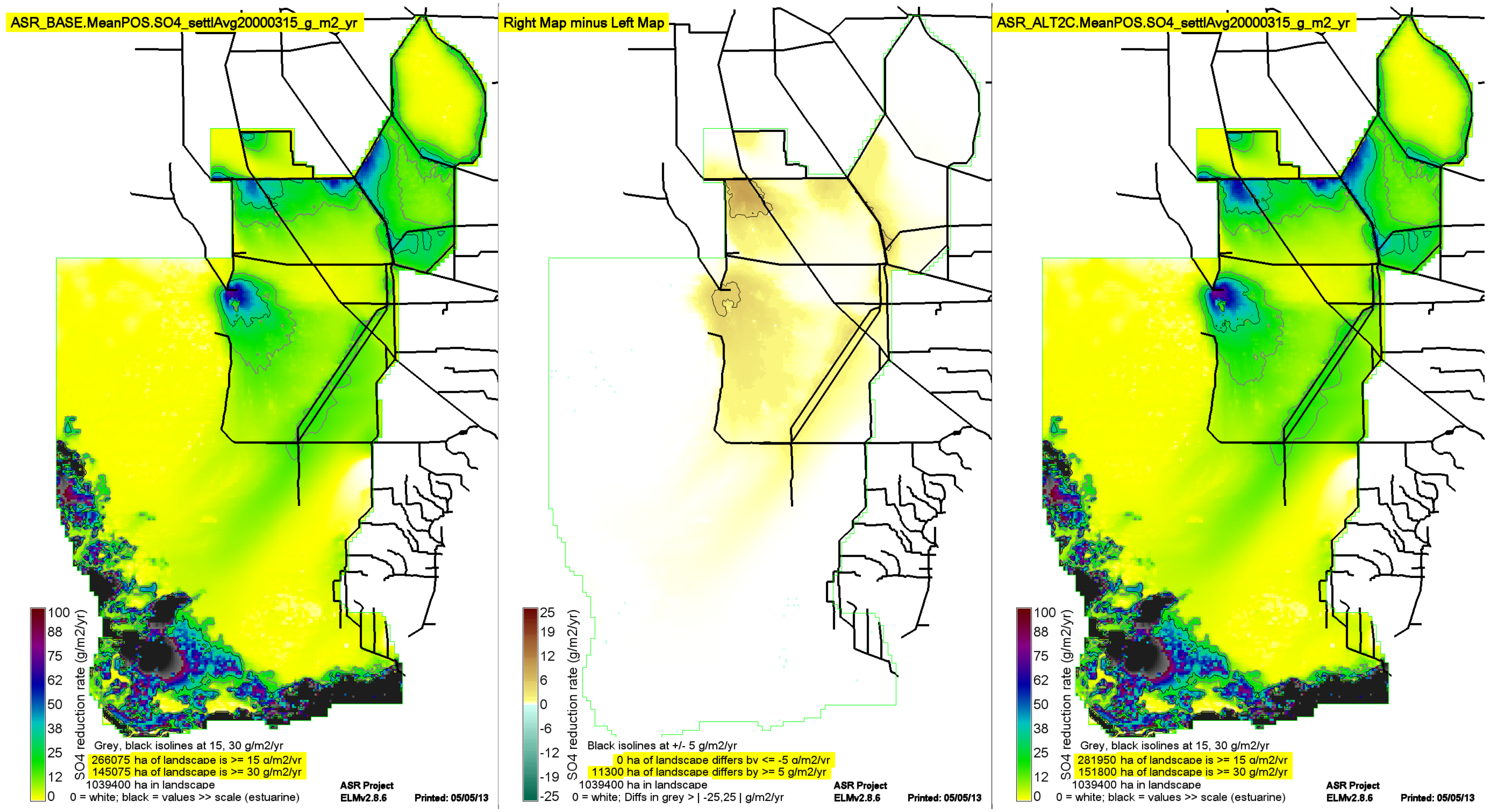

Figure 2. Example of map-based Performance Measure of mean Period of Simulation (POS) sulfate (SO4) reduction rate (loss from surface water, variable name in headers refers to realized "settling" rate). This example compares the ASR_ALTC Alternative (right map) to the ASR_BASE (left map), and their direct cell-to-cell differences (middle map). All color-scale legend units are g m^{-2} yr^{-1}. Footer text shows the marsh area that meets the labeled criteria.

Summary of Performance Measure & Indicator maps

The map-based Performance Measures and Indicators provide both the "big picture" and detailed perspectives. The "big picture" is quickly understood via summing marsh areas that exceed different science-based criteria; the detailed perspective is available via the (visual, semi-quantitative) assessments of spatial patterns in the map-based graphics. However, even the "big picture" marsh-area numbers can be problematic to keep track of, much less to simply convey what may (or may not) be simple conclusions.

This complexity can perhaps best be collapsed into simple bar graph summaries of the relative differences in marsh areas exceedances, for each Performance Measure/Indicator across all ASR Alternatives. Figure 3 provides such an example for both baselines and all three ASR Alternatives, using the sulfate reduction rate Performance Measure that may best reflect long-term sulfate dynamics that are of interest in terms of cumulative responses by the marsh ecosystem. From this single summary graphic, it appears that it may be important to explore other Performance Measure/Indicator details to determine if ASR_ALTC has a greater sulfate eutrophication risk compared to other ASR Alternatives.

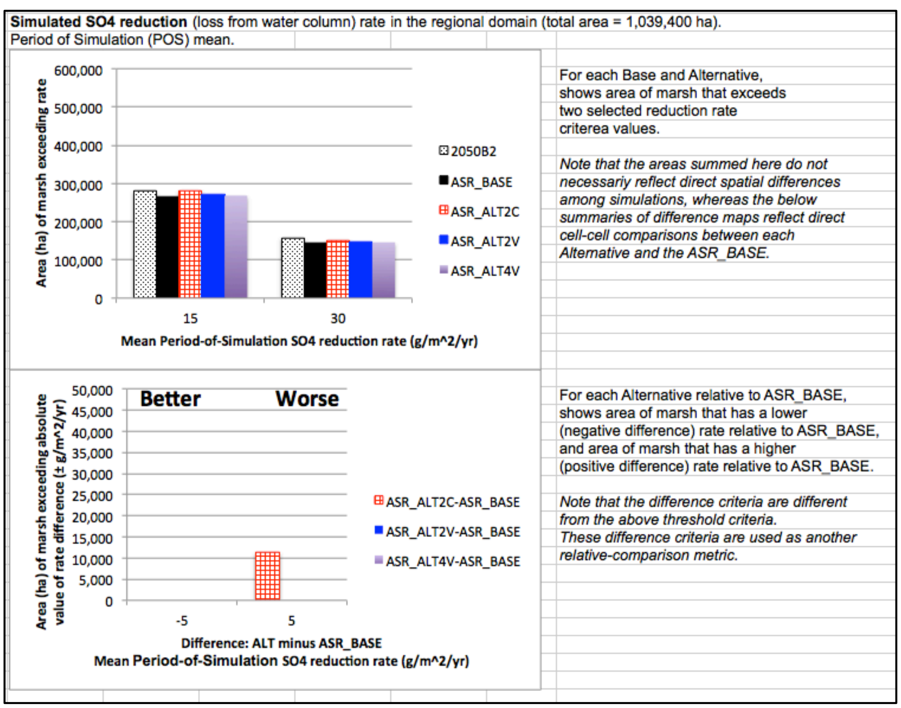

Figure 3. Example summary of the sulfate reduction Performance Measure applied across multiple ASR Study Bases and Alternatives. See text for definitions of acronyms.

ASR sulfate application: Conclusions

Compared to the ASR Study baseline (ASR_BASE), there was increased ASR-derived sulfate loading to the Everglades marshes (WCAs) under each of the three CERP ASR Study Alternatives, and that load varied among Alternatives. However, the total sulfate loading to the WCAs was always dominated by other water/sulfate sources that were not directly impacted by the ASR configurations/operations, thus generally diluting potential among-Alternative differences.

Nevertheless, from evaluations of long-term averages and short term "ASR stress periods", it was apparent that at least one ASR Alternative (ASR_ALT2C) should be considered with caution, regarding the potential to increase sulfate concentrations within important localized regions of the marshes of Water Conservation Area 3A. Substantial areas within WCA-3A had increased sulfate eutrophication under ASR_ALT2C compared to the ASR_BASE. However, the assumptions used to derive ALT2C sulfate boundary conditions were very conservative. This alternative had recovered water sulfate concentrations set to be constantly equivalent to groundwater sulfate concentrations. Actual measurements of sulfate in recovered water at the Kissimmee River ASR Pilot site show that sulfate in recovered water varies in concentration between the surface water sulfate concentration and the groundwater sulfate concentration. When recovered water initially was discharged to surface water, the sulfate concentration in this water was near the surface water concentration. As recovery continued, the sulfate concentration in this water increased in a linear fashion until it reaches the concentration found in the groundwater.. The more realistic ASR alternatives (ALT2V, ALT4V), which include varying sulfate concentrations, exhibited some increases in sulfate eutrophication relative to the ASR_BASE, but that was generally very limited in magnitude and extent.

A primary CERP goal is to increase water flows and levels in the Everglades, while ensuring that the water quality associated with "new" water meets specific water quality/ecological criteria. Along with phosphorus, sulfate loading to the marshes is a potential constraint to be considered in CERP evaluations . Some of the reasons for this relate to the sulfate interactions with plant productivity and soil biogeochemistry, but a primary impetus for minimizing sulfate loads is due to its stimulation of mercury methylation (at least within particular sulfate concentration ranges). Those mercury methylation responses to sulfate availability are the topic of additional analyses by colleagues associated with this ELM application, and are to be reported elsewhere.

Understanding water quality benefits/risks associated with CERP is fundamental to meeting long-term restoration goals. But in this context, an overall evaluation of the CERP Projects - including the ASR Study - requires the consideration of multiple criteria; i.e., weighing the benefits of increased water flows that (at least) minimize imminent Everglades degradation, vs. the potential risks of localized eutrophication that may be associated with increased flows and depths in the system. With respect to sulfate biogeochemistry alone, there does not appear to be any ecologically meaningful risk associated with at least two of three ASR Alternatives.

Acknowledgements

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