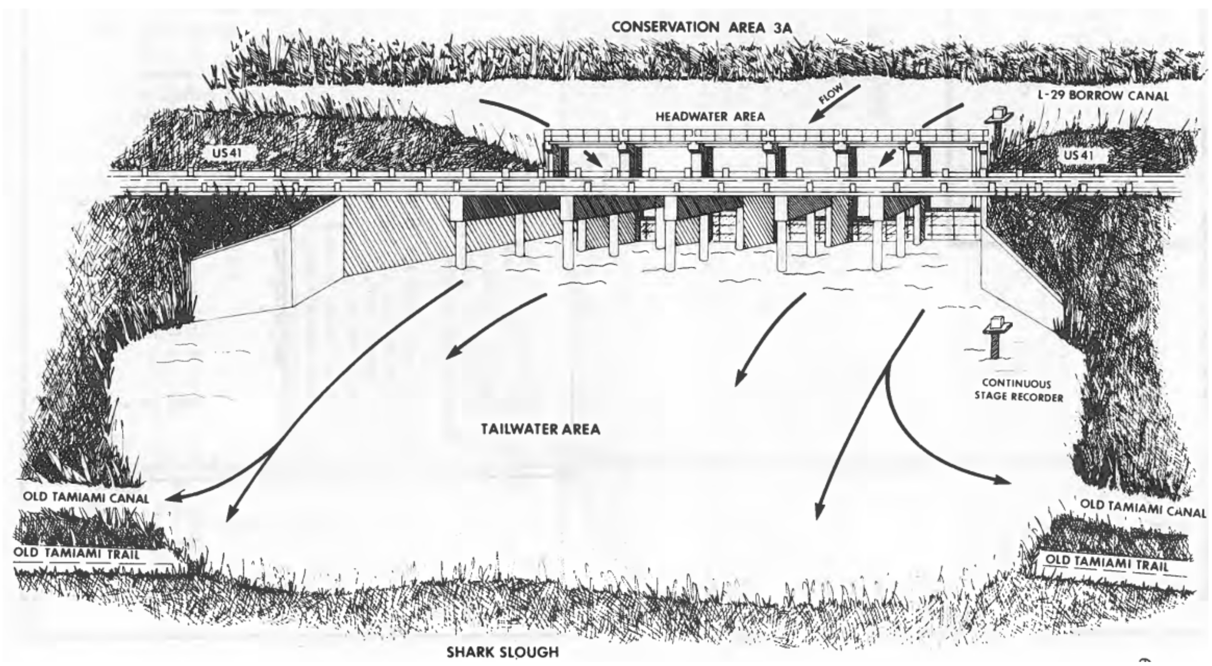
Disentangling effects of rainfall and water management on water levels and flows in Everglades National Park

November 1 2024

South Florida Natural Resources Center

University of California San Diego

Scripps Institution of Oceanography



Cooperative Ecosystem Studies Units, University of California San Diego

Cover picture shows schematic diagram of an S-12 structure.

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EXECUTIVE SUMMARY

This work embodies a partnership between the National Park Service (NPS) South Florida Natural Resources Center (SFNRC) and the Sugihara Lab of the Scripps Institution of Oceanography, University of California San Diego through the Cooperative Ecosystems Studies Units (CESU).

The objective is to address a complex problem with direct relevance to regional watershed management in the UNESCO World Heritage Everglades National Park: How does one disentangle influences of rainfall and water management in the hydrologic response of the Everglades? One way to approach this question is through numerical models running a series of rainfall scenarios to assess hydraulic response. However, such models are resource intensive and can be difficult to recode to represent evolving water management infrastructure and operations. Here, we resort to data–driven analysis exploring statistical and state space perspectives to draw inferences relating marsh rainfall and water levels under evolving water management regimes.

Fundamental results include:

1. Data compilation at 33 stations
   - (a) Period of record 1990-01-01 - 2023-12-04 at 33 stations
   - (b) Period of record 1990-01-01 - 2024-09-15 at 10 stations
   - (c) Quality Assurance vetting
   - (d) Standard formatting with ISO date time
   - (e) Data archived in .csv and binary .RData
2. Statistical Analysis
   - (a) Rainfall
     - i. In relation to ISOP/IOP, COP yearly mean rainfall is 6-7 inches wetter at S12D and Taylor Slough, which is less than one standard deviation from the mean of yearly rainfall at these stations. Northern and central Shark River Slough including NP-205 exhibit no substantial difference in rainfall bewteen ISOP/IOP and COP
     - ii. In relation to IFT, COP yearly mean rainfall is more than 11 inches higher at NP-205 and TSB which is slightly greater than one standard deviation of 8-10 inches. S12D and northern and central Shark River Slough yearly rainfall are

similar to IFT conditions. Since IFT and COP periods are relatively short at roughly four years yearly means should be interpreted with caution.

(b) Yearly Maximum Stage

i. At all indicator stations yearly maximum water levels during COP are higher and statistically improbable under IOP and ERTP conditions.

(c) Trends in Mean Stage

i. Trends of mean water levels were generally declining during IOP with most stations exhibiting increasing trends post-IOP. NP-205 is an exception where a sharp increase is seen only during COP

ii. At all indicator stations except NP-205, mean stage of the trend during COP is statistically improbable under IOP and ERTP conditions.

3. Dynamic Analysis

(a) At all indicator stations except NP-205 state space predictions of water level conditioned on IOP finds IOP dynamical states are incapable of reproducing COP high water levels suggesting a new dynamical state

(b) The rate of change in stage from rain ($\partial S/\partial R$) is a stage–dependent function reflecting hydrogeological conditions. These functions appear to be invariant over water management plans

(c) A model predicting stage from previous rain and stage finds the component (fraction) of stage response attributed to rain has not changed from IFT to COP even though water levels are higher and rain increased.

From a purely data–driven perspective this work investigates stage:rain relationships yielding consistent results between a statistical and dynamic viewpoint. The dynamic analysis aligns with known hydrogeological conditions. Specific to rain as a driver of stage we find the stage:rain relationships ($\partial S/\partial R$) have not changed over the examined water management plans, nor have the distribution of the fraction of stage changes from rain. This indicates the stage:rain response over the examined periods are invariant and even though water levels and management infrastructure have changed, the underlying response of water levels to rain have not. This places us in a position to continue this work with evaluation of management actions as components of the integrated stage response to rain and water management.

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1 Introduction

Everglades. The word is unambiguous. A Google search in October 2024 returned 33 million results, and here we simply marvel at the Everglades as a world renowned natural resource inexorably intertwined with unintended consequences in the name of economic prosperity.

In South Florida hydrology rainfall is *the dominant*, highly dynamic, random forcing. Rainfall sustains the natural system while simultaneously motivating management actions to serve the needs of Floridians. Another management constraint is stipulated by a cornerstone of Everglades restoration: mitigation of post–drainage ecological impacts. The two objectives to protect natural and urban interests can be mutually exclusive imposing additional complexity on comprehensive management.

This document addresses a fundamental issue in Everglades restoration and management: Given the unique hydrologic, ecologic and anthropologic coexistence, can one quantify hydrologic responses attributable to natural forcing, primarily rainfall, as distinct from those of water management?

Several difficulties complicate this question, including:

- Random and nonlinear nature of rainfall
- Nonlinear relation between rainfall and water level
- Evolving water management infrastructure
- Changing water management plans
- Limited data (hydrological and operational)
- Feedback between management action and water level.

A comprehensive accounting of these aspects requires complex analysis. The Regional Simulation Model (RSM) is the preeminent tool designed specifically to predict water level stage and flow across the vast spatial domain of South Florida, however, evaluating management actions and alternatives with RSM is resource intensive requiring model tuning, scenario exploration and data analysis. Here, we adopt a data–driven perspective allowing observational data to reveal changes in water stage across different management regimes. We do this with a complementary statistical and dynamical approach.

Statistical analysis provides insight by fitting data to a frequency of occurrence distribution facilitating estimates of moments and quantiles culminating in a probabilistic assessment. This is effective in describing data and responses, but may not directly address causal drivers and mechanistic clarity. Dynamical analysis rooted in a state space does not rely on fits to distributions or presumptive dependence, for example the requirement of linearity for a correlation to be valid, rather, on state transitions with direct relevance to cause–and–effect understanding. We examine both perspectives over time frames specific to major water management operational plans as listed in table 1.

1.1 Incomplete History

The history of Everglades restoration is a rich and complex subject, one that is not reviewed here. For purposes of this analysis we broadly classify the timeline of major water management plans into five regimes from 1990 through 2024.

Plan	Date	References
Experimental Water Deliveries	1990-01-01 : 1999-12-31	NPS (1979); MacVicar (1985); USGAO (1995); NRC (2006)
Interim (Structural) Operating Plan (ISOP/IOP)	2000-01-01 : 2011-12-31	NPS (2005); USACE E (2006); USACE F (2006)
Everglades Restoration Transition Plan (ERTP)	2012-01-01 : 2015-12-31	USACE (2009, 2010, 2014, 2016); NRC (2021)
Incremental Field Tests (IFT)	2016-01-01 : 2020-08-31	
Combined Operational Plan (COP)	2020-09-01 : 2024	USACE (2020); NRC (2021); USACE (2023)

Table 1. Five water management regimes. Dates are approximate in terms of water management actions, but define periods of record for data analysis.

Everglades restoration embodied in the Comprehensive Everglades Restoration Plan (CERP) is a multidecadal, multiagency consortium encompassing Federal, State, Tribal, corporate and non-governmental organization (NGO) involvement. CERP relies on these partnerships as integral components of the comprehensive restoration. Here, we list a small subset of key water management projects.

Plan	Date	References
C-111 South Dade Project		USACE (2023 A)
Modified Water Deliveries	1992 - 2021	SFWMD (2015); USACE (2015 a)
L-31N Seepage Wall	2012 - 2016	SFWMD (2015a)
Decomp Physical Model	2013 - 2017	USACE (2017); SFWMD (2017)
Florida Bay Plan	2016 - 2019	SFWMD (2018)
Central Everglades Planning Project	2016 - 2024	SFWMD (2016); USACE (2023 B)
Tamiami Trail Next Steps	2009 - 2024	NPS (2010, 2022)

Table 2. A subset of key water management programs.

1.2 Outline

Section 2 details data collection, QA, and formatting to enable consistent analysis along with graphical depictions of the data. Additional data source details are presented in Appendices A and B.

Data analysis pursues a multilateral approach, with statistical analysis assessing the probabilistic viability of water levels under recent management in relation to historic management (section 3), and, a state space approach where dynamic states and their interrelations are probed (section 4).

Section 5 presents conclusions and section 6 a survey of follow–on topics.

2 Data

Data were obtained at 33 monitoring stations from the water conservation areas to the southern Everglades as shown in figure 1. The data inventory and archive are described in Appendix A. All data were downloaded from DBHydro with corresponding metadata listed in Appendix B. All data were aggregated into daily values (mean water level, sum rainfall and flow) by DBHydro.

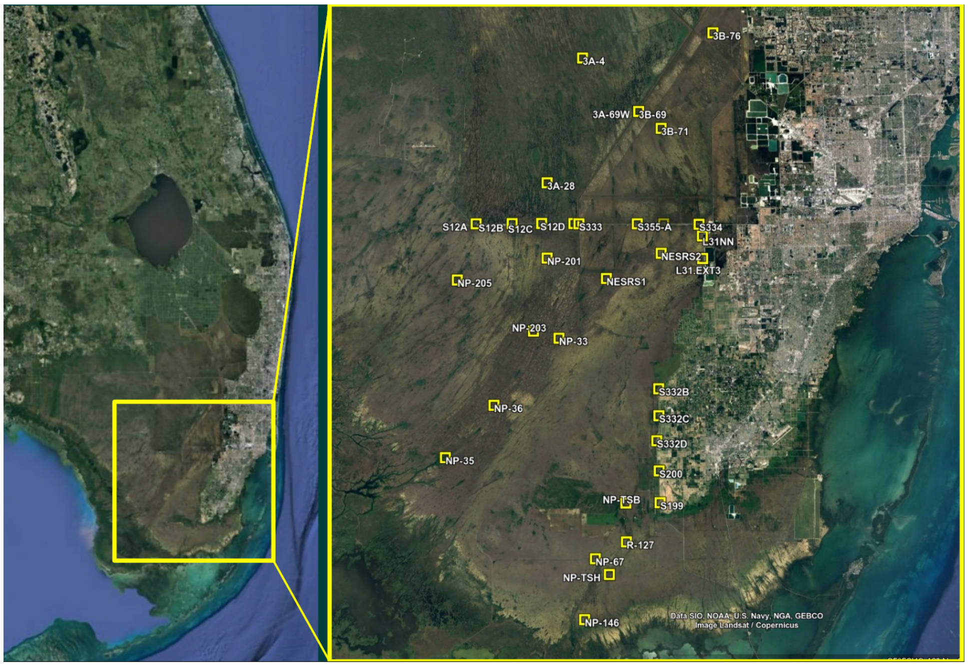

Figure 1. Satellite imagery with data station locations.

A schematic representation of the stations is shown in figure 2.

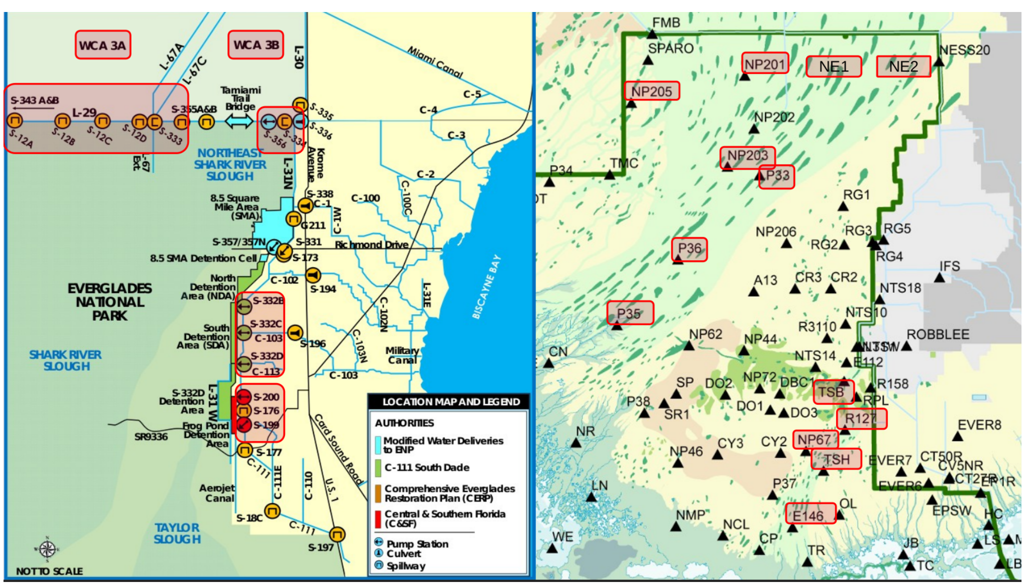

Figure 2. Schematic of data station locations. Data locations are highlighted with red shading.

2.1 Quality Assurance & Data Filling

All data were visually inspected to identify and remove invalid records. This visual process does not ensure all invalid data were identified and removed.

Missing water level (stage) data were estimated by

1. linear interpolation if the span of missing data was less than several days
2. linear regression to a highly correlated station for data longer than several days.

2.2 Rainfall

Daily rainfall data are presented in the region specific plots below. Aggregated data are shown in Appendix C.

2.3 Water Conservation Areas

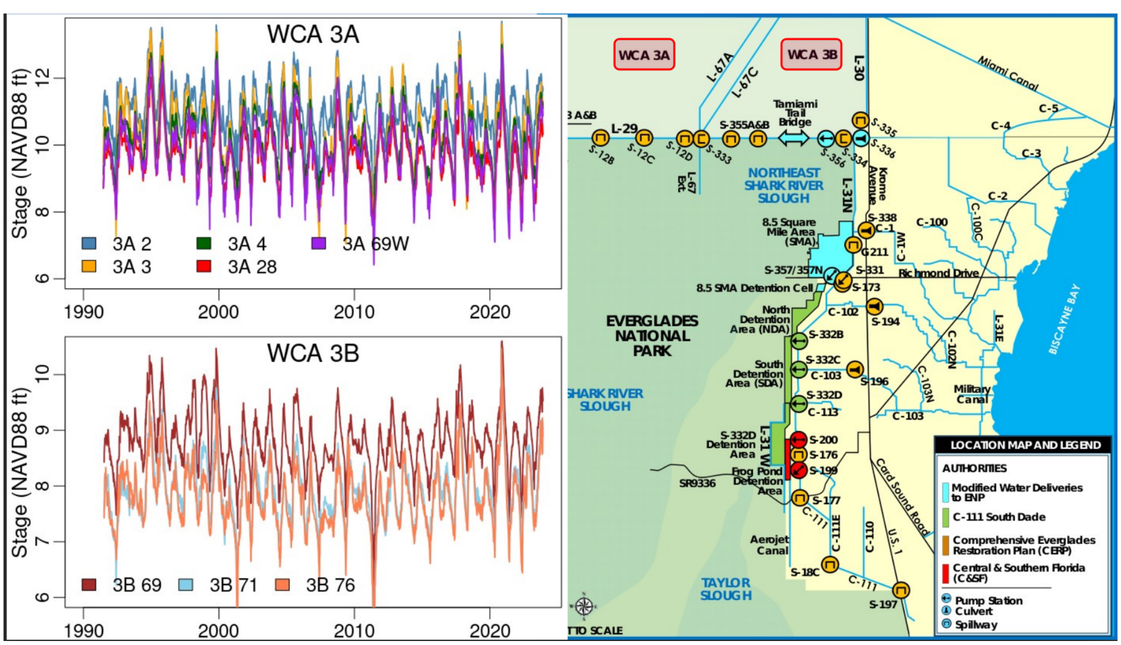

Figure 3. Data from WCA-3A and WCA-3B.

2.4 L-29, S-12

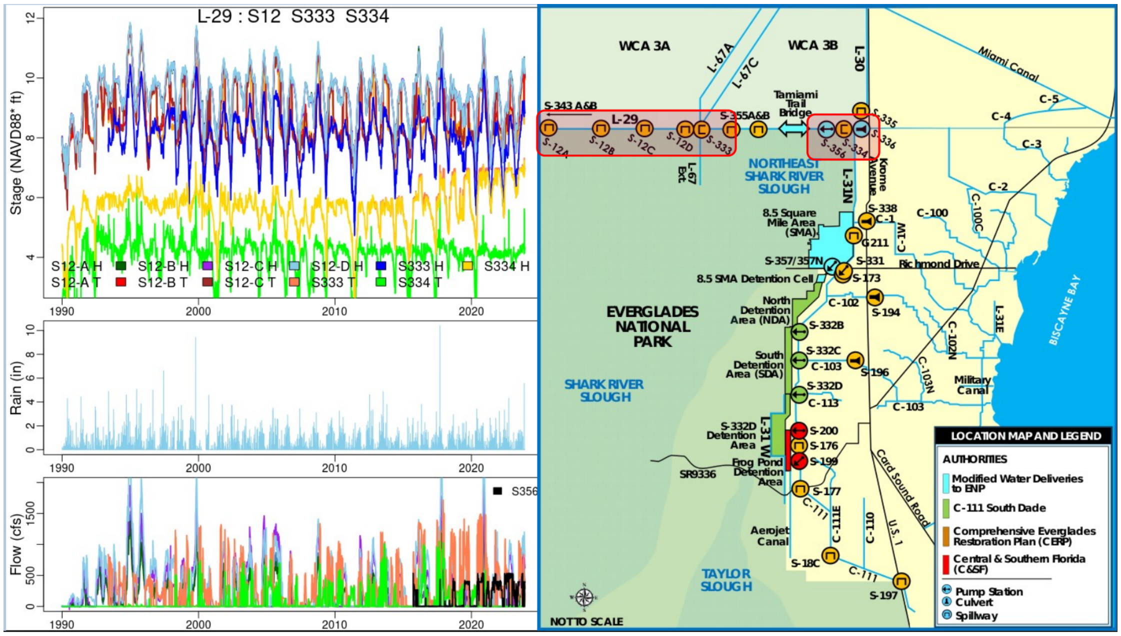

Figure 4. Data from L-29 and S-12.

2.5 Shark River Slough

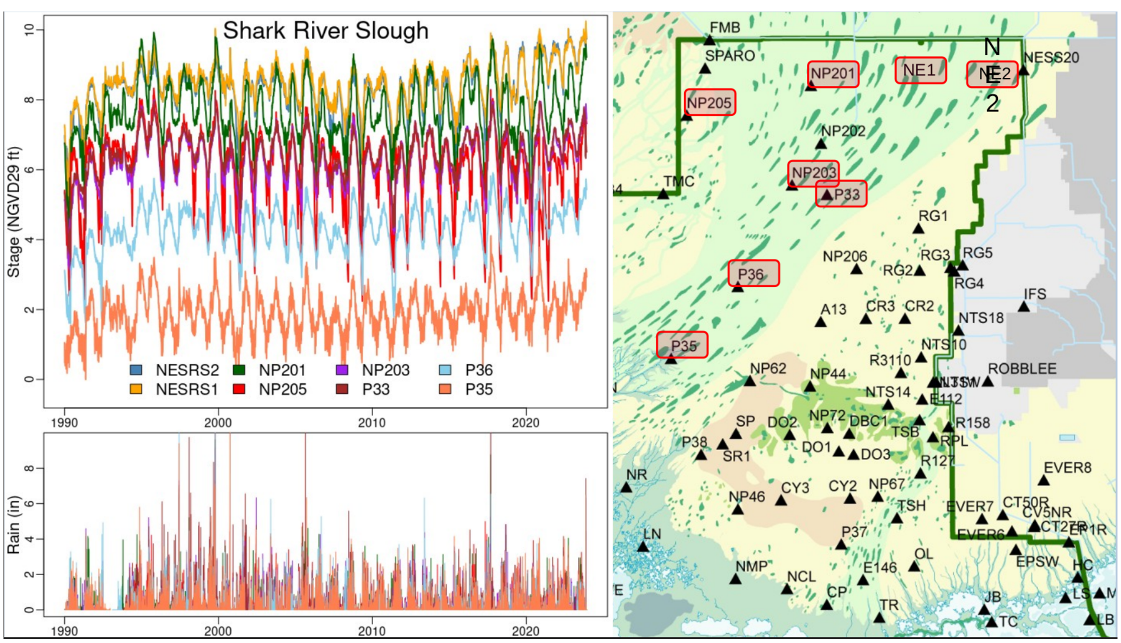

Figure 5. Data from Shark River Slough.

2.6 L-31 S-332

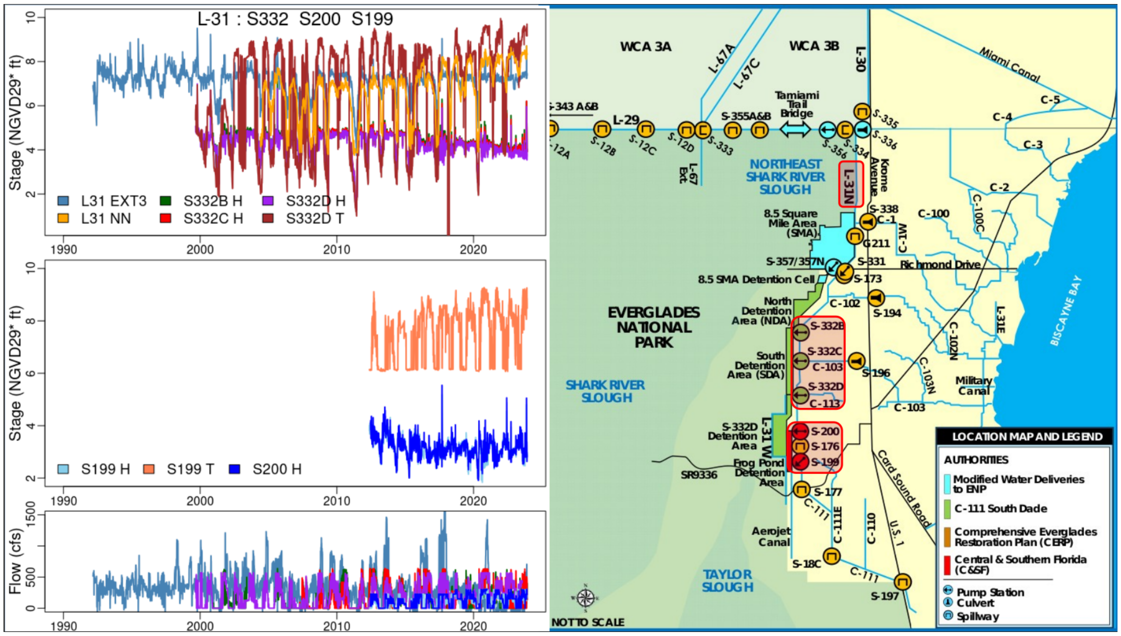

Figure 6. Data from L-31, S-332, S-199.

2.7 Taylor Slough

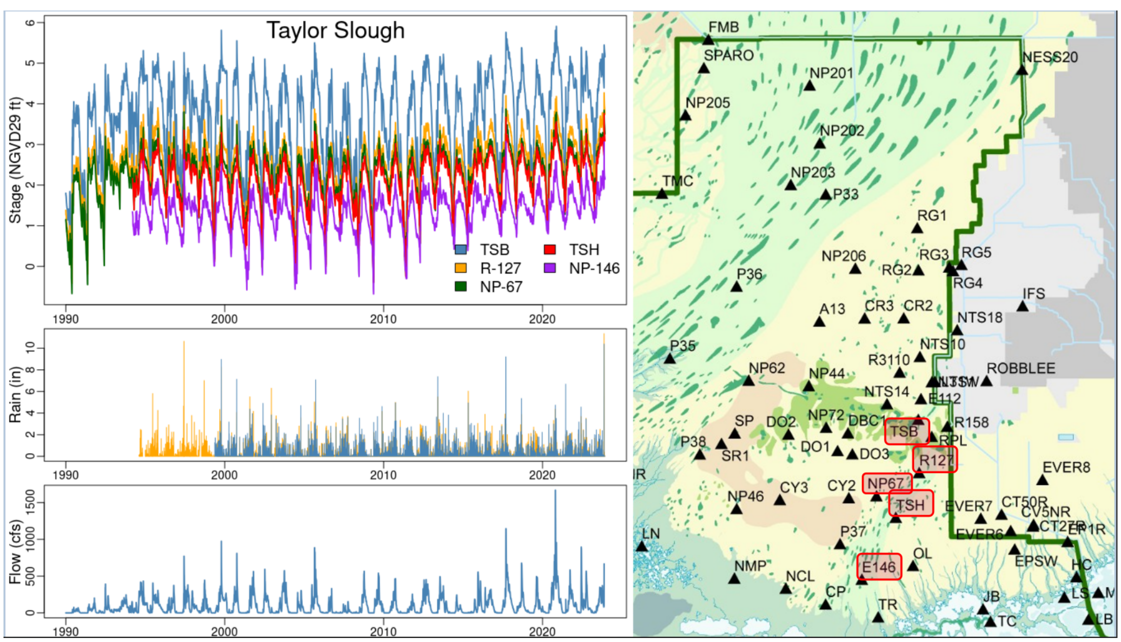

Figure 7. Data from Taylor Slough.

2.8 Indicators : Water Management Plans

To set the stage for statistical and dynamic analysis in the context of evolving water management plans, figure 8 plots key water level records in L-29, Shark River Slough, L-31 and Taylor Slough. These records are considered *indicators* of hydrological conditions. Stations P33 and G620 are not shown.

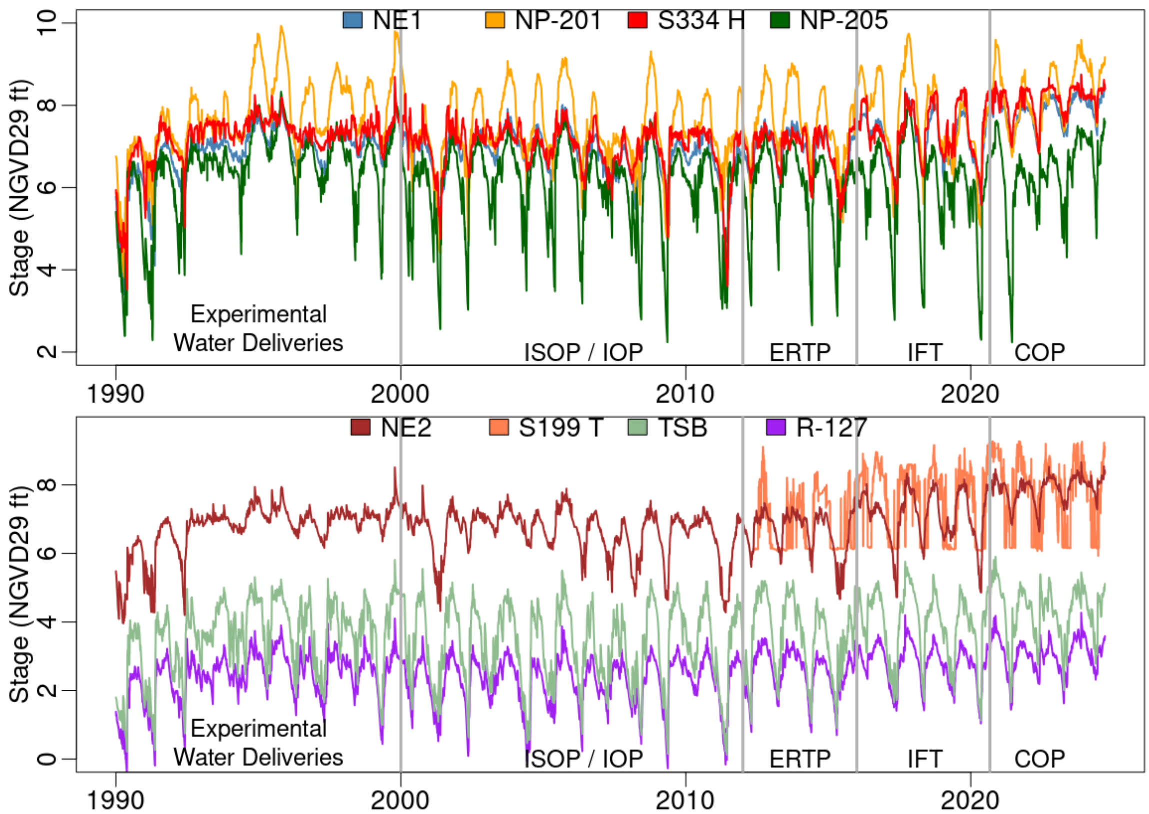

Figure 8. Key water level records examined in this report. ISOP: Interim Structural Operational Plan, IOP: Interim Operational Plan, ERTP: Everglades Restoration Transition Plan, IFT: Incremental Field Tests, COP: Combined Operational Plan. Stations P33 and G620 are not shown.

3 Statistical Analysis

3.1 Rainfall

A fundamental question of this analysis is to what extent can the impact of rainfall be separated from the effect of water management? Accordingly, it is important to know whether rainfall patterns have changed over the period of record in question. An in–depth analysis of rainfall from 1895 to 2019 finds significant natural variability, but no systematic trends (S. FL Cli. Chng. Compact , 2020). We therefore presume rainfall forcing can be considered stationary on long time scales.

3.1.1 Yearly Rainfall

While long term analysis finds no trends in rainfall the COP period analyzed is only 4 years. To assess rainfall differences table 3 lists mean yearly rainfall at the available rain stations suggesting the northern and central Everglades did not experience widely different rainfall averages between the IOP and COP regimes. S12D and Taylor Slough are found to have roughly an additional 6–7 inches of yearly rain during COP than IOP, however, one standard deviation of yearly rain at these stations ranges from 8 to 10 inches (Appendix C). Comparing conditions between IFT and COP, rain at NP-205 and TSB appear significantly higher during COP with approximately 12 and 14 additional inches of yearly rain during COP, the other stations not indicating a substantial difference.

Station	IOP	ERTP	IFT	COP	$\Delta R_{IOP:COP}$	$\Delta R_{IFT:COP}$
S-12D	48.6	52.2	54.0	55.9	7.3	1.9
NP-201	55.4	41.4	51.6	52.5	-2.9	0.9
NP-205	52.4	42.0	43.9	55.6	3.2	11.7
P33	56.9	47.6	54.8	55.6	-1.3	0.8
TSB	55.0	61.0	47.8	61.7	6.7	13.8
R-127	50.8	56.6	50.6	57.3	6.5	6.7

Table 3.

Mean of yearly rain during water management plan periods, and differences between IOP and COP, and IFT and COP.

3.2 S-12 Cumulative Flow

To examine relative flows through the S-12 structures over time figure 9 shows the cumulative value of daily flow at each structure. Horizontal segments indicate no change in flow over time corresponding to dry conditions, while positive slope indicates wet periods with increasing discharge. The slope over a period reflects the mean flow rate during that time. A notable aspect of this data is the increase in slope and cumulative flow of the S-12C and S-12D during the COP reflecting wet conditions and water management directing larger portions of S-12 flows through these two structures.

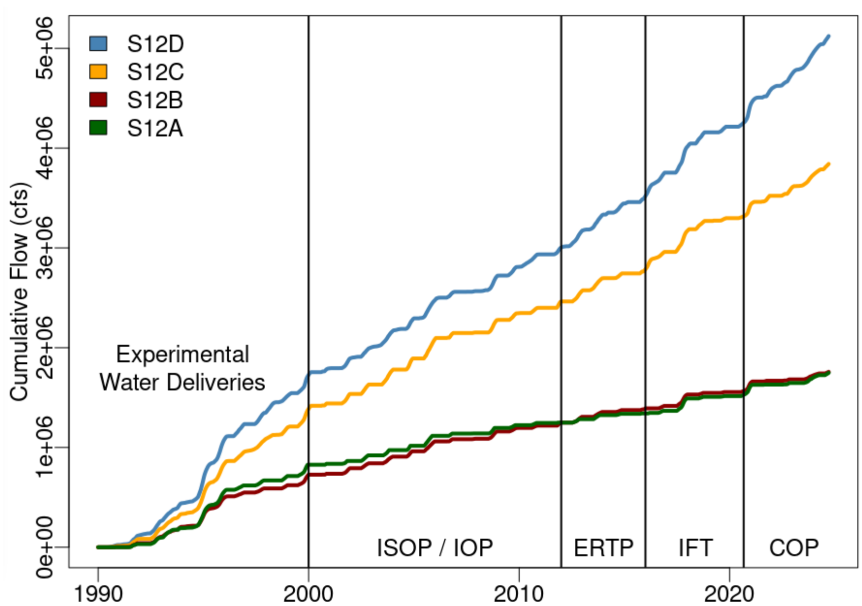

Figure 9. Cumulative flow through S-12. S12 flow data and double mass curves are presented in Appendix D.

3.3 Trends in Minimum and Maximum Stage

Here we ask the question: Has there been a significant change in the mean or trend of yearly water level maxima and minima at the indicator stations? Figure 10 overlays the observed water level data of figure 8 with linear fits to the maxima and minima over each water management regime. Sections with non–zero slope are shown only if the p–value is less than 0.05, otherwise the mean is shown. See table 9 in Appendix E.

General assessment of figure 10 suggests seasonal minima & maxima typically do not show evidence of significant trends within water management regimes. Instead, it appears incremental step changes in water level extrema are associated with varying water management plans and environmental conditions. Notable trends are evidenced in S334 headwater with a decline in maxima during ISOP/IOP, decline in minima during ERTP and increase in maxima over IFT. NESRS1 maxima follow the H334 Headwater decline over ISOP/IOP. In the eastern Everglades and Taylor Slough the only indication of a linear trend is a decline in NESRS2 maxima over ISOP/IOP.

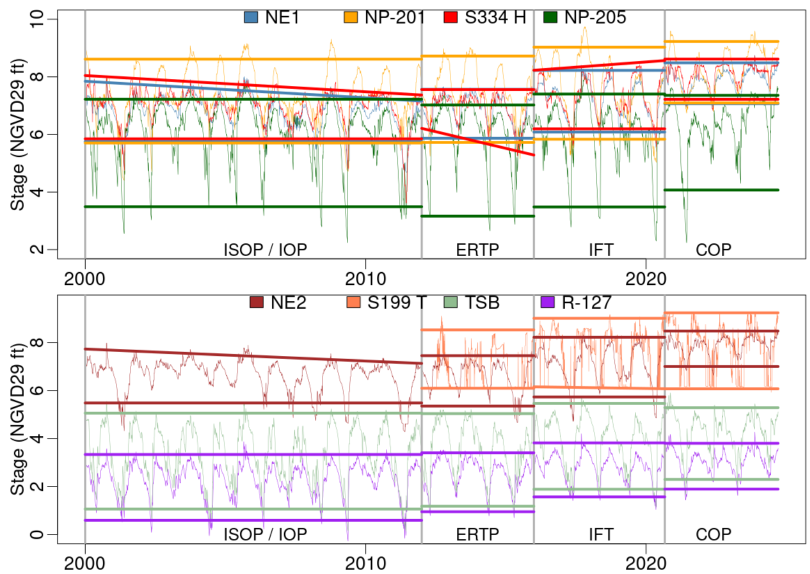

Figure 10. Linear trends of water level yearly minimum and maximum for each water management plan regime starting in 2000. ISOP/IOP: Interim (Structural) Operational Plan, ERTP: Everglades Restoration Transition Plan, IFT: Incremental Field Tests, COP: Combined Operational Plan.

3.3.1 Probability of COP Extremes

Having observed shifts in water level mean maxima and minima from IOP to COP, we ask the question whether the observed water levels are statistically distinct from precedent conditions. Specifically, with what probability would one observe COP extrema during ISOP/IOP + ERTP conditions? That is: $P(S_{IE} > \overline{S_{COP}})$ where S is stage, the subscript IE refers to the ISOP/IOP plus ERTP time period, $P(S_{IE})$ is the distribution of water levels during IE, and $\overline{S_{COP}}$ the mean value of extrema during COP. We estimate the probability that IE water levels exceed the mean COP water level extrema from the empirical distribution function $F(S_{IE})$ as $P(S_{IE_M} > \overline{S_{COP_M}}) = 1 - F(\overline{S_{COP_M}})$ where the subscript M represent water level maxima. The probability that IE water level minima are less than the mean COP water level minima are $P(S_{IE_m} < \overline{S_{COP_m}}) = F(\overline{S_{COP_m}})$ where the subscript m represent water level minima.

Values of $\overline{S_{COP_M}}$ and $\overline{S_{COP_M}}$ along with the probabilities of exceedence are listed in table 4 suggesting that mean water level maxima observed during COP are improbable during ISOP/IOP+ERTP conditions. We note these statistics do not incorporate factors such as rainfall differences.

Station	$\overline{S_{COP_m}}$	$P(S_{IOP_m} < \overline{S_{COP_m}})$	$\overline{S_{COP_M}}$	$P(S_{IOP_M} > \overline{S_{COP_M}})$
	min		Max	
NP-205	4.069	0.06211	7.357	0.02378
NP-201	7.094	0.31057	9.228	0.00034
NESRS1	7.067	0.63107	8.486	0.00000
NESRS2	7.003	0.67659	8.480	0.00000
S334_H	7.220	0.61481	8.617	0.00000
G620	6.285	0.41493	7.900	0.00421
P33	6.277	0.50770	7.716	0.00000
TSB	2.299	0.19216	5.287	0.00290
R-127	1.895	0.23186	3.803	0.00034

Table 4.

Probability that IOP+ERTP (IE) yearly water level minima S_{IOP_m} are below the mean COP yearly water level minima $\overline{S_{COP_m}}$. Probability that IOP+ERTP yearly water level maxima S_{IOP_M} are above the mean COP yearly water level maxima $\overline{S_{COP_M}}$.

3.4 Nonlinear Trends in Stage

To assess central trends in water levels across the management regimes we use empirical mode decomposition (EMD) (Huang and Wu , 2008) to compute intrinsic mode functions (IMF) of indicator records shown in figure 8. Only the lowest frequency IMFs are retained to estimate the nonlinear trends as shown in figure 11. Visual inspection suggests a general increase in water levels for post-IOP conditions at most stations, with a downward shift at NP-205 during ISOP/IOP, nearly constant levels during ERTP/IFT, followed by an increase during COP.

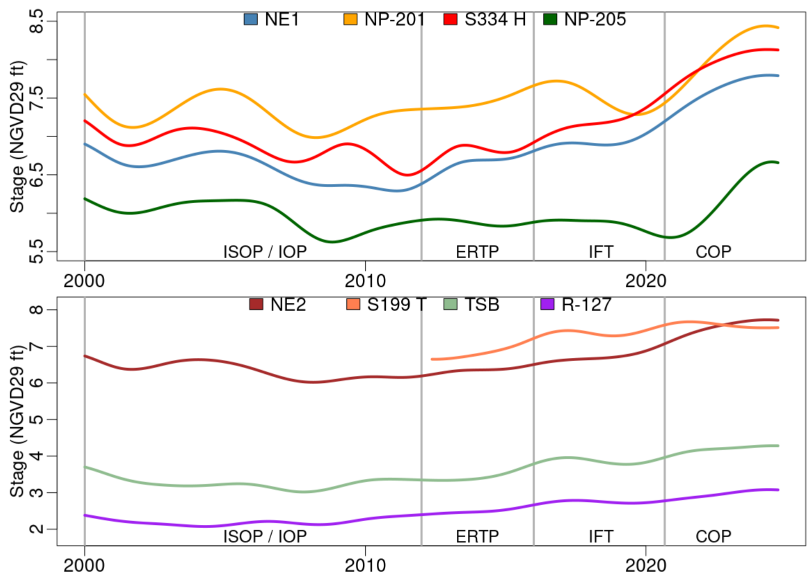

Figure 11. Nonlinear trends of water level at the indicators. Trends are found from the lowest frequency intrinsic mode functions (IMF). ISOP/IOP: Interim (Structural) Operational Plan, ERTP: Everglades Restoration Transition Plan, IFT: Incremental Field Tests, COP: Combined Operational Plan.

To quantify first order change in nonlinear trends, we fit linear regressions to each water management segment of the indicator trends, as shown in figure 12. Regressions are deemed significant if the p–value is less than 0.05. With the exception of NP-205 a picture emerges of a general decrease in water levels during ISOP/IOP followed by increasing water levels in the post ISOP/IOP regimes.

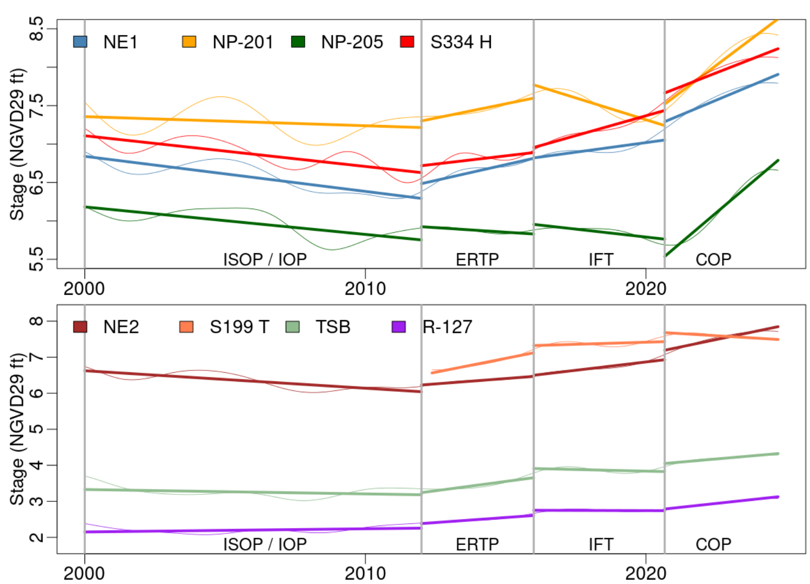

Figure 12. Linear fits to nonlinear trends of water level indicators. ISOP/IOP: Interim (Structural) Operational Plan, ERTP: Everglades Restoration Transition Plan, IFT: Incremental Field Tests, COP: Combined Operational Plan.

To assess statistical plausibility of COP linearized trend mean water levels in relation to IOP+ERTP values, we estimate the probability with which one would observe the mean water level of the COP trend during IOP+ERTP conditions: $P(T_{IE} > \overline{T_{COP}})$ where $P(T_{IE})$ is the distribution of water level trend during IOP+ERTP, $\overline{T_{IE}}$ and $\overline{T_{COP}}$ mean values of water level trends during COP. Results are listed in table 5 suggesting that with the exception of NP-205, mean water levels during COP are statistically improbable under IOP conditions.

Station	$\overline{T_{IE}}$	$\overline{T_{COP}}$	$P(T_{IOP} > \overline{T_{COP}})$
NE1	6.587	7.599	0.00000
NP-201	7.327	8.074	0.00000
NP-205	5.945	6.163	0.08059
G620	6.293	6.918	0.00000
P33	6.283	6.920	0.00000
NE2	6.336	7.520	0.00000
TSB	3.302	4.187	0.00000
R-127	2.275	2.956	0.00000

Table 5.

Probability that IOP+ERTP water level trend values, T_{IE}, exceed the COP yearly water level trend mean value, $\overline{T_{COP}}$.

4 Dynamic Analysis

4.1 COP Predictions from IOP / COP States

Empirical dynamic modeling projects system dynamics in a state space, specifically, a *library* of state space vectors (Chang et al., 2017). A powerful technique to isolate dynamics is *conditional embedding* where library vectors are selected based on specified conditions. A change in projected output reflects a change in the underlying library.

Here, we predict stage during the latter COP period conditioned on an IOP library, and, a non–overlapping COP library. If there are differences in the COP predicted stage values when using the IOP library *vs.* the COP library, it indicates a change in state conditions between the libraries.

We select libraries of equal length and use out–of–sample forecasting to prevent bias in the results. The IOP library extends from 2003-04-01 through 2005-09-15, the COP library from 2020-04-01 to 2022-09-15. Predictions are made over the period 2022-04-01 through 2024-09-15. The data corresponding to the IOP and COP libraries, and the COP prediction time span are shown in figure 13. EDM parameters are described in Appendix F.

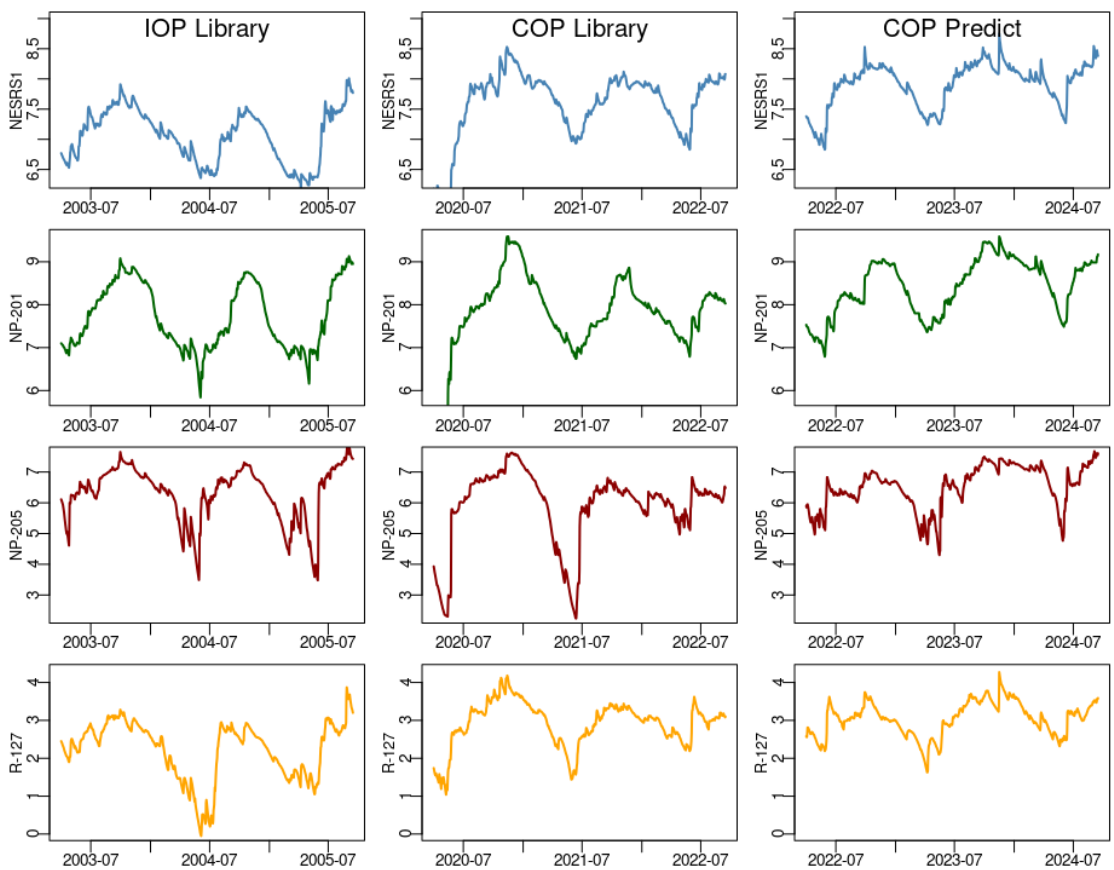

Figure 13. Data used to create IOP libraries (2003-04-01 - 2005-09-15) and COP libraries (2020-04-01 - 2022-09-15) for simplex prediction of stage at NESRS1, NP-201, NP-205, R-127 over the out–of–sample period 2022-04-01 - 2024-09-15. Left column shows data for IOP libraries, middle column data for COP libraries, and right column data to be predicted.

Figure 14 shows simplex prediction (Sugihara and May , 1990) of COP water levels from the IOP and COP libraries. At all stations we find water year 2022 and 2023 are accurately predicted from the COP library, however, the IOP library is unable to predict high water levels at NESRS1, NP-201 and R-127. Since IOP and COP mean yearly rainfall is not widely different at NESRS1 and NP-201 we infer COP water levels at these stations represent a new dynamical state as a result of COP water management. This is consistent with the statistical analysis suggesting it is improbable these stations would observe COP water levels under IOP conditions. However, the dynamic analysis is based on observed states rather than probabilistic estimates.

At NP-205 we find the COP and IOP libraries perform equally well over the prediction set and note this is consistent with the statistical interpretation that COP NP-205 water levels are unremarkable from the perspective of an IOP distribution.

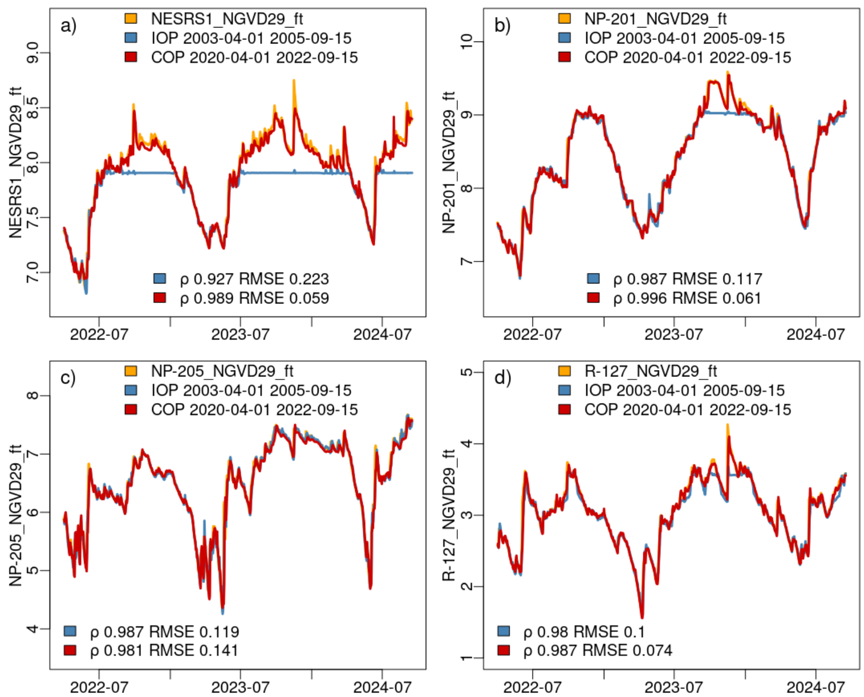

Figure 14.

Comparison of out–of–sample simplex stage predictions during COP from state space libraries of equal length observed during IOP and COP.

4.2 Rainfall as a Driver of Stage

To unravel complex, nonlinear dependencies between variables, sequential locally weighted global linear maps (S-map) estimates derivatives between variables (Sugihara , 1994; Deyle et al, , 2016). Notably the derivatives are dynamic varying in time and state such that complex interactions can be represented. To assess rainfall influence on stage we use a 4–dimensional model (state space) where each state consists of the four variables [stage(t), stage(t-1), rain(t), rain(t-1)]. From this state space we use S-map to predict stage(t+1) and inspect the resulting S-map coefficients $\partial S/\partial R$ where S is stage and R is rain.

For comparison to dynamics predicted solely on stage without explicit rainfall, we compute S-map predictions of stage based on the state space [stage(t), stage(t-1)]. Here, we assess singular values λ of S-map coefficients relating stage(t) to previous stage(t-1). Figures 15 and 16 show data and results from NP-205 and NP-201.

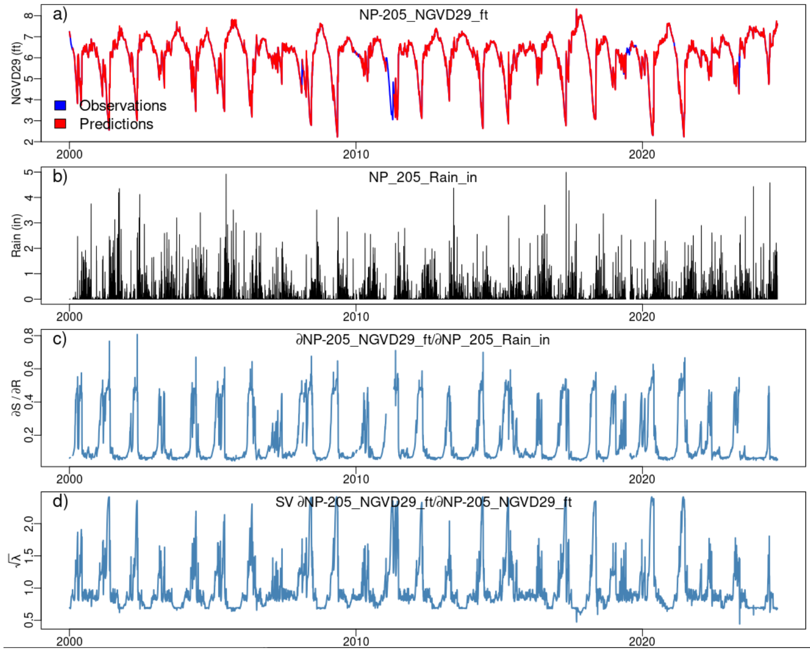

Figure 15. a) S-map prediction of NP-205 stage. b) NP-205 rainfall. c) S-map coefficient $\partial S/\partial R$ where S is NP-205 stage and R is NP-205 rain. d) S-map singular value of $\partial S/\partial S_{t-1}$ where S is NP-205 stage and S_{t-1} is NP-205 previous stage.

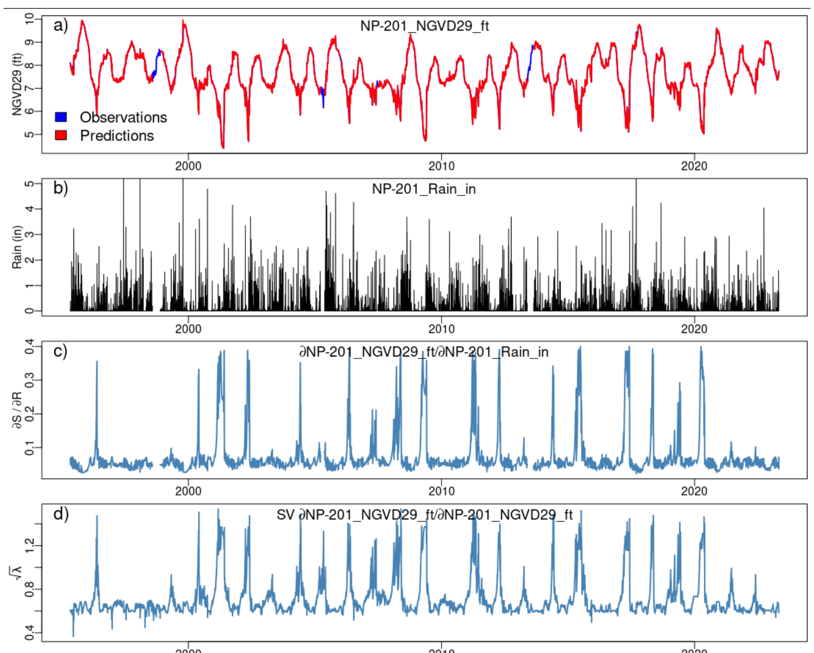

Figure 16. a) S-map prediction of NP-201 stage. b) NP-201 rainfall. c) S-map coefficient $\partial S/\partial R$ where S is NP-201 stage and R is NP-201 rain. d) S-map singular value of $\partial S/\partial S_{t-1}$ where S is NP-201 stage and S_{t-1} is NP-201 previous stage.

Several relationships emerge between stage and rain in figures 15 and 16. First, we note the relationship between change in stage and change in rainfall $\partial S/\partial R$ is larger when stage is low. That is, when stage is low (subterranean) the influence of rainfall is greater in producing changes in stage, an inverse relationship.

Second, we observe a close correspondence between $\partial S/\partial R$ and the singular value $\sqrt{\lambda}$ of $\partial S/\partial S_{t-1}$. Note that $\partial S/\partial R$ is informed from a multivariate model including stage and rain, while $\sqrt{\lambda}$ and $\partial S/\partial S_{t-1}$ are found solely from stage observations. From this we infer that changes in stage as reflected in the singular values of $\partial S/\partial S_{t-1}$ are surrogates for change in stage driven by rainfall $\partial S/\partial R$. That is, without knowledge of physics or mass-balance we infer rainfall is an important and dominant driver of stage at these indicators, and further, have obtained quantitative representations of the time–dependent, nonlinear relationship between stage and rain.

4.2.1 Rainfall Stage Dependence

Since we observe stage–dependence on $\partial S/\partial R$ we seek to isolate the stage–dependence with a 2-D model of [stage(t), rain(t)] predicting stage(t+1) over the period 2000-01-01 through 2024-09-15. Figure 17 plots $\partial S/\partial R$ from this model as a function of stage at eight stations revealing the nonlinear relation of rainfall driven change in stage as a function of stage. As one might expect, when water levels exceed land surface elevation the change in stage is relatively small and decreasing. At water levels below land surface we find nonlinear relations reflecting local hydrogeological features. For example, subterranean NP-205 response is greater than other stations consistent with lower hydraulic transmissivity of Lake Flirt Marl in this region. Stations farther east express lower subterranean rainfall response reflective of the more transmissive Biscayne Aquifer and Miami Oolite surface layer.

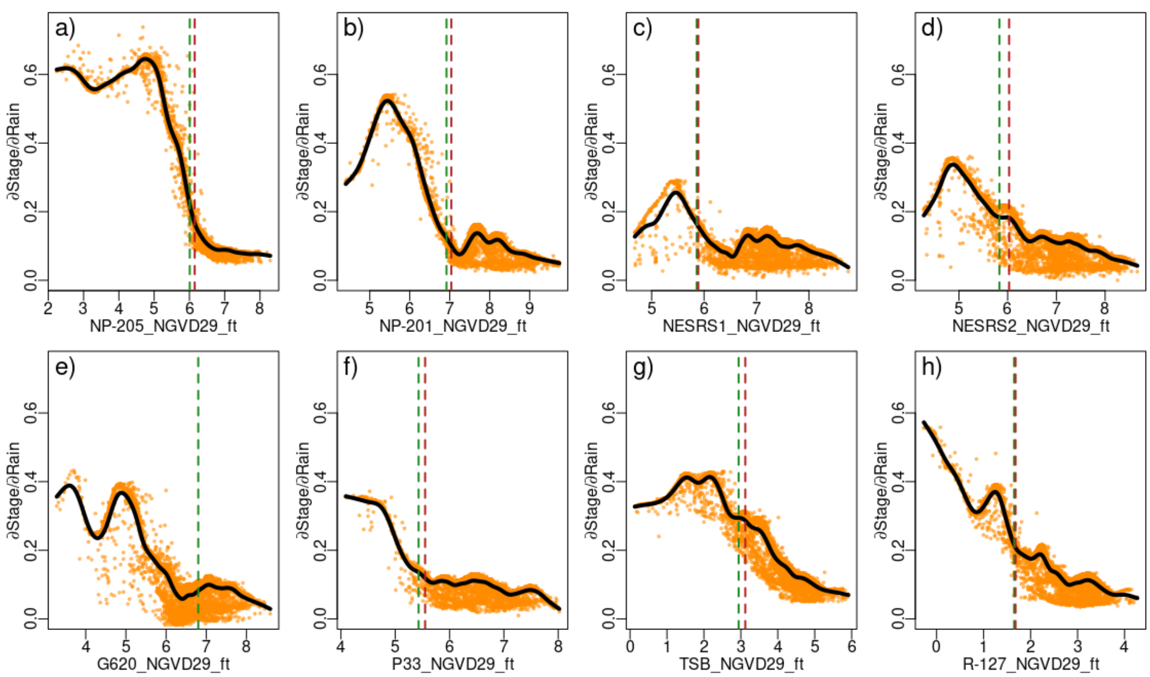

Figure 17. S-map coefficients $\frac{\partial S}{\partial R}$ as a function of stage at eight stations over 2000-2024. Vertical dashed lines indicate average (green) and maximum (red) land surface elevation associated with dominant vegetation. Solid line is cubic spline fit.

We also assessed whether there is a change in response of $\partial S/\partial R$ as a function of stage with COP implementation. Comparison of stage–dependent $\partial S/\partial R$ curves from 2000-01-01 through 2020-8-31 found no significant differences in relation to the period including COP indicating the response has not changed under COP conditions.

4.2.2 IFT/COP Rainfall Response

We now seek to apply these stage/rain relationships to assess the relative influence of rain on marsh stage response. The 2-D model of [stage(t), rain(t)] predicting stage(t+1) is:

$$S(t+1) = C_0 + \frac{\partial S_{t+1}}{\partial R} R(t) + \frac{\partial S_{t+1}}{\partial S} S(t) \quad (1)$$

where we use the subscript $_{t+1}$ to explicitly denote the time advance.

Since the terms in equation 1 sum to the total stage the second term $\frac{\partial S_{t+1}}{\partial R} R(t)$ represents the contribution of rain to the change in stage. If the fraction of rain–driven stage response between two water management regimes remains constant, one can infer the hydrological response of stage to rain has not significantly changed from one management regime to another even though water levels and management differ. Figure 18 shows histograms of the fraction of rain–driven stage response over IFT and COP at eight indicator stations revealing similar distributions between IFT and COP. This suggests that even though water levels and rainfall are higher during COP, and there have been changes in water management infrastructure and operations, the mechanism and relations by which stage responds to rain have not changed establishing a baseline for exploration of the relative response of stage to rain and water management.

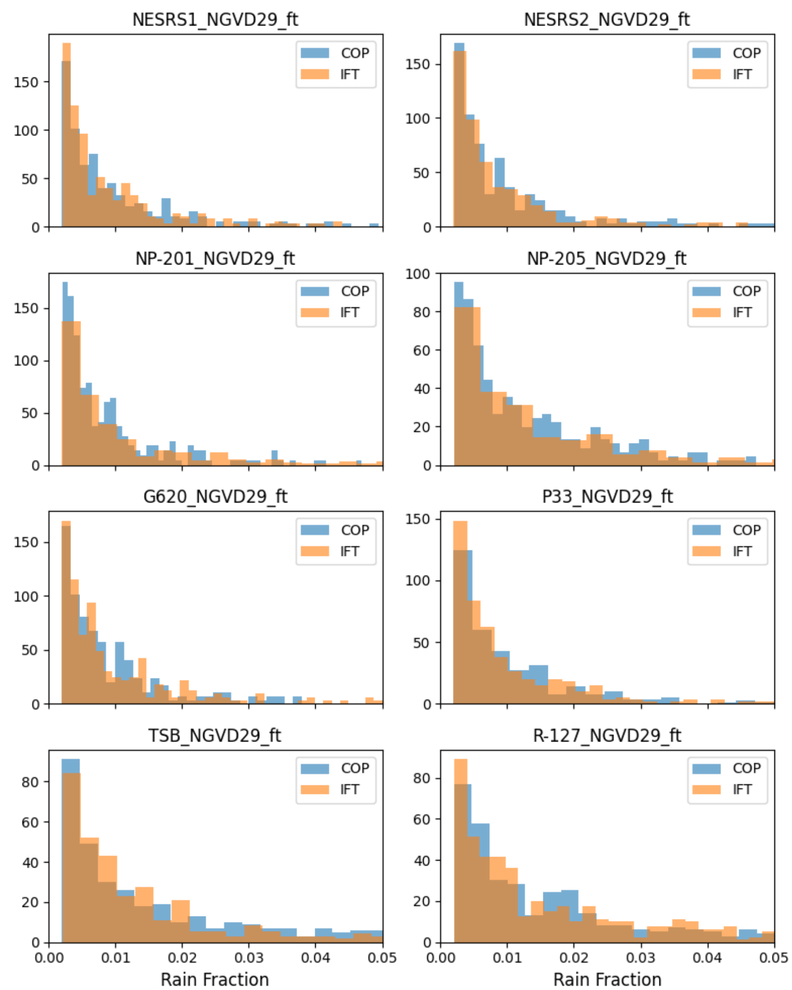

Figure 18. Histograms of fraction of stage change contributed by rain during IFT and COP.

4.3 Summary of dynamic response

Consistent with the statistical viewpoint, conditioning COP stage predictions on IOP finds COP high water levels cannot be produced from IOP conditions, with exception of NP-205. Thus we find support for the notion that COP high water levels represent a new state in relation to IOP conditions.

Although we know rain can increase stage, from an agnostic perspective S-map coefficients of models with and without rain find:

1. When stage is low (subterranean) rainfall produces larger changes in stage

2. Changes in stage reflected in singular values of $\partial S/\partial S_{t-1}$ without explicit rain, are surrogates for change in stage driven by rainfall $\partial S/\partial R$ from which one infers rain is a driver of changes in stage and values of $\partial S/\partial R$ quantifying this relationship are meaningful

3. The rate at which stage changes from rain $\partial S/\partial R$ is a stage–dependent function consistent with item 1. The stage dependence reflects local hydrogeological conditions

4. Stage–dependence of $\partial S/\partial R$ has not changed since 2000

5. The component (fraction) of stage response attributed to rain has not changed from IFT to COP even though water levels and rainfall have increased, and management infrastructure and operations have changed.

Having established fundamental aspects of stage:rain relationships, we are now in a position to add management–dependent variables toward assessing the relative contribution of rain and management to water level dynamics in the Everglades.

5 Conclusion

In partnership with the NPS SFNRC, this work investigates whether data–driven analysis can identify *independent* components of marsh water level response to rainfall and management actions. As the relationship between rainfall and stage is complex and nonlinear, statistical independence is not expected, rather we seek attribution of functional independence. We therefore pursue a multilateral approach using statistics to classify operational regimes avoiding the use of correlation (requiring statistical independence), in conjunction with a state space approach identifying dynamical states of marsh stage response and rainfall under different water management regimes.

Statistical analysis finds yearly maximum water levels during COP are higher and statistically improbable under IOP and ERTP conditions at all indicator stations. State space analysis provides a complimentary and supportive perspective finding IOP conditions are incapable of producing higher water levels observed during COP with exception of NP-205. This may indicate water levels during COP have entered a new state.

Trends of water levels, both linear and nonlinear, exhibit generally declining water levels during IOP with increasing water level trends post-IOP, except at NP-205 where COP conditions produce a sharp increase in water levels. At all stations except NP-205 the mean water level of the trend during COP is statistically implausible under IOP conditions.

A dynamic model of rainfall and stage quantify station specific nonlinear relationships characterizing stage response to rainfall reflecting hydrogeological conditions related to stage–storage relationships. These relationships do not appear to have changed over water management plans. The distribution of the fraction of total stage from the rain–driven component appears to be similar between IFT and COP suggesting that even though rainfall and water management have changed, the underlying response of water levels to rainfall remain constant. Based on these relationships the dynamic model can be expanded to include water management terms to assess relative contributions of rain and management to water level response. Looking forward, section 6 outlines additional ideas to further clarify the rainfall, stage, management interdependence.

6 Future Investigation

The present analysis culminated in a two component dynamic model with rain and stage terms. This model suggests rainfall response is invariant and quantified nonlinear stage:rain responses. The next step is to add a management term to quantify the percent contribution of rainfall and management as independent functional drivers of stage.

The current analysis focuses on northern Shark River Slough, L–29, central Taylor Slough and L–31. Expansion of the analysis to other sites may help clarify regional responses to management regimes.

It may be possible to examine a causal chain from the WCA, through L-29, to the northern ENP, thereby establishing an empirical representation of management actions in L-29 defining a nonlinear transfer function. This may shed light on past and potential future management actions informed by observational dynamics of the system.

Sea level rise is a known driver of marsh water levels around the coastal periphery of ENP Park et al. (2017, 2019). Investigation of sea level rise as a confounding factor of water management driven stage increases can be investigated.

Finally, scenario–based projections might be useful to quantify conjunctive stage and management responses to rainfall. Different rainfall scenarios could be used to create state spaces from which stage response is projected.

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Appendix A Data Archive

Data archive is located at https://doi.org/10.5281/zenodo.14047925.

A.1 Data Functions

R functions are contained in the files `ConvertData.R`, `PlotData.R`, `ProcessData.R`.

1. `ConvertData.R` : Format data. Fill / interpolate missing stage data.
   (a) Convert DBHydro date format to ISO, save _.csv .RData
   (b) QA, interpolate TS missing stage data
   (c) QA, interpolate SRS missing stage data
   (d) QA, interpolate S12 missing stage data
   (e) QA, interpolate WCA3A missing stage data
   (f) QA, interpolate WCA3B missing stage data
   (g) QA, interpolate L-29 missing stage data
   (h) QA, interpolate L-31 missing stage data
   (i) Collate WCA3, S12, L-29, SRS into one .RData/.csv
   (j) Collate TaylorSlough, L-31 into one .RData/.csv
   (k) Aggregate rainfall
2. `PlotData.R` : Plot figures from data
3. `ProcessData.R` : Percent flow of S12 structures

A.2 Analysis Data Files

ASCII .csv	Binary .RData	Notes
Indicators_1990-01-01_2024-09-15.csv		L-29, NE EVER, Taylor Slough
SRS_1990-01-01_2023-12-04.csv	SRS_1990-01-01_2023-12-04.RData	L-29, Shark River Slough
TS_1990-01-01_2023-12-04.csv	TS_1990-01-01_2023-12-04.RData	L-31, Taylor Slough
AggregateRain_Monthly.csv	AggregateRain_Monthly.RData	Monthly rain
AggregateRain_Yearly.csv	AggregateRain_Yearly.RData	Yearly rain

Table 6. Processed data files used in analysis.

A.3 Interim Data Files

ASCII .csv	Binary .RData	Notes
AggregateRain_Monthly.csv	AggregateRain_Monthly.RData	From daily data
AggregateRain_Yearly.csv	AggregateRain_Yearly.RData	
SharkSlough_1990-01-01_2023-12-04_fill.csv	SharkSlough_1990-01-01_2023-12-04_fill.RData	Shark River Slough
TaylorSlough_1990-01-01_2023-12-04_fill.csv	TaylorSlough_1990-01-01_2023-12-04_fill.RData	Taylor Slough
S12_1990-01-01_2023-12-04_fill.csv	S12_1990-01-01_2023-12-04_fill.RData	S-12
L-31_1990-01-01_2023-12-04_fill.csv	L-31_1990-01-01_2023-12-04_fill.RData	L-31
L-29_1990-01-01_2023-12-04_fill.csv	L-29_1990-01-01_2023-12-04_fill.RData	L-29
WCA3_1990-01-01_2023-12-04_fill.csv	WCA3_1990-01-01_2023-12-04_fill.RData	WCA 3

Table 7. Intermediate data files with QA and data filling.

A.4 DBHydro Data Files

File	Notes
SiteCoordinates.csv	Geodetic coordinates
DBHydro_SRS_1.csv	NESRS1 NESRS2 NP-201 NP-205
DBHydro_SRS_2.csv	NP-P36 NP-203 NP-P33 NP-P36 NP-203 NP-P35
DBHydro_TS_1.csv	NP-TSH R-127 NP-P67 NP-TSB
DBHydro_TS_2.csv	NP-146
DBHydro_S12.csv	S12A_H S12A_T S12A_S S12B_H S12B_T S12B_S S12C_H S12C_T S12C_S S12D_H S12D_S S12D_R
DBHydro_WCA-3B.csv	3-76 3-69 3-71
DBHydro_WCA-3A.csv	3-63 3-62 3-64 3-65
DBHydro_L31.EXT3.csv	L31.EXT3 L31NN
DBHydro_S199.csv	S199_H S199_P S199_T
DBHydro_S355.csv	S355B_P S355A_S S355B_S
DBHydro_S200.csv	S200_H S200_P
DBHydro_S332.csv	S332B_H S332C_H S332D_H S332D_T S332B_P S332C_P S332D_P S332B_P
DBHydro_S333.csv	S333_S S333_T S333_H
DBHydro_S334.csv	S334_T S334_S S334_H
DBHydro_S356.csv	S356_P

Table 8. Downloaded DBHydro data files.

Appendix B DBHydro Data Tables

Following pages list the DBHydro data keys, fields, and record metadata.

Taylor Slough

Station: NP-TSB/R-127/NP-P67/NP-TSH
Station: NP-146

Station	Site	Type	Latitude (ddmmss.sss)	Longitude (ddmmss.sss)	X Coord (ft)	Y Coord (ft)	County	Basin	Sec	Twp	Rng	Show Map	Description
NP-P67	NP-67	WELL	251951.888	803903.096	771485.404	362730.078	Miami-Dade	TAYLOR SLOUGH	32	58	37	Map	Everglades National Park NP67
NP-TSB	NP-TSB	WETLAND	252410.512	803626.352	785789.702	388878.735	Miami-Dade	TAYLOR SLOUGH	10	58	37	Map	Everglades National Park TAYLOR SLOUGH BRIDGE
NP-TSH	NP-TSH	WETLAND	251838.628	803751.6	778065.39	355351.922	Miami-Dade	TAYLOR SLOUGH	9	59	37	Map	Everglades National Park TAYLOR SLOUGH HILTON
R-127	R-127	WELL	252110.116	803623.58	786097.477	370667.968	Miami-Dade	TAYLOR SLOUGH	27	58	37	Map	Everglades National Park R127

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
G6164	NP-P67	NP-67	NP-67	STG	DA	MEAN	????	ENP	20-JUN-1962	04-DEC-2023	DAD	251951.888	803903.096	771485.404	362730.078	TAYSLOU		32	58	37
H3153	NP-TSB	NP-TSB	NP-TSB	FLOW	DA	MEAN	????	ENP	08-SEP-1960	16-NOV-2023	DAD	252410.512	803626.352	785789.702	388878.735	TAYSLOU	OPCH	10	58	37
SA605	NP-TSB	NP-TSB	NP-TSB	RAIN	DA	SUM	????	ENP	19-MAY-1999	04-DEC-2023	DAD	252410.512	803626.352	785789.702	388878.735	TAYSLOU		10	58	37
H2442	NP-TSB	NP-TSB	NP-TSB	STG	DA	MEAN	????	ENP	16-AUG-1960	04-DEC-2023	DAD	252410.512	803626.352	785789.702	388878.735	TAYSLOU		10	58	37
07090	NP-TSH	TAYLORS2	NP-TSH	STG	DA	MEAN	????	ENP	12-MAR-1994	04-DEC-2023	DAD	251838.628	803751.6	778065.39	355351.922	TAYSLOU		9	59	37
H1969	R-127	NP-127	R-127	RAIN	DA	SUM	????	ENP	10-AUG-1994	04-DEC-2023	DAD	252110.116	803623.58	786097.477	370667.968	TAYSLOU		27	58	37
07099	R-127	R-127	R-127	WELL	DA	MEAN	????	ENP	11-APR-1984	04-DEC-2023	DAD	252110.116	803623.58	786097.477	370667.968	TAYSLOU		27	58	37

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
H2428	NP-146	NP-146	NP-146	STG	DA	MEAN	????	ENP	24-MAR-1994	04-DEC-2023	DAD	251509.072	803958.536	766469.952	334166.443	TAYSLOU		31	59	37

Shark River Slough

Station: NESRS2/NESRS1/NP-201/NP-205
Station: NP-203/NP-P33/NP-P35/NP-P36

Station	Site	Type	Latitude (ddmmss.sss)	Longitude (ddmmss.sss)	X Coord (ft)	Y Coord (ft)	County	Basin	Sec	Twp	Rng	Show Map	Description
NESRS1	NESRS1	RIVER/STREAM	254129.94	803805.7	776391.739	493788.446	Miami-Dade	EVERGLADES NATIONAL PARK	4	54	31	Map	NORTHEAST SHARK RIVER SLOUGH NO. 1 NR COOPERTOWN, FL
NESRS2	NESRS2	RIVER/STREAM	254326.368	803324.206	802100.227	505620.512	Miami-Dade	EVERGLADES NATIONAL PARK	20	54	38	Map	NORTHEAST SHARK RIVER SLOUGH NO. 2 NR COOPERTOWN, FL
NP-201	NP-201	WETLAND	254304.516	804310.711	748470.84	503268.36	Miami-Dade	EVERGLADES NATIONAL PARK	34	54	36	Map	EVERGLADES 201 NEAR MIAMI, FL
NP-205	NP-205	RIVER/STREAM	254122.992	805053.016	706203.208	492949.711	Miami-Dade	EVERGLADES NATIONAL PARK	5	55	35	Map	EVERGLADES 205-NP NEAR MIAMI, FL

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
01140	NESRS1	NESRS1	NESRS1	GAGHT	DA	MEAN	????	USGS	23-JUL-1976	04-DEC-2023	0		DAD	254129.94	803805.7	776391.739	493788.446	ENP		4	54	31
01218	NESRS2	NESRS2	NESRS2	GAGHT	DA	MEAN	????	USGS	26-JUL-1976	04-DEC-2023	0		DAD	254326.368	803324.206	802100.227	505620.512	ENP		20	54	38
06044	NP-201	NP-201	NP-201	RAIN	DA	SUM	????	ENP	01-OCT-1983	04-DEC-2023	0		DAD	254304.516	804310.711	748470.84	503268.36	ENP		34	54	36
06719	NP-201	NP-201	NP-201	STG	DA	MEAN	????	ENP	09-JUN-1974	04-DEC-2023	0		DAD	254304.516	804310.711	748470.84	503268.36	ENP		34	54	36
G6147	NP-205	NP-205	NP-205	RAIN	DA	SUM	????	ENP	08-JUN-1993	04-DEC-2023	0		DAD	254122.992	805053.016	706203.208	492949.711	ENP		5	55	35
G6146	NP-205	NP-205	NP-205	STG	DA	MEAN	????	ENP	01-OCT-1974	04-DEC-2023	0		DAD	254122.992	805053.016	706203.208	492949.711	ENP		5	55	35

Station	Site	Type	Latitude (ddmmss.sss)	Longitude (ddmmss.sss)	X Coord (ft)	Y Coord (ft)	County	Basin	Sec	Twp	Rng	Show Map	Description
NP-203	NP-203	RIVER/STREAM	253726.22	804420.58	742148.458	469102.235	Miami-Dade	EVERGLADES NATIONAL PARK	25	55	36	Map	EVERGLADES 203-NP NEAR HOMESTEAD, FL
NP-P33	NP-33	WETLAND	253653.568	804209.432	754159.249	465831.124	Miami-Dade	EVERGLADES NATIONAL PARK	11	56	36	Map	Everglades National Park P33 NEAR HOMESTEAD, FL
NP-P35	NP-35	RIVER/STREAM	252739.384	805153.46	700758.769	409796.885	Miami-Dade	EVERGLADES NATIONAL PARK	31	57	35	Map	Everglades National Park P35
NP-P36	NP-36	RIVER/STREAM	253142.528	804743.656	723615.331	434372.294	Miami-Dade	EVERGLADES NATIONAL PARK	2	57	35	Map	Everglades National Park P36

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
06040	NP-203	NP-203	NP-203	RAIN	DA	SUM	????	ENP	13-FEB-1982	04-DEC-2023	DAD	253726.22	804420.58	742148.458	469102.235	ENP		25	55	36
G6154	NP-203	NP-203	NP-203	STG	DA	MEAN	????	ENP	01-OCT-1973	04-DEC-2023	DAD	253726.22	804420.58	742148.458	469102.235	ENP		25	55	36
G6152	NP-P33	NP-33	NP-33	RAIN	DA	SUM	????	ENP	06-NOV-1993	04-DEC-2023	DAD	253653.568	804209.432	754159.249	465831.124	ENP		11	56	36
06717	NP-P33	NP-33	NP-33	STG	DA	MEAN	????	ENP	01-OCT-1952	04-DEC-2023	DAD	253653.568	804209.432	754159.249	465831.124	ENP		11	56	36
H1999	NP-P35	NP-P35	NP-35	RAIN	DA	SUM	????	ENP	11-FEB-1982	04-DEC-2023	DAD	252739.384	805153.46	700758.769	409796.885	ENP		31	57	35
G6170	NP-P35	NP-P35	NP-35	STG	DA	MEAN	????	ENP	16-FEB-1953	04-DEC-2023	DAD	252739.384	805153.46	700758.769	409796.885	ENP		31	57	35
06038	NP-P36	NP-36	NP-36	RAIN	DA	SUM	????	ENP	02-OCT-1983	04-DEC-2023	DAD	253142.528	804743.656	723615.331	434372.294	ENP		2	57	35
06718	NP-P36	NP-36	NP-36	STG	DA	MEAN	????	ENP	01-FEB-1968	04-DEC-2023	DAD	253142.528	804743.656	723615.331	434372.294	ENP		2	57	35

WCA3A

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
16536	3-62	3-62	3A-2	GAGHT	DA	MEAN	????	USGS	09-AUG-1991	03-DEC-2023	0		BRO	261029.307	804504.214	737773.603	669304.206	CA3A			49	36
AI492	3-62	3-62	3A-2	STG	BK	INST	GOES	USGS	05-SEP-2013	04-DEC-2023	0		BRO	261029.307	804504.214	737773.603	669304.206	CA3A			49	36
16532	3-63	3-63	3A-3	GAGHT	DA	MEAN	????	USGS	20-JUN-1991	03-DEC-2023	0		BRO	261118.1	803151.91	809937.763	674431.377	CA3A		15	49	38
AI493	3-63	3-63	3A-3	STG	BK	INST	GOES	USGS	05-SEP-2013	15-NOV-2023	0		BRO	261118.1	803151.91	809937.763	674431.377	CA3A		15	49	38
16537	3-64	3-64	3A-4	GAGHT	DA	MEAN	????	USGS	20-JUN-1991	03-DEC-2023	0		BRO	255832.334	804009.216	764831.947	596977.143	CA3A			51	37
AI494	3-64	3-64	3A-4	STG	BK	INST	GOES	USGS	05-SEP-2013	04-DEC-2023	0		BRO	255832.334	804009.216	764831.947	596977.143	CA3A			51	37
16538	3-65	3-65	3A-28	GAGHT	DA	MEAN	????	USGS	04-JUL-1991	03-DEC-2023	0		DAD	254853.357	804311.219	748348.024	538485.38	CA3A			53	36
AI495	3-65	3-65	3A-28	STG	BK	INST	GOES	USGS	05-SEP-2013	04-DEC-2023	0		DAD	254853.357	804311.219	748348.024	538485.38	CA3A			53	36
OU839	3-69W	3-69	GA3A69W	GAGHT	DA	MEAN	????	USGS	22-OCT-1994	03-DEC-2023	0		DAD	255424.677	803521.112	791203.275	572049.243	CA3A			52	35

WCA-3B

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
PT359	086988-1	086988	086988	RAIN	DA	SUM	NA	NOAA	01-AUG-1948	28-SEP-1951	0		DAD	255600	802700	836917.766	581839.632	CA3B		9	52	39
PT361	086988-3	086988	086988	RAIN	DA	SUM	NA	NOAA			0		DAD	255547	802714	835645.174	580521.782	CA3B		9	52	39
16542	3-34	3-34	3B-34	GAGHT	DA	MEAN	????	USGS	14-APR-1993	02-OCT-1997	0		DAD	255216.346	802909.196	825212.063	559211.49	CA3B		36	52	38
16541	3-69	3-69	GA3B69	GAGHT	DA	MEAN	????	USGS	12-JUL-1991	03-DEC-2023	0		DAD	255423.79	803519.55	791346.181	571960.138	CA3B			52	35
39558	3-69	3-69	GA3B69	STG	BK	INST	GOES	USGS	17-SEP-2014	04-DEC-2023	0		DAD	255423.79	803519.55	791346.181	571960.138	CA3B			52	35
AO076	3-69	3-69	GA3B69	STG88	DA	MEAN	????	USGS	24-JAN-2012	03-DEC-2023	0		DAD	255423.79	803519.55	791346.181	571960.138	CA3B			52	35
16543	3-71	3-71	3B-71	GAGHT	DA	MEAN	????	USGS	17-JUL-1991	03-DEC-2023	0		DAD	255305.345	803324.202	801903.745	564073.513	CA3B			52	35
AI497	3-71	3-71	3B-71	STG	BK	INST	GOES	USGS	22-NOV-2022	04-DEC-2023	0		DAD	255305.345	803324.202	801903.745	564073.513	CA3B			52	35
16539	3-76	3-76	3B-76	GAGHT	DA	MEAN	????	USGS	25-JUL-1991	03-DEC-2023	0		BRO	260028.327	802857.192	826112.245	608886.966	CA3B		18	51	39

Dbkey	Station	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	Basin	Struct
16541	3-69	GA3B69	GAGHT	DA	MEAN	????	USGS	19910712	20231203	DAD	255423.79	803519.55	CA3B	
16543	3-71	3B-71	GAGHT	DA	MEAN	????	USGS	19910717	20231203	DAD	255305.345	803324.202	CA3B	
16539	3-76	3B-76	GAGHT	DA	MEAN	????	USGS	19910725	20231203	BRO	260028.327	802857.192	CA3B	

S12

Dbkey	Station	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	Basin	Struct
90230	S12A_H	S12A	GAGHT	DA	MEAN	????	USGS	19811001	20231203	DAD	254543.263	804916.737	CA3A	
01313	S12A_S	S12A	FLOW	DA	MEAN	????	USGS	19631001	20231203	DAD	254542.443	804915.973	CA3A	SPIL
01312	S12A_T	S12A	GAGHT	DA	MEAN	????	USGS	19811001	20231203	DAD	254541.7	804916.764	ENP	
00604	S12B_H	S12B	GAGHT	DA	MEAN	????	USGS	19691001	20231203	DAD	254544.259	804610.775	CA3A	
00610	S12B_S	S12B	FLOW	DA	MEAN	????	USGS	19631001	20231203	DAD	254542.85	804610.169	ENP	SPIL
00608	S12B_T	S12B	GAGHT	DA	MEAN	????	USGS	19630426	20231203	DAD	254541.822	804610.863	ENP	
90236	S12C_H	S12C	GAGHT	DA	MEAN	????	USGS	19900317	20231203	DAD	254544.648	804338.92	CA3A	
00621	S12C_S	S12C	FLOW	DA	MEAN	????	USGS	19631001	20231203	DAD	254543.073	804336.908	CA3A	SPIL
00619	S12C_T	S12C	STG	DA	MEAN	????	USGS	19691001	20231203	DAD	254542.045	804337.929	ENP	
01307	S12D_H	S12D	GAGHT	DA	MEAN	????	USGS	19811001	20231203	DAD	254544.353	804053.23	CA3A	
06055	S12D_R	S12D	RAIN	DA	SUM	BELF	WMD	19850326	20000331	DAD	254543.77	804053	CA3A	
LS269	S12D_R	S12D	RAIN	DA	SUM	CR10	WMD	20000718	20231203	DAD	254543.77	804053	CA3A	
01310	S12D_S	S12D	FLOW	DA	MEAN	????	USGS	19631001	20231203	DAD	254543.186	804054.483	ENP	SPIL

S333

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
AP486	S333_H	S333_H	S333	STG	DA	MEAN	DRV	WMD	12-OCT-1978	29-NOV-2023	DAD	254543.243	804026.952	763407.684	519327.438	CA3A		6	54	37
91487	S333_S	S333	S333	FLOW	DA	MEAN	DRV	WMD	12-OCT-1978	07-DEC-2023	DAD	254543.183	804026.224	763474.214	519321.577	CA3A	SPIL	6	54	37
LS500	S333_S	S333	S333	GATE	BK	INST	2A35	WMD	12-OCT-1978	01-OCT-1982	DAD	254543.183	804026.224	763474.214	519321.577	CA3A	SPIL	6	54	37
LT356	S333_S	S333	S333	GATE	BK	INST	CR10	WMD	16-MAY-1993	19-OCT-2012	DAD	254543.183	804026.224	763474.214	519321.577	CA3A	SPIL	6	54	37
AJ017	S333_S	S333_S	S333	GATE	BK	INST	TELE	WMD	19-OCT-2012	08-DEC-2023	DAD	254543.183	804026.224	763474.214	519321.577	CA3A	SPIL	6	54	37
AJ015	S333_T	S333_T	S333	STG	DA	MEAN	TELE	WMD	19-OCT-2012	07-DEC-2023	DAD	254542.774	804025.702	763522.122	519280.408	ENP		6	54	37

S355 Search S355%

Get Data	Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
	AI573	S355A_H	S355A_S	S355A	STG	BK	INST	GOES	COE	05-SEP-2013	08-DEC-2023	0		DAD	254543.042	803526.975	790831.806	519383.581	CA3B		11	54	37
	MQ895	S355A_S	S355A_S	S355A	FLOW	DA	MEAN	NA	USGS	01-JUL-1999	13-MAR-2016	0		DAD	254542.135	803527.933	790744.487	519291.805	CA3B	SPIL	11	54	37
	AI575	S355A_S	S355A_S	S355A	GATE	BK	INST	GOES	COE	05-SEP-2013	08-DEC-2023	0	1	DAD	254542.135	803527.933	790744.487	519291.805	CA3B	SPIL	11	54	37
	AI574	S355A_T	S355A_S	S355A	STG	BK	INST	GOES	COE	05-SEP-2013	08-DEC-2023	0		DAD	254541.038	803527.011	790829.202	519181.325	ENP		11	54	37
	AI576	S355B_H	S355B_S	S355B	STG	BK	INST	GOES	COE	30-JAN-2009	08-DEC-2023	0		DAD	254542.841	803311.489	803218.156	519403.5	CA3B		8	54	38
	AM173	S355B_P	S355B_P	S355B	FLOW	DA	MEAN	DRV	WMD	29-FEB-2016	17-OCT-2018	0		DAD	254541.964	803312.319	803142.56	519314.736	CA3B	PUMP	8	54	38
	MQ896	S355B_S	S355B_S	S355B	FLOW	DA	MEAN	NA	USGS	01-JUL-1999	13-MAR-2016	0		DAD	254541.964	803312.319	803142.56	519314.736	CA3B	SPIL	8	54	38
	AI578	S355B_S	S355B_S	S355B	GATE	BK	INST	GOES	COE	30-JAN-2009	08-DEC-2023	0	1	DAD	254541.964	803312.319	803142.56	519314.736	CA3B	SPIL	8	54	38
	AI577	S355B_T	S355B_S	S355B	STG	BK	INST	GOES	COE	30-JAN-2009	08-DEC-2023	0		DAD	254540.975	803311.458	803221.628	519215.132	ENP		8	54	38

S356

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
92190	S356_P	S356_P	S356	FLOW	BK	INST	DRV	WMD	19-SEP-2015	15-DEC-2023	0		DAD	254541.417	803007.872	820003.51	519318.832	ENP	PUMP			
64136	S356_P	S356_P	S356	FLOW	DA	MEAN	DRV	WMD	13-AUG-2015	07-DEC-2023	0		DAD	254541.417	803007.872	820003.51	519318.832	ENP	PUMP			

S334

Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
AP488	S334_H	S334_H	S334	STG	DA	MEAN	DRV	WMD	12-OCT-1978	05-DEC-2023	0		DAD	254540.509	803009.305	819874.539	519227.796	ENP		2	54	38
FB752	S334_S	S334	S334	FLOW	DA	MEAN	PREF	WMD	12-OCT-1978	30-SEP-2023	0		DAD	254540.776	803008.562	819942.408	519254.951	ENP	SPIL	2	54	38
91488	S334_S	S334	S334	FLOW	DA	MEAN	DRV	WMD	12-OCT-1978	07-DEC-2023	0		DAD	254540.776	803008.562	819942.408	519254.951	ENP	SPIL	2	54	38
LS501	S334_S	S334	S334	GATE	BK	INST	DWR	WMD	12-OCT-1978	28-JAN-1994	0	1	DAD	254540.776	803008.562	819942.408	519254.951	ENP	SPIL	2	54	38
LT357	S334_S	S334	S334	GATE	BK	INST	CR10	WMD	14-JUL-1993	03-DEC-1997	0	1	DAD	254540.776	803008.562	819942.408	519254.951	ENP	SPIL	2	54	38
LT457	S334_S	S334	S334	GATE	BK	INST	TELE	WMD	11-APR-1996	08-DEC-2023	0	1	DAD	254540.776	803008.562	819942.408	519254.951	ENP	SPIL	2	54	38
65509	S334_T	S334_T	S334	STG	DA	MEAN	DRV	WMD	12-OCT-1978	07-DEC-2023	0		DAD	254540.554	803008.046	819989.66	519232.73	L-29 CC		2	54	38

S332

Get Data	Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
	65530	S332B_H	S332B_H	S332B	STG	DA	MEAN	DRV	WMD	01-DEC-2000	07-DEC-2023	0		DAD	253259.42	803337.376	801107.549	442322.769	L-31NS		19	56	38
	MX225	S332B_P	S332B_P	S332B	FLOW	DA	MEAN	PLOG	WMD	30-NOV-2000	31-MAY-2003	0		DAD	253258.295	803338.092	801042.419	442208.955	L-31NS	PUMP	19	56	38
	TB064	S332B_P	S332B_P	S332B	FLOW	DA	MEAN	PREF	WMD	01-JUL-2005	30-SEP-2023	0		DAD	253258.295	803338.092	801042.419	442208.955	L-31NS	PUMP	19	56	38
	91482	S332B_P	S332B_P	S332B	FLOW	DA	MEAN	NA	WMD	01-JAN-2015	07-DEC-2023	0		DAD	253258.295	803338.092	801042.419	442208.955	L-31NS	PUMP	19	56	38

	65532	S332C_H	S332C_H	S332C	STG	DA	MEAN	DRV	WMD	27-MAR-2007	07-DEC-2023	0		DAD	253054.543	803336.431	801234.172	429715.111	L-31NS		31	56	38
	91483	S332C_P	S332C_P	S332C	FLOW	DA	MEAN	DRV	WMD	27-MAR-2007	07-DEC-2023	0		DAD	253054.438	803336.708	801210.542	429705.301	L-31NS	PUMP	31	56	38

	65534	S332D_H	S332D_H	S332D	STG	DA	MEAN	DRV	WMD	30-AUG-1999	07-DEC-2023	0		DAD	252858.866	803347.535	800256.95	418034.516	L-31NS		7	57	38
	91485	S332D_P	S332	S332D	FLOW	DA	MEAN	DRV	WMD	30-AUG-1999	06-DEC-2023	0		DAD	252858.653	803349.61	800066.845	418012.381	L-31NS	PUMP	7	57	38

	AP492	S332D_T	S332D_T	S332D	STG	DA	MEAN	DRV	WMD	30-AUG-1999	06-DEC-2023	0		DAD	252858.898	803351.214	799919.794	418036.682	S332DDA		7	57	38

S200

Get Data	Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
	66042	S200_H	S200_H	S200	STG	DA	MEAN	DRV	WMD	08-FEB-2012	07-DEC-2023	0		DAD	252639.239	803335.466	801409.431	403942.173	C111_AG		30	57	38
	91437	S200_P	S200_P	S200	FLOW	DA	MEAN	DRV	WMD	04-MAR-2012	07-DEC-2023	0		DAD	252638.911	803337.115	801258.365	403908.585	C111_AG	PUMP	30	57	38

S199 Search: S199%

Get Data	Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
	88891	S199_H	S199_H	S199	STG	BK	INST	TELE	WMD	21-DEC-2011	09-DEC-2023	0		DAD	252411.944	803330.838	801882.833	389073.555	C111_AG		7	58	38
	91436	S199_P	S199_P	S199	FLOW	DA	MEAN	DRV	WMD	05-APR-2012	08-DEC-2023	0		DAD	252411.601	803332.551	801725.913	389038.443	C111_AG	PUMP	7	58	38
	AP211	S199_T	S199_T	S199	STG	DA	MEAN	DRV	WMD	21-DEC-2011	05-DEC-2023	0		DAD	252411.908	803334.521	801545.136	389068.806	C111_CO		7	58	38

L-31N

Get Data	Dbkey	Station	Group	Site	Data Type	Freq	Stat	Recorder	Agency	Start Date	End Date	Strata	Op Num	County	Latitude	Longitude	X Coord	Y Coord	Basin	Struct	Sec	Twp	Rng
	88748	L31.EXT3	L31.EXT3	L31.EXT3	FLOW	DA	MEAN	????	USGS	01-MAR-1992	14-DEC-2023	0		DAD	254302.368	802951.201	821588.83	503267.301	ENP	OPCH	26	54	38
	12866	L31.EXT3	L31.EXT3	L31.EXT3	GAGHT	DA	MEAN	????	USGS	07-NOV-1988	14-DEC-2023	0		DAD	254302.368	802951.201	821588.83	503267.301	ENP		26	54	38
	S3102	L31NN	L31NN	L31NN	STG	DA	MEAN	CR10	WMD	28-MAY-2004	14-DEC-2023	0		DAD	254446.526	802952.591	821421.695	513782.49	ENP		14	54	38

Get Data	Dbkey	Station	Site	Data Type	Freq	Stat	Strata	Op Num	Recorder	Agency	Start Date	End Date	County	Latitude	Longitude	Basin	Struct
	88748	L31.EXT3	L31.EXT3	FLOW	DA	MEAN	0		????	USGS	19920301	20231214	DAD	254302.368	802951.201	ENP	OPCH
	12866	L31.EXT3	L31.EXT3	GAGHT	DA	MEAN	0		????	USGS	19881107	20231214	DAD	254302.368	802951.201	ENP	
	S3102	L31NN	L31NN	STG	DA	MEAN	0		CR10	WMD	20040528	20231214	DAD	254446.526	802952.591	ENP	

Appendix C Aggregated Rainfall

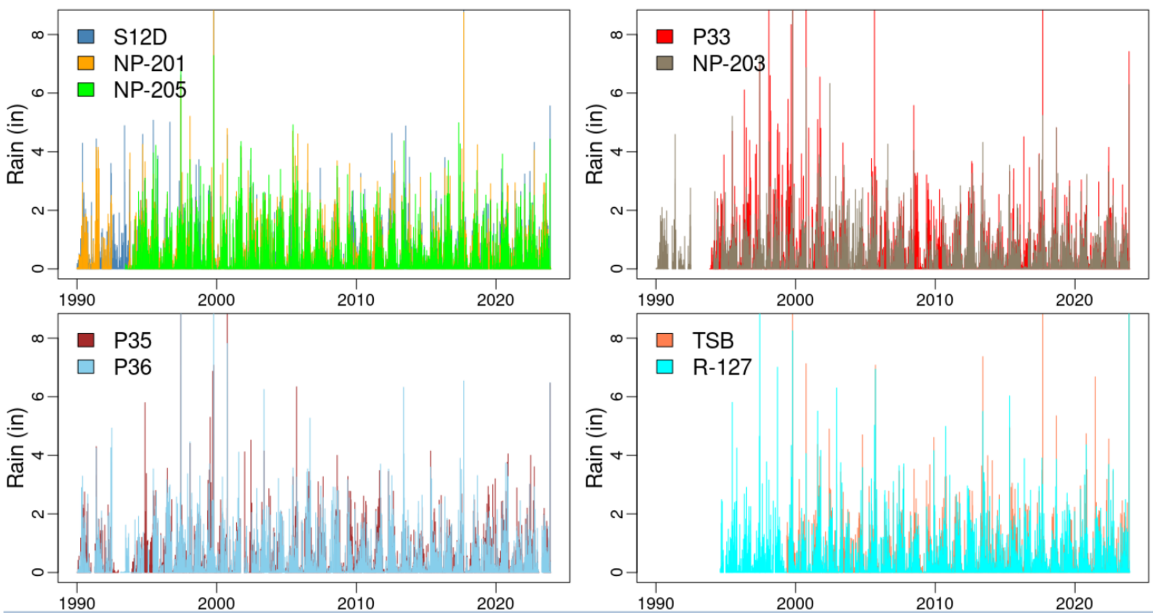

Figure 19. Daily rainfall.

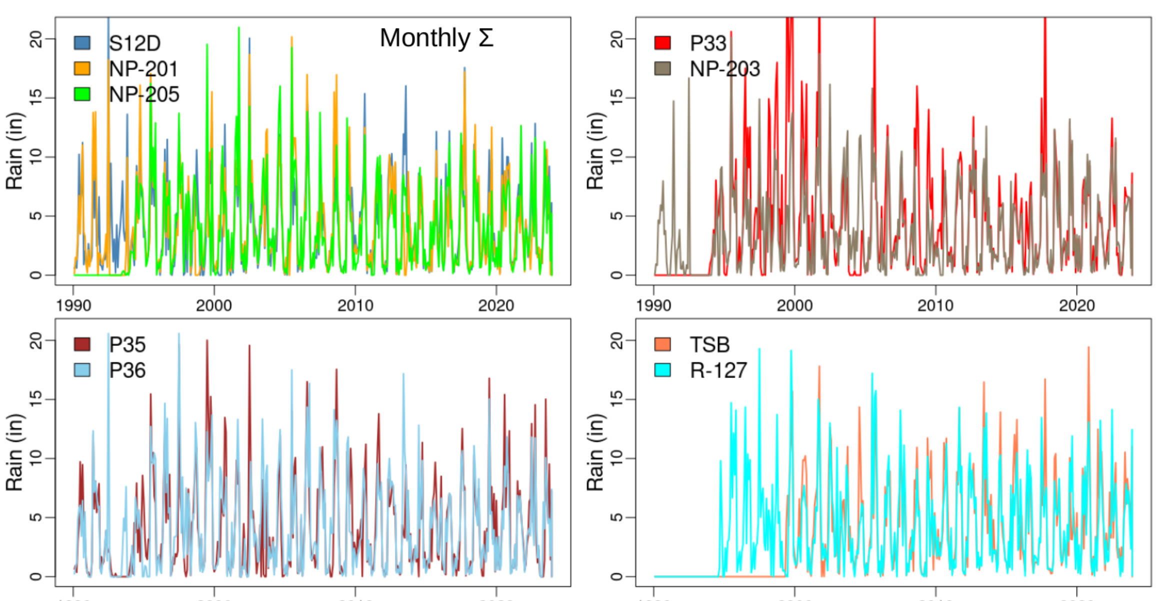

Figure 20. Monthly rainfall.

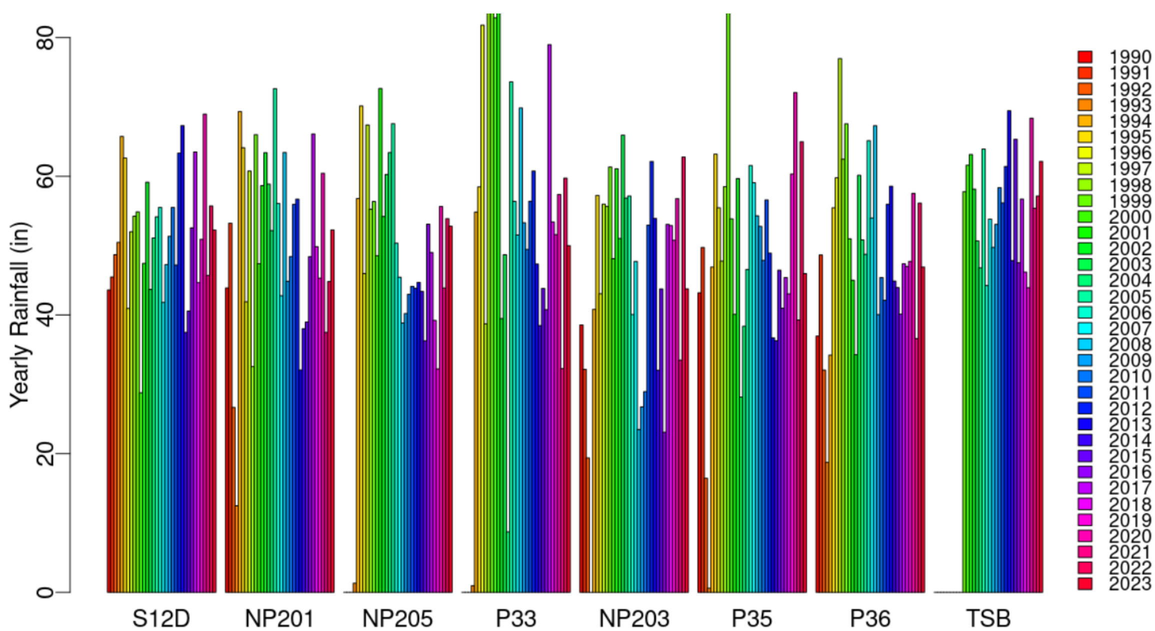

Figure 21. Yearly rainfall.

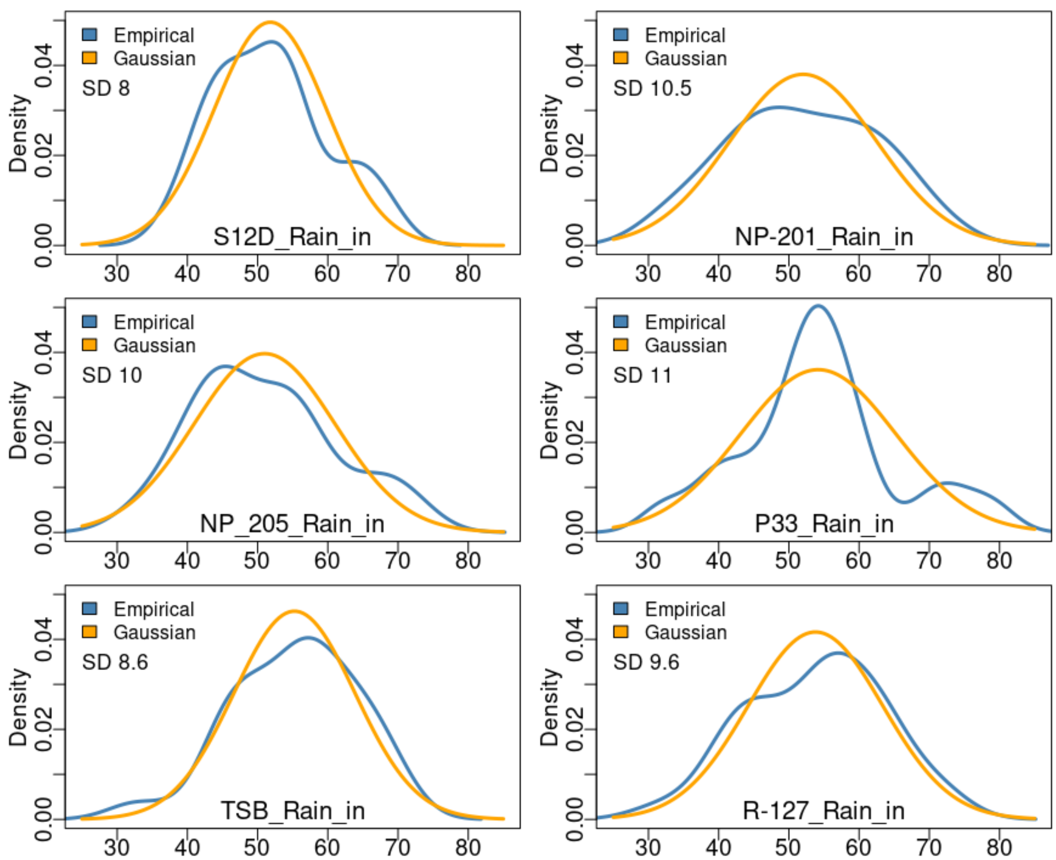

Figure 22. Empirical and Gaussian fits to yearly rainfall totals. SD is the Gaussian standard deviation.

Appendix D S-12 Flow

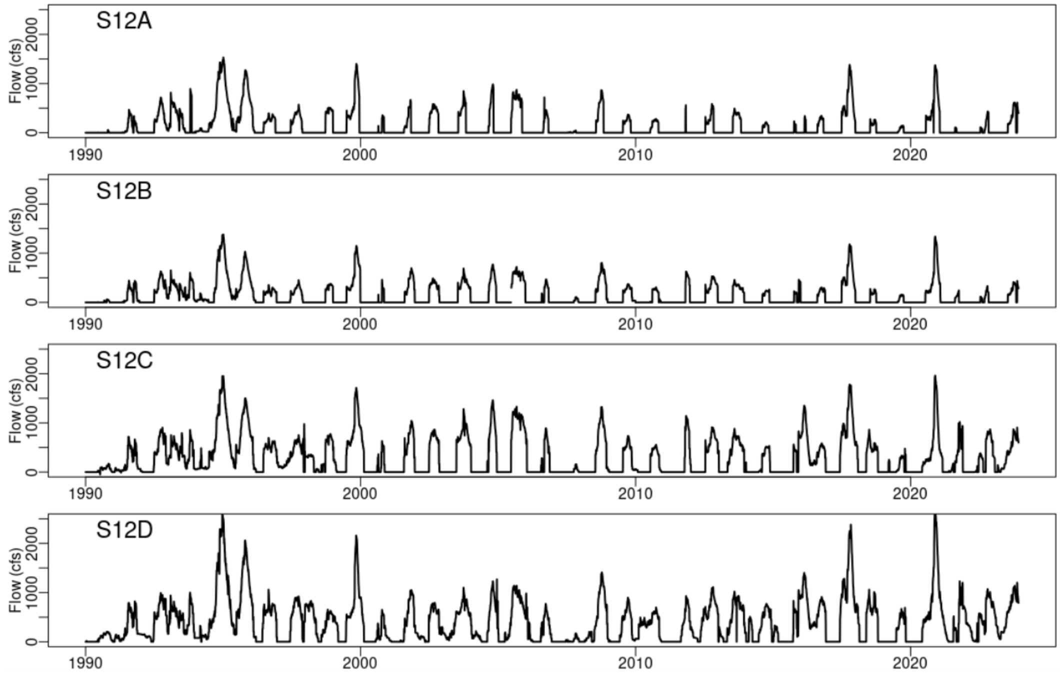

Figure 23. Daily accumulated flow at S-12.

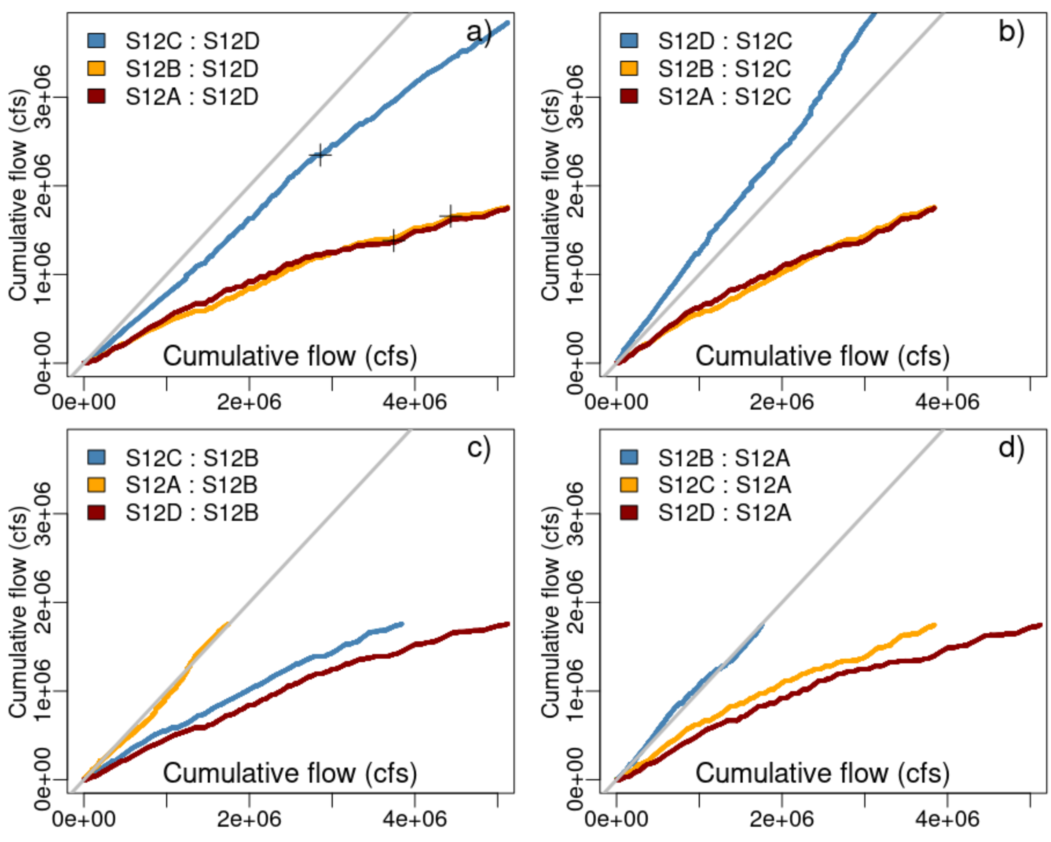

Figure 24. Double mass curves of S-12.

Appendix E Water Level Extrema Table

Table 9 lists the mean minima and maxima of the indicator water levels, along with the linear model fit coefficients and p–values. These data are shown in figure 10 where trends are shown only if the p–value is less than 0.05.

Station	Plan	Min Mean	Max Mean	Min C	Max C	Min p	Max p
NE1	IOP	5.753	7.526	-1.855e-04	-1.570e-04	0.2626	0.0212
NE1	ERTP	5.867	7.567	-5.265e-04	-8.541e-05	0.2052	0.4477
NE1	IFT	6.082	8.224	-6.721e-04	1.881e-04	0.1392	0.3696
NE1	COP	7.067	8.486	2.847e-04	2.864e-04	0.1980	0.3255
NP201	IOP	5.702	8.613	1.156e-04	-1.166e-04	0.5521	0.3368
NP201	ERTP	5.722	8.723	-3.460e-04	-4.377e-04	0.6884	0.1504
NP201	IFT	5.834	9.030	-8.788e-04	-5.680e-06	0.2708	0.9928
NP201	COP	7.094	9.228	5.673e-04	1.242e-04	0.0822	0.6859
NP205	IOP	3.490	7.223	1.236e-05	-1.254e-04	0.9523	0.1046
NP205	ERTP	3.162	7.022	-4.155e-04	-5.254e-04	0.5576	0.0671
NP205	IFT	3.482	7.402	-8.286e-04	-1.089e-04	0.3865	0.8435
NP205	COP	4.069	7.357	1.436e-03	3.754e-04	0.2866	0.1788
S334	IOP	5.848	7.730	-3.018e-04	-1.543e-04	0.1731	0.0009
S334	ERTP	5.805	7.558	-6.340e-04	8.367e-05	0.0292	0.4054
S334	IFT	6.194	8.382	-4.249e-04	1.981e-04	0.4189	0.0011
S334	COP	7.219	8.617	4.914e-04	1.111e-04	0.1745	0.4354
P33	IOP	5.329	7.062	-1.910e-04	-1.233e-04	0.1605	0.10039
P33	ERTP	5.530	7.115	-6.058e-06	-3.461e-04	0.9749	0.10804
P33	IFT	5.436	7.562	-7.793e-04	1.337e-04	0.0815	0.72339
P33	COP	6.276	7.716	2.960e-04	1.683e-04	0.0171	0.55110
G620	IOP	4.525	7.447	2.568e-07	-9.885e-05	0.9990	0.25453
G620	ERTP	4.820	7.428	-1.625e-04	-3.986e-04	0.7836	0.11706
G620	IFT	4.976	7.766	-1.138e-03	-1.059e-04	0.1761	0.82970
G620	COP	6.285	7.900	2.713e-04	3.686e-04	0.0665	0.20220
NE2	IOP	5.484	7.452	-2.734e-04	-1.368e-04	0.1705	0.0302
NE2	ERTP	5.355	7.455	-6.934e-04	1.361e-04	0.0754	0.3707
NE2	IFT	5.734	8.222	-6.319e-04	1.827e-04	0.4549	0.1918
NE2	COP	7.003	8.480	3.928e-04	2.297e-04	0.2364	0.2937
TSB	IOP	1.064	5.059	-1.081e-04	-6.899e-05	0.5167	0.3276
TSB	ERTP	1.181	5.041	-2.553e-04	-1.515e-04	0.5794	0.6113
TSB	IFT	1.889	5.466	-8.915e-04	2.205e-04	0.1032	0.4936
TSB	COP	2.298	5.287	5.929e-04	-5.975e-05	0.3396	0.7641
R127	IOP	0.594	3.337	-5.757e-05	-3.545e-05	0.7179	0.5439
R127	ERTP	0.952	3.408	-2.400e-04	-7.609e-05	0.6200	0.7180
R127	IFT	1.570	3.820	-5.730e-04	1.262e-04	0.1164	0.6960
R127	COP	1.894	3.803	4.687e-04	1.106e-04	0.3153	0.7853
S199	ERTP	6.097	8.530	-7.959e-07	-3.324e-04	0.9605	0.4784
S199	IFT	6.120	9.012	-4.697e-05	2.653e-04	0.0306	0.2065
S199	COP	6.074	9.241	-1.322e-04	-1.217e-05	0.2118	0.7580

Table 9. Linear fits to water level yearly minima and maxima during management regimes IOP, ERTP, IFT, COP. Min C and Max C are the fit coefficients (ft/day), Min p and Max p the p–values of the fit.

Appendix F Dynamic Analysis

Hydrologic time series often exhibit significant serial dependence, or, in the linear sense, autocorrelation. To identify the extent of serial dependence on representative stage data, figure 25 plots the lag mutual information and lag correlation of NP-205 stage data. As expected there is significant serial dependence with 1/e decay at roughly 7 days. If one wishes to exclude serial correlation from the analyzed dynamics, a temporal exclusion radius of at least 7 days is reasonable.

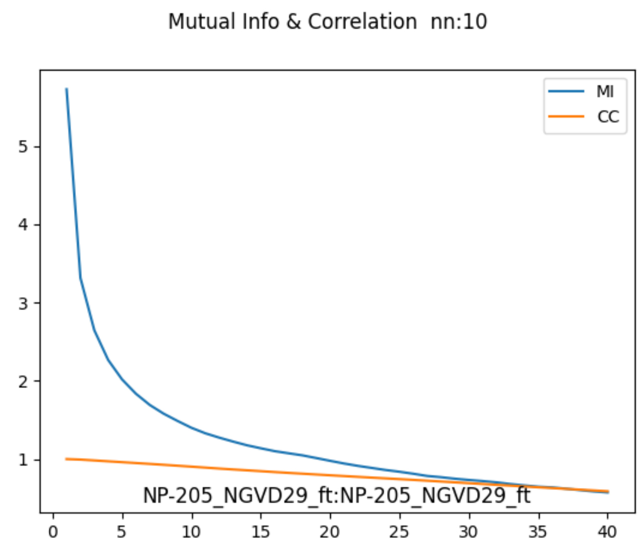

Figure 25. Lag mutual information and lag correlation of NP-205 stage.

To estimate a minimum embedding dimension for state space analysis, figure 26 plots EDM Simplex prediction skill ρ of NP-205 stage as a function of embedding dimension E. An embedding dimension of $E = 3$ is a reasonable lower bound.

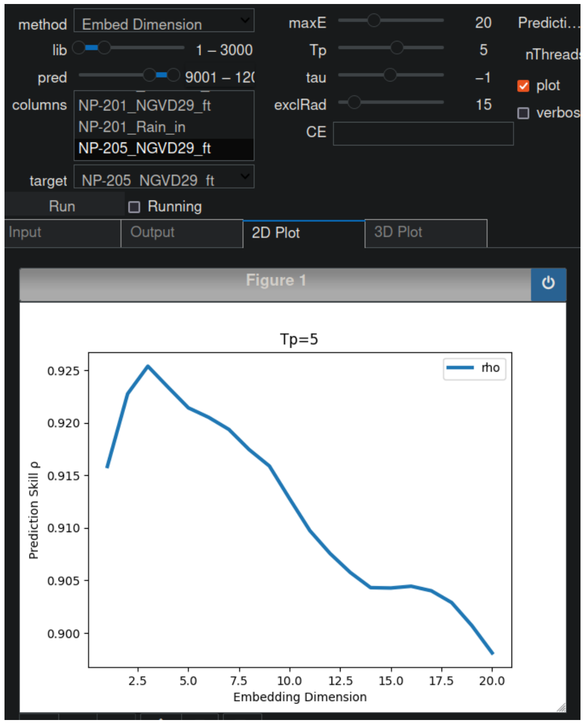

Figure 26. EDM Simplex prediction skill ρ of NP-205 stage as a function of embedding dimension E.

Figure 27 plots EDM S–map prediction skill ρ of NP-205 stage as a function of S-map localization parameter θ, suggesting that a value of $\theta = 4$ provides good state space localization.

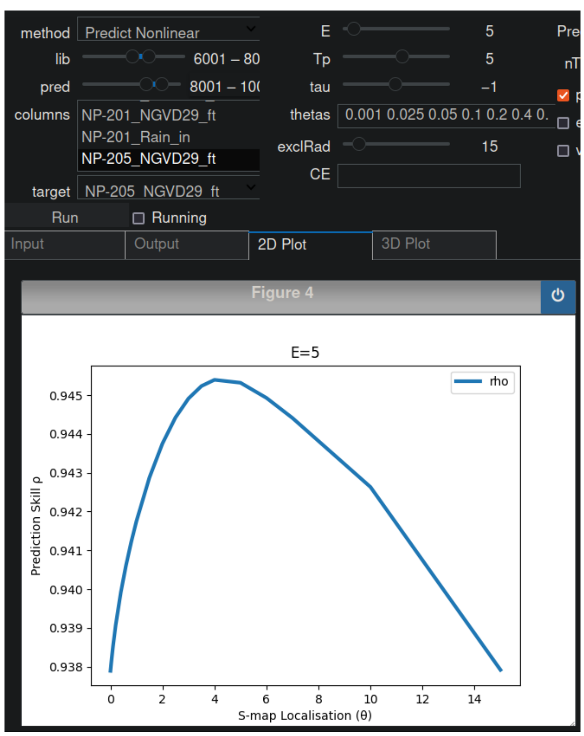

Figure 27. EDM S–map prediction skill ρ of NP-205 stage as a function of S-map localization parameter θ.