APPENDIX H

COMBINED OPERATIONAL PLAN

HYDRAULICS & HYDROLOGY

ANNEX 8
TAMIAMI TRAIL FLOW FORMULA

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H-8 TAMIAMI TRAIL FLOW FORMULA

Combined Operational Plan for Water Deliveries from Water Conservation Area 3A to Everglades National Park: Tamiami Trail Flow Formula

South Florida Water Management District

Hydrology and Hydraulics Bureau

In Partnership with

Everglades National Park and

the Jacksonville District of the

United States Army Corps of Engineers

November 2019

Acknowledgments

This document and data were a product of detailed research and model development conducted by individuals and government agencies as noted in the literature cited.

Significant contributions to understanding and implementing of this data analysis were possible through the efforts of Dr. Alaa Ali. This development on the Tamiami Trail Flow Formula is a significant effort leveraging years of pro-active tool development under the Interagency Modeling Center spearheaded by the vision and expertise of Dr. Ali and the outcome and techniques employed will serve as a quantitative aid in decision making for the foreseeable future.

We would like to thank Walter Wilcox and Clay Brown for keeping everyone on track, facilitating meetings, and providing guidance. Additional recognition goes to Cal Neidrauer, Raul Novoa, Jeffry Iudicello, Oscar Robayo, the National Park Service, U.S. Army Corps of Engineers and The Everglades Foundation for providing support, review, and numerous technical contributions and spirited discussions.

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Multiply	By	To Obtain
	Length	
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	640.0	acre
	Volume	
cubic foot (ft^3)	0.2832	cubic meter (m^3)
acre-foot	1233.48	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1233.046	cubic meter per year (m3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per day (ft^3/d)	0.2832	cubic meter per day (m3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Velocity	
inch per second (in/s)	25.4	millimeter per second (mm/s)
inch per day (in/d)	2.54	centimeter per day (cm/d)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
	Datums	
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).		
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) - High Accuracy Range Network (HARN).		

CERP	Comprehensive Everglades Restoration Plan
COP	Combined Operational Plan; a multi-agency partnership (USACE, DOI, SFWMD) that leverages existing and new infrastructure to send optimal flows south of Tamiami Trail using optimum water deliveries from WCA3A.
District / SFWMD	South Florida Water Management District
DOI	Department of Interior (includes National Park Service)
DSS	Data Storage System
ENP	Everglades National Park

IMC	Interagency Modeling Center consisting of USACE and SFWMD
LEC	Lower East Coast
NPS	National Park Service
RFP	Rainfall Plan
RSM	Regional Simulation Model
RSMGL	Regional Simulation Model – Glades – LECSA, a RSM implementation covering the WCAs, ENP and the LEC
SRS	Shark River Slough
SFWMD	South Florida Water Management District
TTFF	Tamiami Trail Flow Formula
USACE	United States Army Corps of Engineers
WCA	Water Conservation Area

1 INTRODUCTION

The current operational Rainfall Plan (RFP) (Neidrauer and Cooper, Appendix A)[1] establishes a target flow release from Water Conservation Area (WCA) 3A to Everglades National Park (ENP) at Tamiami Trail based on a linear function of rainfall and potential evapotranspiration (PET) at predefined gage locations. The RFP consists of independent environmental and regulatory components. The environmental component is a linear regression formula representing the 1941-1952 hydrologic system; a function of weekly rainfall and PET over the preceding 10 weeks and discharge of the last week. The regulatory component is an empirical formula based on the stage position above Zone D. The reliance on several meteorological stations over preceding number of weeks make the prediction sensitive to both the temporal and spatial selections.

For more than two decades the Comprehensive Everglades Restoration Plan (CERP) and other plans have sought to implement more robust real-time "rainfall driven operations" that are constrained to existing system limitations and are geared towards more scientifically-based ecological targets. In planning, the "natural system", other targets and constraints can be leveraged to drive modeled operations, but the means to translate these concepts into real-time operations is a challenging problem. To address these challenges, a variety of tools culminating with the iModel (Ali 2015) have been proactively developed through CERP's Interagency Modeling Center (IMC) and are being used in the Combined Operational Plan (COP).

2 OBJECTIVE

The COP seeks to develop a set of water management operating protocols for WCA3A and WCA3B key outlet structures to Everglades National Park (ENP) that leverage decades of infrastructure improvement. The operational protocols shift the system towards enhanced ecosystem and landscape performance while recognizing constrains imposed by flood protection, water supply and other key systems requirements. Additionally, the operational protocols also include updating the "Rainfall Plan" into a new "Tamiami Trail Flow Formula" (TTFF). This document describes the processes, data, tools and outcomes of the Combined Operational Plan's effort to identify this new and robust TTFF. In general, the approach can be summarized as leveraging the advanced iModel optimization tool and stochastic techniques to detect and characterize an optimal flow signal for achieving desired outcomes from the COP effort while ensuring physical consistency through testing with the Regional Simulation Model Glades-LECSA (RSMGL) regional model (the primary tool for COP alternative evaluation).

[1] The Rainfall Plan was authored by Mr. Thomas K. MacVicar; technical details are provided in Appendix A of the Neidrauer and Cooper SFWMD technical publication 89-3 (DRE-277).

3 CURRENT AND PROPOSED OPERATIONAL PLAN

The current "operational" Rainfall Plan is driven by rainfall. The formula is sensitive to the selection of rainfall stations and its prior data. In addition, it relies on the previous week's predicted flow with its uncertainties and uses independent environmental and regulatory components. The proposed flow formula could take many forms, but it will provide an updated target flow release from WCA3A to ENP at Tamiami Trail. The formula is driven by the current week's rainfall, prior week's stage and observed flow. A comparison of the current and proposed flow formula is summarized in Table 2. The intent is to capture a combination of the COP's desired natural response with the current limited water budget (pre-CERP) and the inclusion of a regulatory component. Other formulation considerations include data source reliability, transparency and ease of use. The final form of the formula was developed by the COP Team [Jacksonville District U.S. Army Corps of Engineers (USACE), ENP, and the South Florida Water Management District (SFWMD)].

Table 2. Similarities and differences of current and proposed flow formulas.

	Current Rainfall Plan (RFP)	Tamiami Trail Flow Formula (TTFF)
Type of "Signal" to be captured	A direct simulation of a previous version of "environmental" system targets.	Managed system flow that best achieves multi-objectives of the COP.
Data used	Historical Data (1941-1952 post-drainage)	Alternative O flows (1965-2005 climate operated to achieve desired COP benefits)
Formula Form	Linear Approximation	Linear Approximation
Climate Inputs (Rainfall & Potential Evapo-transpiration)	Multiple stations over preceding 10 weeks	Multiple stations over current week only
Previous week's Flow	Yes (predicted)	Yes (observed)
Previous week's Stage	No	Yes, both in WCA3A and ENP
Regulatory Component	Estimated separately	Included in the formula

4 APPROACH

The new rainfall driven formula was developed using the following procedure.

1) A set of objectives and desired outcomes (benefits) was identified by the COP team based on initial RSMGL analysis, evaluation through public engagement, scientifically based ecological targets and system limitations (e.g., available water budget, flood protection and Zone A of the regulatory schedule).
2) The iModel (Ali, 2009 and 2015) was developed and implemented to obtain an optimal operational scheme that enables the system to achieve "agreed upon" benefits. One key to this step is verification of the iModel's Hydrologic Model Emulators (HME) to ensure consistency between the statistical modeling of the HMEs and the physical system representation in the RSMGL.
3) The iModel transformed optimal flows were applied to the RSMGL base model to establish a physically based indicator or "signal" between flow and other variables such as stage, rainfall and PET.
4) A statistical model was developed to predict optimal flow at the key structures using the flow, stage, rainfall and PET time series generated in step 3. The statistical model emulates the optimal signal and provides real-time operational flow guidance from WCA3A to ENP.

A detailed description of the iModel and the approach for developing the new rainfall driven formula are provided below.

4.1 RSMGL and iModel Development

COP plan formulation has used of a mix of traditional approaches (such as iterative modeling of expert ideas) and application of optimization tools to help identify outcomes desired by the team. Using COP's RSMGL Round 2 modeling, initial iModel testing was used for verification of Hydrologic Model Emulators (HME). In this round, team input was leveraged. In addition, the iModel was developed, implemented and the output was transformed into a statistical model using the physically based relationship between flow and key variables. The statistical model was implemented in the plan optimized RSMGL as the new rainfall formula. The steps are shown in Figure 1.

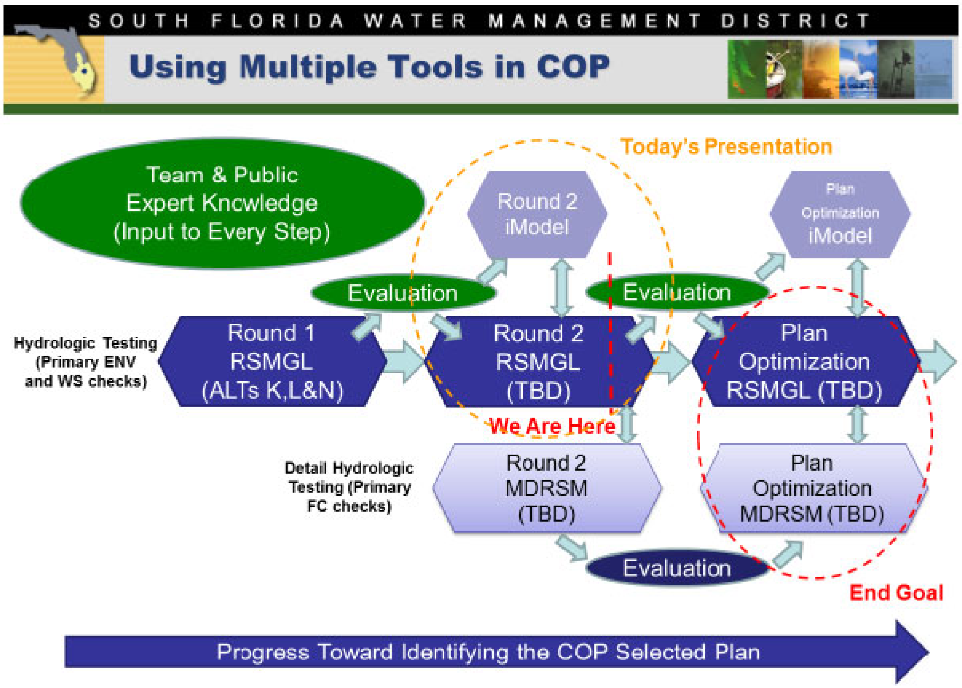

Figure 1. Procedural schematic for development of rainfall driven formula using the COP framework.

4.1.1 iModel Application

iModel (Ali 2015) is a simulation-optimization tool that calculates optimal flow releases (inflows, intra-flows, and outflows) at control points along the partitioning levees of a network of managed wetland systems to achieve target performance subject to the system's stressors, demands, and constraints.

Tamiami Trail Flow formula | 10

The iModel Simulation Engine provides metamodeling capability to simulate wetland systems (e.g., water level [stage] spatial variability) in fractions of the time needed by physically based models. Such simulation capability is embedded into an Optimization Engine that can handle complex problems with numerous decision variables, highly dimensional systems with discontinuity, and linear and nonlinear constraints. Refer to Ali (2009 and 2015) for full monographs of iModel theories and applications. Below is a brief description of both iModel engines.

4.1.2 Simulation Engine

The Simulation Engine consists of a network of Hydrologic Model Emulators (HMEs). Each HME represents a water system such as a conservation area, the ENP or even a canal reach. An HME is represented by an autoregressive Artificial Neural Network with exogenous input to simulate stage field in that system. The exogeneous input includes rainfall, PET, inflow and outflow points as depicted schematically in Figure 2.

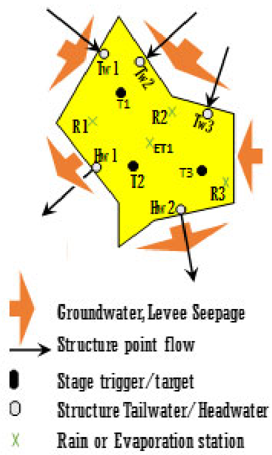

Figure 2. Sample HME schematic of exogenous input to simulate stage field.

According to Ali (2009), the multivariate R-S residual time series relationship is expressed as follows:

$$s_t = \sum_{i=0}^{q-1} \Gamma_i \, u_{t-i} + \sum_{j=1}^{p} \Phi_j \, s_{t-j} + \nu + \omega_t \qquad (1)$$

Where q and p are the model orders, given n and m user defined state and exogenous variables respectively at time t, s is the p x n residual state variable (stage) matrix, Φ is the p x p state transition matrix, u is the m x q residual exogenous input (rainfall and PET) matrix, Γ is the n x m exogenous coefficient matrix, ν is the bias vector, and ω is a random vector with zero mean and covariance matrix. Input and output data are residuals of the original time series after subtracting the corresponding periodic mean based on the development data period of record.

Given a model order of q=1 and p=0 (a managed system's memory is disrupted by structure flows), a nonlinear form of the model can be represented by a two-layer recurrent time-delayed dynamic network with feedback connections to approximate a nonlinear characteristics function $\wp$ in a nonlinear multivariate framework. A nonlinear representation of Equation 1 for a noise-free non-linear system can be expressed as:

$$s_t = \wp(s_{t-1}^1 \quad \cdots \quad s_{t-1}^n \quad \cdots \quad u_t^1 \quad \cdots \quad u_t^m) \qquad (2)$$

4.1.3 Optimization Engine

In this study, real-coded genetic algorithm (GA) is used as the optimization method for a complex multiple wetland system with unique technical and policy characteristics.

4.1.4 Fitness Function

If a flow release at a given control point represents a gene (or a component), the coding of all genes into one string represents a chromosome (or flow vector) that corresponds to a solution. The entire population of chromosomes represents a generation. Chromosome fitness, at time step t, is evaluated through the system's performance as represented by Equation 3 and a user defined target as calculated by the following fitness function:

$$\mathcal{F}(q) = \sum_{c=1}^{nc} \omega_c * (S_c(q) - T_c)^2 \qquad (3)$$

Where c is target location, nc are number of target locations, S_c HME simulated stage (or seepage) (Equation 3) and note that S_c is function of the decision variable q, T_c is restoration target (stage or seepage), ω_c is prescribed weights (default is 1), and $\mathcal{F}(q)$ is fitness function score for a given chromosome vector "q".

4.1.5 Constraints

Fitness function $\mathcal{F}(q)$ is minimized subject to system constraints such as flow capacities, hydraulic conveyance capacities, flood regulations, and budget as follows:

$$\frac{min}{\mathcal{F}(q)} \begin{cases} 1) nlCinq = Q_{max} - \alpha * (S_{hw} - S_{tw})^{\beta} \leq 0\rfloor_{all\ spillways} \\ 2)\ nlCeq = q_{in} - q_{out} + Net\ rain - Net\ seepage + area * \partial S/\partial t = 0\rfloor_{entire\ system} \\ 3)\ qq - C = 0\rfloor_{total\ sum\ of\ system\ inflows\ is\ constant} \\ 4)\ lb \leq q \leq ub\rfloor_{flow\ structure\ capacity} \end{cases} \qquad (4)$$

Constraint specifics are provided in the application section.

4.1.6 iModel Utility

The iModel simulation engine consists of randomly selected HME for each area from pre-trained HME repository. The Simulation Engine and Optimization Engine are integrated in the framework to form the iModel utility, shown in Figure 3.

For time step t, the first step is data preparation for HME representation including flow coding, population selection, and optimization constraint data. The initial population of flow vectors (chromosomes) is randomly selected and fed into the representative HMEs to simulate all the system's responses at multiple areas and locations as required by optimization (e.g., target locations, headwater and tailwater for hydraulic conveyance constraint calculation, etc.). The optimization engine proceeds as previously described. The simulation-optimization scheme, iModel, continuously improves the chromosome selection governed by minimizing the objective function Equation 3 and constrained by Equation 4 linear and nonlinear constraints to cause the desired changes in the system's response (stage) until the optimal solution is reached according to the stopping criteria.

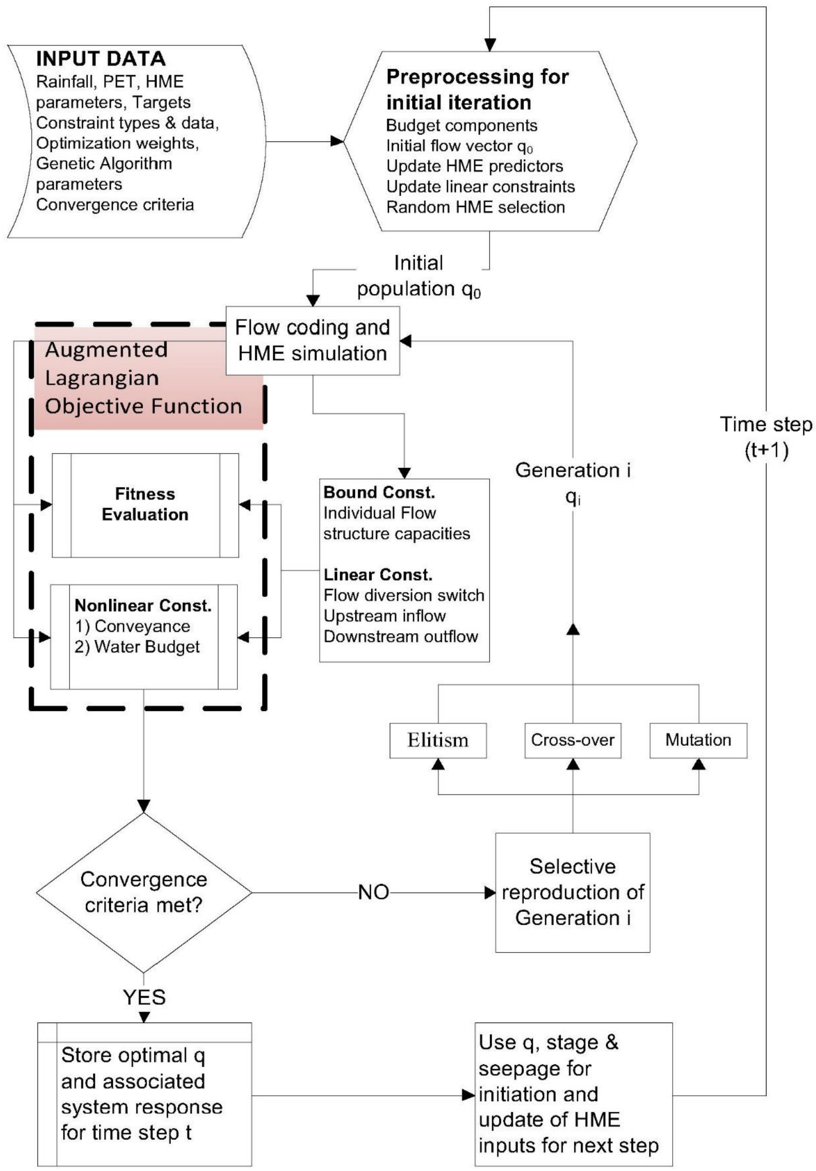

Figure 3. iModel framework for simulation and optimization engines (Ali, 2015).

4.2 Hydrologic Model Emulator Verification

HME's were developed for each WCA, ENP and the Lower East Coast (LEC)/ENP canal systems. Data trained were extracted from an initial COP RSMGL (Round 2) base run output and includes structure flows, stages, rainfall and PET. This RSMGL base run is a version of the current condition, ECB19R scenario with "perturbed" operations to ensure a high variability in flow and stage conditions to help maximize the robustness of the HME training process. Period of record used for training is 1965-1989 while period of record 1990-2005 was used for HME verification. Example results for this application are depicted in Figures 4 through 7 which show substantial matching between the RSMGL and HME simulated stages for the verification period. The graphs also show small mean square errors less than 0.05 ft., bias less than 0.15 ft., and correlation greater than 0.97.

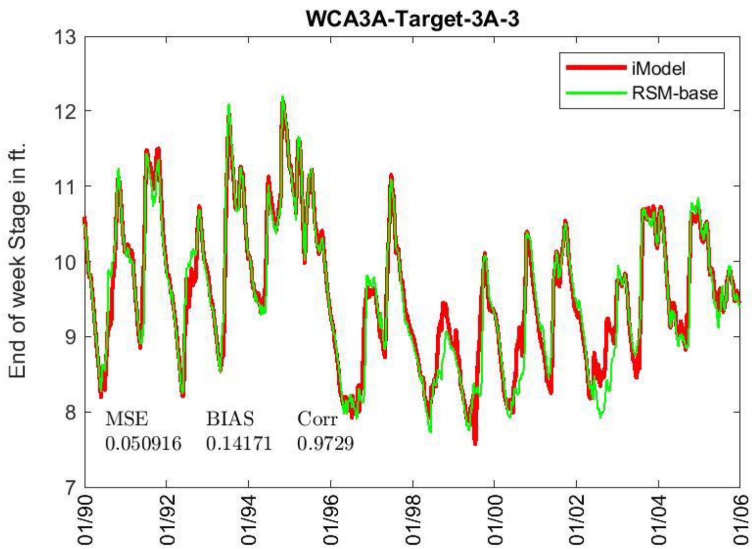

Figure 4. iModel HME verification results at WCA3A at target 3.

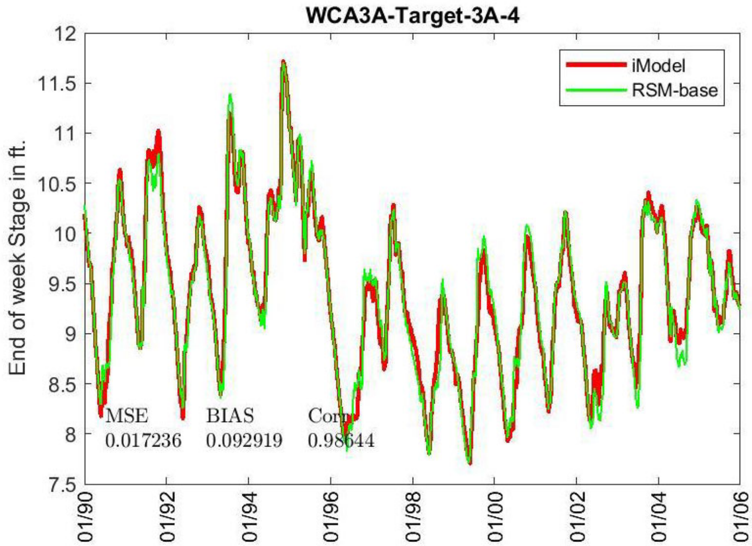

Figure 5. iModel HME verification results at WCA3A at target 4.

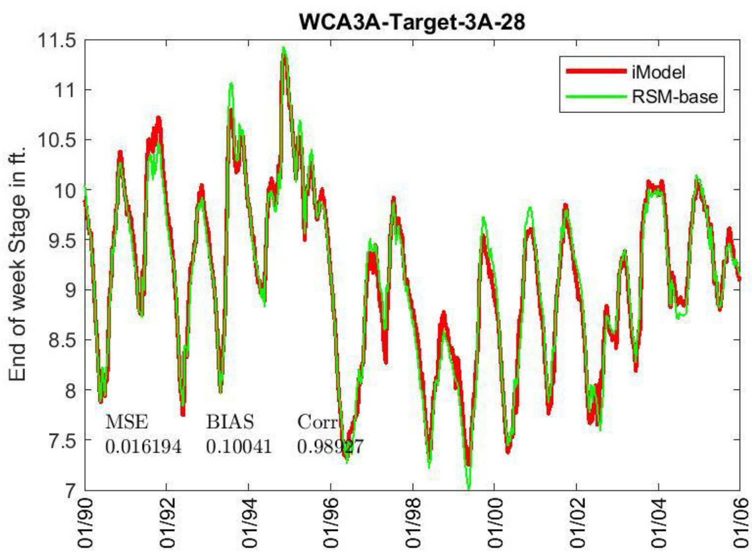

Figure 6. iModel HME verification results at WCA3A at target 28.

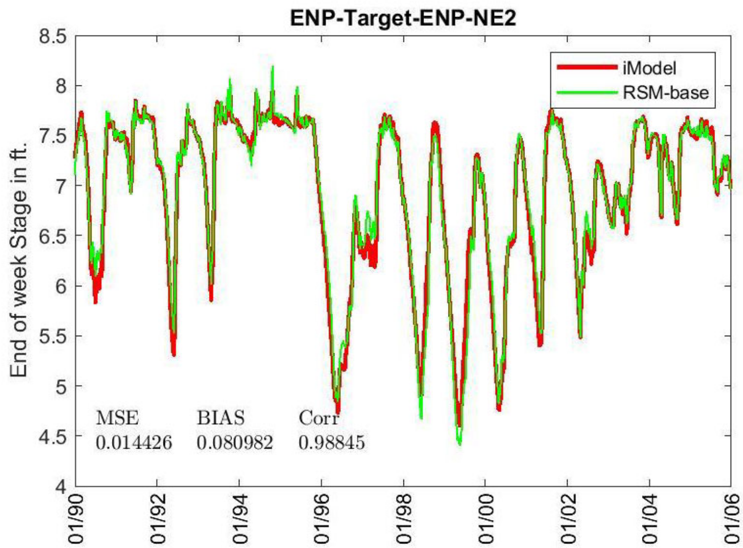

Figure 7. iModel HME verification results at ENP at target NE2.

4.3 iModel Application

The iModel was used to develop real-time operational flow guidance (e.g. the optimal indicator or signal) from WCA3A to ENP to achieve COP objectives while meeting regulatory release and other system constraints. In this step, the iModel was used to determine the optimal indicator or signal in terms of flow releases at S12C, S12D and S333. The sections below describe the restoration targets, objective functions, constraints and iModel results using the optimal signal.

4.3.1 Objective Function

The goal is to apply Equation 3 to minimize the difference between the iModel-achieved stage and the corresponding stage target. The COP Ecological Sub-team prioritized provided stage targets at 24 "Marsh" equally-weighted locations in WCA3A, WCA3B and ENP, shown in Figure 8 (COP Ecological Sub-Team, 2019). These targets are largely based on RECOVER[2] efforts and are consistent with previous planning efforts including the development of the Central Everglades Plan. Figures 9 through 12 illustrate that the iModel has performance outcomes more consistent with targets when compared to RSMGL ECB19R for all sites.

[2] RECOVER (Restoration Coordination and Verification) is an interagency, interdisciplinary team sponsored by USACE and SFWMD.

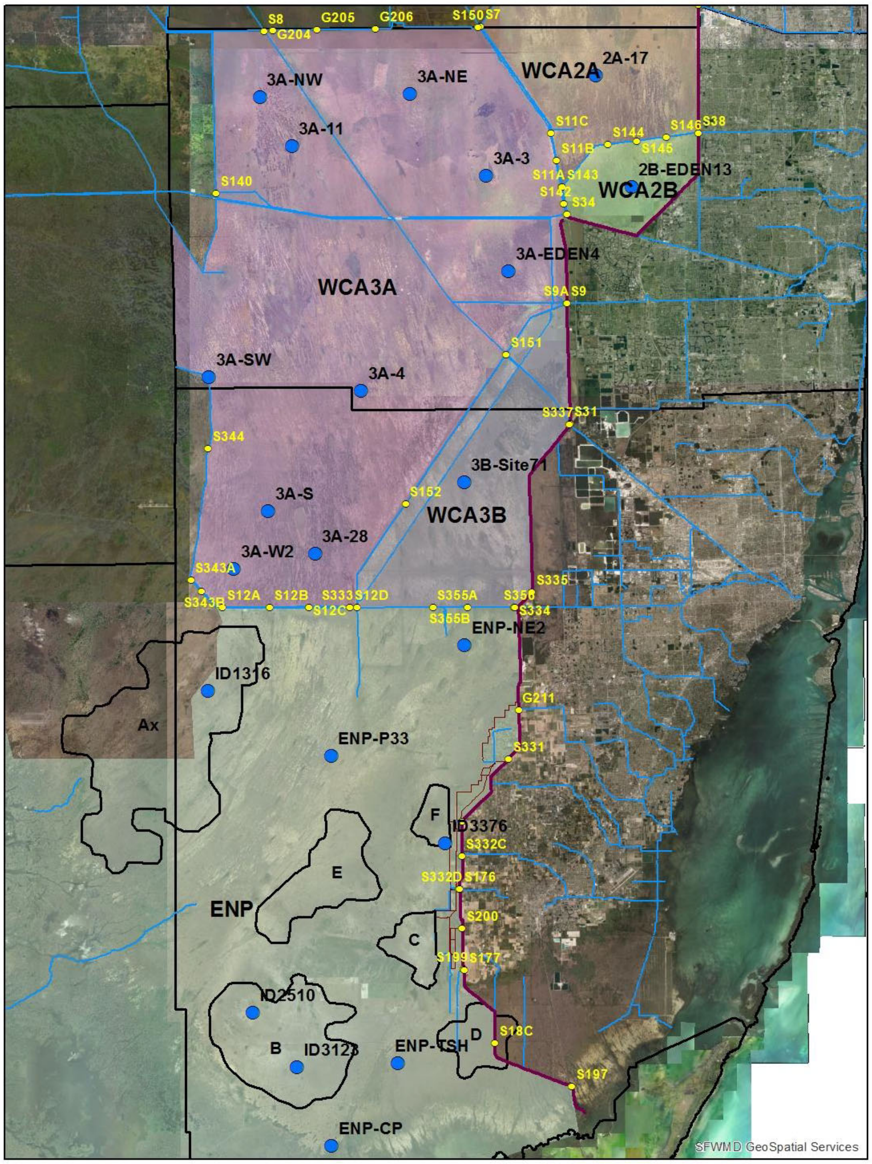

Figure 8. Stage targets used by the iModel.

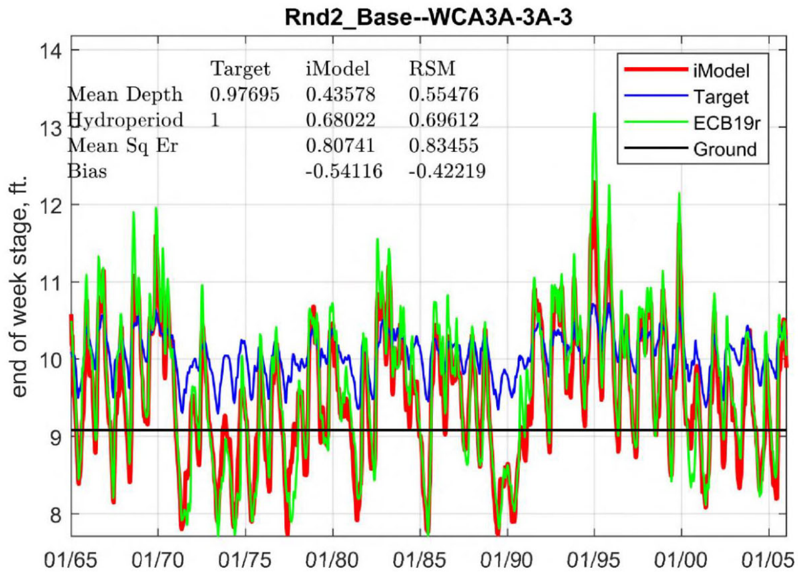

Figure 9. iModel application results at WCA3A-3.

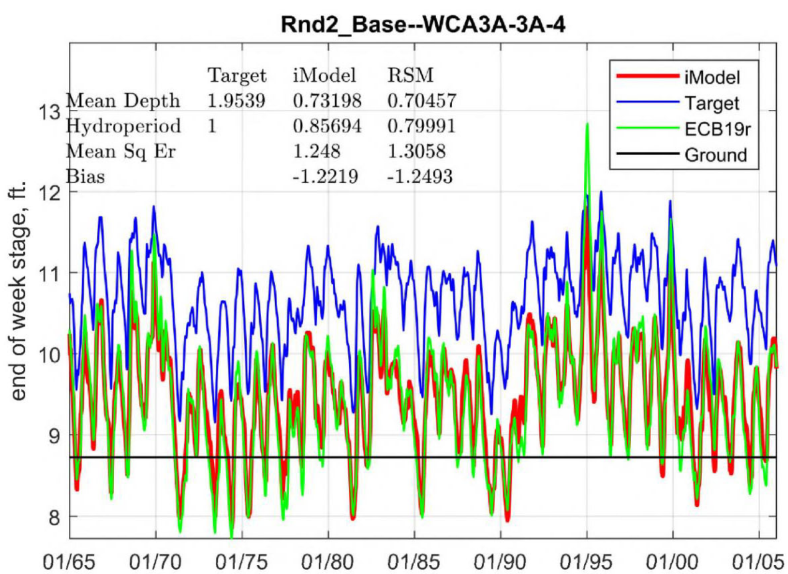

Figure 10. iModel application results at WCA3A-4.

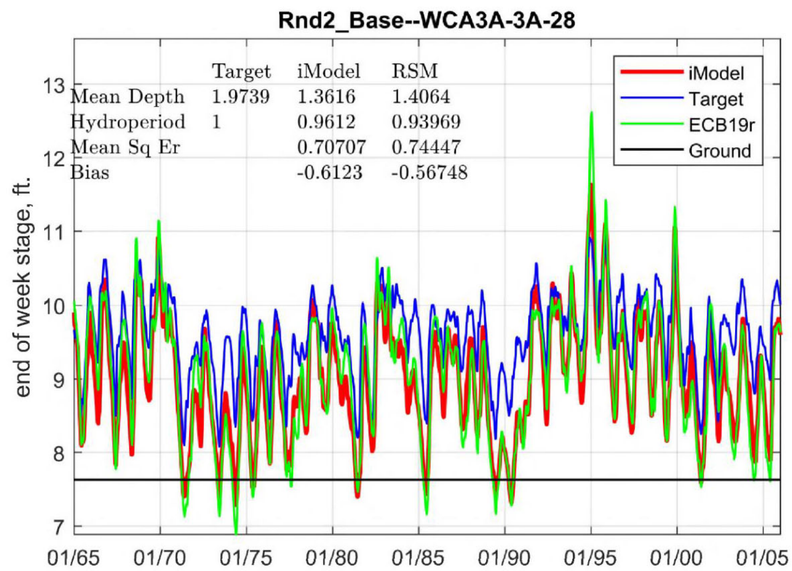

Figure 11. iModel application results at WCA3A-28.

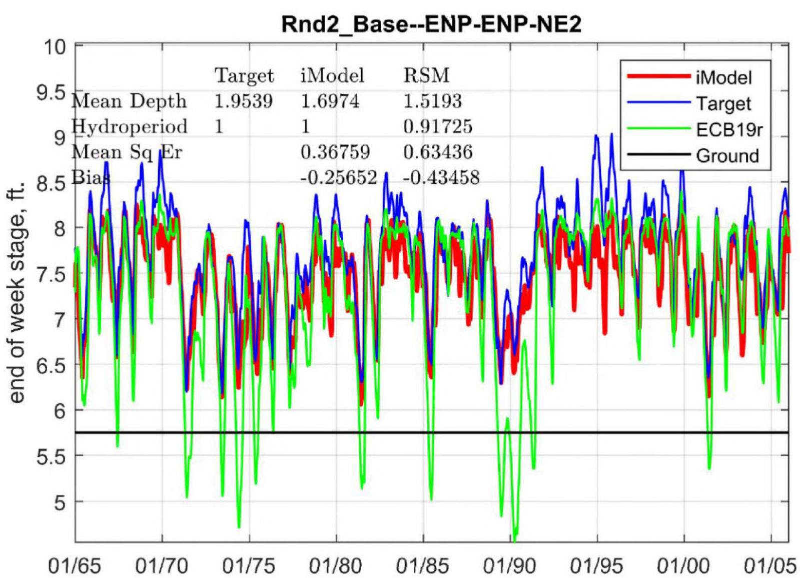

Figure 12. iModel application results at ENP-NE2.

4.3.2 Constraints

In addition to the targets provided by the project team at the desired gauge locations, a variety of constraints are also implemented per team direction or as a means of helping the statistical simulation honor physical realities. Constraints can be characterized as hard or soft. Hard constraints are explicitly included in the constraint matrix and the solution candidacy is rejected if any of such constraints are not met (deemed infeasible outcomes). These constraints are typically flow constraints like structure capacity. Soft constraints are typically a high or low stage threshold. It is the sum of the squared (or exponential) error between HME simulated stage and the corresponding threshold. This score is zero (0.0) if the requirement is met regardless how well the condition is met (e.g. approaching the threshold is the same as in the middle of the "acceptable" range). Violations (outside the "acceptable" range) are heavily penalized to discourage such an excursion, but is allowed to occur. For example, if the stage measure goes below Zone A, then solution candidacy is not rejected regardless of how lower to Zone A; but if it is higher than Zone A, then the higher the stage the quadratically higher the penalty.

Table 3. Everglades objective function constraints.

Location		Constraint Type
Flow structure capacities		Hard constraint
All simulated gravity structures are constrained by hydraulic conveyance capacity (e.g., headwater, tailwater and structure hydraulic parameters)		Hard constraint
L29 (8.4 ft)		Hard constraint
Flow Closure of S344, S343A, S343B, S12A and S12B from 10/1 to 7/15		Hard constraint
Zone A		Soft constraint
Overall Budget		Soft constraint
WCA3A recession rates (ft/week) as follows:		Soft constraint
Undesirable	>0.10	
Marginal	0.07 – 0.10	
Preferred	0.03 – 0.06	
Marginal	0.00 – 0.20	
Undesirable	<0.00	

Table 4. LEC/ENP canal system objective constraints.

Location	Constraint Type
G21 < S331	Hard constraint
S331 < 1.3 G211	Hard constraint
S177 < S18C	Hard constraint
S18C < 1.25 S177	Hard constraint
This canal system's high and low canal water level is based on SDCS canal operational ranges derived from RSMGL 2012 Water Control Plan scenario	Soft constraint

4.3.3 iModel Optimal Signal

The iModel application produced an optimized flow signal that was used as input to the subsequent development of RSMGL ALTO scenario. Optimal flows at Tamiami Trail (the sum of the S333, S12D and S12C structures) identified by the iModel were input to the RSMGL using an iterative adjustment strategy (to account for the RSMGL limitation that it still simulated the regulatory portion of the legacy WCA-3A regulation schedule) resulting in ALTO which demonstrated high correspondence in the RSMGL with iModel flow characteristics. The COP project team evaluated the RSMGL ALTO scenario, concluding that performance was improved relative to other alternatives and was achieving the desired optimal benefits envisioned in the COP effort. Extraction of ALTO data from the physically-based RSMGL model enabled the team to obtain a full data set of flows, stage, rainfall and PET whose embedded relationship (dynamic) represents the signal required to achieve the target benefits yet constrained by the system's limitations listed above. This section describes the ALTO captured signal and develop a statistically based model that can predict the signal's flow as a function of stage, rain, PET and other terms. It is desired to develop a model that is transparent, simple to understand and to apply.

4.4 Tamiami Trail Flow Formula (TTFF)

As described above, the iModel optimized flows were transformed and fed into RSMGL producing the ALTO scenario. ALTO input (flow, rainfall and PET) and output (stage) data whose embedded relationship (dynamic) represents the signal required to achieve the target benefits yet constrained by the system's limitations listed above. This section describes the development of a statistically-based model that can predict the ALTO flow signal as a function of stage, rain, and PET. Initially, three models were considered: a) a nonlinear model based on Artificial Neural Network that exploits the techniques offered by the iModel tools (refer to section 4.2 above regarding HME Verification), b) a linear model with reduced dimensionality using Principal Component Analysis and c) a simple linear model. In this study earlier efforts to develop models with embedded layers of complexities (a and b), were found to capture some dynamics that are not captured by the simpler models (c)which resulted in a slightly better performance. However, these models are more difficult to use and their results need greater efforts to understand and interpret especially those that are counterintuitive. On the other hand, simpler models whose formulation is understood by the majority of the professional community were found to demonstrate reasonable performance. The prevailing opinion was unless linear models perform poorly, their simplicity gain far outweighs the slight improvement in performance gained from the complex models. In this section the selected multiple linear regression based TTFF model is provided.

The Formula

Considering weekly data of the above mentioned daily data, the TTFF is a linear regression based formula that is expressed as follows:

$$Q_t^{sum} = \beta^1 * S_t^{avg1} + \beta^2 * S_t^{nesrs2} + \beta^3 * Q_{t-1}^{sum} + \beta^4 * R_t^{Avg} + \beta^5 * PET_t + \beta^6 * ZA_t$$

where; $\boldsymbol{Q_t^{sum}}$ is the target daily releases (sum of S-12A, S-12B, S-12C, S-12D and S-333) for the current (upcoming) week, t (cfs)

$\boldsymbol{S_t^{avg1}}$ is the spatial average of observed stages (ft, NGVD) at WCA 3A stages A-3 (Site 63), A-4 (Site 64) and A3-28 (Site 65) for the start of the current week t,

$\boldsymbol{S_t^{nesrs2}}$ is observed stage (ft, NGVD) at ENP stage NESRS2 for the start of the current week t,

$\boldsymbol{Q_{t-1}^{sum}}$ is the daily average of **observed** releases (sum of S-12C, S-12D, S-333, S-333N, S-12A, and S-12B) for the previous week t-1 (cfs),

$\boldsymbol{R_t^{avg}}$ is the areal average for the total weekly rainfall (in) for the entire WCA 3A and Mullet Slough. see map),

$\boldsymbol{PET_t^1}$ is the total weekly potential evapotranspiration (in) at the 3AS3WX location, and

$\boldsymbol{ZA_t}$ is the Zone A regulation stage (ft, NGVD) value for time step t (beginning of current week).

Table 5. TTFF coefficients and associated standard error.

Parameter	S_t^{avg1}	S_t^{nesrs2}	Q_{t-1}^{sum}	R_t^{avg}	PET_t^1	ZA_t
Coefficient	318.42	-44.62	0.644	24.32	-96.31	-221.79
Standard Error	18.22	18.50	0.016	7.23	28.83	13.67

Note: Although application of this formula may rarely result in negative flows, the formula outcome is always applied to operations constrained as greater than or equal to zero; hence, negative flows are not utilized to identify targets releases. In ALTQ, the TTFF is only applied below Zone A when S12A and S12B are closed, but for completeness in the WCP and during transition out of Zone A, S12A and S12B flows (if any) are considered in the flow input.

4.4.1 Coefficient Interpretation and Formula Applicability

The final form of the TTFF is clearly a generalized version of the optimal signal identified in the iModel and ALTO. As previously stated, the interagency team made this choice consciously knowing that typical limitations associated with linear regression approaches would be carried forward (relatively better data matching on average and poorer performance on the extremes, knowledge that all variables are not fully independent, etc…). Despite these limitations, the TTFF as identified in the COP process exhibits many positive characteristics and this section attempts to describe the behavior of the formula. The TTFF coefficients all have relatively small standard error relative to coefficient magnitude as shown in Table 5 and exhibit the following influences on the total target flow:

S_t^{avg1} + sign → The higher the stage average in WCA3A the higher the release to ENP

S_t^{nesrs2} – sign → The lower the stage at NESRS2 the higher the need for a flow to ENP.

Q_{t-1}^{sum} + sign → This is the only sign that is feasible.

R_t^{avg} + sign → The higher the WCA3A rainfall the higher the flow to ENP

PET_t^1 -sign → The higher the PET the lower the release to ENP

ZA_t -sign → Zone A reflects an operation intent to lower or raise stage in WCA3A. The lower this regulation line, the more the pressure to release flow to ENP to avoid excursion into Zone A.

As recognized previously, the selected variables in the formula are not all independent and exhibit a degree of multicollinearity. To test the severity of this effect on the TTFF formulation, Variance Inflation Factors were calculated (Table 6) and demonstrate that all terms have values less than 5 which indicate that for the TTFF, multicollinearity is not considered high and that the formulation does not violate statistical best practices.

Table 6. TTFF coefficients Variance Inflation Factor.

Parameter	S_t^{avg1}	S_t^{nesrs2}	Q_{t-1}^{sum}	R_t^{avg}	PET_t^1	ZA_t
Coefficient	4.9	3.4	3.3	1.2	3.6	4.2

As part of the COP process, the TTFF was coded into the RSMGL and simulated (along with other model assumption changes) in a new RSMGL scenario called ALTQ. This effort allowed for comparison between the TTFF and the legacy RFP. The TTFF demonstrates higher dry season flow targets than the RFP ENV component, shown in Figure 13. The TTFF also illustrates higher annual flow targets, except for the wettest year, shown in Figure 14. When compared back to the "optimal" flows from ALTO, a weekly flow comparison demonstrates a smooth behavior that generally captures the intent of the formula, (red line) shown in Figure 15. Some of the inherent biases propagated by the linear approximation approach are also evident as not all short-term events or extreme conditions are captured. The COP project team evaluated the RSMGL ALTQ scenario in a manner similar ALTO scenario, concluding that performance was at times different, but in the same vicinity as the ALTO scenario and was achieving the desired "optimal" benefits envisioned in the COP effort including significant improvements over the legacy operations.

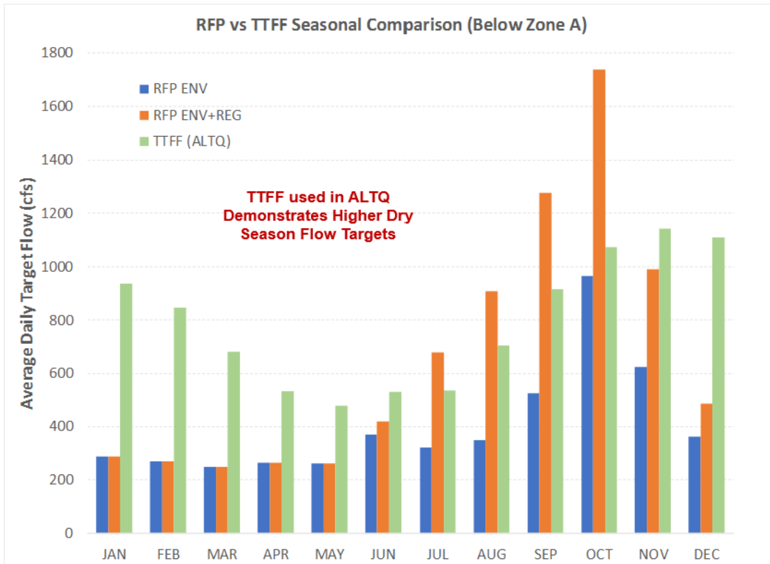

Figure 13. Seasonal comparison between RFP and TTFF.

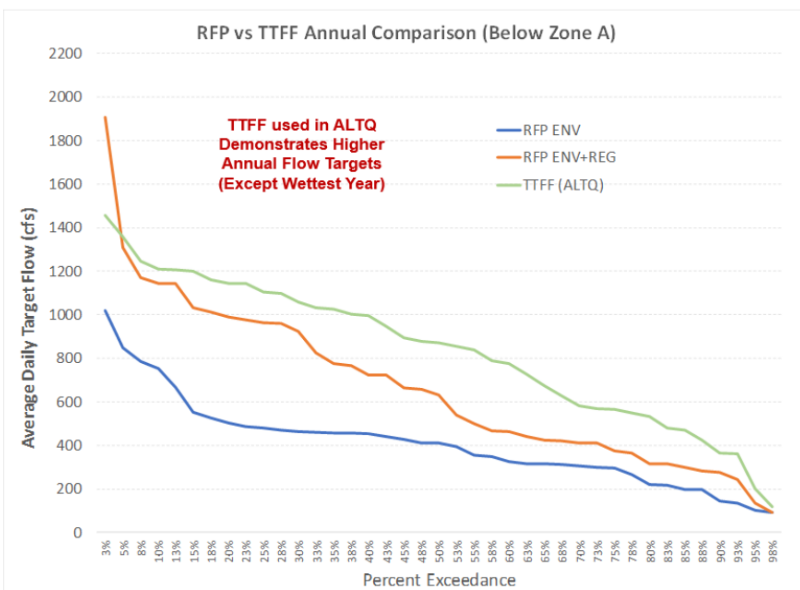

Figure 14. Inter-annual comparison between RFP and TTFF.

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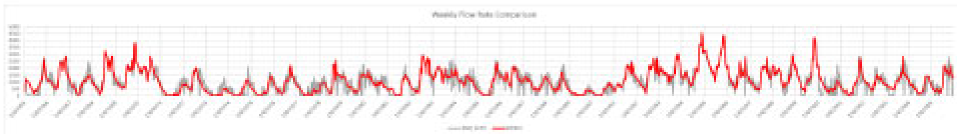

Figure 15. Weekly flow comparison results from initial testing of the rainfall formula in RSMGL.

As an additional check, a comparison was performed between the TTFF and legacy RFP targets and operation over the recent historical record, shown in Figure 16. Also displayed are flows computed using the RFP and observed flows from S12C, S12D, and S333. The RFP, shown in Figure 16, is only the environmental component while the observed trace includes both environmental and regulatory components. The TTFF is a single series that accounts for both the environmental and regulatory components. The potential flow increase from the TTFF is shown as the shaded green portion. This exploratory application of the proposed TTFF shows trends consistent with COP desired outcomes.

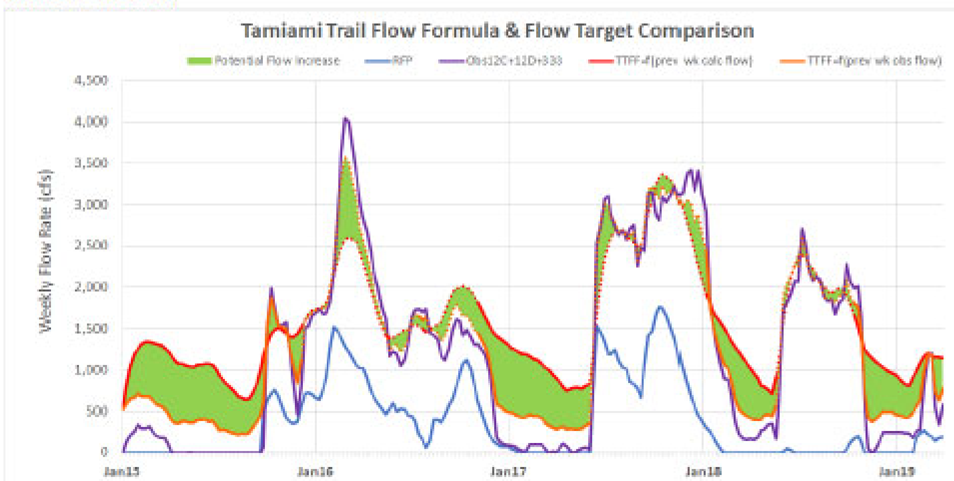

Figure 16. Comparison between TTFF formula and COP flow targets.

4.4.2 Residuals Statistics

As a final check, Figure 17 shows multiple residual statistics graphs comparing the ALTO optimal flows and the performance of the TTFF independent of other influences (e.g. other assumption changes in RSMGL ALTQ). The upper left graph shows residuals histogram to be symmetric which is consistent with the CDF comparison (upper right graph) between normal and empirical distributions. The lower left graph shows now trend of residuals with the fitted value. The lower right graph shows a reasonably symmetric residual tail distribution around the mean.

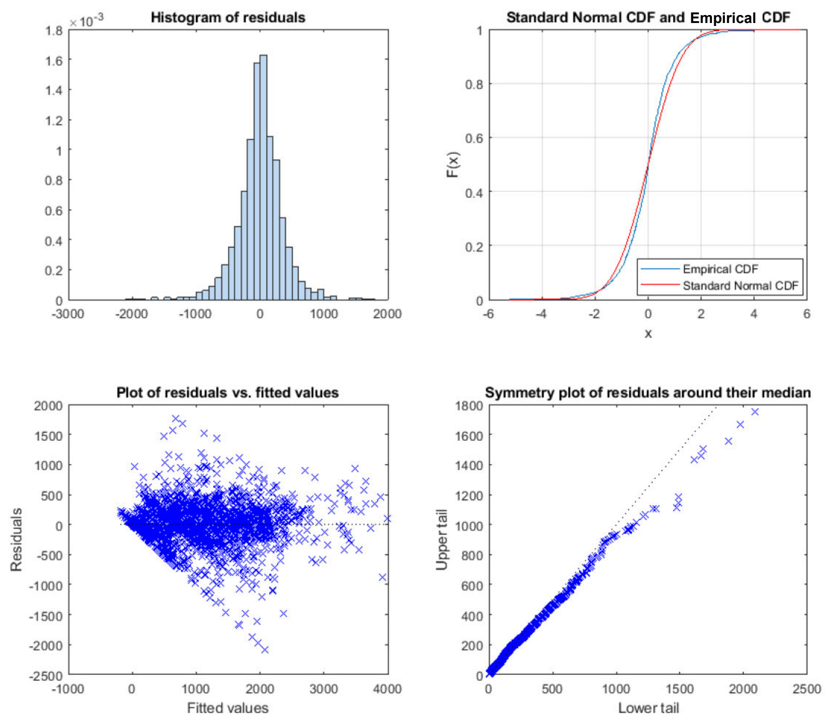

Figure 17. Residual statistics.

4.4.3 TTFF with forecasted rainfall

Rainfall and PET terms of the above TTFF equation are historical averages of the current week t (since actual rainfall and PET are unknown). Rainfall data was computed using the basin average of NEXRAD (SFWMD, 2019) data for WCA3 (CONSERVAREA3 polygon available at https://www.sfwmd.gov/weather-radar/rainfall-historical/sites-and-basins) and PET from station 3AS3WX, shown in Figure 18. Errors resulting from this approximation are not significant unless a storm event is anticipated. A more precise implementation of TTFF is expressed as

$$Q_t^{sum} = TTFF(p,t) + AdjTerm$$

$$AdjTerm = TTFF(a,t-1) - TTFF(p,t-1)$$

where;

$TTFF(p,t)$ is TTFF estimated releases for the current week "t" based on **projected** rainfall and pet. This can be historical averages for week "t" or "skillfully" forecasted quantities.

$TTFF(p,t-1)$ is TTFF estimated releases for the past week "t-1" based on **projected** rainfall and pet. This can be historical averages for week t-1 or "reasonably forecasted" quantities.

$TTFF(a,t-1)$ is TTFF estimated releases for the past week "t-1" based on **actual** rainfall and pet.

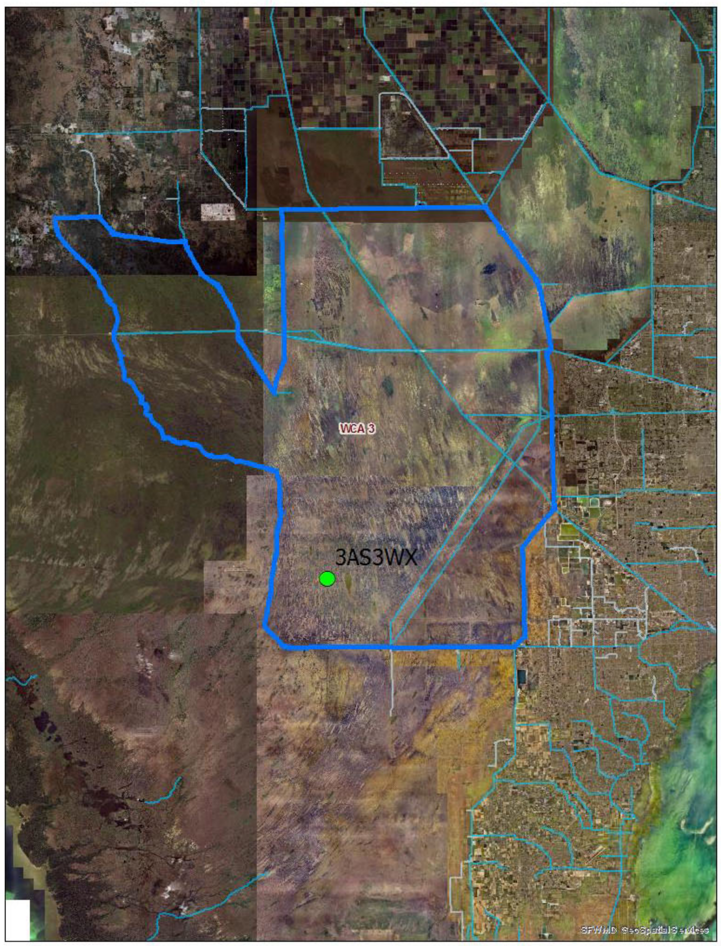

Figure 18. WCA3 polygon and PET station used to compute historical averages.

In practical application of the formula, projected rainfall and ET must be estimated at the time of formula application. Any skilled projection of these terms could be utilized in real time at the discretion of water manager judgement with the understanding that error propagation in target releases due to inaccuracies in forecasting methods would be addressed by the weekly adjustment utilizing actual observed rainfall in the subsequent application. As modeled with the RSMGL during COP planning, a seasonal median and 90th percentile value for the WCA3 polygon was calculated for each calendar day based on observed rainfall from the 1965 to 2005 period of record. During normal operations, the median value was used as a forecast value in formula application and during the 5-day window in advance of a potential tropical storm event the 90th percentile value was used as a forecast value in formula application. In both cases when running the RSMGL model, the subsequent week applied an adjustment using observed rainfall as would be done in real-time formula application.

5 CONCLUSIONS

This report provides a detailed description of the development and testing of the proposed COP Tamiami Trail Flow Formula. The TTFF is one aspect of water management operating protocols designed to provide environmental benefit anticipated in the COP effort including rehydration of ENP. This objective is accomplished by returning the hydrology of the WCAs and ENP to conditions more consistent with the natural environment while honoring know constraints.

The TTFF improves upon the RFP, achieves hydrologic targets including: 1) surface water flow deliveries that resemble more natural processes, 2) gradual rate changes to deliver surface water flows and 3) surface water flow distributed across the entire slough.

Based on the figures and tables, there are several observations that can be made:

1) The HME verification proved successful which is required for the iModel adequately to represent the hydrologic system (Figures 4 through 7).
2) Once the objectives and constraints were imposed (Table 3), the iModel results were closely correlated with the desired stages (Figures 9 through 12).
3) A weekly comparison demonstrates the TTFF shows surface water flow releases are consistent with the optimal signal identified by the iModel and similar to flows that resemble natural processes (Figures 13 through 16).

These observations coupled with the statistical / performance checks on the formula summarized in Section 4 and the COP team evaluation concluding that the RSMGL ALTQ (utilizing the TTFF) was acceptable lead to the conclusion that the desired outcomes of COP have been realized in the TTFF. This significant achievement represents the first update to an environmentally driven operation for Tamiami Trail in decades and the culmination of two decades of effort to realize the vision dreamed possible when the CERP concept of "rainfall driven operations" was first proposed. While additional refinement to improve upon some of the inherent limitations acknowledged in linear generalization of the optimal signal are possible, these efforts can be pursued under the COP adaptive management framework or in subsequent CEPP operational plan development activities anticipated in upcoming years.

6 REFERENCES

Ali, Alaa. "Nonlinear multivariate rainfall–stage model for large wetland systems." Journal of Hydrology 374 (2009): 338-350.

Ali, Alaa. "Multi-objective operations of multi-wetland ecosystem: iModel applied to the Everglades restoration." Journal of Water Resources Planning and Management 141.9 (2015): 04015008.

COP Ecological Sub-team. Summary report. 2019.

Neidrauer, Calvin J., and Richard M. Cooper. "A Two-year Field Test of the Rainfall Plan: A Management Plan for Water Deliveries to Everglades National Park, July 1985-July 1987." Technical Publication 89-3 (DRE-277), Water Resources Division, Resource Planning Department, South Florida Water Management District, 1989. http://my.sfwmd.gov/portal/page/portal/pg_grp_tech_pubs/portlet_tech_pubs/dre-277.pdf.

SFWMD. 2019. https://apps.sfwmd.gov/nexrad2/nrdmain.action

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