Horse Creek Water Quality Analysis Using Generalized Linear Mixed Models
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Introduction

Environmental data tend to deviate from a normal distribution and can be impacted by the unique characteristics of a sampling location. Generalized linear mixed models (GLMMs) can be used to predict the probability of an outcome (including a binary response) using inputs of fixed and random effects. Fixed effects are those variables are those assumed to have a constant effect on an outcome. Random effects are characteristics unique to a given sample, such as the influence of unquantified aspects of the sampling location. Input data may be normal or non-parametric and either continuous or categorical (Bolker et al., 2009).

In this analysis, GLMMs were used to predict the probability of exceeding State water quality thresholds (per Chapter 62-302.531, F.A.C.) for Class I and Class III waters in Horse Creek under the proposed minimum flows for the system (Ghile et al., 2023). A similar application of GLMMs was used by Janicki Environmental, Inc. (JEI) through Applied Technology & Management, Inc. (ATM) in their 2018 analysis of water quality in the Chassahowitzka River (ATM and JEI 2018).

Most of Horse Creek is considered Class III water, however, approximately 10 miles of the creek is classified as a Class I surface water as it approaches the confluence with the Peace River, in Florida Department of Environmental Protection (DEP) waterbody identification number (WBID) 1787A2 (Figure 1, ATM and JEI 2021). The most recently adopted Verified List for Horse Creek (July 15, 2022) designates one WBID impaired for *Escherichia coli* (WBID 1939; Figure 1). Two WBIDs were added to the Study List to investigate dissolved oxygen percent saturation impairment (WBIDs 1826A and 1915; Figure 1). One WBID (WBID 1787B) had previously been listed for total phosphorus impairment but has recently been delisted. Apart from a statewide total maximum daily load (TMDL) for mercury (DEP 2013), the DEP has not established a TMDL or basin management plan for any waterbody within the Horse Creek.
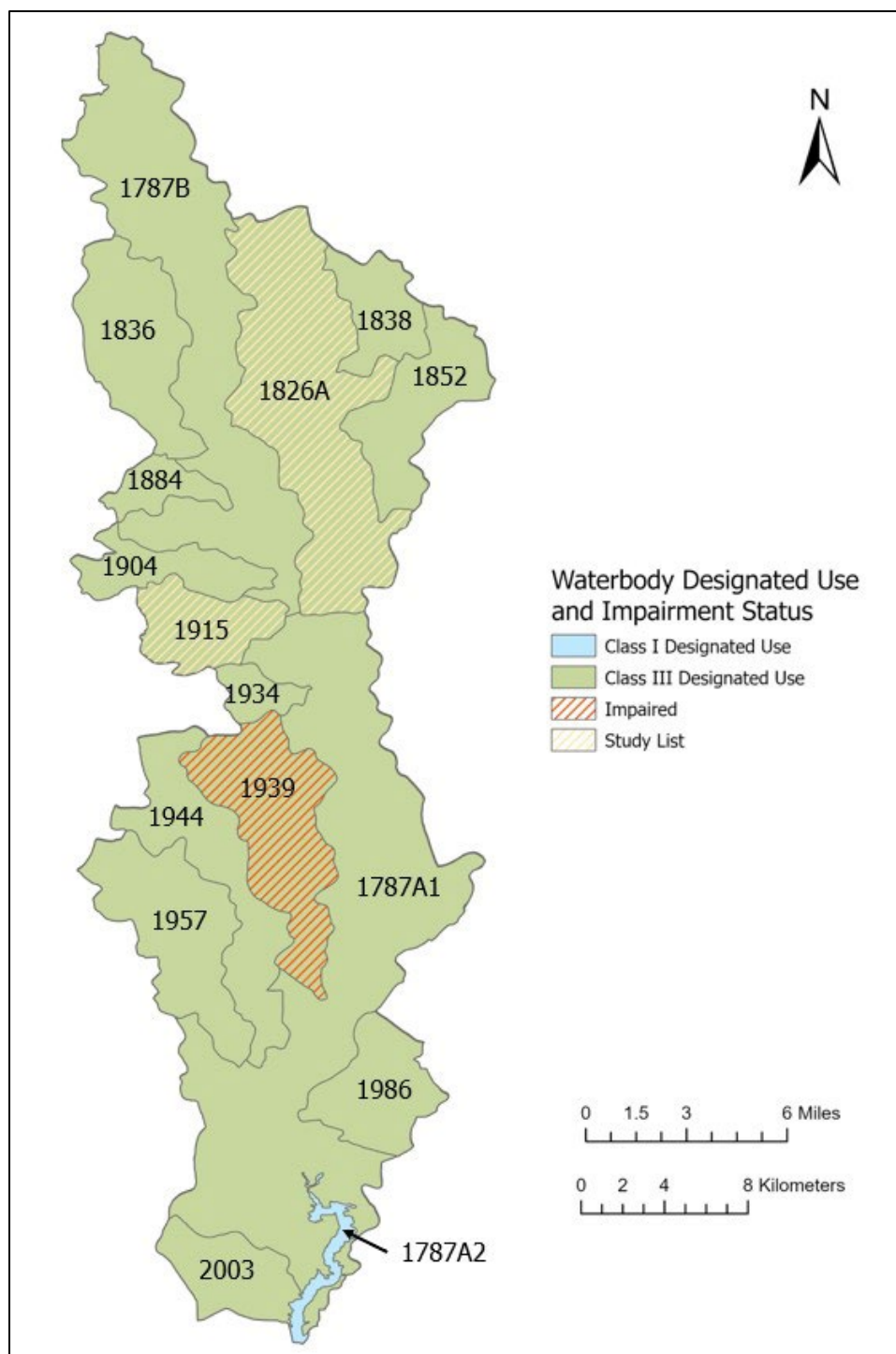
Figure 1. Location of waterbodies by waterbody identification number (WBID) within the Horse Creek watershed, colored according to designated use classification, impairment status, and inclusion on the study list, according to the DEP's Impaired Waters Rule Run 60 and the Verified List adopted in 2022.

Data

Water quality samples from the DEP, Horse Creek Stewardship Program (HCSP), Southwest Florida Water Management District (SWFWMD) and United States Geological Survey (USGS) were used in this analysis (Figure 2). The available period of record and frequency of sampling varied by the sampling agency (Table 1). For consistency with data quality assurance, all water quality data used were pulled from the DEP Impaired Waters Rule Run 59 database, provided by Janicki Environmental, Inc (JEI) through Applied Technology and Management, Inc (ATM and JEI 2021). Flow data were queried from the USGS website for the USGS Horse Creek at SR72 near Arcadia, FL (No. 02297310) gage and matched to dates of sample collection. Antecedent flows were not considered in this modeling exercise.
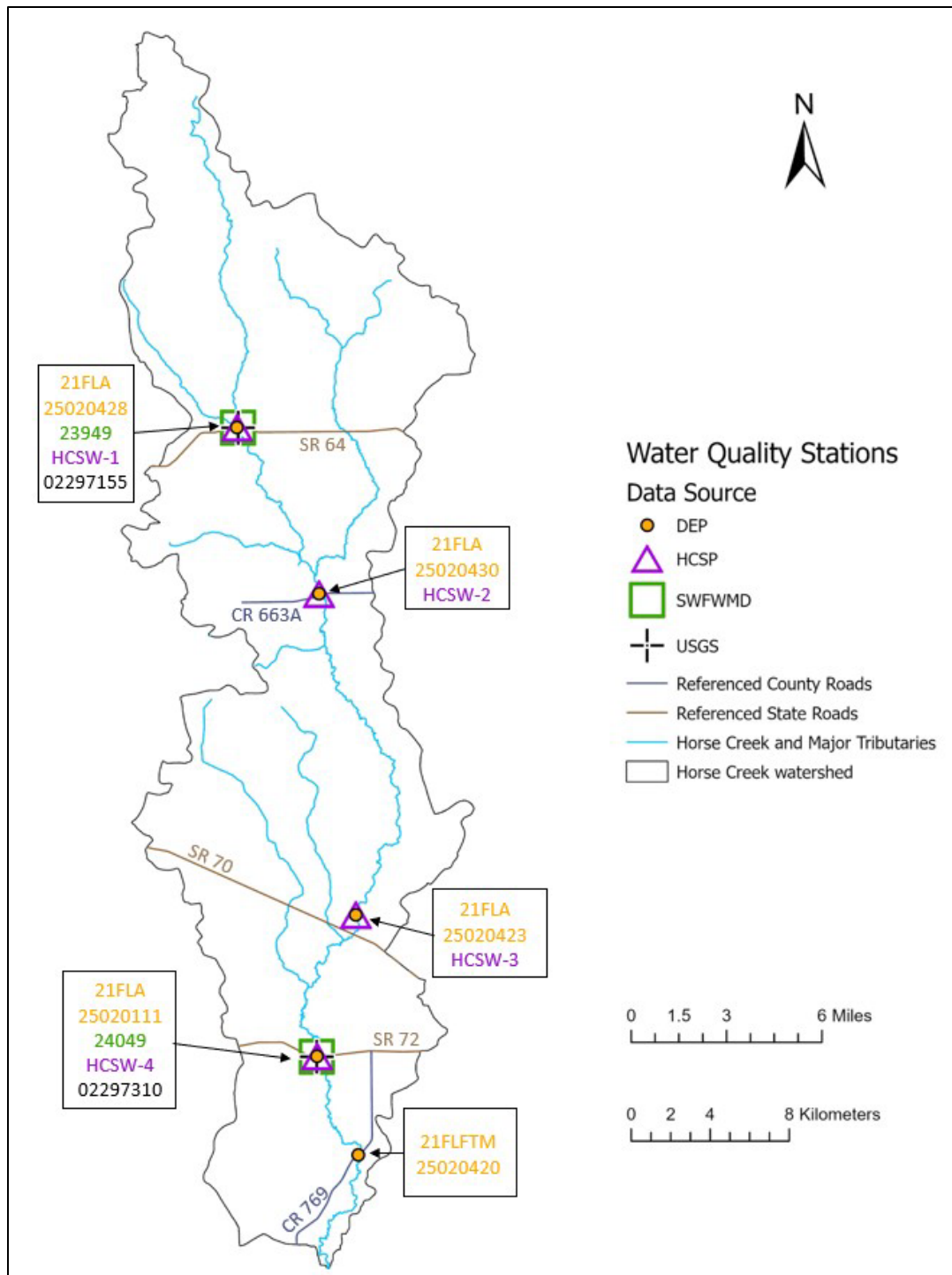
Figure 2. Locations of the water quality sampling sites throughout Horse Creek considered during analysis. Flow data was obtained from USGS station 02297310 (USGS Horse Creek at SR72 near Arcadia, FL).

Table 1: Sampling information for each water quality parameter in the GLMM analysis, including station name data source, number (n) of samples, the start and end dates of the period of record (POR), and the approximate sampling frequency over the POR.

Parameter	Station Name	Source	Samples (n)	POR	Approximate Sampling Frequency
Total Dissolved Solids	HCSW-1	HCSP	175	10/2003 - 12/2018	Monthly
	HCSW-2	HCSP	167	10/2003 - 12/2018	Monthly
	HCSW-3	HCSP	177	10/2003 - 12/2018	Monthly
	HCSW-4	HCSP	180	10/2003 - 12/2018	Monthly
	23949	SWFWMD	86	1/2006 - 3/2019	Monthly 2006 -2011, bimonthly through 2019
	24049	SWFWMD	93	1/2006 - 3/2019	Monthly 2006 -2011, bimonthly through 2019
Dissolved Calcium	HCSW-1	HCSP	172	10/2003 - 12/2018	Monthly
	HCSW-2	HCSP	164	10/2003 - 12/2018	Monthly
	HCSW-3	HCSP	174	10/2003 - 12/2018	Monthly
	HCSW-4	HCSP	177	10/2003 - 12/2018	Monthly
	23949	SWFWMD	152	1/2000 - 3/2019	Monthly 2000 - 2011; bimonthly through 2019
	24049	SWFWMD	169	1/2000 - 3/2019	Monthly 2000 - 2011; bimonthly through 2019
Dissolved Sulfate	HCSW-1	HCSP	176	10/2003 - 12/2018	Monthly
	HCSW-2	HCSP	168	10/2003 - 12/2018	Monthly
	HCSW-3	HCSP	178	10/2003 - 12/2018	Monthly
	HCSW-4	HCSP	181	10/2003 - 12/2018	Monthly
	23949	SWFWMD	135	1/2000 - 11/2015	Monthly 2000 - 2011; bimonthly through 2015
	24049	SWFWMD	152	1/2000 - 11/2015	Monthly 2000 - 2011; bimonthly through 2015
Total Nitrogen	HCSW-1	HCSP	176	10/2003 - 12/2018	Monthly
	HCSW-2	HCSP	168	10/2003 - 12/2018	Monthly

	HCSW-3	HCSP	178	10/2003 - 12/2018	Monthly
	HCSW-4	HCSP	181	10/2003 - 12/2018	Monthly
	23949	SWFWMD	180	8/1997 - 3/2019	Monthly 1997 - 2011; bimonthly through 2015
	24049	SWFWMD	193	8/1997 - 3/2019	Monthly 1997 - 2011; bimonthly through 2015
Total Phosphorus	211FLA 25020111	DEP	174	7/1972 - 4/1998	Variable; from 1 to 14 times per year
	23949	SWFWMD	182	8/1997 - 3/2019	Monthly 1997 - 2011; bimonthly through 2015
	24049	SWFWMD	195	8/1997 - 3/2019	Monthly 1997 - 2011; bimonthly through 2015
	02297310	USGS	126	5/1968 - 9/1999	Variable; from 1 to 7 times per year
Dissolved Oxygen Percent Saturation	21FLA 25020428	DEP	52	5/1972 - 7/1990	Variable; from 1 to 11 times per year
	21FLA 25020430	DEP	44	12/1972 - 7/1990	Variable; from 1 to 10 times per year
	21FLA 25020423	DEP	44	5/1972 - 8/1991	Variable; from 1 to 10 times per year
	211FLA 25020111	DEP	286	5/1972 - 4/1998	Variable; from 1 to 28 times per year
	21FLTM 25020420	DEP	190	5/2005 - 1/2018	Variable; from 1 to 26 times per year
	HCSW-1	HCSP	66	1/2013 - 12/2018	Monthly
	HCSW-2	HCSP	56	1/2013 - 12/2018	Monthly
	HCSW-3	HCSP	67	1/2013 - 12/2018	Monthly
	HCSW-4	HCSP	66	1/2013 - 12/2018	Monthly
	02297310	USGS	177	5/1968 - 9/1999	Variable; from 1 to 9 times per year

Methods

To predict the probability of State water quality threshold exceedances with flow reductions (a binomial response), GLMMs were created for total dissolved solids, sulfate, dissolved calcium, total nitrogen, total phosphorus, and dissolved oxygen percent saturation using the glmer function in the lme4 package in R programming language (Bates et al. 2015, R Core Team 2021). Models were run for each analyte, considering combinations of the continuous variables (flow) and categorical variables (season, river

kilometer) and the interaction terms among them. "Season" referred to the quarter of the year in which samples were taken, beginning in January. If the model failed to converge with raw flows, the log of flows was taken. The successful model with the lowest Akaiki Information Criteria (AIC) score was selected for further analysis. The predict function in R was then applied to the selected model to predict the probability of State water quality threshold exceedance at a given flow and location. Flow reduction scenarios were run from 1-20% to determine if such a reduction increased the likelihood of 0.5 probability threshold exceedance of State water quality criteria by more than 15% compared to baseline conditions. The proposed minimum flows for all flow-based blocks were included in the range of flow reduction scenarios.

Results

Total Dissolved Solids

Data from HCSP stations HCSW-1 through HCSW-4 and SWFWMD stations 23949 and 24049 were utilized in the creation of GLMMs for total dissolved solids. Their sample distribution regardless of flow block is presented in Figure 3. Exceedance of the State Class I water threshold of 500 mg/L TDS was utilized as the binary response. Over the POR for total dissolved solids data, exceedance was rare above Block 1 (>15 cfs) flows. Occasional exceedance (3 out of 58 samples, or 5.17% of samples) occurred at station HCSW-4 during Block 2.

The GLMM model for total dissolved solids with the lowest AIC (331.1) considered flow, season (quarter), river kilometer, and the interaction between flow and river kilometer (model parameters in Table 2). When all data were visualized, the probability of exceeding the 0.5 probability threshold for total dissolved solids occurred only during block 1 flows, which are protected under the low flow threshold (Figure 4). Flow reductions of up to 20% did not have a significant impact on the likelihood of TDS 0.5 probability threshold exceedance during Blocks 2, 3a, and 3b. The most sensitive station to flow reduction was HCSW-4. The recommended allowable flow reduction of 12% in Block 2 is predicted to cause 13.56% of samples to exceed the 0.5 probability threshold at this station, as compared to 8.47% of samples, a risk difference of 5.08%.
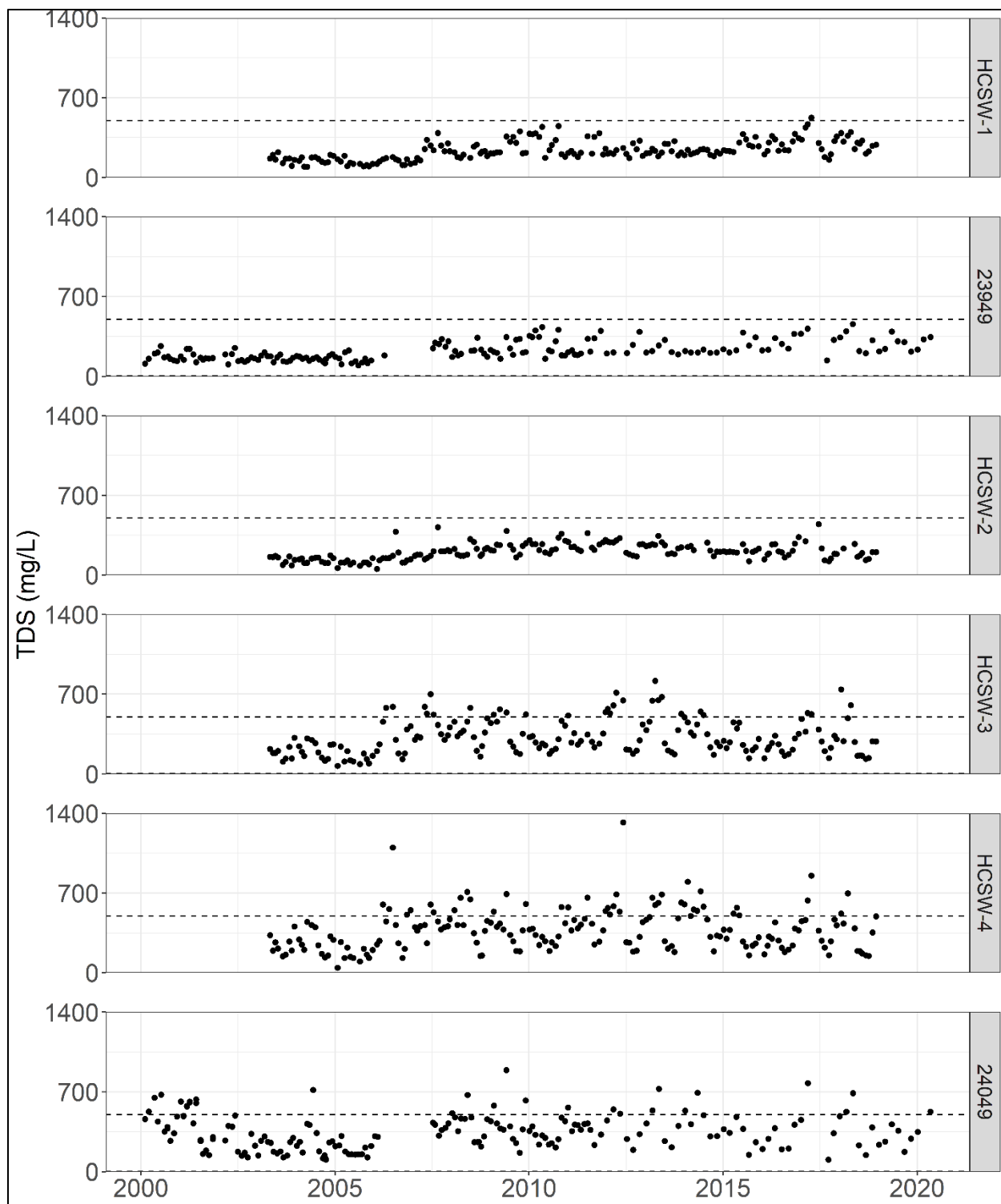
Figure 3. Sample distribution for total dissolved solids (TDS) at HCSP (HCSW-1 through -4) and SWFWMD (23949 and 24049) stations, listed from upstream to downstream. The dashed line indicates the State water quality threshold for Class I waterbodies (>500 mg/L). Note this threshold is for the annual geometric mean rather than for individual samples.

Table 2. Solutions table for fixed effects for the generalized mixed model to predict total dissolved solids exceedances.

Fixed effects	Estimate	p-value
Intercept	2.33956	0.001
Flow	-0.05756	0.001
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	0.27187	0.544
Quarter 3 (Jul-Sep)	1.79390	0.228
Quarter 4 (Oct-Dec)	-0.01473	0.986
RKM	-0.10693	<0.001
Flow*Quarter 1 (Jan-Mar)	0	
Flow*Quarter 2 (Apr-Jun)	0.03615	0.064
Flow*Quarter 3 (Jul-Sep)	-0.04115	0.410
Flow*Quarter 4 (Oct-Dec)	-0.06422	0.218
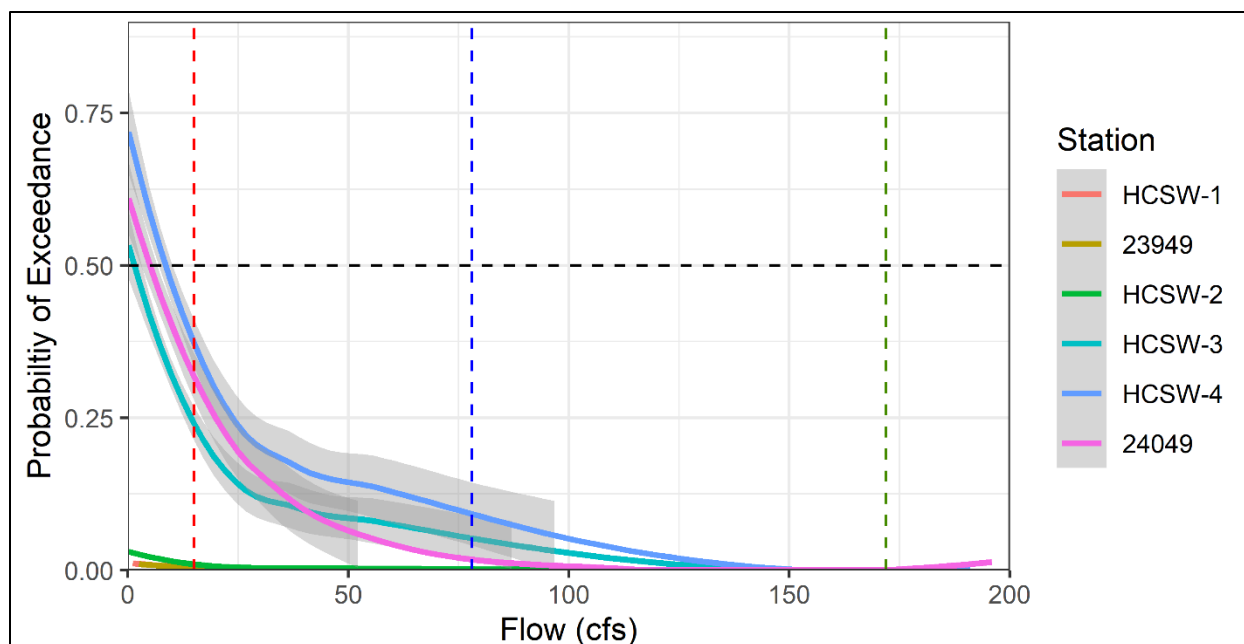
Figure 4: Predicted probability of exceedance of the DEP criteria for total dissolved solids in Class I waters (>500 mg/L) with flow at the USGS Horse Creek at SR72 near Arcadia, FL gage (No. 02297310). The dashed black line indicates the 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3a (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Dissolved Calcium

Data from HCSP stations HCSW-1 through HCSW-4 and SWFWMD stations 23949 and 24049 were utilized in the creation of GLMMs for dissolved calcium. Their sample distribution regardless of flow block is presented in Figure 5. Exceedance of the State Class I water quality threshold of 100 mg/L for dissolved calcium was utilized as the binary response. Using the GLMM described in Table 3 with an AIC of 199.6, the predicted probability of exceedance was below the 0.5 probability threshold during Blocks 2, 3a, and 3b at each station (Figure 6). Flow reductions up to 20% in Blocks 2, 3a, and 3b did not affect the probability of dissolved calcium exceedance above the 0.5 probability threshold.
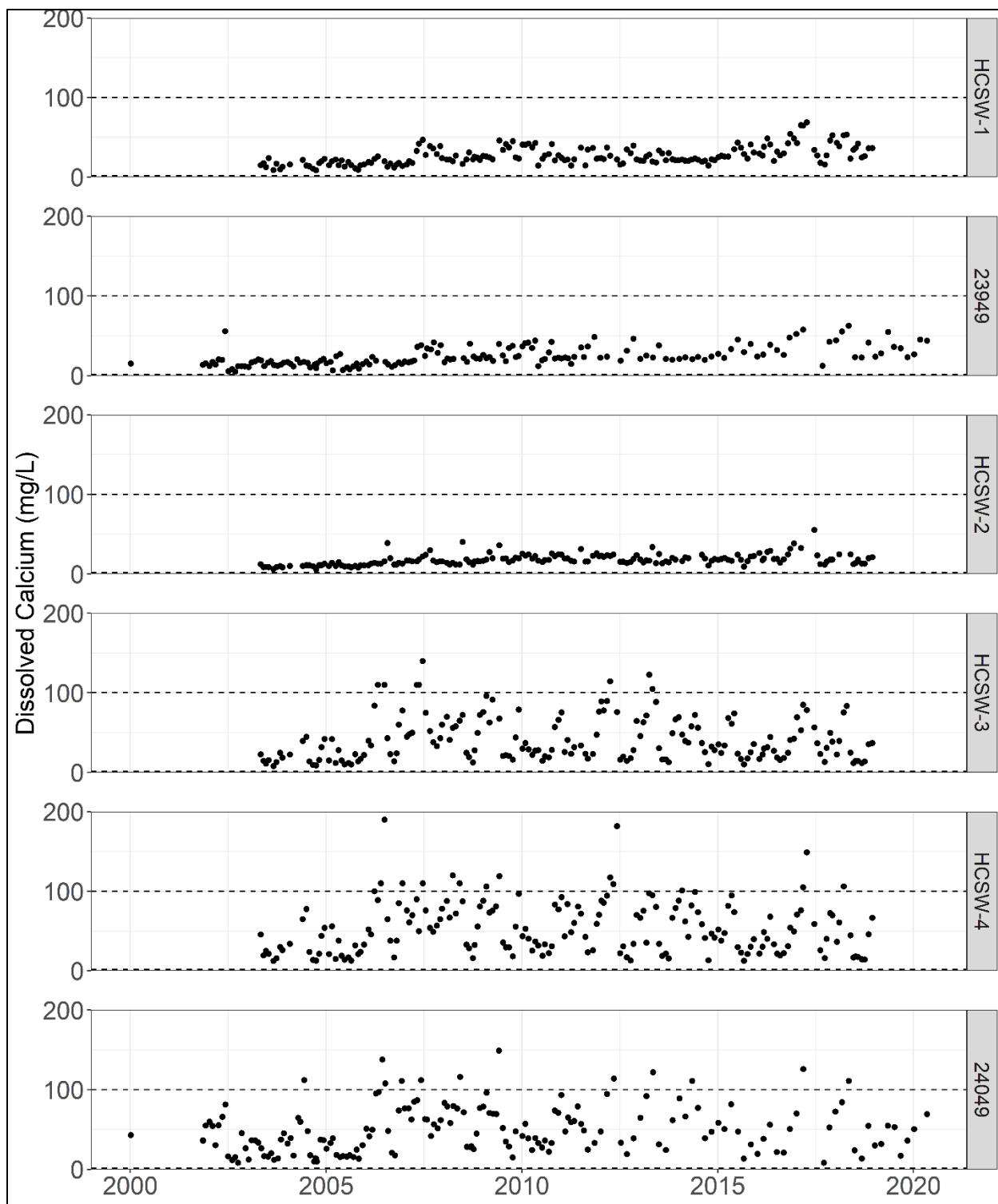
Figure 5. Sample distribution for dissolved calcium at HCSP (HCSW-1 through -4) and SWFWMD (23949 and 24049) stations, listed from upstream to downstream. The dashed line indicates the State water quality threshold for Class I waterbodies (>100 mg/L). Note this threshold is for the annual geometric mean rather than for individual samples.

Table 3. Solutions table for fixed effects for the generalized mixed model to predict State water quality threshold exceedances for dissolved calcium.

Fixed effects	Estimate	p-value
Intercept	1.75477	0.025
Log(Flow)	-0.25247	<0.001
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	1.38670	0.004
Quarter 3 (Jul-Sep)	0.53227	0.544
Quarter 4 (Oct-Dec)	-0.73273	0.375
RKM	-0.10223	<0.001
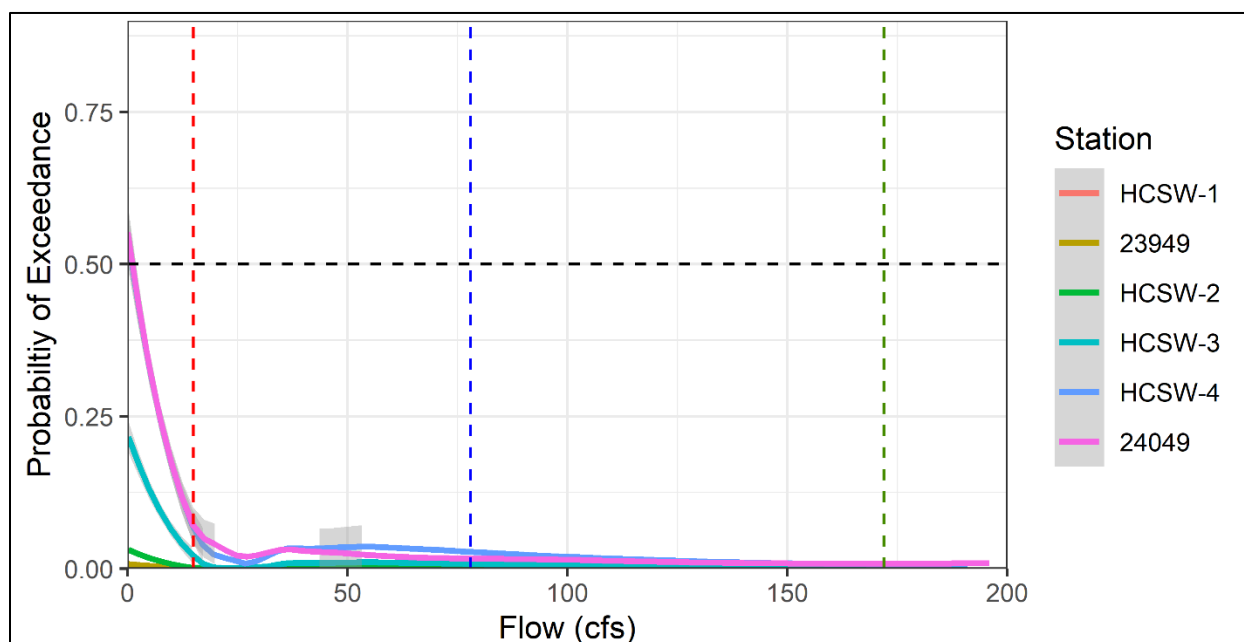
Figure 6: Predicted probability of exceedance of the DEP criteria for dissolved calcium in Class I waters (>100 mg/L) with flow at the USGS Horse Creek at SR72 near Arcadia, FL gage (No. 02297310). The dashed black line indicates the 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3 (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Dissolved Sulfate

Data from HCSP stations HCSW-1 through HCSW-4 and SWFWMD stations 23949 and 24049 were utilized in the creation of GLMMs for dissolved sulfate. Their sample distribution regardless of flow block is presented in Figure 7. Exceedance of the State Class I water quality threshold of 250 mg/L for dissolved sulfate was utilized as the binary response. Using the GLMM described in Table 4 with an AIC of 327.7, the predicted probability of exceedance was below the 0.5 probability threshold outside of Block 1 for

each station (Figure 8). Flow reductions up to 20% in Blocks 2, 3a, and 3b did not impact the probability of dissolved sulfate exceedance above the 0.5 threshold.
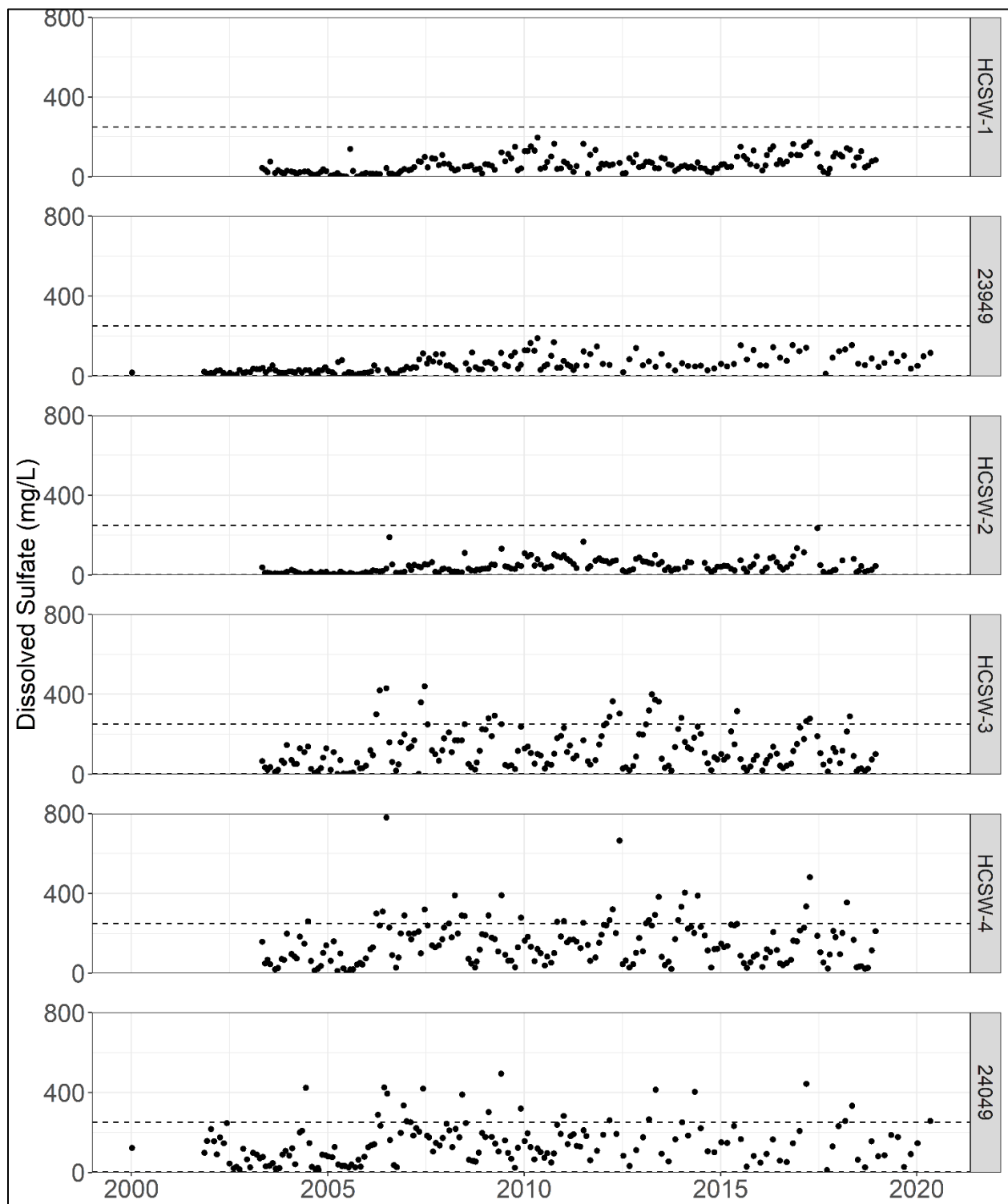

Figure 7. Sample distribution for dissolved calcium at HCSP (HCSW-1 through -4) and SWFWMD (23949 and 24049) stations, listed from upstream to downstream. The dashed line indicates the State water

quality threshold for Class I waterbodies (>250 mg/L). Note this threshold is for the annual geometric mean rather than for individual samples.

Table 4. Solutions table for fixed effects for the generalized mixed model to predict State water quality threshold exceedances for dissolved sulfate.

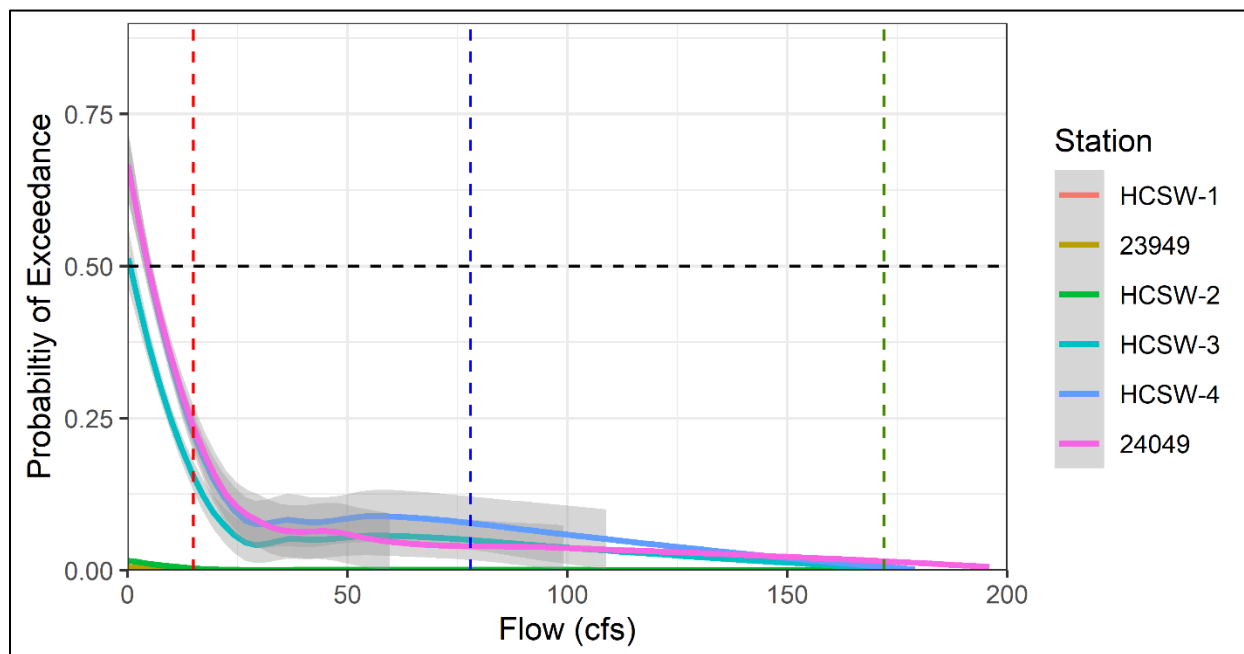| Fixed effects	Estimate	p-value
Intercept	6.429207	<0.001
Log(Flow)	-4.28349	<0.001
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	-3.36054	0.001
Quarter 3 (Jul-Sep)	2.21109	0.546
Quarter 4 (Oct-Dec)	-2.31538	0.296
RKM	-0.12937	<0.001
Log(Flow)*Quarter 1 (Jan-Mar)	0	
Log(Flow)*Quarter 2 (Apr-Jun)	3.33577	<0.001
Log(Flow)*Quarter 3 (Jul-Sep)	-1.24522	0.627
Log(Flow)*Quarter 4 (Oct-Dec)	0.66739	0.733

Figure 8: Predicted probability of exceedance of the DEP criteria for dissolved sulfate in Class I waters (>250 mg/L) with flow at the USGS Horse Creek at SR72 near Arcadia gage (No. 02297310). The dashed black line indicates a 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3a (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Total Nitrogen

Data from HCSP stations HCSW-1 through HCSW-4 and SWFWMD stations 23949 and 24049 were utilized in the creation of GLMMs for total nitrogen. Their sample distribution regardless of flow block is presented in Figure 9. Exceedance of the State Class III water quality threshold of 1.65 mg/L for total nitrogen was utilized as the binary response. Using the GLMM described in Table 5 with an AIC of 905.6, the predicted probability of exceedance was below the 0.5 probability threshold within each block (Figure 10). Flow reduction scenarios up to 20% did not increase the 0.5 probability of exceedance in Blocks 2, 3a, or 3b.
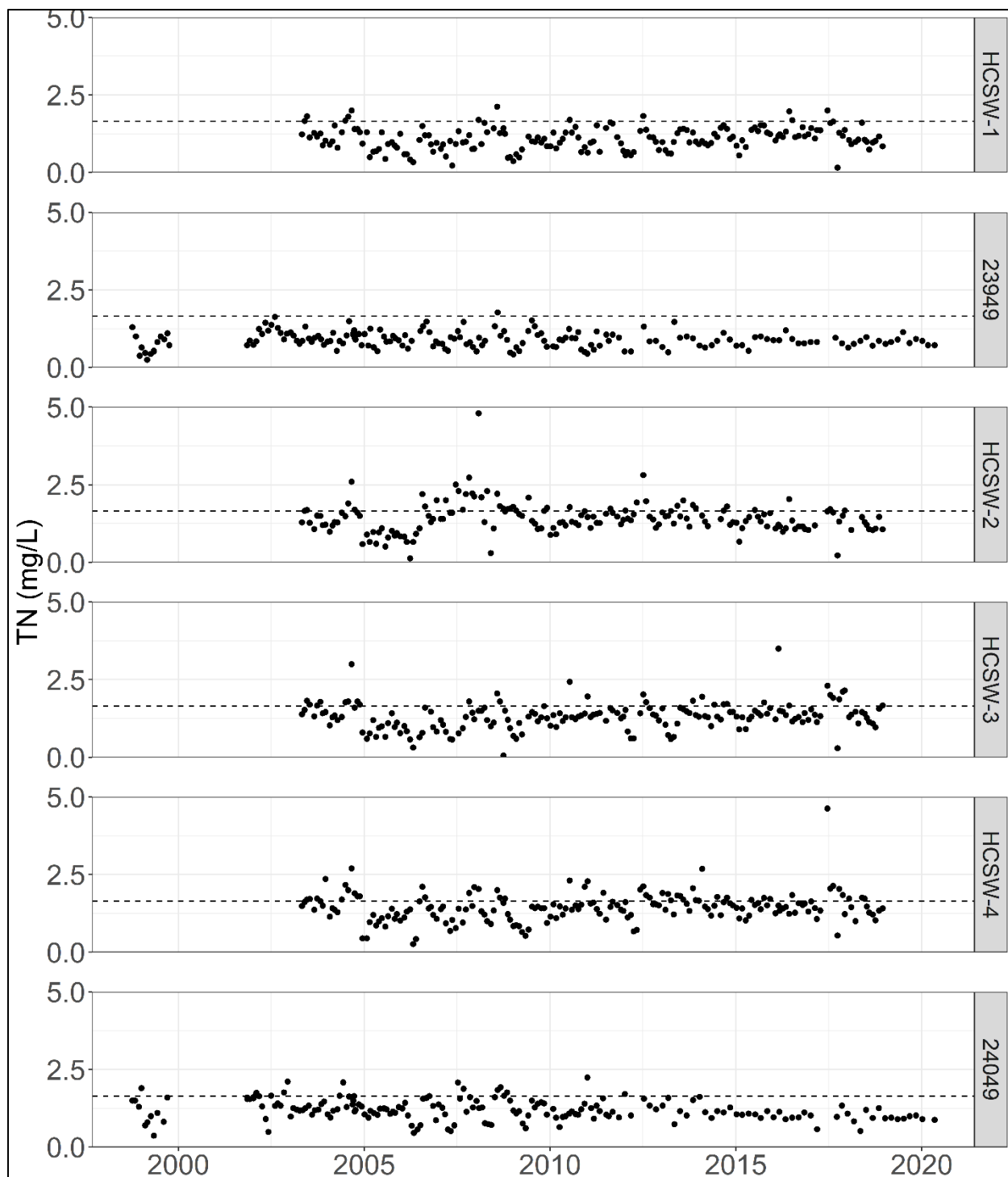
Figure 9. Sample distribution for total nitrogen (TN) at HCSP (HCSW-1 through -4) and SWFWMD (23949 and 24049) stations, listed from upstream to downstream. The dashed line indicates the State water quality threshold for Class III waterbodies (>1.65 mg/L). Note this threshold is for the annual geometric mean rather than for individual samples.

Table 5. Solutions table for fixed effects for the generalized mixed model to predict State water quality threshold exceedances for total nitrogen.

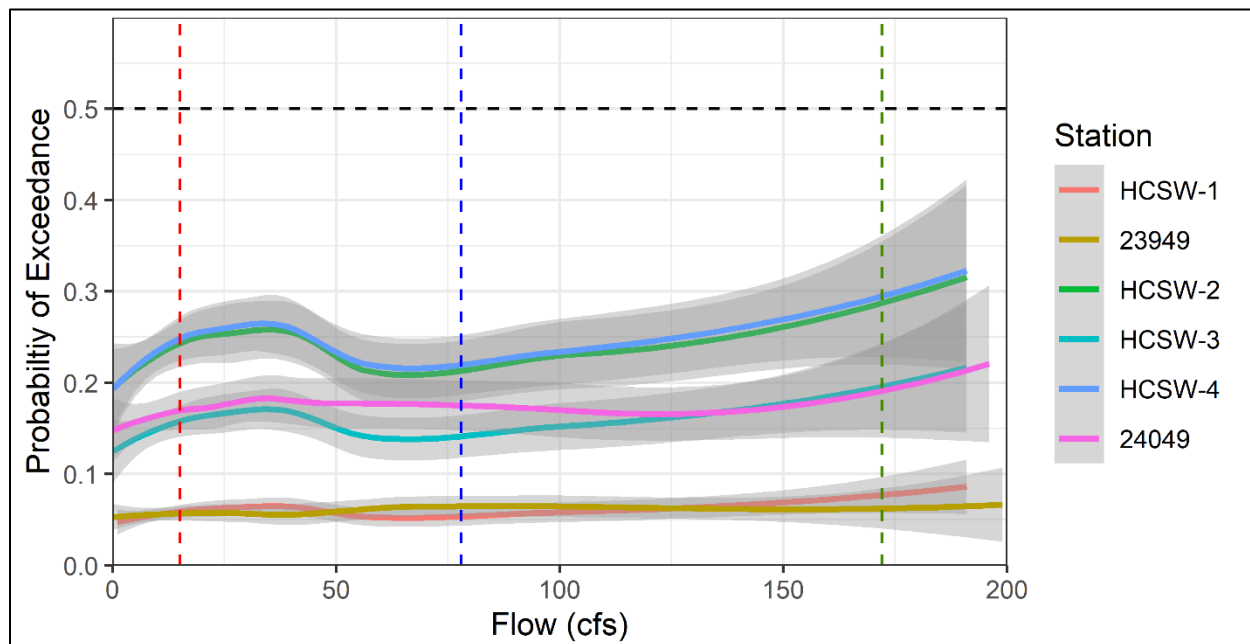| Fixed effects	Estimate	p-value
Intercept	-0.8660	0.227
Log(Flow)	-1.2553	0.013
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	-1.5918	0.037
Quarter 3 (Jul-Sep)	-0.3612	0.687
Quarter 4 (Oct-Dec)	-0.2670	0.746
Log(Flow)*Quarter 1 (Jan-Mar)	0	
Log(Flow)*Quarter 2 (Apr-Jun)	1.6333	0.004
Log(Flow)*Quarter 3 (Jul-Sep)	1.2899	0.023
Log(Flow)*Quarter 4 (Oct-Dec)	0.8662	0.143

Figure 10: Predicted probability of exceedance of the DEP criteria for total nitrogen in Class III waters (>1.65 mg/L) with flow at the USGS Horse Creek at SR72 near Arcadia, FL gage (No. 02297310). The dashed black line indicates the 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3a (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Total Phosphorus

Data from DEP station 21FLA 025020111, SWFWMD stations 23949 and 24049, and the USGS Horse Creek at SR72 near Arcadia, FL (No. 02297310) gage were utilized in the creation of GLMMs for total phosphorus. The HCSP program collects orthophosphate data, rather than total phosphorus. The sample distribution for total phosphorus in Horse Creek, regardless of flow block, is presented in Figure 11.

Exceedance of the DEP Class III water threshold of 0.49 mg/L for total phosphorus was utilized as the binary response. Using the GLMM described in Table 6 with an AIC of 863.5, the predicted probabilities of exceedance were above the 0.5 threshold for discontinued DEP station 21FLA 25020111 during portions of all blocks, and for discontinued USGS station 02297310 during Blocks 3a and 3b (Figure 12). Flow reductions of up to 20% did not affect the 0.5 probability of threshold exceedances at any station. Results from modeling for this analyte should be interpreted with caution, as three of the stations occurred at the same geographic location, albeit over different periods of record, and sample collection frequencies.
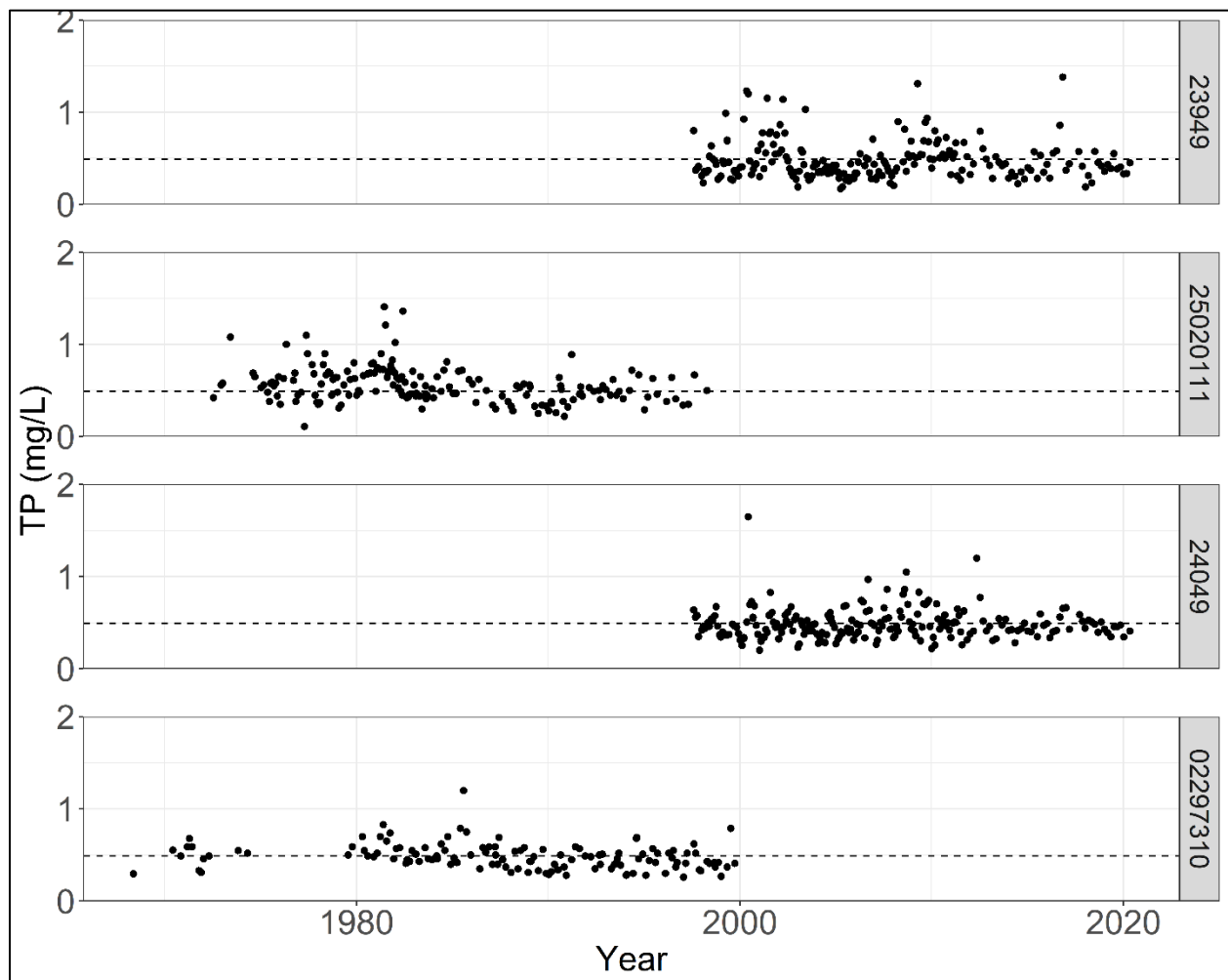

Figure 11. Sample distribution for total phosphorus (TP) at DEP ((21FLA) 25020111), SWFWMD (23949 and 24049), and USGS (02297310) stations listed from upstream to downstream. The dashed line

indicates the State water quality threshold for total phosphorus in Class III waterbodies (>0.49 mg/L). Note this threshold is for the annual geometric mean rather than for individual samples.

Table 6. Solutions table for fixed effects for the generalized mixed model to predict State water quality threshold exceedances for total phosphorus.

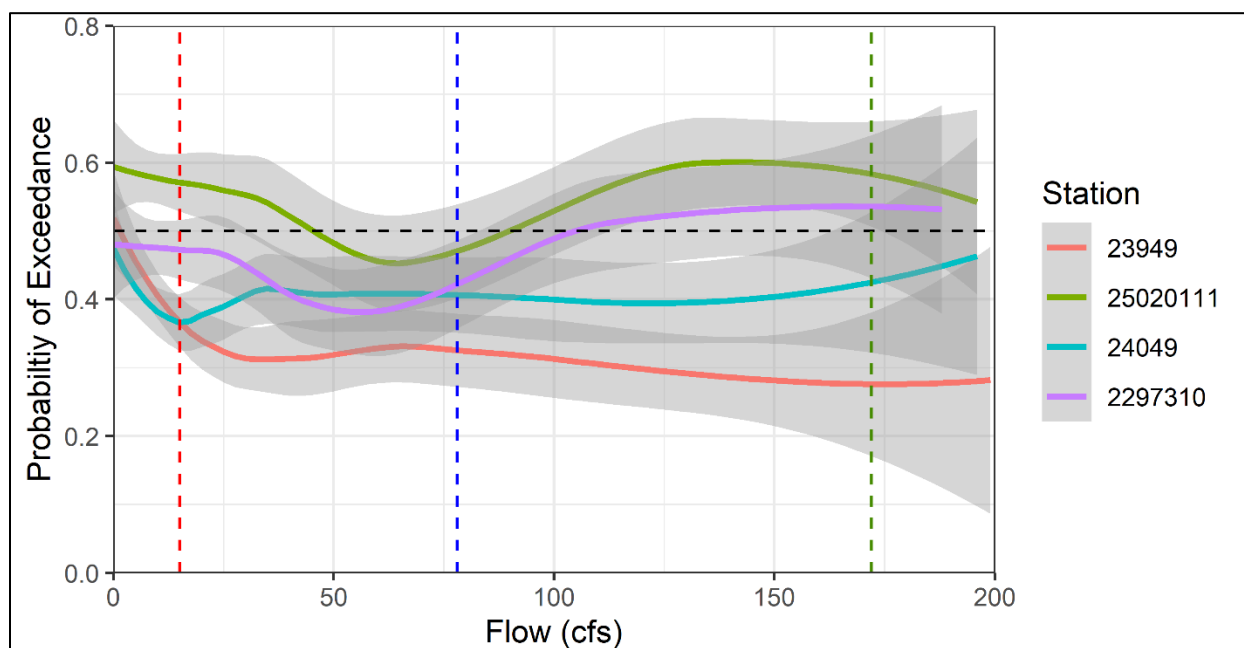| Fixed effects	Estimate	p-value
Intercept	-0.984333	0.034
Log(Flow)	0.044087	0.824
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	1.343361	<0.001
Quarter 3 (Jul-Sep)	1.798233	<0.001
Quarter 4 (Oct-Dec)	1.061446	<0.001
RKM	0.005491	0.644
Log(Flow)*RKM	-0.010724	0.040

Figure 12: Predicted probability of exceedance of the DEP criteria for total phosphorus in Class III waters (>0.49 mg/L) with flow at the USGS Horse Creek at SR72 near Arcadia, FL gage (No. 02297310). The dashed black line indicates the 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3 (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Dissolved Oxygen Percent Saturation

Data from DEP stations (21FLA 25020428, 21FLA 25020430, 21FLA 25020423, 21FLA 25020111, and 21FLTM 25020420), HCSP stations (HCSW-1, -2, -3, and -4) and USGS Horse Creek at SR72 near Arcadia (No. 02297310) were utilized in the creation of GLMMs for dissolved oxygen percent saturation. Their sample distribution regardless of flow block is presented in Figure 13. Sample values below the State Class III water quality threshold of 38% for dissolved oxygen were utilized as the binary response. Using the GLMM described in Table 7 with an AIC of 287.4, the predicted probabilities of exceedance were above the 0.5 threshold for discontinued DEP station 21FLA 25020430 in all blocks and for HCSP station HCSW-2 in Blocks 2, 3a, and 3b (Figure 14). Flow reductions of up to 20% did not increase the probability of threshold exceedance for any station.
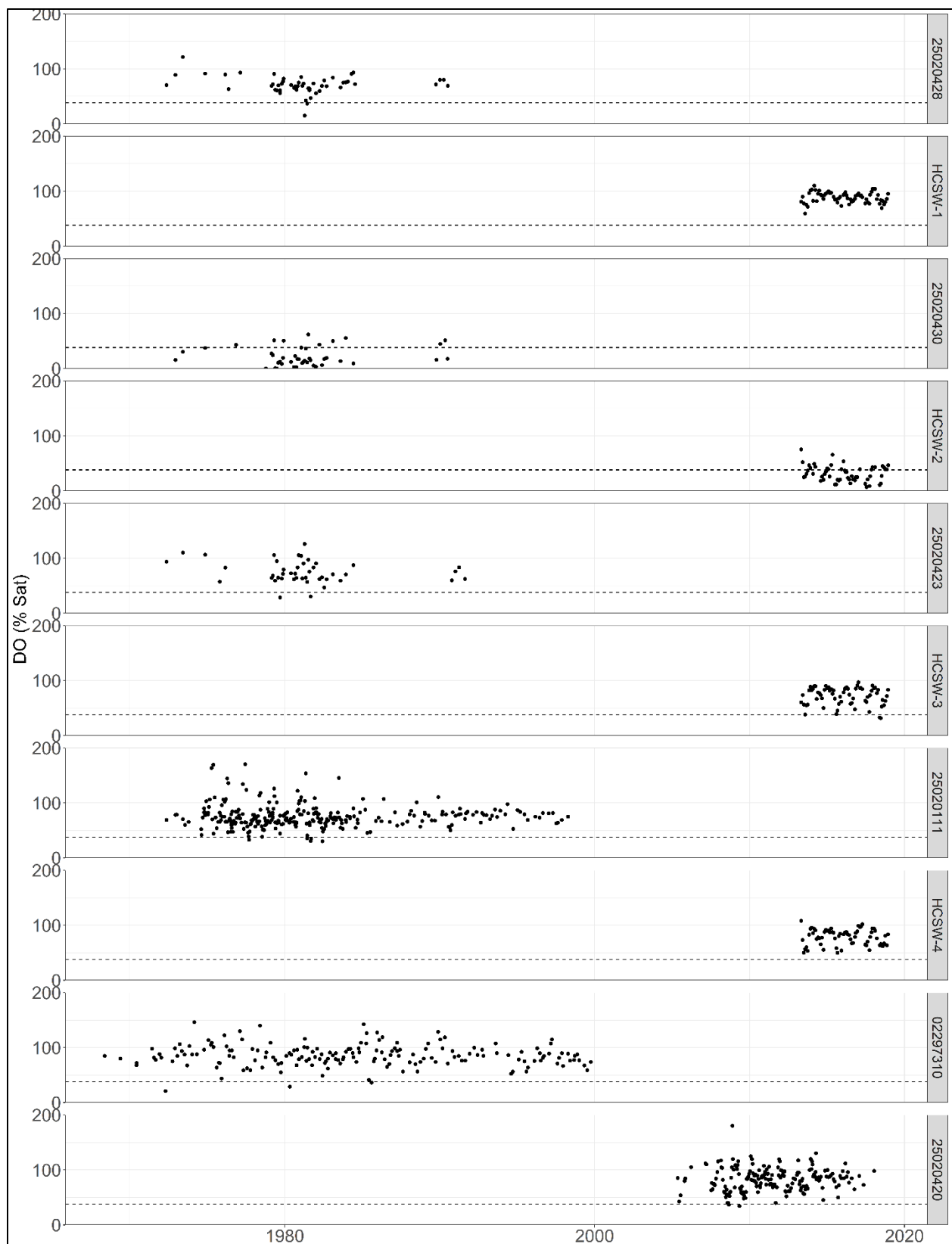
Figure 13. Sample distribution for dissolved oxygen percent saturation (DO % Sat) at DEP ((21FLA) 25020428, (21FLA) 25020430, (21FLA) 25020423, (21FLA) 25020111, and (21 FLTM) 25020420), HCSP

(HCSW-1, -2, -3, and -4), and USGS (Gage No. 02297310) listed from upstream to downstream. The dashed line indicates the State water quality threshold for dissolved oxygen percent saturation (<38%).

Table 7. Solutions table for fixed effects for the generalized mixed model to predict State water quality threshold exceedances for dissolved oxygen percent saturation.

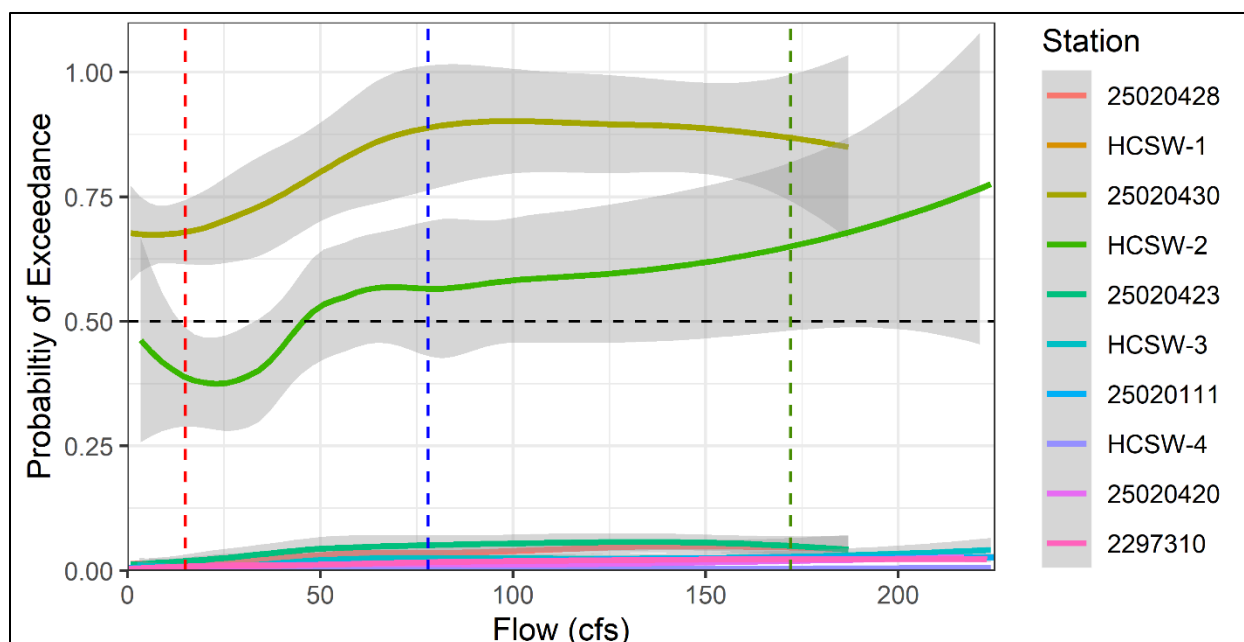| Fixed effects	Estimate	p-value
Intercept	-6.6168	<0.001
Log(Flow)	1.0671	<0.001
Quarter 1 (Jan-Mar)	0	
Quarter 2 (Apr-Jun)	1.9600	0.001
Quarter 3 (Jul-Sep)	1.4087	0.019
Quarter 4 (Oct-Dec)	0.5877	0.302

Figure 14: Predicted probability of exceedance of the DEP criteria for dissolved oxygen percent saturation in Class III waters (<38%) with flow at the USGS Horse Creek at SR72 near Arcadia, FL gage (No. 02297310). The dashed black line indicates the 0.5 probability of exceedance. The dashed red line indicates the border of Block 1 and Block 2 (15 cfs), the dashed blue line delineates the border between Block 2 and Block 3a (78 cfs) and the dashed green line shows the border between Block 3a and Block 3b (172 cfs). For visualization purposes, the relationship with flow is only shown through 200 cfs. Stations are listed in the key from upstream to downstream.

Summary

All State water quality thresholds mentioned, apart from dissolved oxygen percent saturation, are based upon the annual geometric mean over a period of time. The State water quality threshold for dissolved oxygen percent saturation is exceeded if more than 10% of the daily average dissolved oxygen percent

saturation values are below 38%. While the statistics calculated below are modeled off available sample data, and therefore, reflect the probability of exceedance on a per sample basis, it is assumed that if the number of samples exceeding the threshold is not substantially increased by flow reduction, the probability of exceeding the State water quality threshold once an annual geometric mean or 10% of daily averages is calculated would also not increase.

After the analysis was conducted, the only somewhat sensitive water quality parameter to flow reductions up to 20% was TDS at station HCSW-4 during Block 2 flows. For this station, the recommended minimum flows were predicted to cause 13.56% of samples at HCSW-4 to be above the 0.5 probability threshold for exceeding the NNC, as compared to 8.47% of samples under baseline conditions. This is not a substantial change and is not expected to change the overall probability of the station exceeding the State water quality threshold for TDS when annual geometric means are calculated.

Therefore, water quality constituents in Horse Creek are not expected to substantially change in response to flow reductions associated with implementation of the recommended minimum flows. The recommended minimum flows for Horse Creek are, therefore, not expected to negatively affect water quality or impair the water designated use of either water body.

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