2017 Chesapeake Bay Program Midpoint Assessment Document

Diagnostics of the Chesapeake Bay Nonattaining Dissolved Oxygen Criteria Segments

Photo by Will Parson

Chesapeake Bay Program
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Table of Contents

Introduction and Background

To support the 2017 CBP Midpoint Assessment, the bay-wide Phase 2 Watershed Implementation Plan (WIP2) planning scenarios developed in 2011 by the jurisdictions using the Phase 5 CBP modeling tools were run on the updated 2018 modeling suite, which includes the Phase 6 Watershed Model (WSM) and the 2017 Water Quality and Sediment Transport Model (WQSTM). Scenarios were evaluated for attainment of applicable dissolved oxygen (DO) criteria as described in 2010 TMDL documentation (USEPA, 2010). The estimated Phase 6 WIP2 loads, which are roughly equivalent to the Phase 3 WIP draft planning targets, deliver 195 million pounds of total nitrogen and 13.7 million pounds of total phosphorus to the tidal waters of the Bay. At the level of nutrient reductions estimated in the Phase 6 WIP2 scenario, ten segment-designated use combinations failed to attain applicable DO standards for the 1993 to 1995 assessment period, i.e., the critical period of water quality assessment (USEPA, 2010). Eight of these are in Open Water DO designated uses (DU), one is a Deep Water DU, and one is a Deep Channel DU.

The purpose of this report is to document estimated DO concentration responses and associated criteria attainment to Phase 6 WIP2 scenario loads, in the ten segments. Historical and current water quality in each of these segment-DUs is explored, as well as any evidence of responsiveness to observed load reductions.

Each WIP2 non-attaining segment was evaluated to determine the observed (both historical and current) patterns of water quality and the WQSTM-simulated patterns of water quality response to load reductions. The analysis will help decision makers and stakeholders refine the draft Phase III Watershed Implementation Plans and to determine if variances are necessary for designated uses in some segments.

Scenario attainment assessment methods

An understanding of the methods of the scenario attainment assessment of DO is essential to understanding the nonattainment results. For each segment, the scenario assessment process follows these steps: 1) match monitoring stations to WQSTM grid cells; 2) generate linear regressions representing modeled response to load reductions; 3) scenario-modify the monitoring data by applying the regression; 4) assess the monitoring data and combine the monthly interpolations to assess violation rates against reference curve of allowable criteria exceedance (Keisman and Shenk, 2013).

List of Segments failing to attain the Dissolved Oxygen Standards

Table 1 shows segment-DUs failing to attain applicable DO criteria for the 1993 to 1995 assessment period. Locations are highlighted in Figure 1. Segments identified are the Gunpowder River (GUNOH), Patuxent Tidal Fresh (PAXTF), Wicomico River (WICMH), Corrotoman River (CRRMH), Upper Pamunkey Tidal Fresh (PMKTF), Eastern, Western, and Southern Branch of Elizabeth River (EBEMH, WBEMH, and SBEMH), South River (SOUMH), and Eastern Bay (EASMH). Excluded from this list are segment-DUs with nonattainment rates less than 1.4 percent and those with special restoration variances at the WIP2 scenario level, as these are in attainment per TMDL decision rules.

Table 1: List of Segments failing to attain the Dissolved Oxygen Standards at WIP2 195 TN AND 13.7 TP (Red stands for not attaining the WQS and Green stands for attaining WQS)

Designated Use	CBSeg	1985Progress 347TN 30.4TP	2013Progress 253TN 15.9TP	WIP2 195TN 13.7TP	E3 133TN 8.6TP	All_Forest 40TN 3.9TP
Open Water	GUNOH	5%	5%	5%	0%	0%
	PAXTF	9%	3%	8%	0%	0%
	CRRMH	25%	16%	5%	2%	0%
	PMKTF	9%	9%	9%	5%	0%
	WBEMH	8%	8%	8%	3%	0%
	SBEMH	48%	34%	26%	12%	3%
	EBEMH	23%	18%	8%	0%	0%
	WICMH	11%	11%	5%	5%	1%
Deep Water	SOUMH	20%	3%	3%	0%	0%
Deep Channel	EASMH	21%	13%	6%	0%	0%

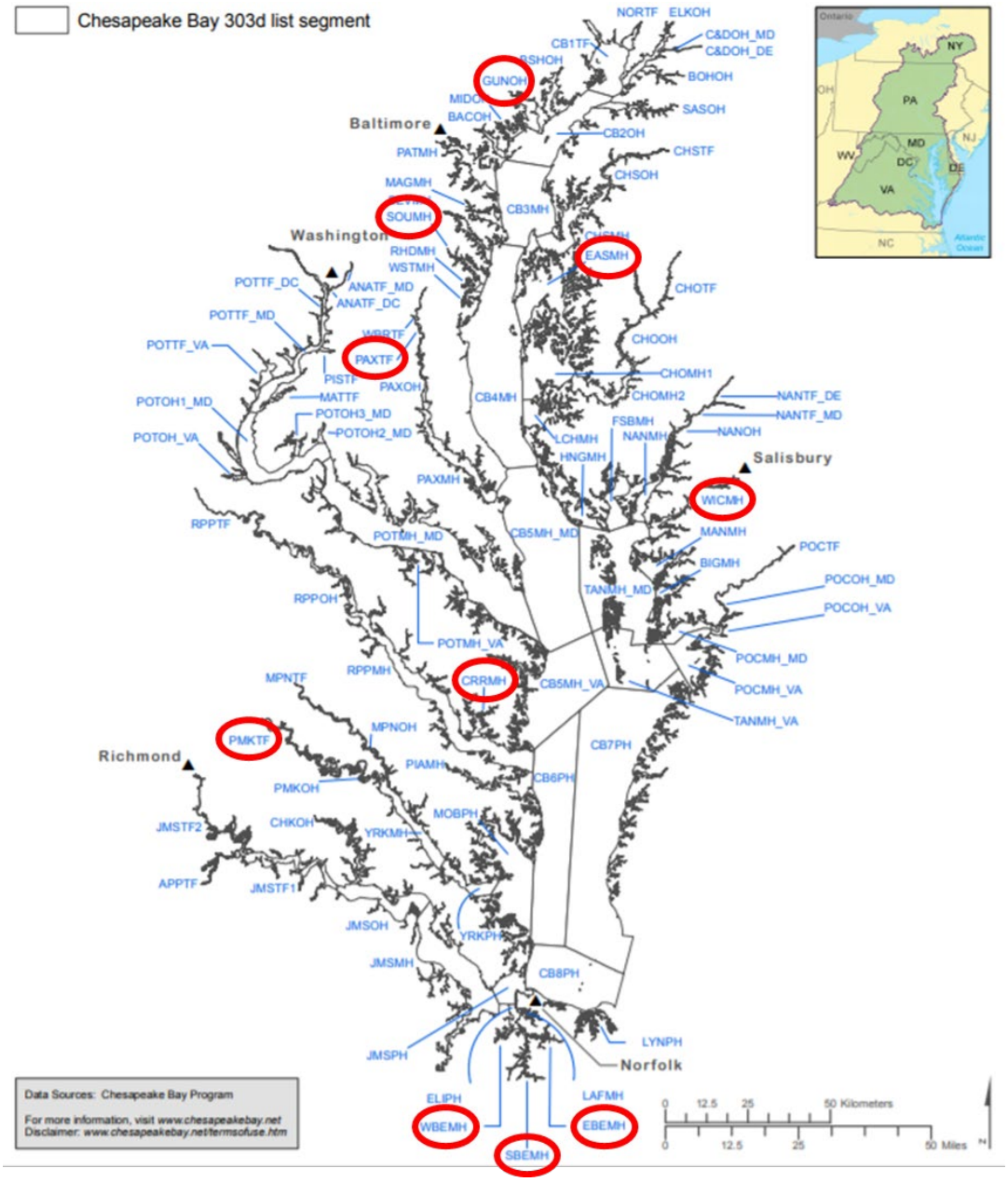


Figure 1: Location of the non-attaining segments

Preliminary observations of the nonattainment rates are as follows. For five of the ten segments, nonattainment rates decrease by 6-11 percent between the 2013 Progress scenario and the WIP2 Scenario. In contrast, percent nonattainment shows no change between these scenarios for the GUNOH, PMKTF, WBEMH, and SOUMH segments. The nonattainment rate for PAXTF decreases to 3 percent from 1985 Progress to 2013 Progress, but increases to 8 percent at the WIP2 level. Change in loads between the 2013 Progress and WIP2 scenarios differs from bay-wide reductions and varies across non-attaining segments.

Characterization of WIP2 non-attaining segments

The analysis of WIP2 non-attaining segments relies on both historical observations and simulated results. Each of the ten segments was evaluated in the following aspects: 1) historical record of observed dissolved oxygen (DO) and chlorophyll-*a* concentrations and trends; 2) historical record of dissolved oxygen criteria attainment; 3) CBP Watershed Model (WSM)-estimated load reductions to non-attaining segments; 4) WQSTM-simulated response to estimated load reductions in non-attaining segments; and 5) combination of 1993-1995 historical observations and the scenario modified results driving nonattainment.

Open-Water Segments

Open-Water Gunpowder River (GUNOH)

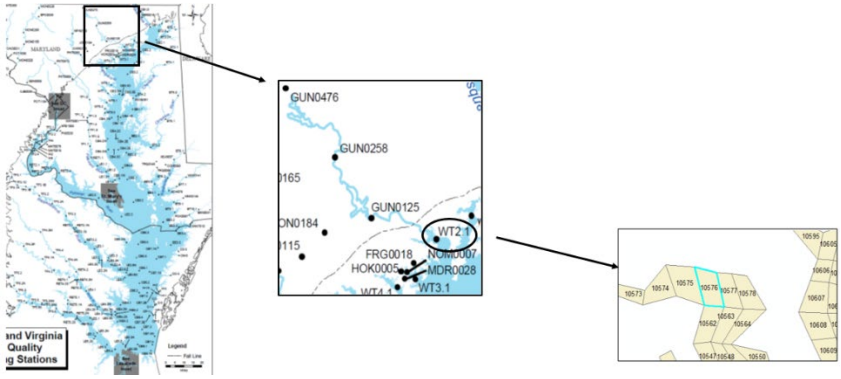


Figure 2: Location of GUNOH and the monitoring station WT2.1 WQSTM grid cell location

There is a single tidal Bay monitoring station in the Gunpowder River GUNOH segment, WT2.1 (Figure 2). The historical water quality DO monitoring time series data and histogram in summer (June, July, August, and September) from 1985 to 2016 for this location (Figure 3) indicate that summer DO concentrations below 5 mg/L in the Gunpowder River have been rare. Two of these instances were in July 1994 with DO of 4.4 mg/L and 4.6 mg/L. The red line at 5.5mg/l DO in Figure 3 marks the DO water quality criteria for tidal fresh waters in the Chesapeake. Figure 4 indicates the spring and summer chlorophyll-*a* concentrations have been fluctuating since 1985. The concentrations spike in 1997 and 2012, and the mode is between 10 to 20 ug/L.

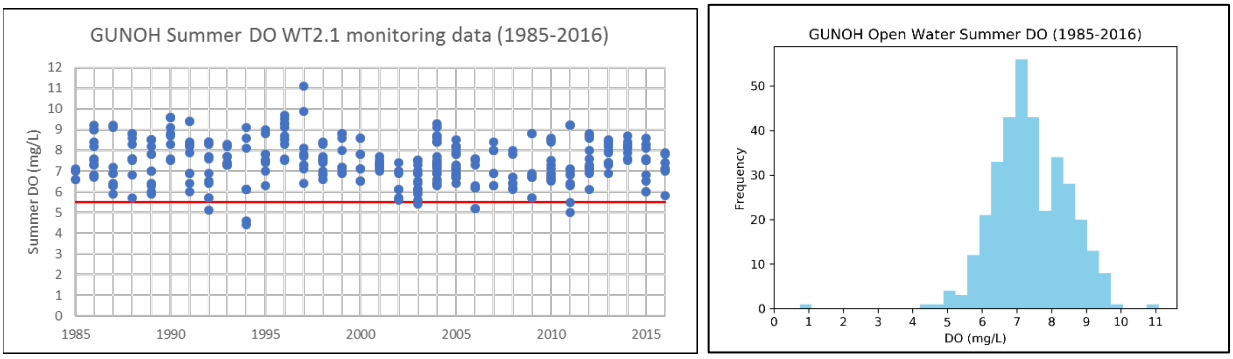


Figure 3: Summer DO measurement taken in summer months (June-September) at water quality monitoring station WT2.1 in the Gunpower River 1985-2016.

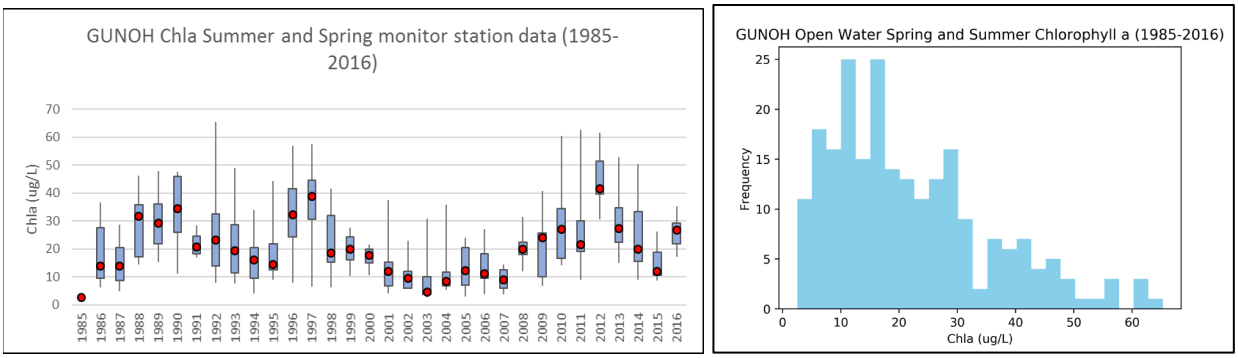


Figure 4: Boxplot of GUNOH chlorophyll-a measurement taken in spring and summer at the station WT2.1 in the Gunpowder River

Table 2 is the analysis of trend in water quality for the monitoring station WT2.1 using Generalized Additive Models (GAMs) (Murphy and Perry, 2018). The GAM's trend result indicates that the surface chlorophyll-*a* concentration has increased by 67 percent compared to 2007 (p value < 0.01). Both long-term and short-term summer bottom DO concentration has increased at the 5 percent significance level. The red line in Figure 6 is the GAM trend for summer bottom DO concentration. There is no significant trend with either nitrogen or phosphorous at the 5 percent significance level. The GUNOH attained the DO summer 30-day mean criterion in all but 6 assessment periods between 1985-2015 (Figure 5). Failing periods were those containing the July 1994 and June 2011 sampling events.

Table 2: Analysis of monitoring station WT2.1 water quality trends using GAM

	Parameters	Period Start	Percent Change	p value
Station WT2.1	Chla (surface)	2007	67.40	p<0.01
	DO (Summer bottom)	1985	11.88	0.01
	DO (Summer bottom)	2007	7.93	0.03

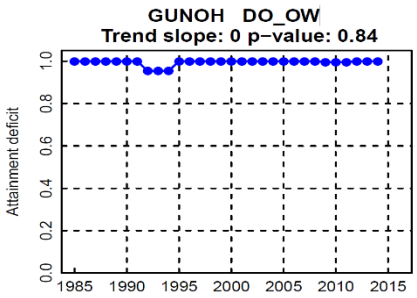


Figure 5: Summer 30-day mean criterion assessment in GUNOH

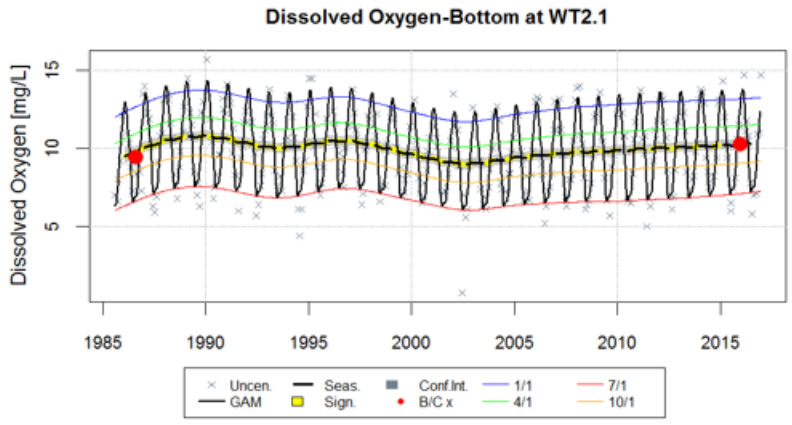


Figure 6: Analysis of monitoring station WT2.1 bottom DO trends using GAM

The estimated loads for the four scenarios is generated using the Chesapeake Assessment Scenario Tool (CAST), which is an online interface to the Phase 6 Watershed Model (WSM). CAST estimated 254 thousand pounds (14 percent) of nitrogen and 57 thousand pounds (46 percent) of phosphorous reduction to GUNOH from 1985 to 2013 (Figure 7). An additional 13 percent of nitrogen and 28 percent of phosphorous reduction is estimated from the 2013 Progress to WIP2 Scenario. The criteria assessment results of GUNOH (Table 3) shows that the nonattainment rate remained at 5 percent for 1985 Progress, 2013 Progress, and the WIP2 Scenario even though the nutrient loads decreased in the GUNOH segment.

Figure 7: Nutrient loads (EOT) in GUNOH

Table 3: OW GUNOH Criteria Assessment

CBSeg	1985Progress	2013Progress	WIP2	E3	All_Forest
	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
GUNOH	5%	5%	5%	0%	0%

The cumulative frequency distribution (CFD) curves for the base scenario and WIP2 Scenario show one monthly violation persisted in the WIP2 Scenario in the 1993 to 1995 period (Figure 8). The assessment results identify that the violation corresponds with July 1994. Figure 9 demonstrates the scenario simulated response at the WIP2 and E3 load level in July 1994 in the WQSTM grid cell 10576. The black solid line represents a one-to-one reference line, the grey dashed line is the scenario-simulated response in DO at the WIP2 level, and the green line simulates response at the E3 level. The red dots on the one-to-one line are the observed DO concentrations for the two sampling events in July 1994 at monitoring station WT2.1, and the red triangles are the scenario-modified DO concentrations at the WIP2

Table 4: Monthly open water DO criterion nonattainment percentages for GUNOH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	0%	0%
1993	8	0%	0%
1993	9	0%	0%
1994	6	0%	0%
1994	7	100%	100%
1994	8	0%	0%
1994	9	0%	0%
1995	6	0%	0%
1995	7	0%	0%
1995	8	0%	0%
1995	9	0%	0%

level. The WQSTM estimates that DO improved by 17 percent at the WIP2 level and the 25 percent at the E3 level.

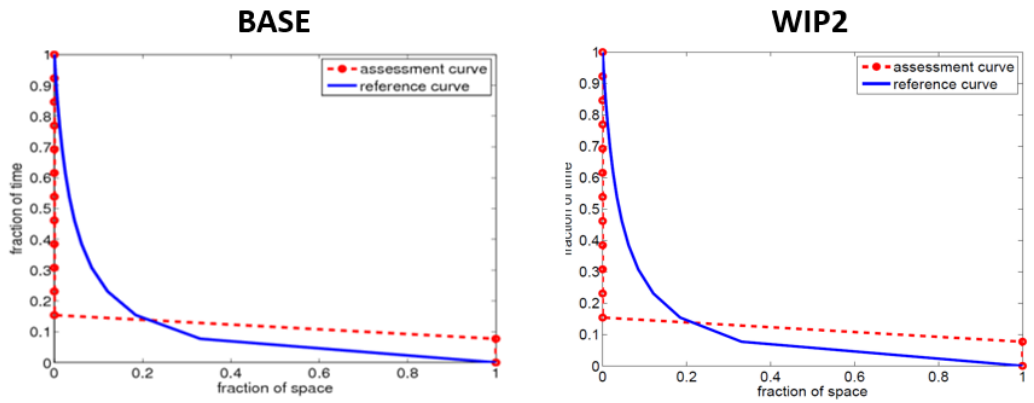


Figure 8: CFD curves for the Base scenario and WIP2 scenario - GUNOH

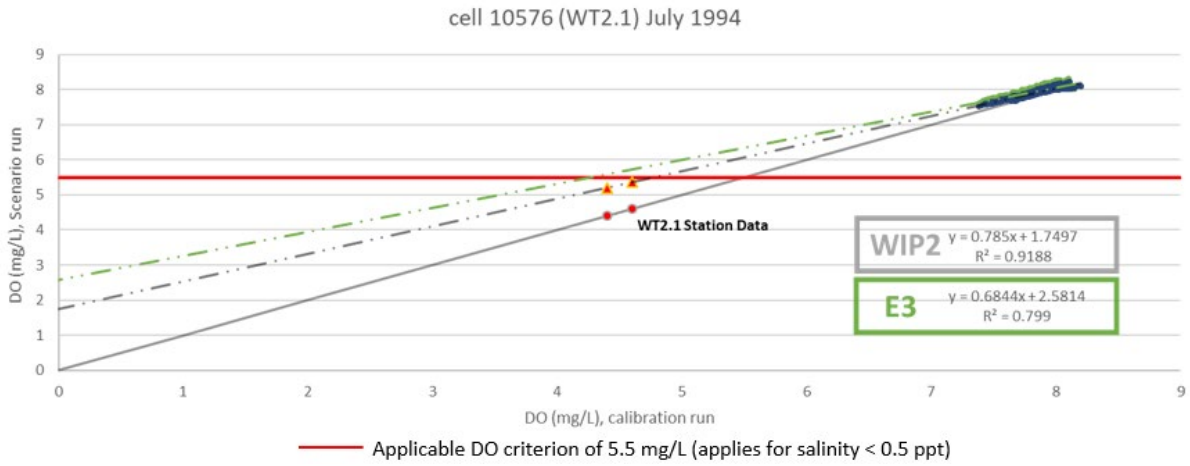


Figure 9: Scenario simulated response of July 1994 in cell 10576

The violin plot (Figure 10) compares the distributions of the observed DO concentrations at the WT2.1 station and the WIP2 scenario-modified observations from 1993 to 1995. The dashed lines each represented the 25 percent, 50 percent, and 75 percent quantiles of each distribution. There is a noticeable improvement in the 25 percent and 75 percent quantiles but slight improvement in the median.

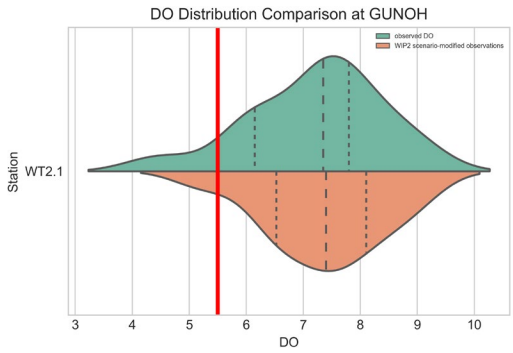


Figure 10: Comparison of the distributions of the observed DO at WT2.1 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, DO concentrations are almost always above the criterion at the Gunpowder station but there are mixed responses in the water quality condition. The summer bottom DO concentration has improved slightly but the surface chlorophyll-*a* has increased significantly. The WQSTM is simulating some degree of improvement in DO concentrations, however, the WQSTM results are extrapolated from a simulation of DO between 7 and 8 mg/l to observations below 5 mg/L (Figure 9).

Open-Water Patuxent Tidal Fresh Diagnostics (PAXTF)

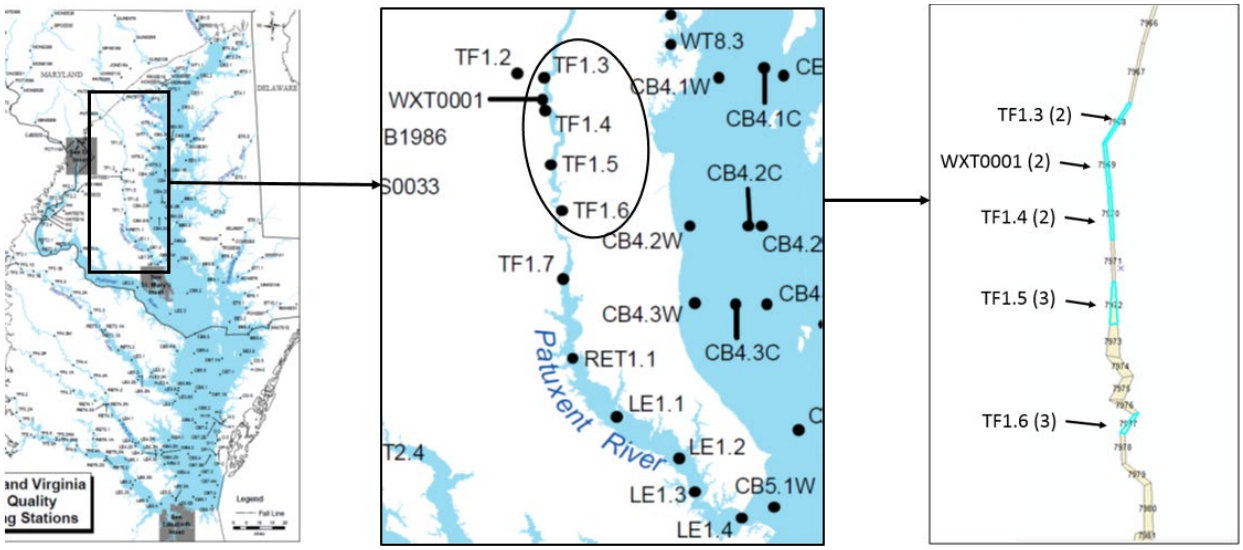


Figure 11: Location of PAXTF and the monitoring stations WQSTM grid cell location

There are five monitoring stations in the Patuxent Tidal Fresh segment (PAXTF): TF1.3, TF1.4, TF1.5, TF1.6, and WXT0001 (Figure 11). Violations of the 5.0 mg/L Open Water DO criterion were observed in the tidal fresh Patuxent River during summer months, particularly between 1999 to 2003 (Figure 12). There were also observed violations during the critical period of 1993 to 1995.

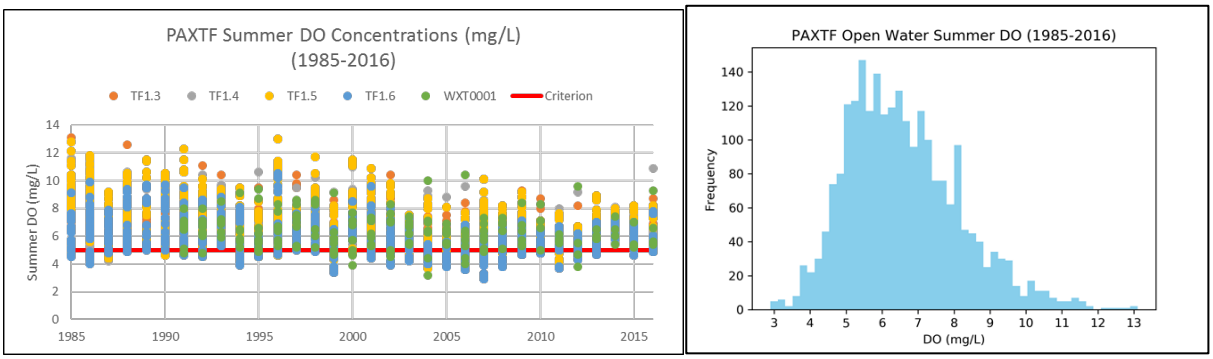


Figure 12: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Patuxent Tidal Fresh River 1985-2016.

There is an observable trend of decreasing high values of DO and increasing low values of DO from 1985 to 2016. Figure 13 shows that the both incidences of summer DO saturation percentage over 100percent and the percentage amount of over saturation are decreasing indicating lower and healthier algal biomass. Figure 14 indicates the mean and the extreme value of spring and summer

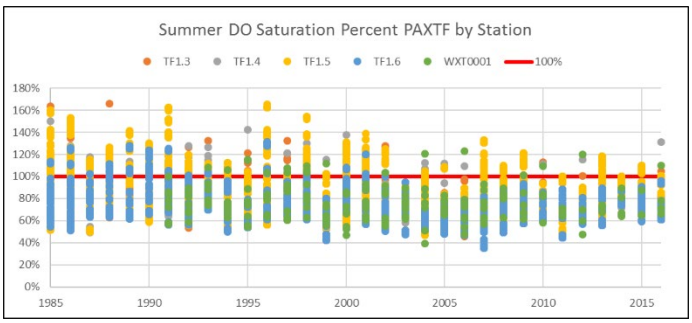


Figure 13: Summer DO saturation percent in PAXTF 1985-2016

chlorophyll-*a* concentrations have been lower since 2002.

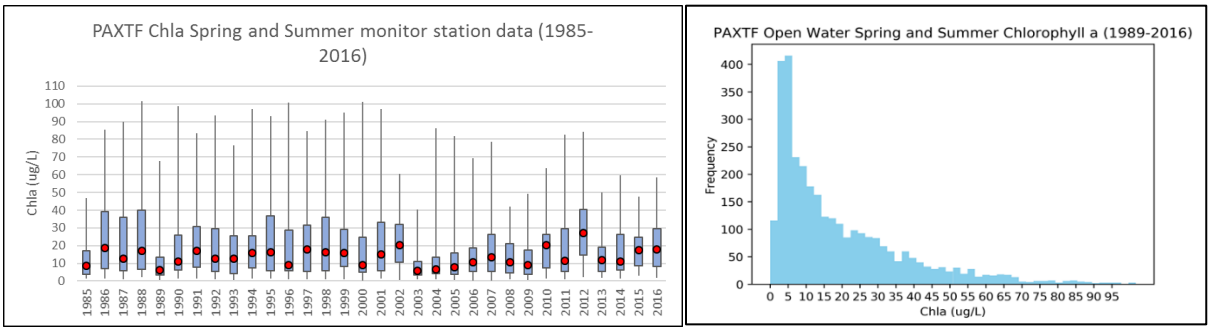


Figure 14: Boxplot of PAXTF chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trend result shows that the surface TN and TP concentration declined at all stations in PAXTF from 1999 to 2016 (Figure 15). The surface chlorophyll-*a* concentrations increased at three stations since 2007 and showed no change for the other two. Note that the surface chlorophyll-*a* concentrations increased 125 percent since 2007 (p value< 0.0001). The summer bottom DO at TF 1.5 fluctuated: DO concentrations decreased since 1985 but increase since 2007 (red line in Figure 16) is the summer bottom trend). Summer bottom DO at TF1.6 has increased 24 percent since 2007 (Figure 17). There is no significant summer bottom DO trend for other monitoring stations.

	Parameters	Period Start	Percent Change	p value
Station TF1.3	TN (surface)	1999	-23.38	p < 0.0001
	TN (surface)	2007	-16.28	p < 0.0001
	TP (surface)	1999	-33.51	p < 0.0001
Station TF1.4	TN (surface)	1999	-28.58	p < 0.0001
	TN (surface)	2007	-9.72	p<0.01
	TP (surface)	1999	-28.98	p < 0.0001
Station TF1.5	Chla (surface)	2007	46.23	0.01
	TN (surface)	1999	-22.99	p < 0.0001
	TN (surface)	2007	-8.19	0.02
	TP (surface)	1999	-16.47	p<0.001
	DO (Summer bottom)	1985	-12.20	0.02
	DO (Summer bottom)	2007	13.07	0.04
Station TF1.6	Chla (surface)	2007	125.12	p < 0.0001
	TN (surface)	1999	-17.99	p < 0.0001
	TN (surface)	2007	-7.14	0.05
	TP (surface)	1999	-10.40	0.02
	DO (Summer bottom)	2007	24.27	p<0.01
Station WXT0001	Chla (surface)	2007	37.61	0.04
	TN (surface)	1999	-43.08	p < 0.0001
	TP (surface)	1999	-33.14	p < 0.0001
	TP (surface)	2007	-25.15	p<0.01

Figure 15: Analysis of water quality trends at monitoring stations TF1.3, TF1.4, TF1.5, TF1.6, and WXT0001 using GAM

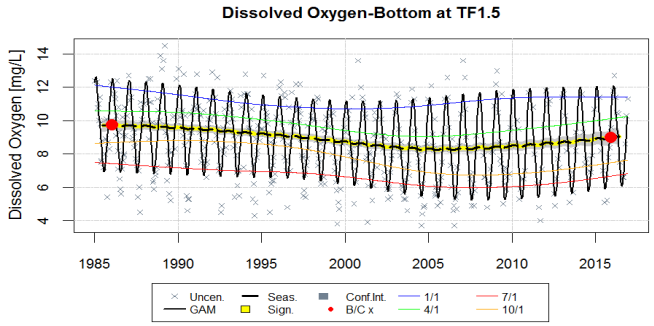


Figure 16: GAM trends of DO at monitoring station TF1.5

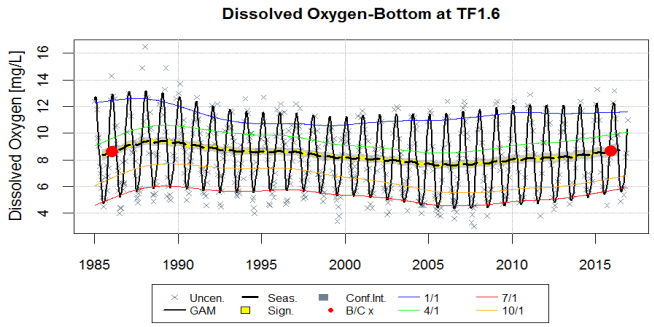


Figure 17: GAM trends of DO at monitoring station TF1.6

Figure 18 shows that the percent attainment of the Open Water summer 30-day mean criterion has declined over the 30 assessment periods between 1985 and 2016 ($p < 0.001$). Seven of the ten attaining periods were prior to 1992. The PAXTF has not attained the DO Open Water summer 30-day mean since 2002.

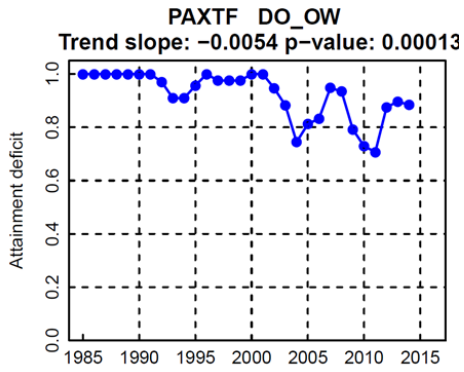


Figure 18: Summer 30-day mean criterion assessment in PAXTF

The CAST estimated a 39 percent decrease of nitrogen and a 66 percent decrease of phosphorous to PAXTF from 1985 to 2013 (Figure 19). From 2013 to WIP2 scenario, it is estimated that nitrogen increase by 22 percent and phosphorous increase by 0.4 percent. Figure 20 shows that increasing nutrient loads to PAXTF under WIP2 scenario are driven by waste water treatment plants (WWTPs) (WW N and WWP in Figure 20). While the nutrient loads decreased with increased WWTP treatment WWTP

flow estimates increased from 56.3 MGD for 2013 to 85.4 MGD for the WIP2 Scenario because design WWTP flows are always applied in the WIP Scenario for policy reasons. The nonattainment rates of PAXTF match the load change. The estimated nonattainment rate decreases 6 percent from the 1985 Progress to 2013 Progress loads, and then increase 5 percent from the 2013 Progress to the WIP2 Scenario (Table 5).

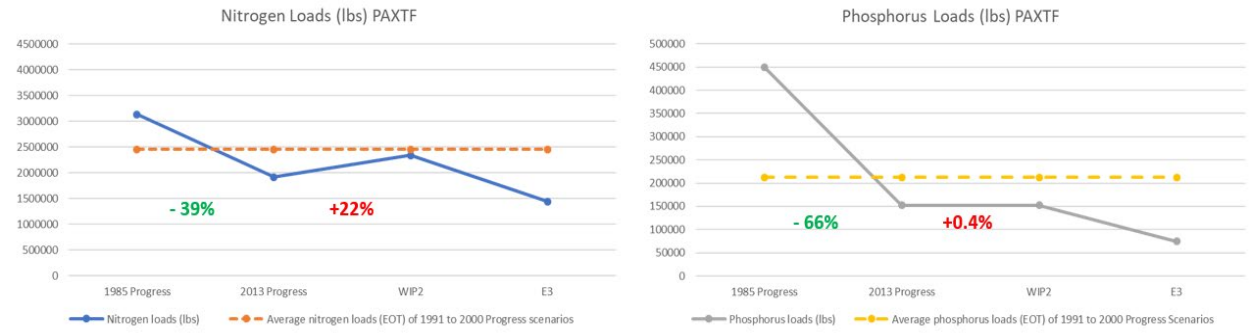


Figure 19: Nutrient loads (EOT) in PAXTF

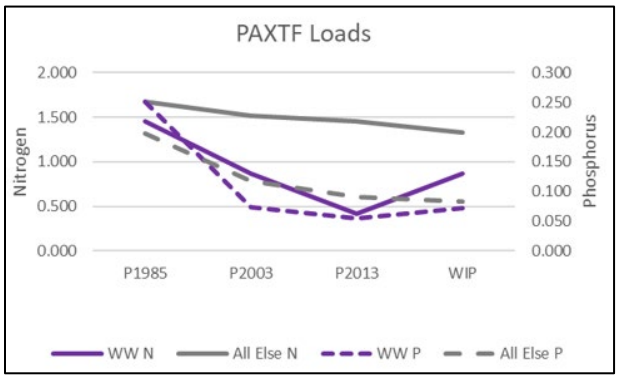


Figure 20: Waste water treatment loads change in PAXTF

Table 5: OW PAXTF criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
PAXTF	9%	3%	8%	0%	0%

The base CFD curve of the PAXTF segment indicates that there were 2 out of 12 summer months in the 1993-1995 period failed the criterion (Figure 21). Comparatively, the violation rate in the WIP2 Scenario was slightly lower. According to the assessment results, these violations correspond with August 1994

and June 1995 sampling events (Table 6).

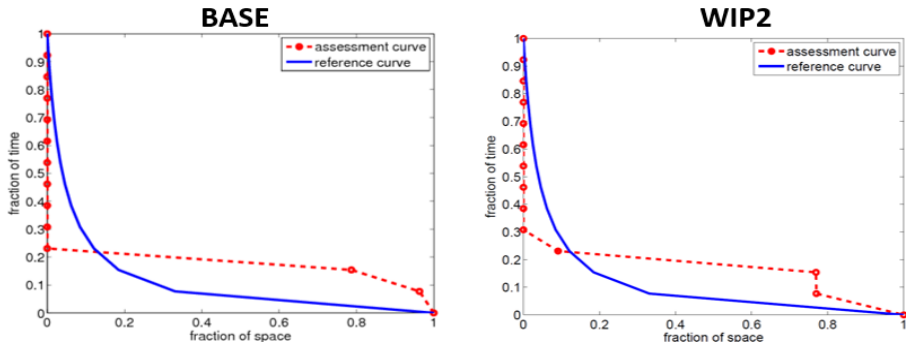


Figure 21: CFD curves for the Base scenario and WIP2 Scenario - PAXTF

Table 6: Monthly Open Water DO criterion nonattainment percentages for PAXTF in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	0%	0%
1993	8	0%	0%
1993	9	0%	0%
1994	6	0%	0%
1994	7	0%	9%
1994	8	79%	77%
1994	9	0%	0%
1995	6	96%	77%
1995	7	0%	0%
1995	8	0%	0%
1995	9	0%	0%

There are four regressions for monitoring station 1.3 to 1.6 for August 1994 in Figure 22 and they all represented different degree of WIP2 scenario-simulated responses. The WQSTM predicted a 10 percent to 27 percent increase in DO concentrations from base to WIP2 Scenario for Station 1.3, 1.4, and 1.6 and 6 percent decrease in Station 1.5. Simulated response over time varies between August 1994 and June 1995 (Figure 23). The WQSTM predicted a 6 percent decrease in August 1994 and 5 percent to 10 percent increase in June 1995.

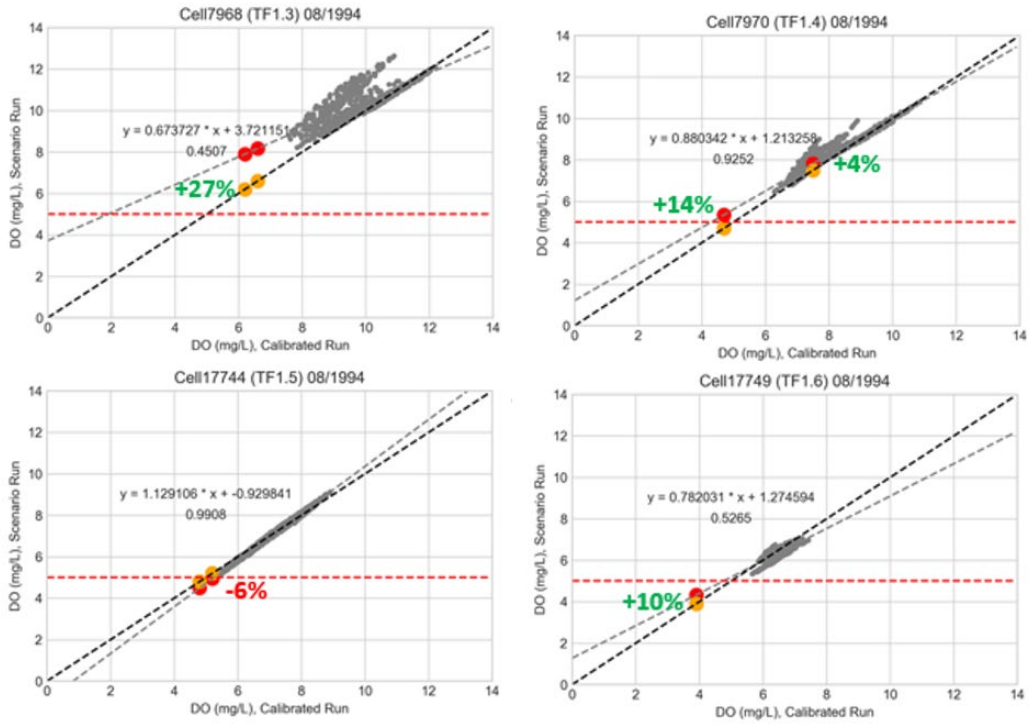


Figure 22: Scenario simulated response of August 1994 in at various cells of the monitoring stations at PAXTF

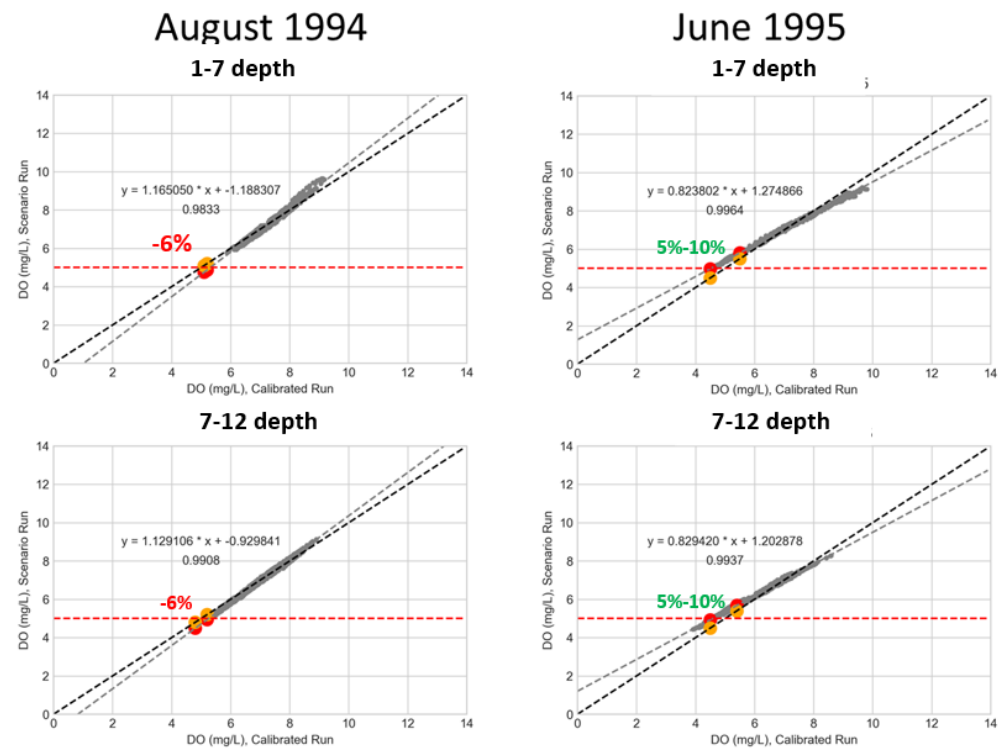


Figure 23: Scenario simulated response of August 1994 and July 1995 at PAXTF

The violin plot compares the distributions of observed DO concentrations at the 5 stations in PAXTF and the WIP2 scenario-modified observations from 1993 to 1995 (Figure 24). The median of the WIP2 scenario-modified observations for TF1.5 and TF1.6 are smaller than the median of the observed DO distribution. All other stations have varied degree of increase in the median of the WIP scenario-modified observations.

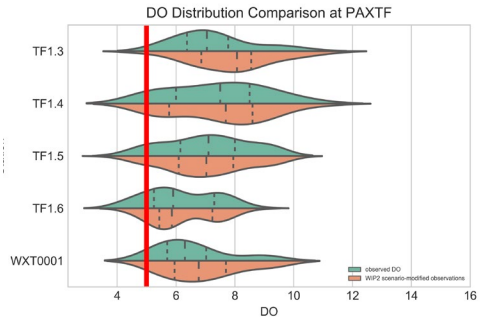


Figure 24: Comparison of the distributions of the observed DO from 1993 to 1995 and the WIP2 scenario-modified DO observations at various monitoring stations at PAXTF

In conclusion, moderate violations are observed in this segment WQSTM is simulating responses reflective of the load change to the PAXTF. Nitrogen and phosphorous concentrations are improving in the PAXTF, which is consistent with waste water load reductions into the Patuxent. The water quality response is mixed with some degradation in chlorophyll-*a* and DO but there is also less supersaturation of oxygen which is consistent with fewer high chlorophyll-*a* values observed in the recent years. The trend of the nonattainment value is consistent with the loads trend in the PAXTF.

Open-Water Southern Branch of Elizabeth River (SBEMH)

Figure 25 shows that there are six monitoring stations in the Southern Branch of Elizabeth River segment (SBEMH): SBA1, SBE2, SBC1, SBD1, SBE5, and SBD4 (from north to south). Frequent violations of the 5.0 mg/L Open Water DO criterion were observed during the summer months in the southern branch of Elizabeth River, particularly between 1993 and 1995 (Figure 26). About half of the DO concentration measurements between 1989 and 2016 were below 5.0 mg/L. Even though the means of the summer and spring chlorophyll-*a* concentrations are relative constant between 1989 and 2016, the extreme values of chlorophyll-*a* concentration were increasing (Figure 27).

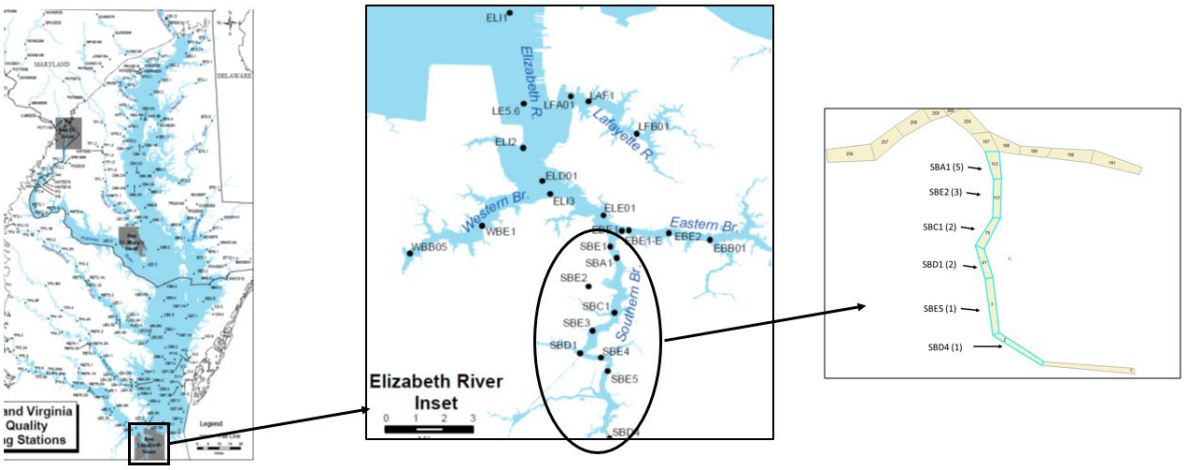


Figure 25: Location of SBEMH and the monitoring stations WQSTM grid cell location

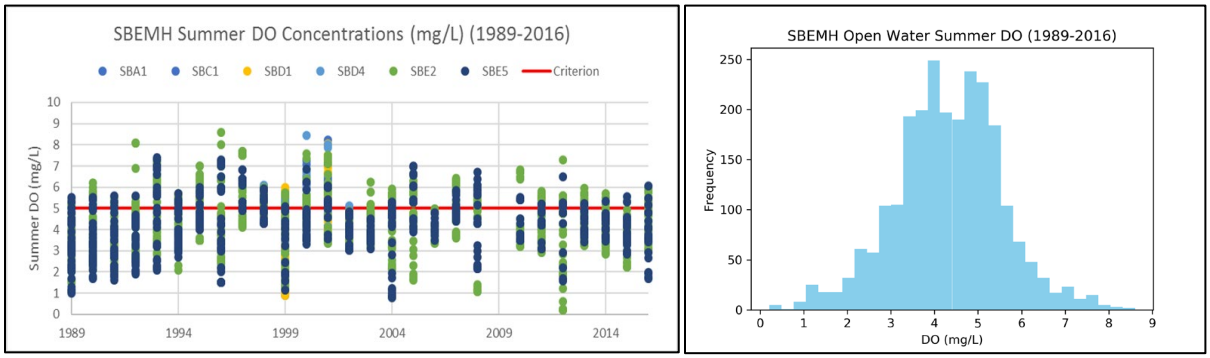


Figure 26: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Southern Branch of Elizabeth River 1985-2016

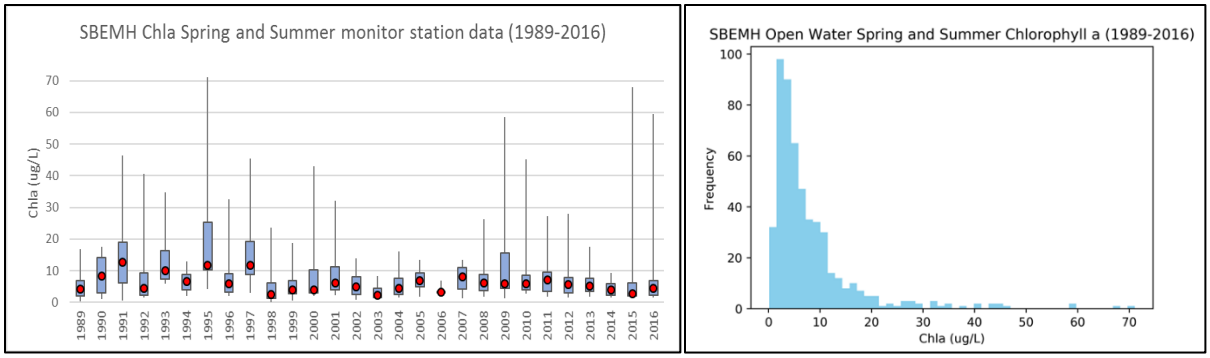


Figure 27: Boxplot of SBEMH chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trends of the both Stations SBE2 and SBE5 are positive (Table 7). For both stations, total surface nitrogen has decreased 20 percent since 1999; summer bottom DO at SBE2 (Figure 28) and SBE5 (Figure 29) has increased 40 percent and 42 percent respectively since 1989; surface chlorophyll-*a* has decreased at least 40 percent since 2007. There is no significant trend of total surface phosphorous for these stations.

Table 7: Analysis of water quality trends using GAM at monitoring stations SBE2 and SBE5

	Parameters	Period Start	Percent Change	p value
Station SBE2	Chla (surface)	2007	-40.50	p<0.01
	TN (surface)	2007	-15.62	0.01
	TN (surface)	1999	-26.43	p < 0.0001
	DO (Summer bottom)	1989	23.40	p<0.01
Station SBE5	Chla (surface)	2007	-48.52	p<0.001
	TN (surface)	1999	-20.88	p<0.001
	DO (Summer bottom)	1989	41.60	p < 0.0001

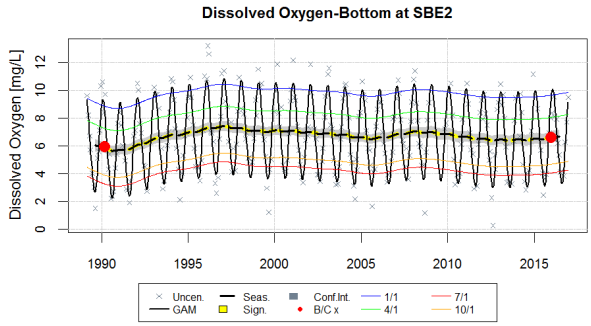


Figure 28: GAM trends of DO at monitoring station SBE2

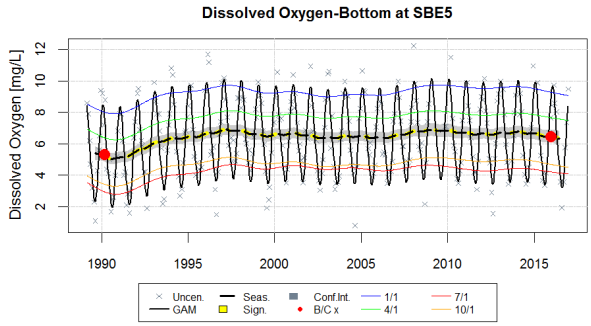


Figure 29: GAM trends of DO at monitoring station SBE5

Figure 30 shows that the percent attainment of Open Water summer 30-day mean criterion fluctuated and has no significant change from 1987 to 2016 (p = 0.94). The SBEMH is in nonattainment of the DO Open Water summer 30-day mean since 1987. The nonattainment rates are consistently below 80 percent.

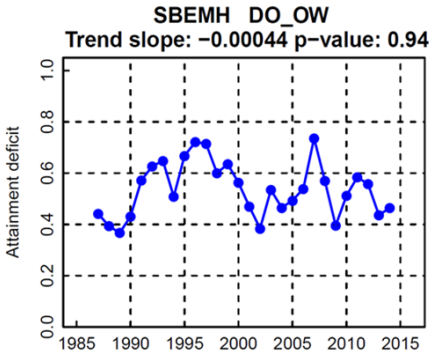


Figure 30: Summer 30-day mean criterion assessment in SBEMH

The CAST estimated the total nitrogen and total phosphorous loads increase from 1985 to 2013 and WIP2 (Figure 31). From 1985 to 2013, CAST estimated a 19 percent increase in nitrogen and 13 percent increase of phosphorous to SBEMH. The estimated nonattainment rate decreases 14 percent from 1985 Progress to 2013 Progress (Table 8). From 2013 to the WIP2 Scenario, it is estimated that nitrogen increased by 1 percent and phosphorous increased by 5 percent. The nonattainment rate decreases 8 percent from the 2013 Progress to WIP2 Scenario.

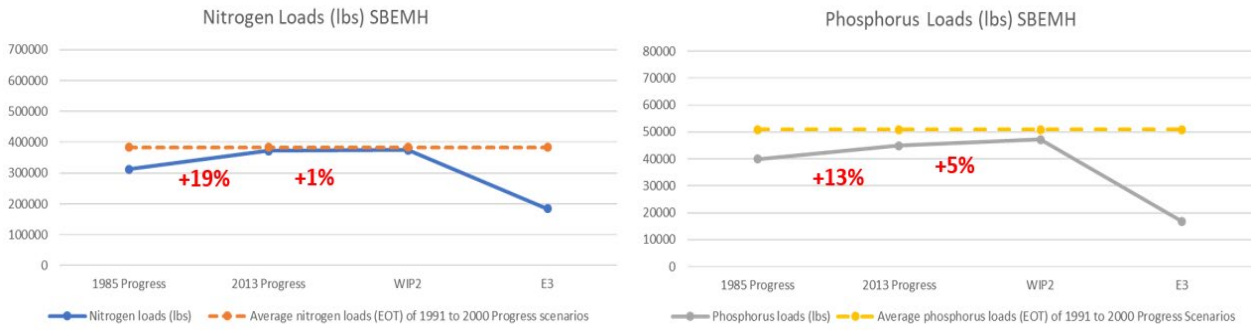


Figure 31: Nutrient loads (EOT) - SBEMH

Table 8: OW SBEMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
SBEMH	48%	34%	26%	12%	3%

The base CFD curve of the SBEMH indicates that there were ten out of twelve summer months in the 1993-1995 period failed the criterion (Figure 32). At the WIP2 Scenario, nine violations rate decreased compared to the base scenario and one violation rate had no improvement. The assessment results identify that the violations correspond with July and August 1993, June to August 1994, and July to September 1995 sampling events (Table 9).

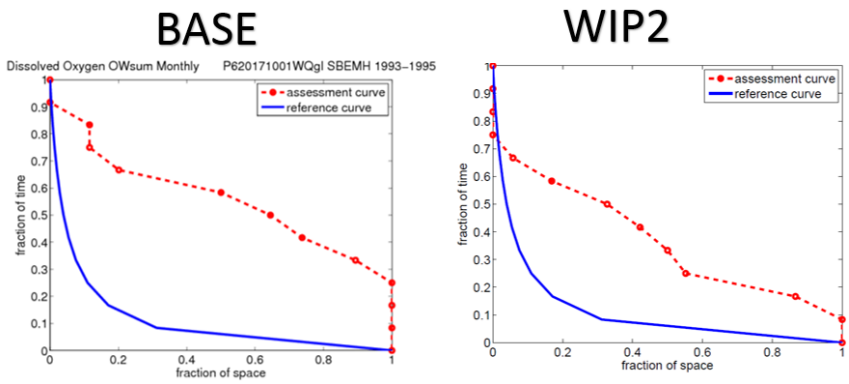


Figure 32: CFD curves for the Base scenario and WIP2 Scenario - SBEMH

Table 9: Monthly Open Water DO criterion nonattainment percentages for SBEMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	74%	50%
1993	8	50%	33%
1994	6	64%	17%
1994	7	100%	87%
1994	8	100%	42%
1994	9	12%	0%
1995	6	20%	0%
1995	7	12%	6%
1995	8	89%	55%
1995	9	100%	100%
1995	9	0%	0%

The scenario-simulated response of DO varies between SBE2 and SBE5. The DO concentrations improved by various percentage in July 1993, ranging from 4percent to 84percent (Figure 33).

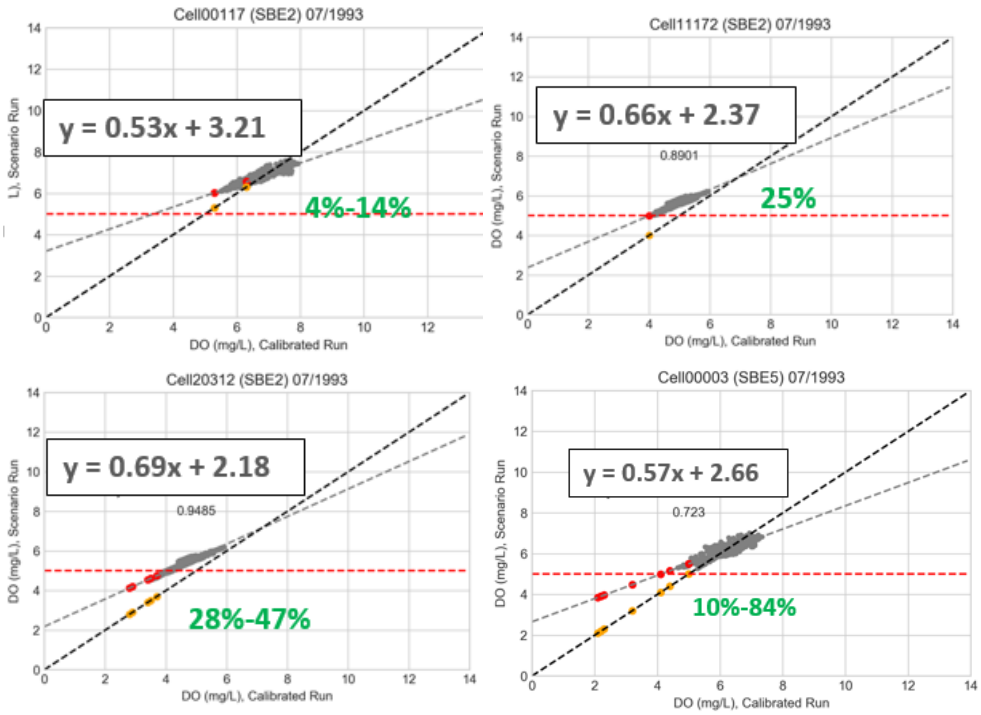


Figure 33: Scenario simulated response of July 1993 in at various cells of the monitoring stations in SBEMH

The violin plot shows that the medians of DO for the WIP2 scenario-modified observations from 1993 to 1995 for both stations have increased but in various degree (Figure 34). The distributions of scenario modified results for both stations decrease in range and have higher percentage of DO concentrations that are greater than OW DO criterion, 5.0 mg/L.

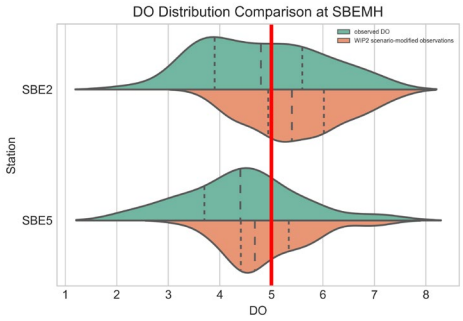


Figure 34: Comparison of the distributions of the observed DO at SBE2 and SBE5 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the trends are moving in the right direction but significant progress is needed. The water quality is improving but DO concentrations are frequently below the 5.0 mg/L Open Water criteria. Nitrogen concentrations have improved significantly in recent years, but there has been little estimated change in phosphorus. The surface chlorophyll-*a* trend is decreasing since 2007, but high chlorophyll-*a* incidences were observed. The loads in the SBEMH segment increased from 1984 to 2013 but the nonattainment rates decreased which could be because of nutrient reduction in the mainstem Bay, however more investigation is needed to determine the degree of the main Bay influence on the SBEMH segment. The WQSTM simulates improvement in the scenario modified DO concentrations but the SBEMH is unlikely to attain the Open Water DO water quality standard by 2025.

Open-Water Western Branch Elizabeth River (WBEMH)

There are two monitoring stations in the Western Branch Elizabeth River segment (WBEMH): WBB05 and WBE1 (Figure 35). Violations of the 5.0 mg/L Open Water DO criterion were not uncommon in the WBEMH during summer months, particularly between 1993 to 1995 (Figure 36). About half of the summer observations between 1985 to 2016 are below 5.0 mg/L. The chlorophyll-*a* concentrations fluctuate but most of the concentrations are below 20 ug/L (Figure 37).

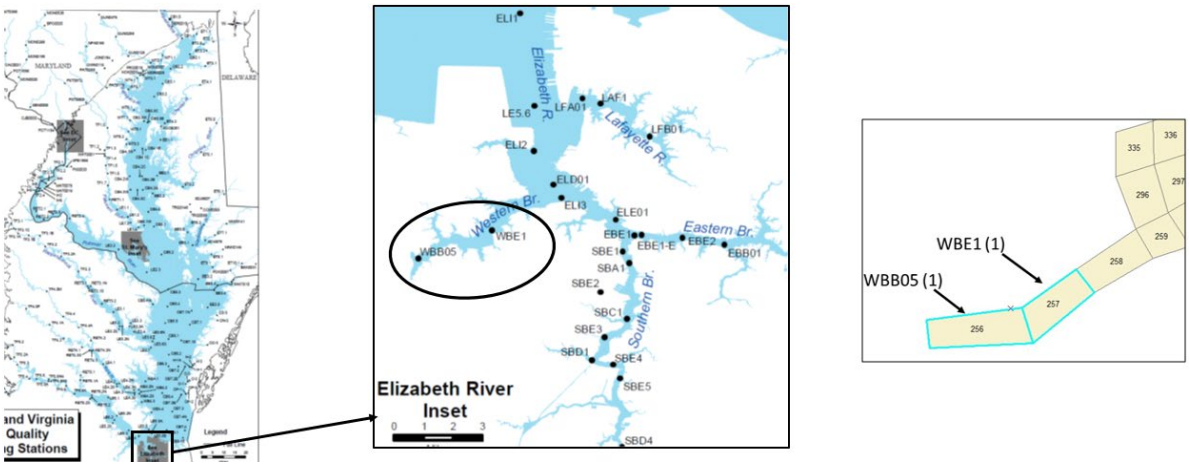


Figure 35: Location of WBEMH and the monitoring stations WQSTM grid cell location

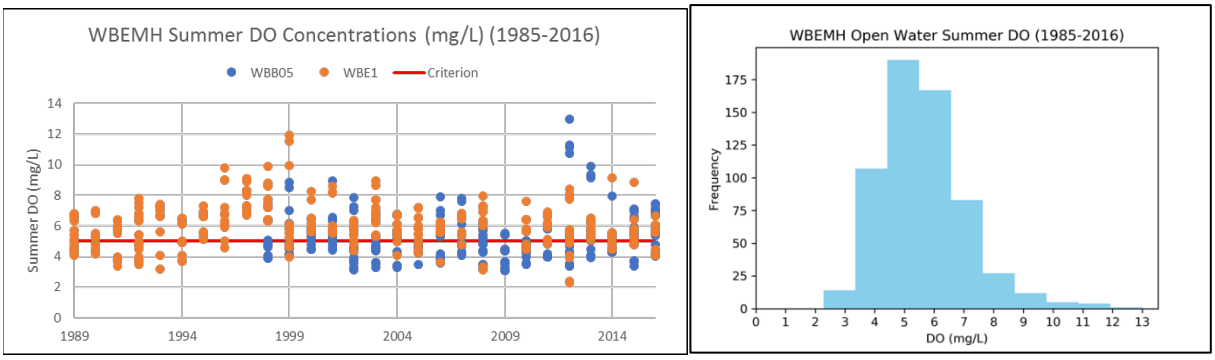


Figure 36: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Western Branch of Elizabeth River 1985-2016

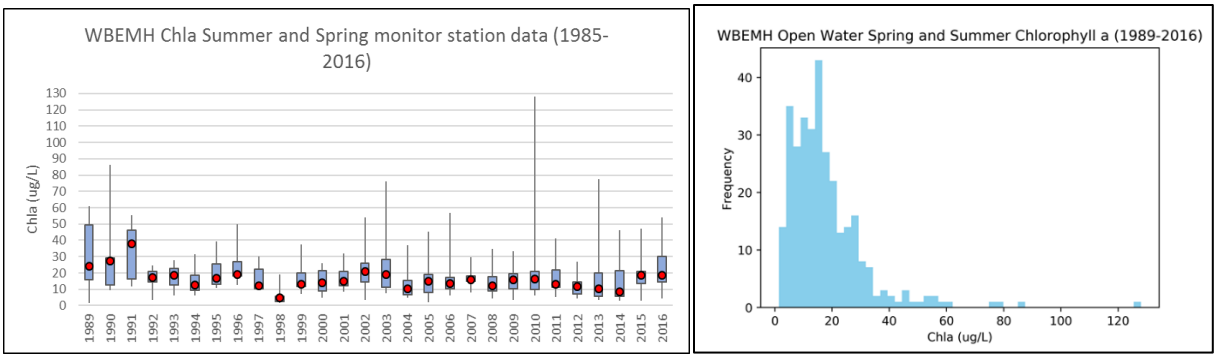


Figure 37: Boxplot of WBEMH chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trend of surface chlorophyll-*a* decreased 27 percent from 2007 at the monitoring station WBE1 (Table 10). However, total surface phosphorus has increased 14 percent and summer bottom DO has decreased 14 percent since 1999 (Figure 38). Figure 39 shows that percent attainment of the OW summer 30-day mean criterion has no significant change in WBEMH from 1987 to 2016 (p = 0.9). WBEMH has been unable to attain the DO Open Water summer 30-day mean at any time since 1987.

Table 10: Analysis of water quality trends using GAM at monitoring station WBE1

	Parameters	Period Start	Percent Change	p value
Station WBE1	Chla (surface)	2007	-26.91	0.04
	TP (surface)	2007	11.76	0.03
	TP (surface)	1999	14.28	0.04
	DO (summer bottom)	1999	-13.77	p<0.01

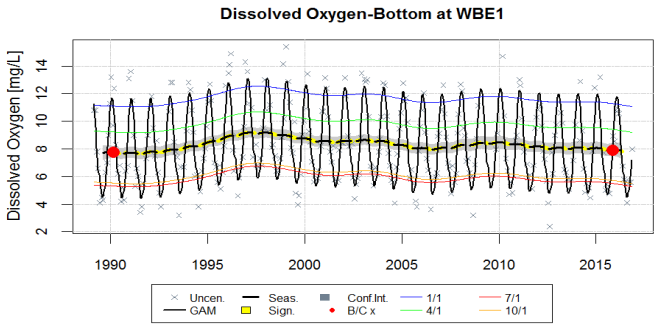


Figure 38: GAM trends of DO at monitoring station WBE1

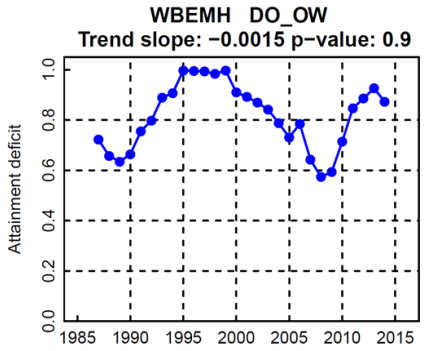


Figure 39: Summer 30-day mean criterion assessment in WBEMH

The CAST estimated the nitrogen loads decreased 5 percent from 1985 to 2013 and 7 percent from 2013 to WIP2 (Figure 40). However, the estimated phosphorous loads increased 33 percent between the 1985 and 2013 scenarios and the WIP2 Scenario estimated phosphorous loads were also elevated relative to the 1985 Scenario. The estimated nonattainment rates for the 1985, 2013, and WIP2 scenarios were unchanged at 8 percent nonattainment (Table 11).

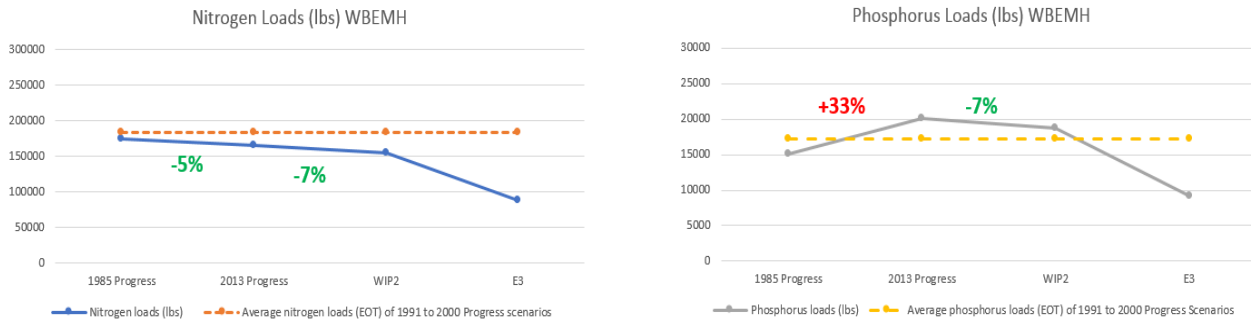


Figure 40: Nutrient loads (EOT) - WBEMH

Table 11: OW WBEMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
WBEMH	8%	8%	8%	3%	0%

At the base scenario, three out of the twelve summer months in the 1993-1995 period failed the criterion (Figure 41). At the WIP2 Scenario, two out of three violations rates have no improvement, which correspond to the sampling event in July 1993 and July 1994. The WQSTM predicted 0 percent to 5 percent improvement in scenario modified DO concentrations for July 1993 observations (Figure 42), and predicted 9 percent to 11 percent improvement for July 1994 observations (Figure 43).

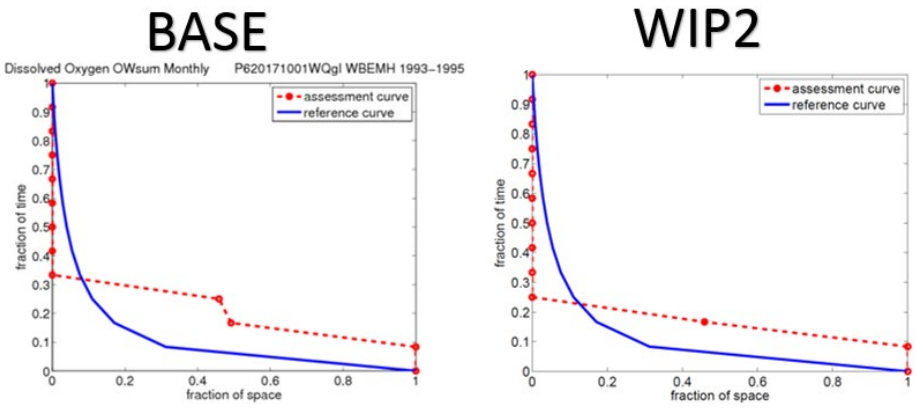


Figure 41: CFD curves for the Base scenario and WIP2 Scenario - WBEMH

Table 12: Monthly Open Water DO criterion nonattainment percentages for WBEMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	46%	46%
1993	8	0%	0%
1994	6	0%	0%
1994	7	100%	100%
1994	8	49%	0%
1994	9	0%	0%
1995	6	0%	0%
1995	7	0%	0%
1995	8	0%	0%
1995	9	0%	0%

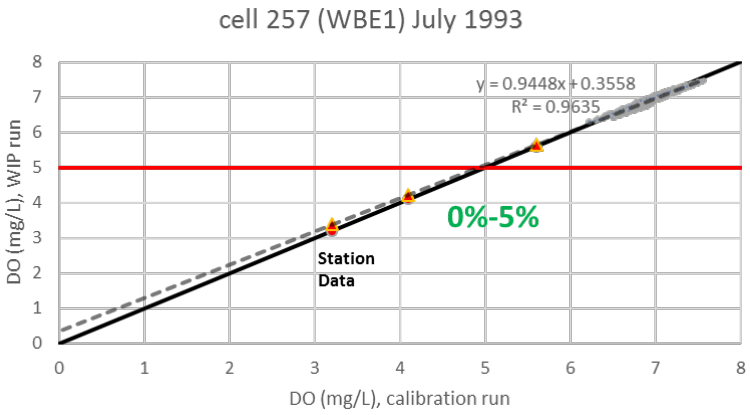


Figure 42: Scenario simulated response of July 1993 in at cell 257 of the monitoring stations WBE1

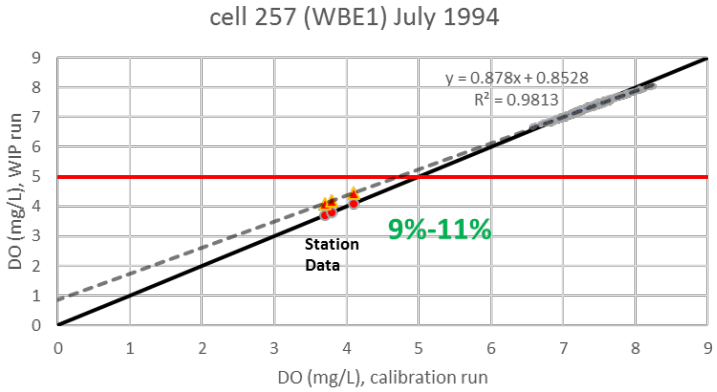


Figure 43: Scenario simulated response of July 1994 in at cell 257 of the monitoring stations WBE1

The violin plot indicates that there is minimal improvement in the distribution of the WIP2 scenario-modified observations from 1993 to 1995 compared to the DO observations (Figure 44). The percentage of scenario modified DO that is greater than 5.0 mg/L increases. There is no change in the second quantile and the third quantile.

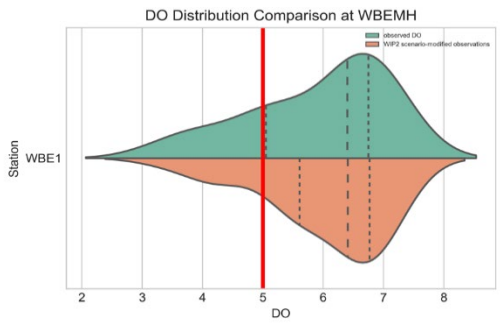


Figure 44: Comparison of the distributions of the observed DO at WBE1 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the water quality trend is unclear and significant progress is needed in this segment. The surface chlorophyll-*a* is decreasing but the summer bottom DO is degrading and surface total phosphorous is increasing. Unlike the SBEMH segment, there is little evidence in the WBEMH segment to demonstrate any Bay related change in nonattainment rate. There is much to investigate why the nonattainment rate remains the same from 1985 Progress to WIP2 Scenario. The estimated nitrogen loads to WBEMH have decreased somewhat but the estimated phosphorous loads have increased between the 1985 and WIP2 scenarios.

Open-Water Eastern Branch of Elizabeth River (EBEMH)

Figure 45: Location of EBEMH and the monitoring stations WQSTM grid cell location

There are two monitoring stations in the Eastern Branch Elizabeth River segment (EBEMH): EBB05 and EBE1 (Figure 45). Violations of the 5.0 mg/L Open Water DO criterion were frequent in the EBEMH during summer months, particularly between 1993 to 1995 (Figure 46). About half of the summer observations between 1985 and 2016 are below 5.0 mg/L. The chlorophyll-*a* concentrations fluctuated but most of the concentrations are below 20 ug/L (Figure 47).

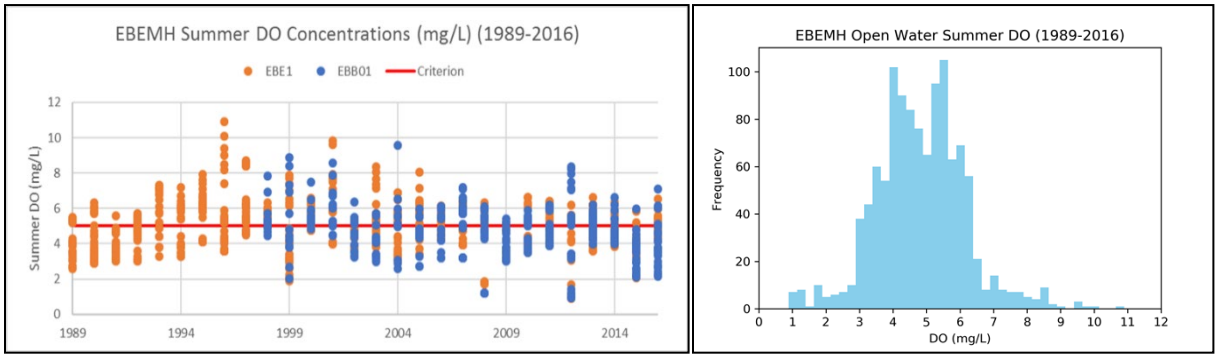


Figure 46: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Eastern Branch of Elizabeth River 1985-2016

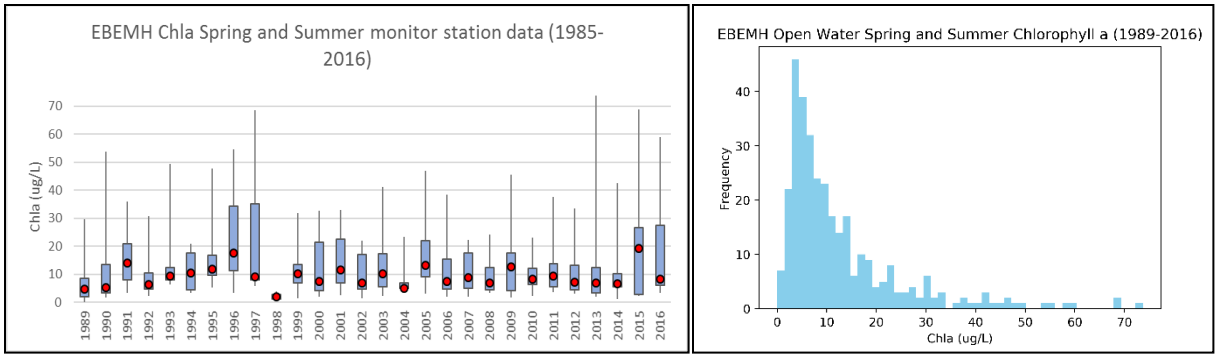


Figure 47: Boxplot of EBEMH chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trends of monitoring station EBE1 show that the water quality in this station is making progress except summer bottom DO (Table 13). The total surface chlorophyll-*a* decreased 37 percent since 2007 and the total surface nitrogen has decreased both from 1999 and from 2007. There is no significant trend for total surface phosphorous at this station. The summer bottom DO increase 19 percent from 1989 but decrease 13 percent from 1999 (Figure 49). Figure 48Figure 39 shows that percent attainment of the OW summer 30-day mean criterion has no significant change in EBEMH from 1987 to 2016 (p = 0.37). The EBEMH segment has not attained the DO Open Water summer 30-day mean since 1987. The nonattainment rates are consistently below 80 percent except one 3-year assessment period between 1996 to 1998.

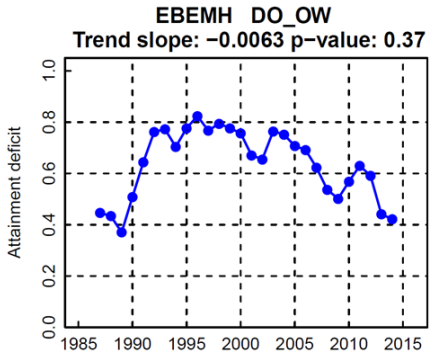


Figure 48: Summer 30-day mean criterion assessment in EBEMH

Table 13: Analysis of water quality trends using GAM at monitoring station EBE1

	Parameters	Period Start	Percent Change	p value
Station EBE1	Chla (surface)	2007	-36.69	p<0.01
	TN (surface)	2007	-16.67	p<0.01
	TN (surface)	1999	-20.49	p<0.001
	DO (Summer Bottom)	1989	19.14	0.01
	DO (Summer Bottom)	1999	-13.00	0.01

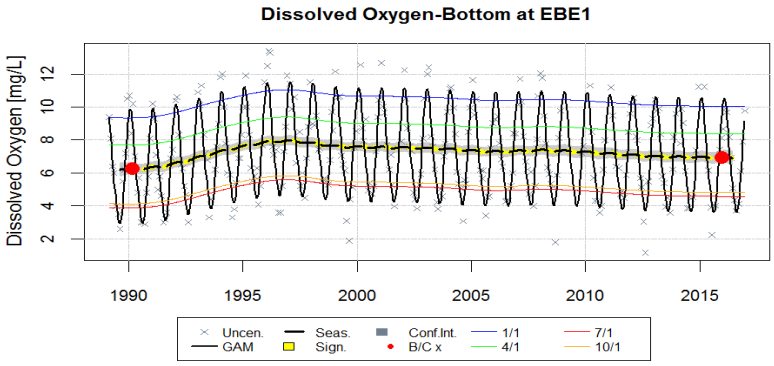


Figure 49: GAM trends of DO at monitoring station EBE1

The nutrient loads to the EBEMH segment estimated by CAST show that loads decreased from 1985 Progress to 2013 Progress (Figure 50). The nitrogen decreased by 3 percent and the phosphorous decreased by 11 percent. From the 2013 Progress to WIP2 scenarios, the nitrogen decreased by 5 percent but the phosphorous increased 2 percent. The criteria assessment result for EBEMH shows that the nonattainment rates have been decreasing but are greater than 1 percent at the WIP2 Scenario (Table 14). Given the slight nutrient reductions estimated in the EBEMH segment the improvement in nonattainment rates is likely related to the nutrient reductions in the mainstem Bay.

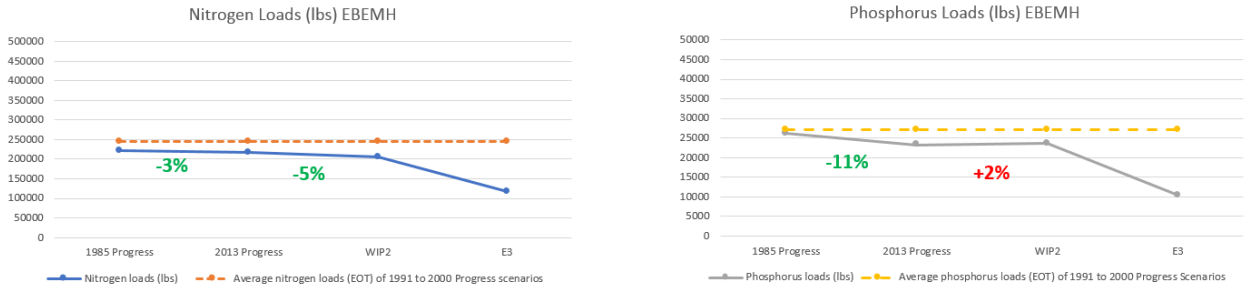


Figure 50: Nutrient loads (EOT) - EBEMH

Table 14: OW EBEMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
EBEMH	23%	18%	8%	0%	0%

At the base scenario, four out of the twelve summer months in the 1993-1995 period failed the criterion (Figure 51). At the WIP2 Scenario, three out of the four violations rates have no improvement, which correspond to the July 1993, July 1994, and September 1995 sampling events (Table 15). The WQSTM predicted 11 percent to 41 percent improvement in scenario modified DO concentrations for July 1993 observations, and predicted 10 percent to 15 percent improvement for July 1994 observations (Figure 52).

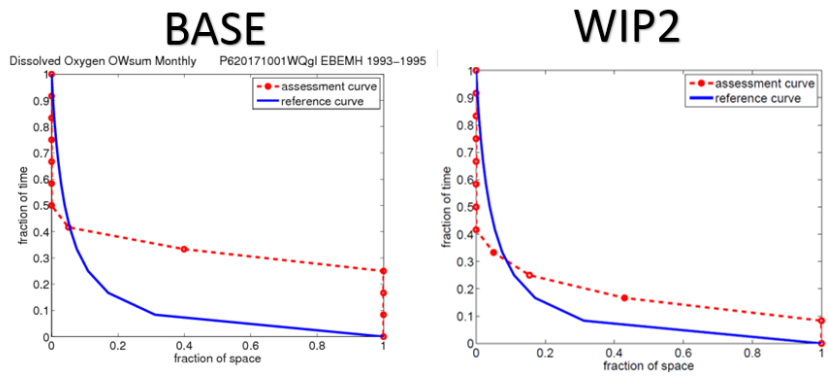
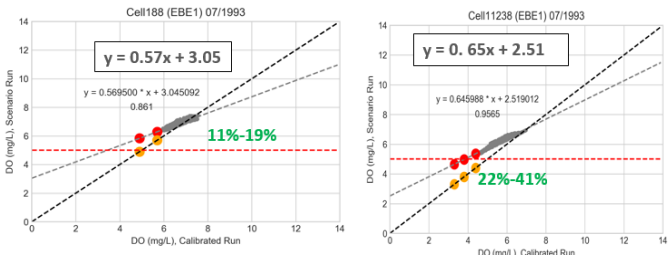


Figure 51: CFD curves for the Base scenario and WIP2 Scenario - EBEMH

Table 15: Monthly Open Water DO criterion nonattainment percentages for EBEMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	40%	15%
1993	8	5%	0%
1994	6	0%	0%
1994	7	100%	43%
1994	8	100%	5%
1994	9	0%	0%
1995	6	0%	0%
1995	7	0%	0%
1995	8	0%	0%
1995	9	100%	100%
1995	9	0%	0%



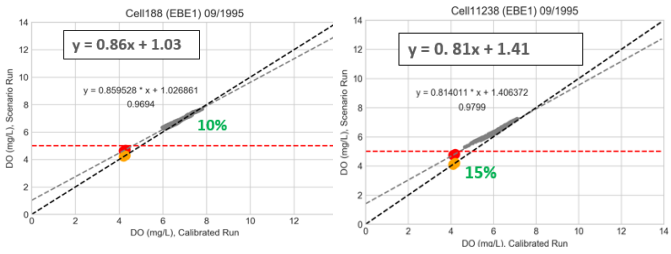


Figure 52: Scenario simulated response of July 1993 and September 1995 at the monitoring stations EBE1

The violin plot (Figure 53) compares the distributions of the observed DO concentrations at the EBE1 station and the WIP2 scenario-modified observations from 1993 to 1995. There is some degree of increase in each of the three quantities of the distribution. There are 75 percent of the distribution of scenario modified WIP2 DO greater than the 5.0 mg/L Open Water DO criterion. The range of the DO values is smaller compared to the observed DO concentrations between 1993 and 1995.

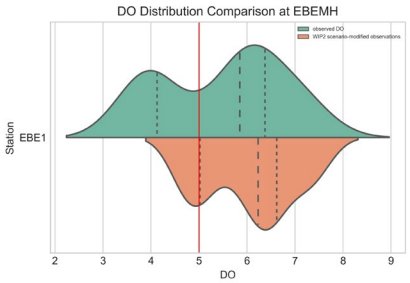


Figure 53: The distribution comparison of the observed DO at EBE1 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the water quality is unclear and significant progress is needed in this segment in this segment. The surface chlorophyll-*a* and surface total nitrogen are improving but the summer bottom DO is degrading. Extensive violations of Open Water criterion are observed. There was limited progress in load reductions estimated by CAST, but the nonattainment rates are decreasing and there is some degree of response simulated by the WQSTM. The EBEMH segment will need to make significant progress in load reductions to attain the Open Water DO criterion by 2025.

Open-Water Corrotoman River (CRRMH)

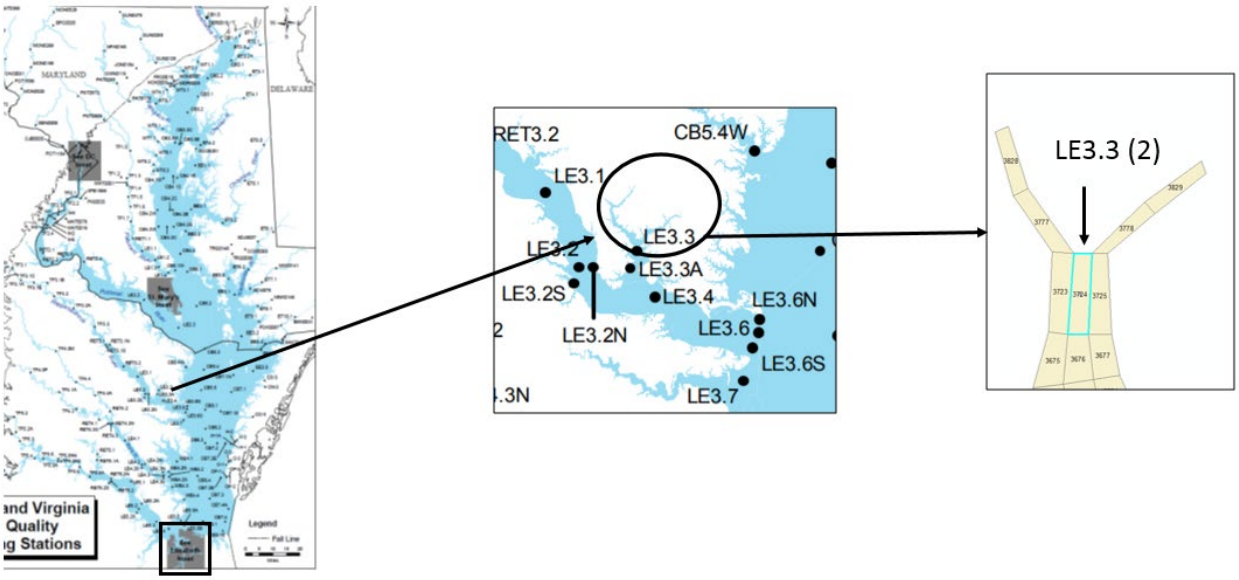


Figure 54: Location of CRRMH and the monitoring stations WQSTM grid cell location

There is one monitoring station in the Corrotoman River segment (CRRMH): LE3.3 (Figure 54). Extensive violations the 5.0 mg/L Open Water DO criterion were observed in this segment (Figure 55). Dissolved oxygen concentrations under 1 mg/L were not uncommon, especially between the 1993 and 1995 critical period. The chlorophyll-*a* concentrations fluctuated but most of the concentrations are below 20 ug/L (Figure 56).

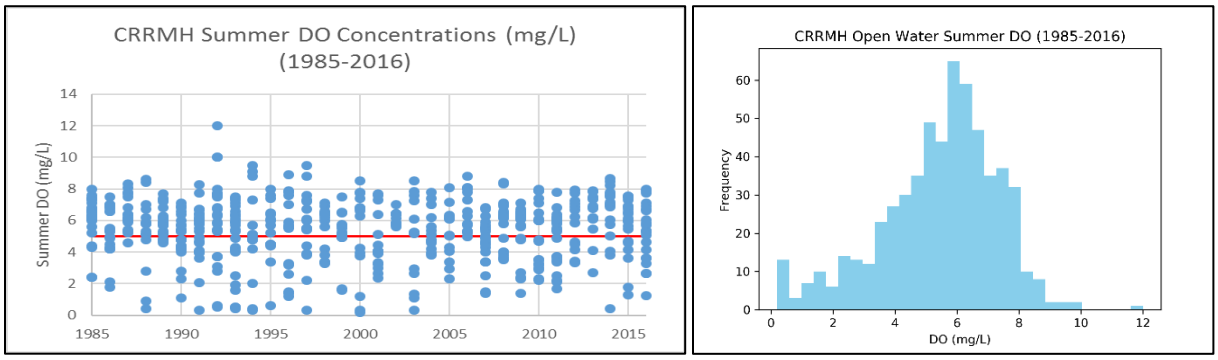


Figure 55: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Corrotoman River 1985-2016

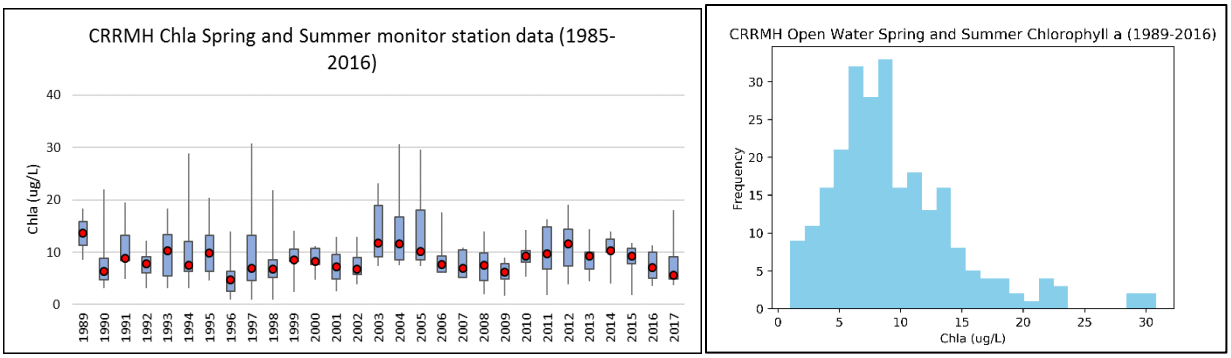


Figure 56: Boxplot of CRRMH chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trend result indicates that there is no significant trend for surface chlorophyll-*a* at the station LE3.3 (Table 16). The GAM trends for both total surface nitrogen and total surface phosphorous at this station decreased from 1999. The summer bottom DO concentrations trend estimated using GAM are consistently below the 5.0 mg/L Open Water DO criterion and has decreased 22.78 percent compared to 1985 (Figure 58). The CRRMH has not attained the DO OW summer 30-day mean since 1985 (Figure 57). The nonattainment rates are consistently above 80 percent except one 3-year assessment period between 1993 and 1995.

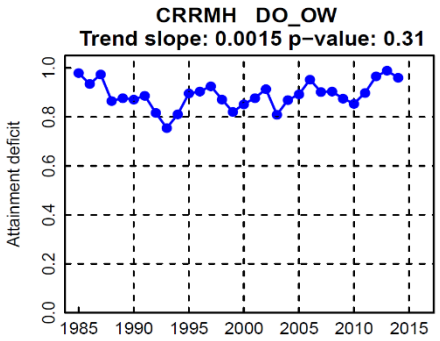


Figure 57: Summer 30-day mean criterion assessment in CRRMH

Table 16: Analysis of water quality trends using GAM at monitoring station LE3.3

	Parameters	Period Start	Percent Change	p value
Station LE3.3	TN (surface)	2007	-17.85	p<0.001
	TN (surface)	1999	-11.87	0.04
	TP (surface)	2007	-21.03	p<0.01
	TP (surface)	1999	-25.13	p<0.01
	DO (summer bottom)	1985	-22.78	0.02

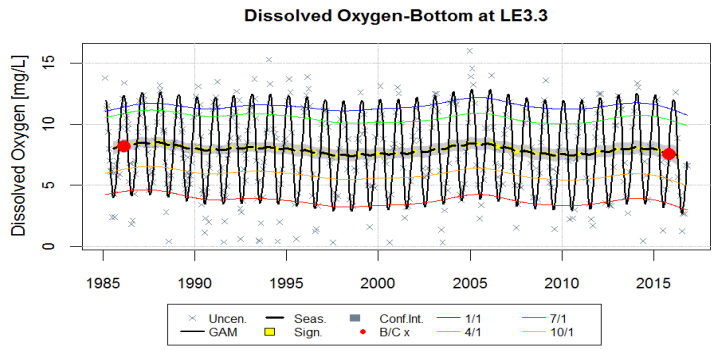


Figure 58: GAM trends of DO at monitoring station LE3.3

The nutrient loads to CRRMH estimated by CAST shows that loads decreased both from 1985 Progress to 2013 Progress and from 2013 Progress to the WIP2 Scenario (Figure 59). For the first period, the nitrogen decreased by 4 percent and the phosphorous decreased by 4 percent. At the same period, criteria assessment result shows that the nonattainment rates at CRRMH decreased 9 percent (Table 17). From 2013 progress to WIP2 scenario, the nitrogen decreased by 23 percent and the phosphorous decreased 4 percent, and the nonattainment rate decreased 11 percent. The improvement in nonattainment rates in the CRRMH segment is likely is related to nutrient reductions in the mainstem Bay.

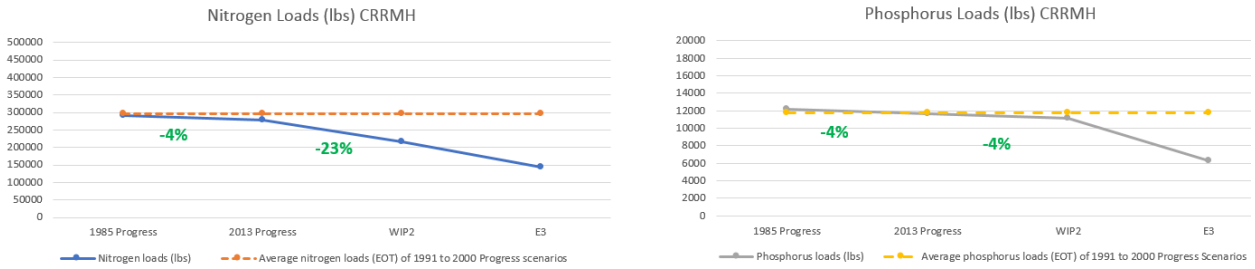


Figure 59: Nutrient loads (EOT) in CRRMH

Table 17: OW CRRMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
CRRMH	25%	16%	5%	2%	0%

At the base scenario, ten out of the twelve summer months in the 1993-1995 period failed the criterion (Figure 60). At the WIP2 Scenario, the violation rates decreased compared to the base scenario except one violation correspond with July 1995 sampling event (Table 18). The scenario modified response in DO varies in time. For the July 1995 scenario modified DO concentrations, the WQSTM predicted 0 percent improvement for the upper cell, and 562 percent and -1 percent at the lower cell (Figure 61). For the July 1994 scenario modified DO, WQSTM predicted 24 percent to 1065 percent (Figure 62).

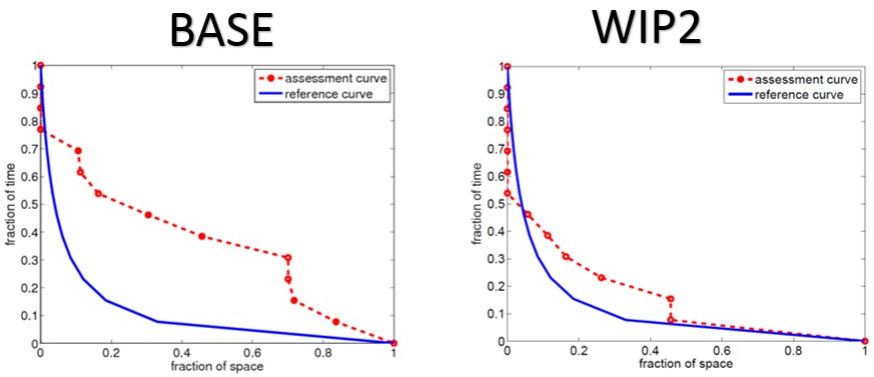


Figure 60: CFD curves for the Base scenario and WIP2 Scenario – CRRMH

Table 18: Monthly open water DO criterion nonattainment percentages for CRRMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	11%	0%
1993	7	70%	46%
1993	8	70%	46%
1993	9	0%	0%
1994	6	0%	0%
1994	7	31%	16%
1994	8	46%	26%
1994	9	84%	0%
1995	6	16%	6%
1995	7	11%	11%
1995	8	72%	0%
1995	9	0%	0%

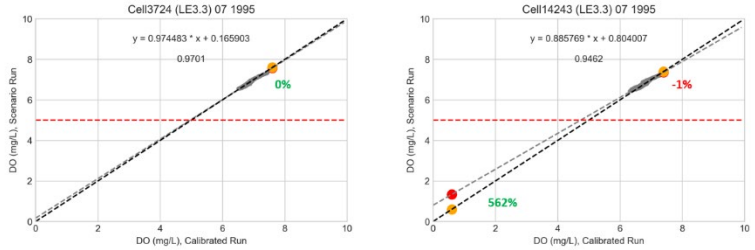


Figure 61: Scenario simulated response of LE3.3 of July 1995 in upper cell (3724) and lower cell (14243)

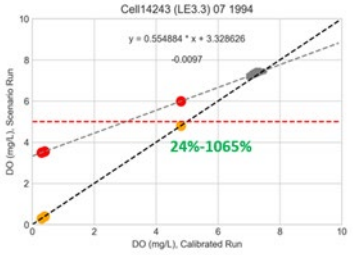


Figure 62: Scenario simulated response of LE3.3 of July 1994 in cell 14243

The violin plot (Figure 63) compares the distributions of the observed DO concentrations at the LE3.3 monitoring station and the WIP2 scenario-modified observations from 1993 to 1995. There is some degree of increase in each of the three quantities of the distribution. There are 75 percent of the

distribution of scenario modified WIP2 DO greater than the 5.0 mg/L Open Water DO criterion. The range of the DO values is smaller compared to the observed DO concentrations between 1993 and 1995.

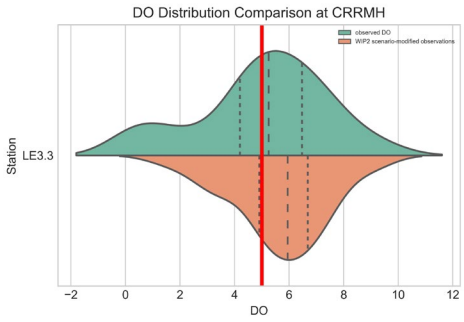


Figure 63: Comparison of the distributions of the observed DO at LE3.3 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the water quality in CRRMH is insufficient to achieve the Open Water DO standard and significant progress in nutrient reduction is estimated to be needed in this segment. The summer bottom DO is degrading but the surface nutrient concentrations are improving. There has been little change in surface chlorophyll-*a* concentration. Extensive violations of Open Water criterion are observed. There was limited progress in load reductions estimated by CAST, but the nonattainment rates are decreasing. There is some degree of responses simulated by WQSTM. The CRRMH will need to make significant progress in load reductions to attain the Open Water DO criterion by 2025.

Open-Water Upper Pamunkey Tidal Fresh (PMKTF)

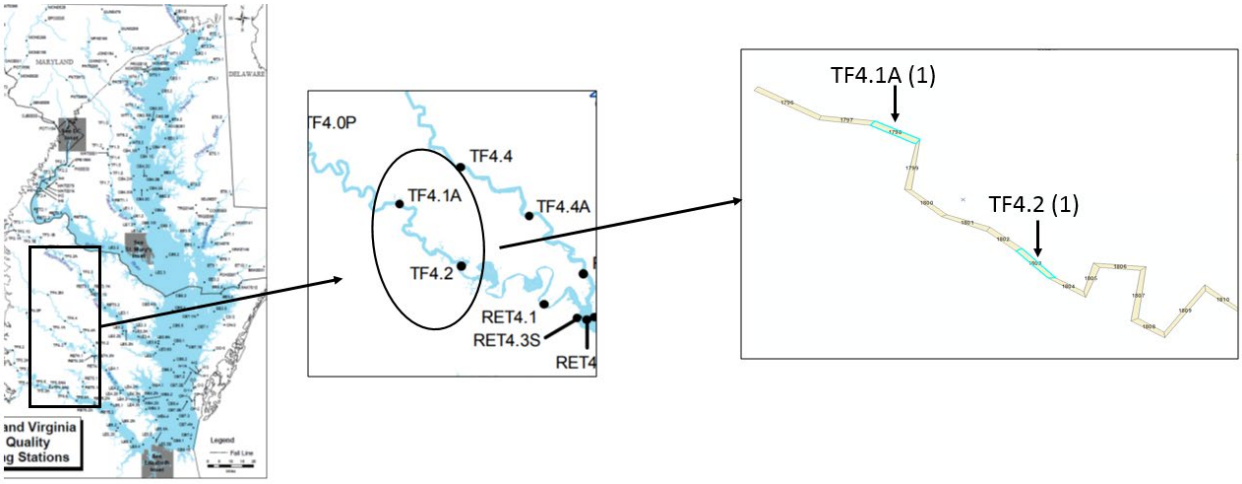


Figure 64: Location of PMKTF and the monitoring stations WQSTM grid cell location

There are two monitoring stations in Upper Pamunkey Tidal Fresh segment (PMKTF): TF4.1A and TF4.2 (Figure 64). The PMKTF segment has a DO criteria of 4 mg/L DO because of the extensive tidal wetlands in the PMKTF exert a naturally caused oxygen demand in the system. The historical water quality DO monitoring time series data and histogram in summer (June, July, August, and September) from 1985 to 2016 for this location (Figure 65) indicate that the summer DO concentration below 4 mg/L in the Upper Pamunkey have been rare from 2000 to 2016. Occasional violations were observed during early years of monitoring, especially between 1993 and 1995. Figure 66 indicates the spring and summer chlorophyll-*a* concentrations have been fluctuating since 1985, with majority of the concentrations below 10 ug/L. The concentrations spike in 2012, and the mode is 3 ug/L.

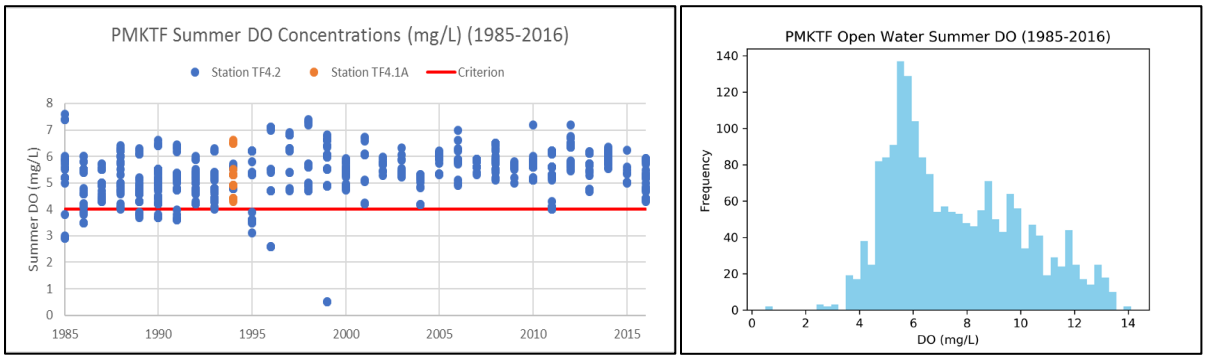


Figure 65: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Upper Pamunkey Tidal Fresh River 1985-2016

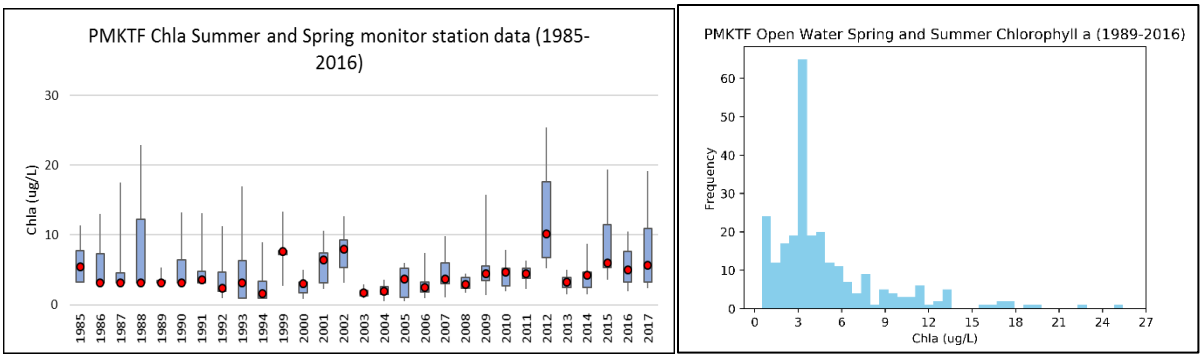


Figure 66: Boxplot of PMKTF chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

The GAM trend at station TF4.2 shows the water quality trend is unclear (Table 19). The summer bottom DO has increased 11 percent since 1985 and 5 percent since 1999 (Figure 68) and total surface phosphorous has decreased 22 percent since 1999 and 18 percent since 2007. There is no significant trend for surface total nitrogen. The surface chlorophyll-*a* has increased 46 percent since 1999. Figure 67 shows that percent attainment of the Open Water summer 30-day mean criterion has no change in CRRMH from 1985 to 2016 (p = 0.018). The CRRMH has attained the Open Water DO summer 30-day mean since 1997 and the nonattainment rates are consistently above 80 percent.

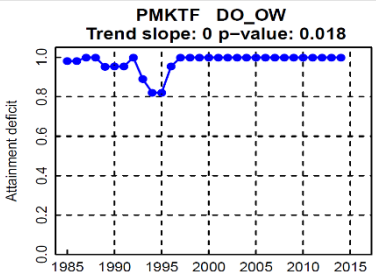


Figure 67: Summer 30-day mean criterion assessment in PMKTF

Table 19: Analysis of water quality trends at monitoring station TF4.2 using GAM

	Parameters	Period Start	Percent Change	p value
Station TF4.2	Chla (surface)	1999	45.77	0.03
	TP (surface)	2007	-17.93	p<0.01
	TP (surface)	1999	-21.96	p<0.001
	DO (summer bottom)	1985	10.74	p<0.01
	DO (summer bottom)	1999	4.88	0.02

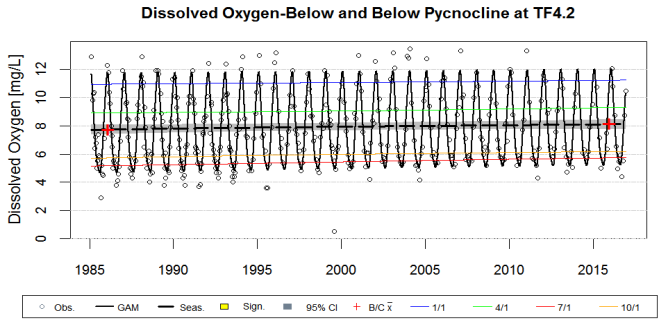


Figure 68: GAM trends of DO at monitoring station TF4.2

The nutrient loadings in PMKTF estimated by CAST indicate that there is minimal change in the nutrient loading (Figure 69). From 1985 to 2013, nitrogen increased 2 percent and phosphorous decreased 12 percent. From 2013 to the WIP2 Scenario, nitrogen decreased 16 percent and the phosphorous decreased 5 percent. During these two periods, the nonattainment rates had no change and remained at 9 percent (Table 20).

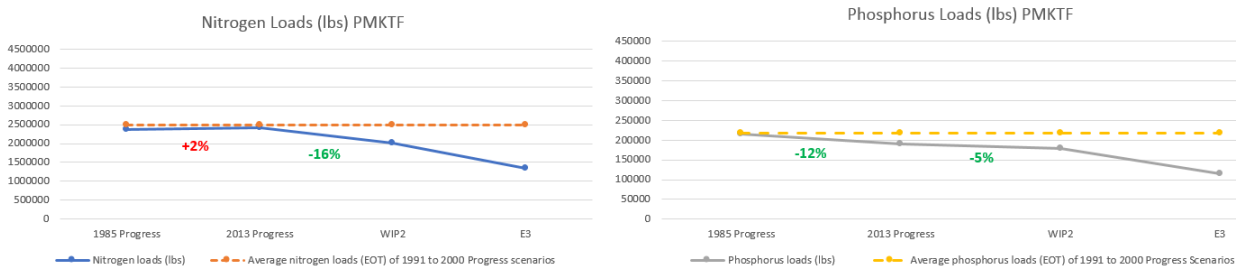


Figure 69: Nutrient loads (EOT) in PMKTF

Table 20: OW PMKTF criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
PMKTF	9%	9%	9%	5%	0%

At the base scenario, two out of the twelve summer months in the 1993-1995 period failed the criterion (Figure 70). At the WIP2 Scenario, one violation rate decreased slightly and the other one had no improvement, which correspond to the July 1995 and August 1995 sampling events (Table 21). The WQSTM predicted 5 percent to 6 percent improvement in scenario modified DO concentrations for July 1995 observations, and predicted 6 percent to 8 percent improvement for August 1995 observations (Figure 71).

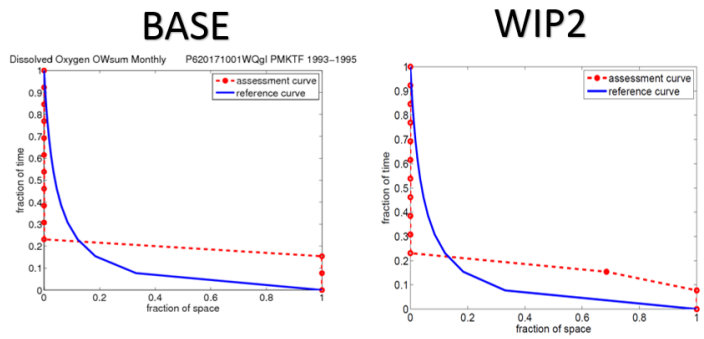


Figure 70: CFD curves for the Base scenario and WIP2 Scenario – PMKTF

Table 21: Monthly Open Water DO criterion nonattainment percentages for PMKTF in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	0%	0%
1993	8	0%	0%
1993	9	0%	0%
1994	6	0%	0%
1994	7	0%	0%
1994	8	0%	0%
1994	9	0%	0%
1995	6	0%	0%
1995	7	100%	68%
1995	8	100%	100%
1995	9	0%	0%

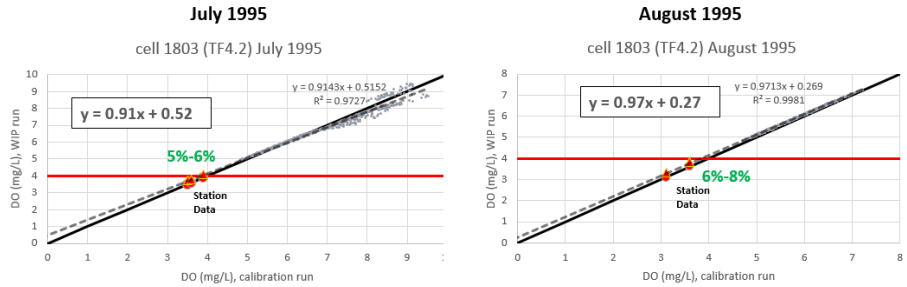


Figure 71: Scenario simulated response of July 1995 and August 1995 in cell 1803 of the monitoring stations at TF4.2

The violin plot (Figure 72) compares the distributions of the observed DO concentrations at the monitoring stations in this segment and the WIP2 scenario-modified observations from 1993 to 1995. There is a slight improvement in 25 percent and 75 percent quantiles for the scenario-modified distribution for both stations. The 50 percent quantile at the station TF4.1A is lower but higher for station TF4.2 compared to the distributions of the observed DO concentrations.

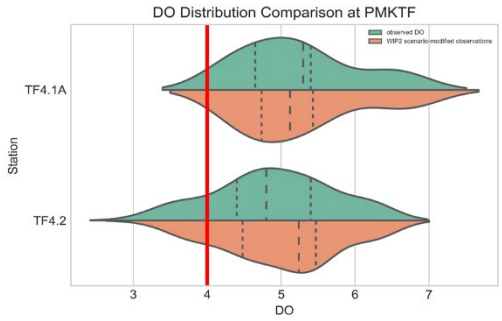


Figure 72: Comparison of the distributions of the observed DO at monitoring stations TF4.1A and TF4.2 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, DO concentrations are almost always above the criterion in PMKTF during later years but there are mixed responses in the water quality condition. The summer bottom DO concentration has improved but the surface chlorophyll-*a* has increased significantly. Increasing chlorophyll-*a* concentrations may indicate the water quality may change. The WQSTM is simulating some degree of

improvement in DO concentrations, however, the WQSTM results are extrapolated from a simulation of DO between 7 and 9 mg/l to observations below 4 mg/L.

Open-Water Wicomico River (WICMH)

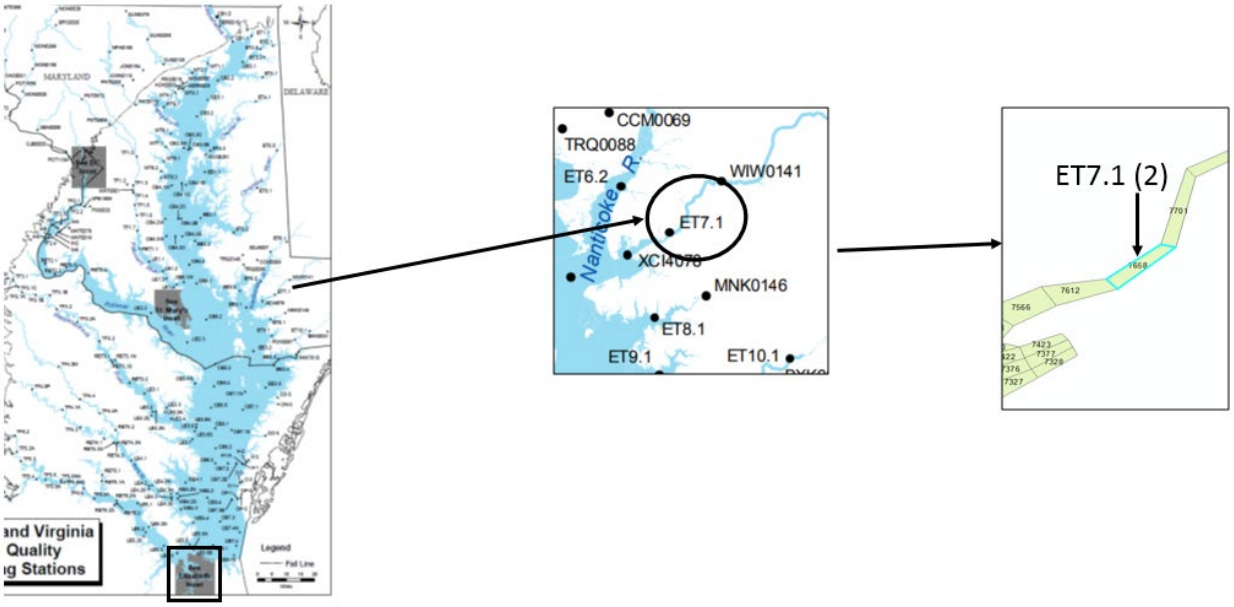


Figure 73: Location of WICMH and the monitoring station WQSTM grid cell location

There is one monitoring station in Wicomico River segment (WICMH): ET7.1 (Figure 73). There are moderate violations of the 5.0 mg/L Open Water DO criterion during the summer months in this station, especially between 1993 and 1995 (Figure 74). The chlorophyll-*a* concentrations fluctuated with fewer extreme values during recent years (Figure 75).

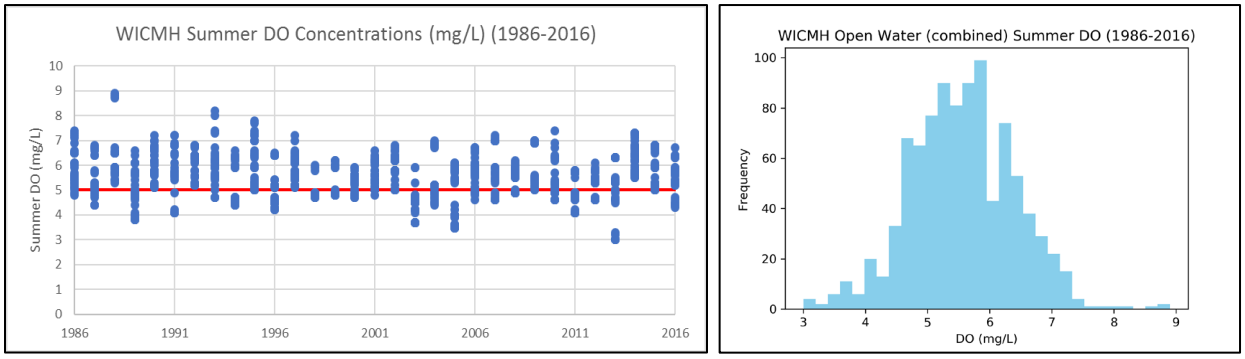


Figure 74: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Wicomico River 1985-2016

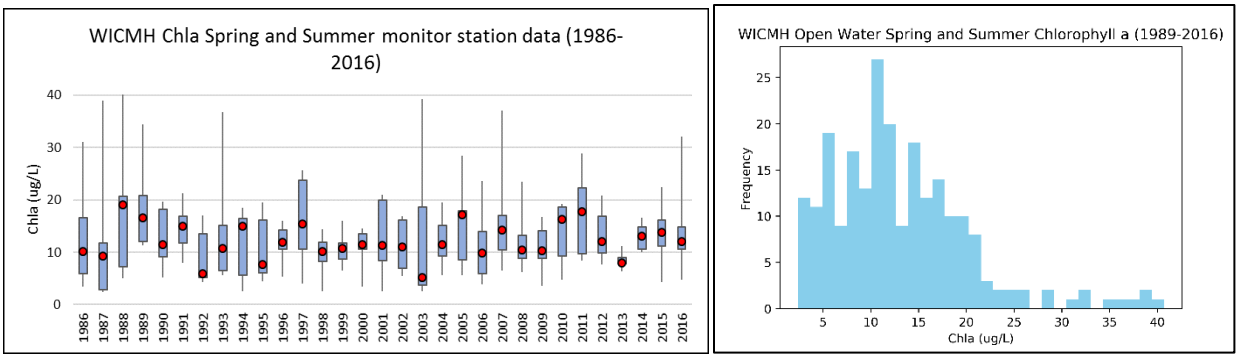


Figure 75: Boxplot of WICMH chlorophyll-a measurement taken in spring and summer at monitoring station from 1985-2016

The GAM trend of station ET7.1 indicate that the surface chlorophyll-*a* has increased 38 percent from 1999 (Table 22). Total surface phosphorous has decreased and there is no significant trend for total surface phosphorous or summer bottom DO (Figure 77). Figure 76 shows that percent attainment of the Open Water summer 30-day mean criterion has no significant change in WICMH from 1985 to 2016 (p = 0.089). The WICMH has not attained the DO summer 30-day mean since 1992.

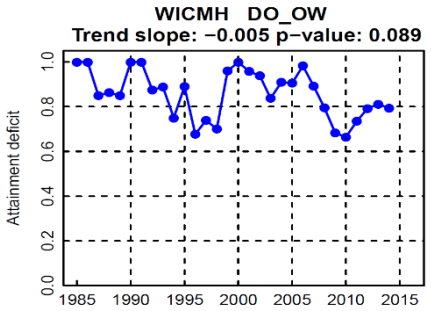


Figure 76: Summer 30-day mean criterion assessment in WICMH

Table 22: Analysis of monitoring station ET7.1 water quality trends using GAM

	Parameters	Period Start	Percent Change	p value
Station ET7.1	Chla (surface)	1999	38.46	p<0.01
	Chla (surface)	2007	17.69	p<0.01
	TP (surface)	1999	-15.34	0.02
	TP (surface)	2007	-12.09	0.05

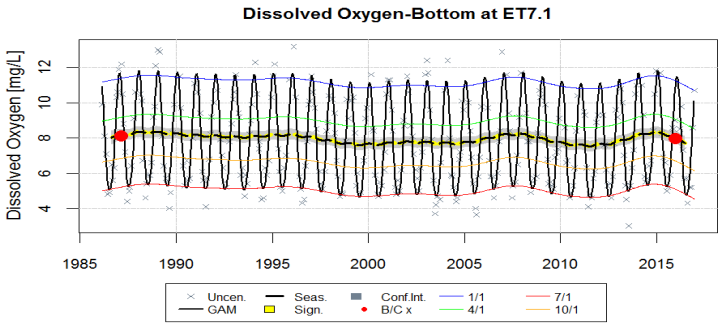


Figure 77: GAM trends of DO at monitoring station ET7.1

The nutrient loads to WICMH estimated by CAST shows that loads decreased both from 1985 Progress to 2013 Progress and from 2013 Progress to the WIP2 Scenario (Figure 78). For the first period, the nitrogen decreased by 12 percent and the phosphorous decreased by 65 percent. At the same period, criteria assessment result shows that the nonattainment rates at CRRMH had no change (Table 23). From 2013 Progress to the WIP2 Scenario, the nitrogen is estimated to have decreased by 32 percent and the phosphorous decreased 23 percent, and the nonattainment rate decreased 6 percent.

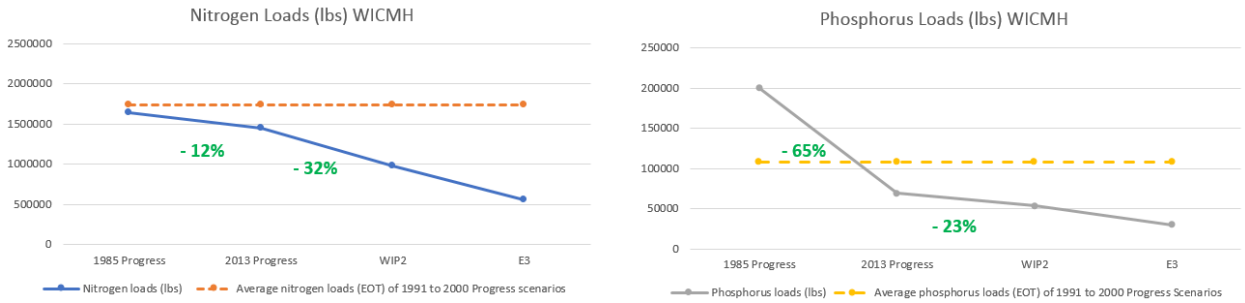


Figure 78: Nutrient loads (EOT) – WICMH

Table 23: OW WICMH criteria assessment

CBSeg	1985Progress	2013Progress	WIP2	E3	All_Forest
	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
WICMH	11%	11%	5%	5%	1%

At the base scenario, two out of the twelve summer months in the 1993-1995 period failed the criterion (Figure 79). At the WIP2 Scenario, one violation rate decreased slightly but below the reference curve and the other one had no improvement. The violation at the WIP2 Scenario corresponds to the June 1994 sampling events (Table 24). For the June 1994 scenario modified DO concentrations, the WQSTM predicted 5 percent improvement for the upper cell, and 6 percent at the lower cell (Figure 80).

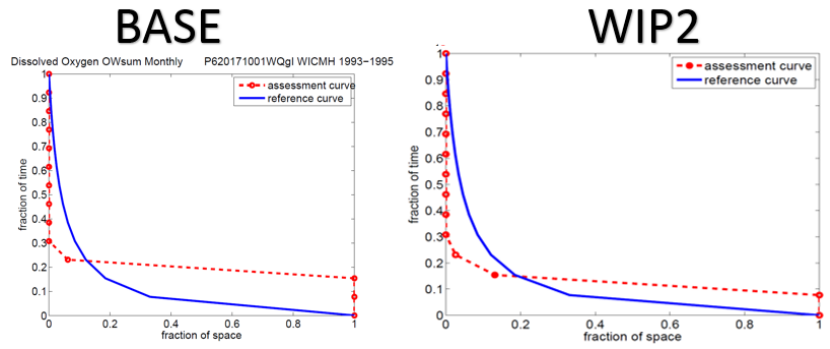


Figure 79: CFD curves for the Base scenario and WIP2 Scenario – WICMH

Table 24: Monthly Open Water DO criterion nonattainment percentages for WICMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	6%	3%
1993	8	0%	0%
1993	9	0%	0%
1994	6	100%	100%
1994	7	100%	13%
1994	8	0%	0%
1994	9	0%	0%
1995	6	0%	0%
1995	7	0%	0%
1995	8	0%	0%
1995	9	0%	0%

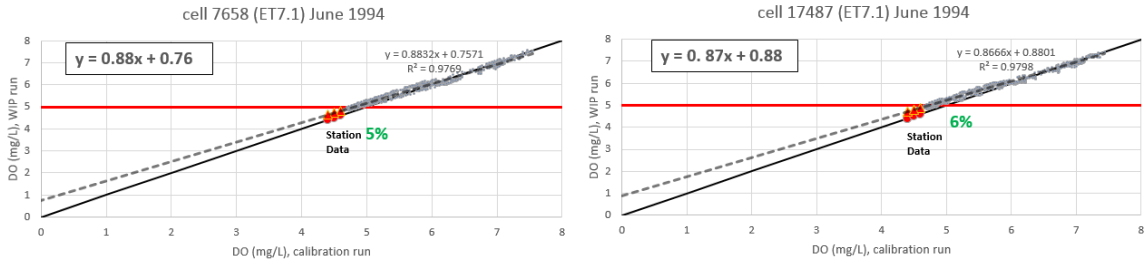


Figure 80: Scenario simulated response of June 1994 in at cells 7568 and 17487 of the monitoring stations ET7.1

The violin plot (Figure 81) compares the distributions of the observed DO concentrations at the ET7.1 monitoring station and the WIP2 scenario-modified observations from 1993 to 1995. There is some degree of increase in the first quantile of the WIP2 scenario-modified DO distribution compared to the overserved DO distribution. However, the second and third quantiles are slightly lower for the scenario modified distribution.

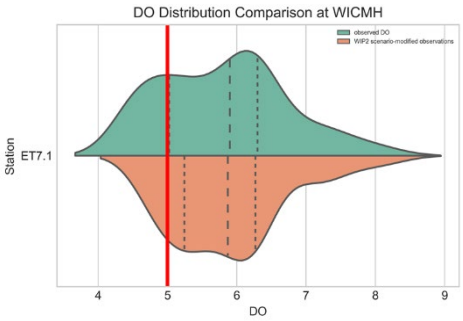


Figure 81: Comparison of the distributions of the observed DO at ET7.1 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, there are minimal indications that the water quality is improving in WICMH. The chlorophyll-*a* is degrading at this station but the total surface phosphorous is improving. There is no significant change in summer bottom DO and the total surface nitrogen. The WICMH has not attained the Open Water summer 30-day mean criterion since 1992. The attainment rate has not changed from

1985 Progress to 2013 Progress despite the estimated load reduction in this segment. The scenario modified response is slight shown by the violin graph.

Deep-Water Segment

Deep-Water South River (SOUMH)

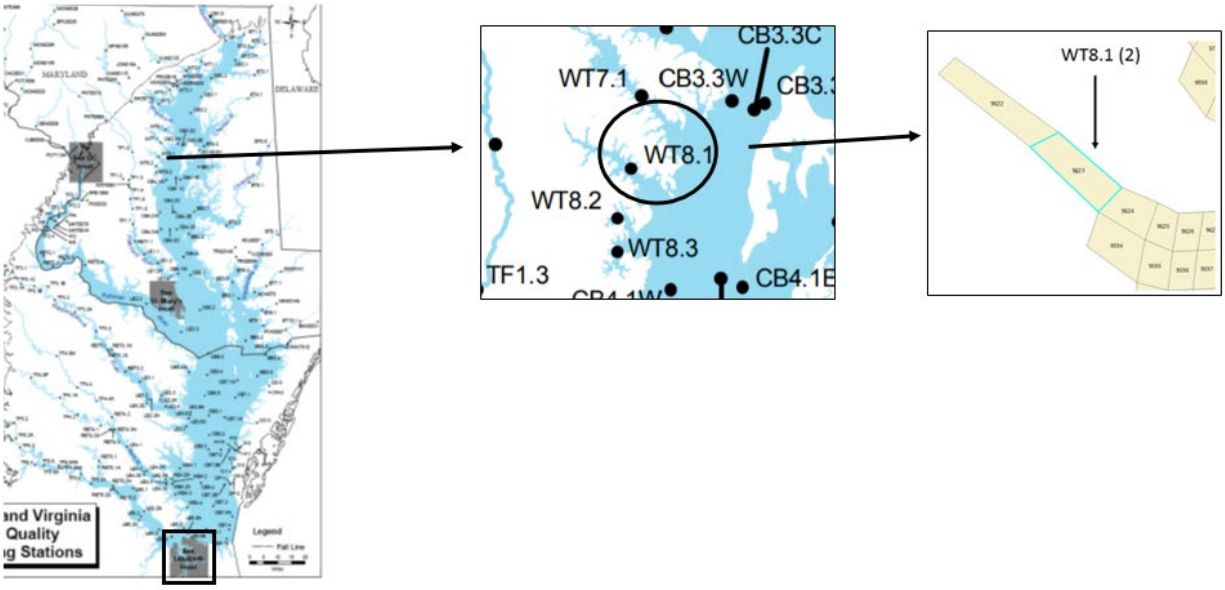


Figure 82: Location of SOUMH and the monitoring station WQSTM grid cell location

There is one monitoring station in South River segment (SOUMH): WT8.1 (Figure 82). Figure 83 shows the summer DO concentrations in SOUMH Open Water (orange dots) and deep water (blue dots). Violations of the 5.0 mg/L Open Water DO criterion (green solid line) and the 3.0 mg/L deep water DO criterion (red line) were not uncommon in the South River during summer months. Dissolved oxygen concentrations in SOUMH reached 0 mg/L more than 65 times during 1985 to 2016, and some occurred during 1993 and 1995. The high values of the observed chlorophyll-*a* concentrations during spring and summer have been decreasing but the mean of annual chlorophyll-*a* concentrations is consistently greater than 10 mg/L (Figure 84).

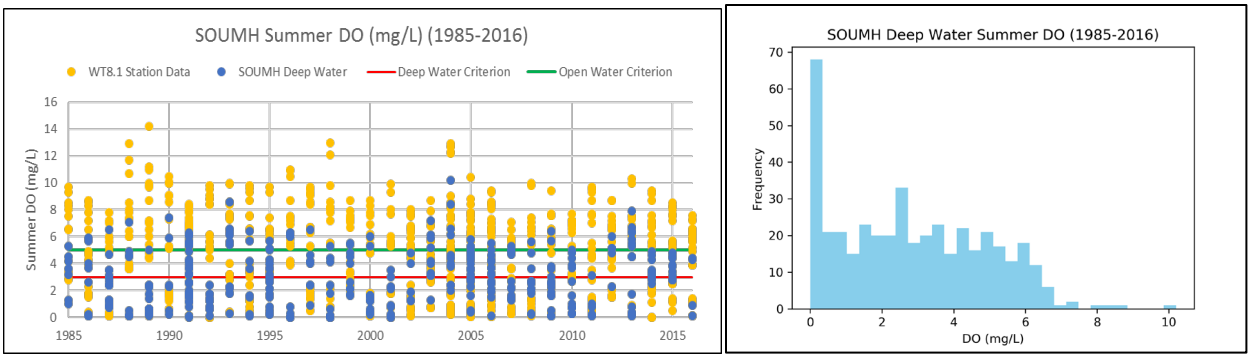


Figure 83: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the South River 1985-2016

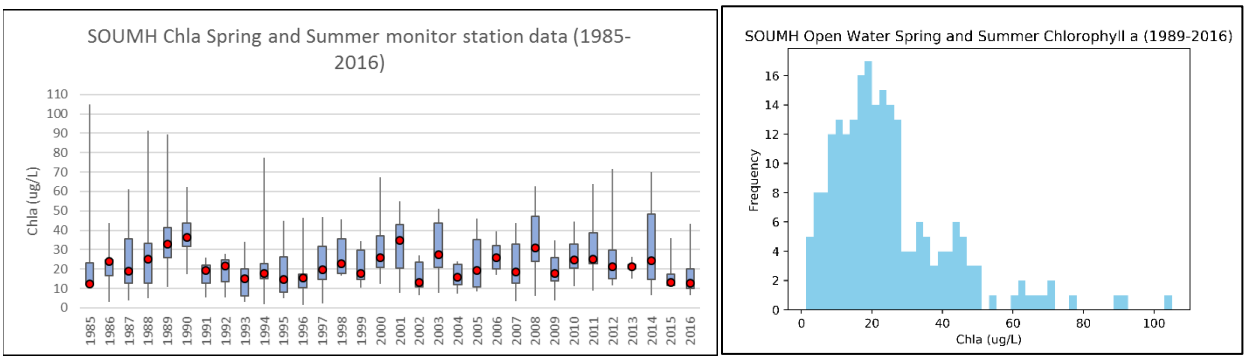


Figure 84: Boxplot of SOUMH chlorophyll-a measurement taken in spring and summer at monitoring stations from 1985-2016

GAM trend result shows that the surface total nitrogen and bottom total phosphorous concentration declined at monitoring station WT8.1 from 2007 to 2016 (Table 25). Surface chlorophyll-*a* concentrations decreased 34 percent ($p < 0.01$) since 2007. There is no significant trend with summer bottom DO however, summer surface DO has declined slightly since 1985 and since 1999 (Figure 86). Figure 85 shows that the percent attainment of DW summer 30-day mean criterion fluctuated and has no significant change from 1985 to 2016 ($p = 0.051$). The SOUMH has not attained DW summer 30-day mean criterion since 1985. However, the percent of attainment rates from 2010 have increased compared to previous periods and are greater than 95 percent.

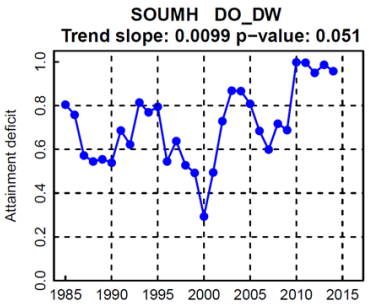


Figure 85: Summer 30-day mean criterion assessment in SOUMH

Table 25: Analysis of water quality trends using GAM at monitoring station WT8.1

	Parameters	Period Start	Percent Change	p value
Station WT8.1	Chla (surface)	2007	-34.03	p<0.01
	TN (surface)	2007	-15.90	p<0.01
	TP (surface)	1985	-22.93	p<0.001
	TP (below)	2007	-15.95	p<0.01
	DO (summer surface)	1985	-9.50	0.05
	DO (summer surface)	1999	-8.25	0.04

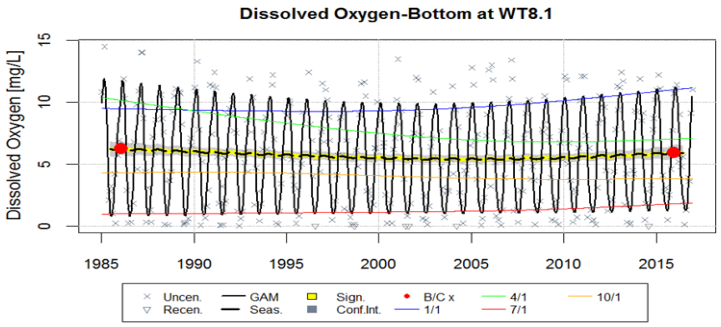


Figure 86: GAM trend of DO at monitoring station WT8.1

CAST estimated the total nitrogen and total phosphorous loads decrease from 1985 to 2013 and WIP2 in SOUMH (Figure 87). From 1985 to 2013, CAST estimated a 2 percent decrease in nitrogen and a 44 percent decrease of phosphorous to the SOUMH segment. The nonattainment rates of Deep Water SOUMH decreases 17 percent from 1985 Progress and 2013 Progress (Table 26Table 8). From 2013 to the WIP2 Scenario, it is estimated that nitrogen decrease by 15 percent and phosphorous increase by 20 percent. The estimated nonattainment rates of Deep Water SOUMH were unchanged from the 2013 Progress to WIP2 Scenario loads and remained at 3 percent. The nonattainment rates estimated by WQSTM are inconsistent with the loads change estimated by CAST.

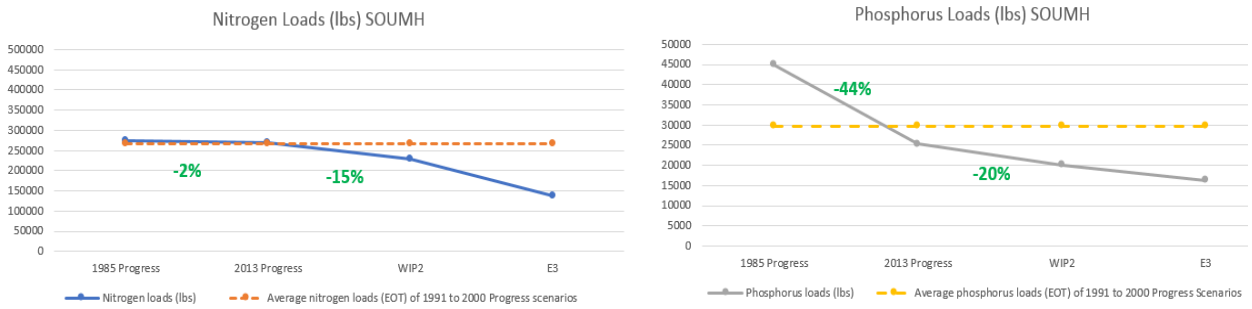


Figure 87: Nutrient loads (EOT) -- SOUMH

Table 26: DW SOUMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
SOUMH	20%	3%	3%	0%	0%

The base CFD curve of the Deep Water SOUMH indicates that there were eight out of twelve summer months in the 1993-1995 period failed the criterion (Figure 89). At the WIP2 Scenario, one violation rate had no improvement. The assessment results identify that the violations correspond with July 1993, sampling events (Table 27). For the July 1993 scenario modified DO concentrations, the WQSTM predicted 437 percent and 591 percent improvement in the DO concentrations (Figure 88). However, the WQSTM results are extrapolated from a simulation of DO between 6 and 8 mg/l to observations below 1 mg/L.

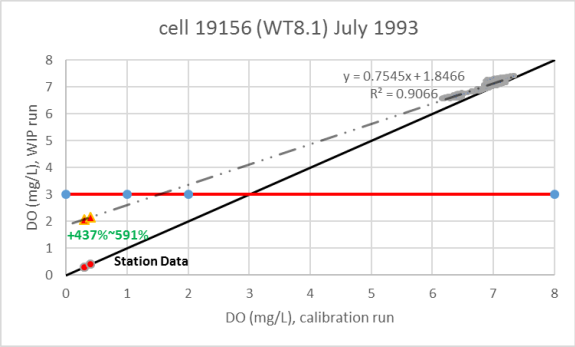


Figure 88: Scenario simulated response of July 1993 in cell 19156

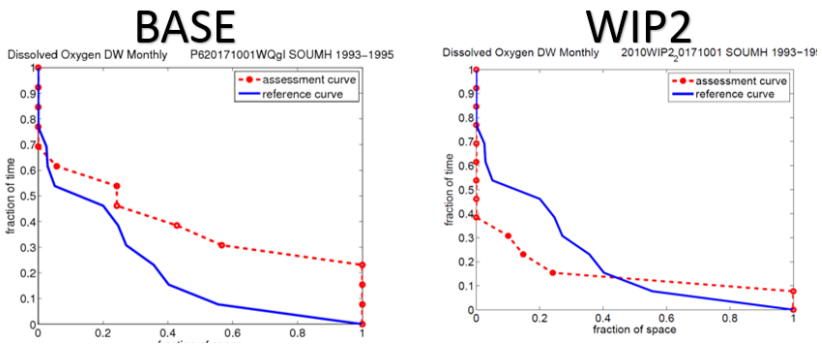


Figure 89: CFD curves for the Base scenario and WIP2 Scenario - SOUMH

Table 27: Monthly Open Water DO criterion nonattainment percentages for SOUMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	0%	0%
1993	7	100%	100%
1993	8	24%	0%
1993	9	0%	0%
1994	6	24%	0%
1994	7	100%	15%
1994	8	100%	0%
1994	9	0%	0%
1995	6	0%	0%
1995	7	57%	24%
1995	8	6%	0%
1995	9	43%	10%

The violin plot (Figure 90) compares the distributions of the observed DO concentrations at the WT8.1 monitoring station and the WIP2 scenario-modified observations from 1993 to 1995. There is some degree of increase in each of the three quantities of the distribution. For the observed DO concentrations in deep water SOUMH, 50 percent of the observations have met the 3.0 mg/L deep-water DO criterion. For the WIP2 scenario-modified DO concentrations, there are more than 75 percent of the distribution have attained the criterion. The range of the DO values is slightly smaller compared to the observed DO concentrations between 1993 and 1995. The three quantiles of the WIP2 scenario-modified distribution have increased respectively.

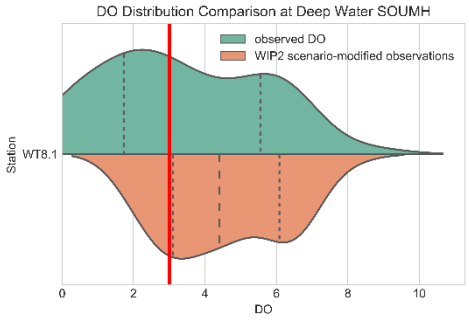


Figure 90: Comparison of the distributions of the observed DO at monitoring station WT8.1 from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the trend is improving in the right direction but significant improvement is needed to meet the water quality standards by 2025. The surface chlorophyll-*a* concentration and the surface nutrients concentrations have improved since 2007. The summer surface DO is degrading and there is no significant trend with summer bottom DO. However, percent of attainment rates from 2010 have increased compared to previous periods and are greater than 95 percent. The nonattainment rates estimated by WSM are inconsistent with the load change estimated by CAST. The WQSTM simulates some degree of improvement in the WIP2 scenario-modified DO concentrations compared to observed DO, however, the WQSTM results are extrapolated from a simulation of DO between 6 and 8 mg/l to observations below 1 mg/L.

Deep-Channel Segment

Deep-Channel Eastern Bay (EASMH)

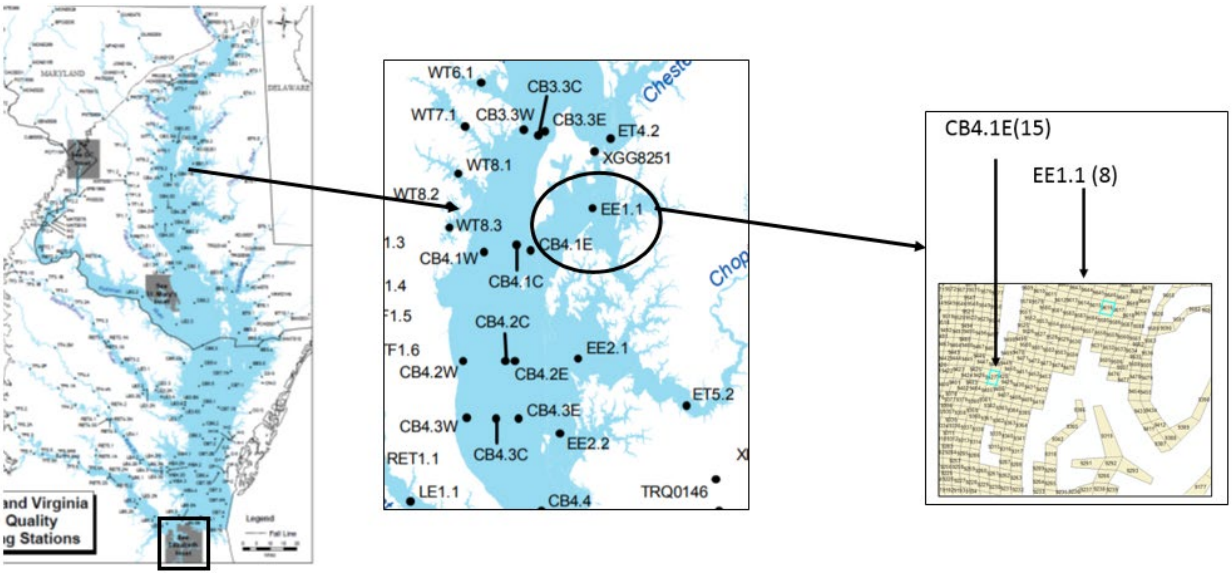


Figure 91: Location of EASMH and the monitoring stations WQSTM grid cell location

There are two monitoring stations in Eastern Bay segment (EASMH): CB4.1E and EE1.1 (Figure 91). Frequent violations of the 1.0 mg/L deep-channel DO criterion were observed during the summer months in the Eastern Bay, particularly between 1993 and 1995 (Figure 92). The majority of the summer DO concentrations are less than 1.0 mg/L. Figure 93 indicates the spring and summer chlorophyll-*a* concentrations have been fluctuating since 1985. The concentrations spike in 2003 and 2013, and the mode is around 10 ug/L.

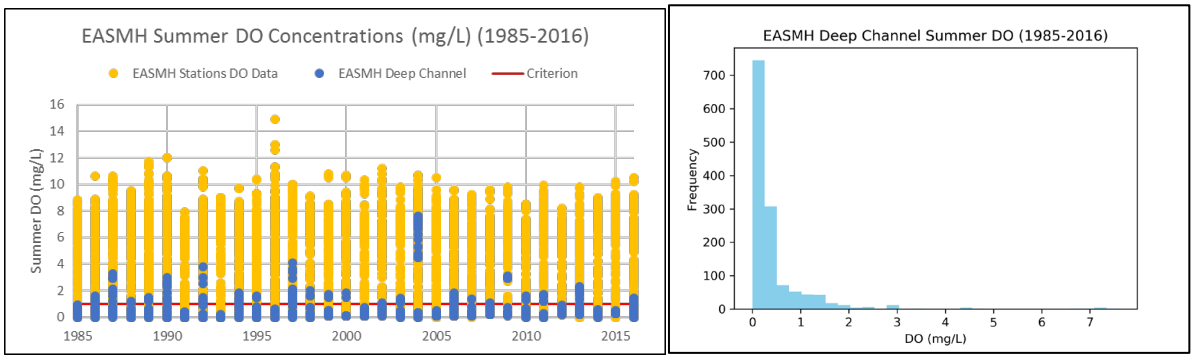


Figure 92: Summer DO measurement taken in summer months (June-September) at water quality monitoring stations in the Eastern Bay 1985-2016

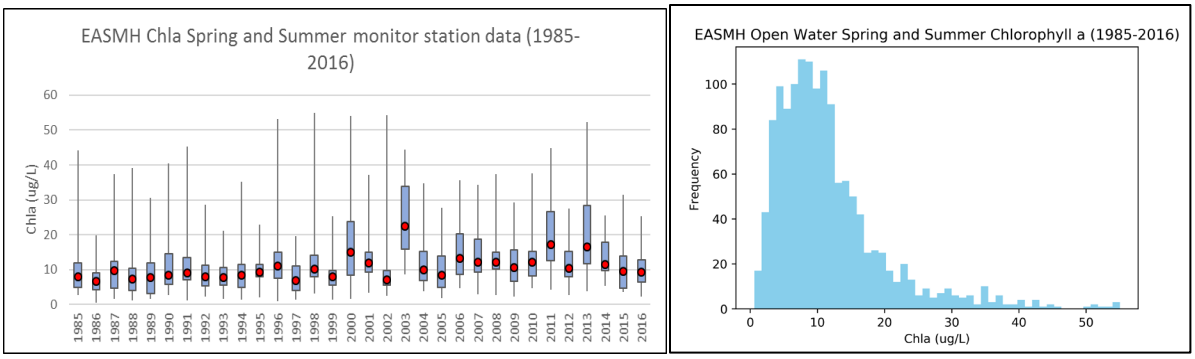


Figure 93: Boxplot of EASMH chlorophyll-a measurement taken in spring and summer at monitoring station from 1985-2016

GAM trend shows that the water quality at the monitoring stations EE1.1 and CB4.1E are improving (Table 28). The surface chlorophyll-*a* has decreased 41 percent since 2007 at station EE1.1, and both surface and bottom nitrogen and phosphorous are decreasing since 2007. For station CB4.1E, summer surface DO concentrations have increased since 1985 and 2007. There is no significant trend of summer bottom DO for either of the stations (Figure 95 and Figure 96). The EASMH has not attained the DC OW summer 30-day mean since 1985 (Figure 94). The nonattainment rates are consistently above 60 percent. There is no change in the attainment rate since 1985 (p= 0.018).

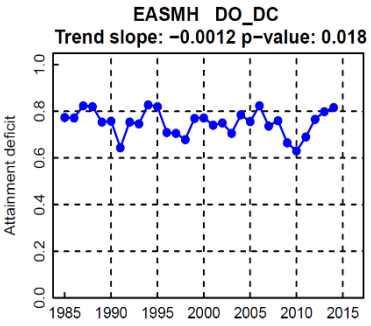


Figure 94: Summer 30-day mean criterion assessment in EASMH

Table 28: Analysis of monitoring stations EE1.1 and CB4.1E water quality trends using GAM

	Parameters	Period Start	Percent Change	p value
Station EE1.1	Chl-a (surface)	2007	-40.61	p<0.001
	TN (surface)	2007	-17.52	p < 0.0001
	TN (below)	2007	-21.20	p < 0.0001
	TP (surface)	2007	-15.80	p<0.01
	TP (below)	2007	-18.26	p<0.01
Station CB4.1E	DO (summer surface)	1985	12.61	0.01
	DO (summer surface)	2007	14.28	p<0.01

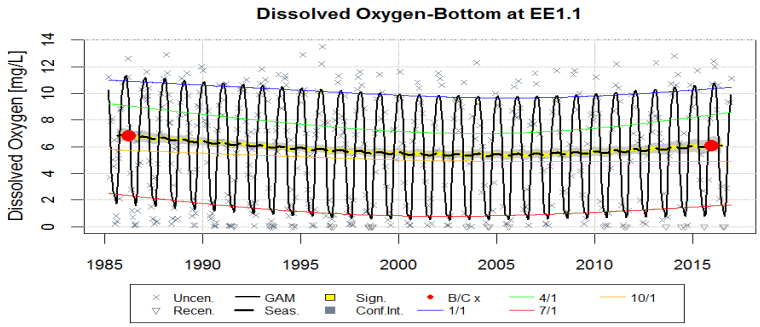


Figure 95: GAM trends of DO at monitoring station EE1.1

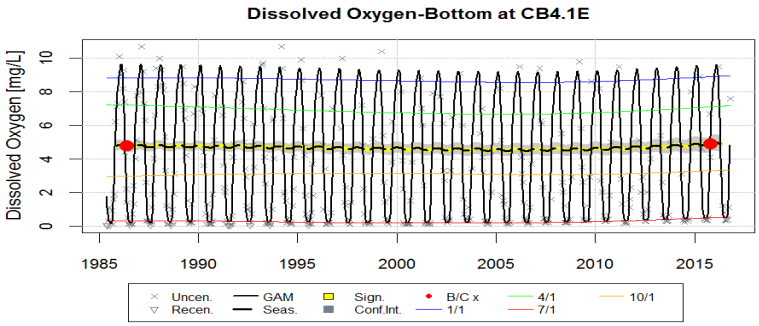


Figure 96: GAM trends of DO at monitoring station CB4.1E

The nutrient loads to EASMH estimated by CAST shows that loads decreased both from 1985 Progress to 2013 Progress and from 2013 Progress to WIP2 Scenario (Figure 97). For the first period, the nitrogen decreased by 18 percent and the phosphorous decreased by 40 percent. At the same period, criteria assessment result shows that the nonattainment rates at EASMH decreased 8 percent (Table 29). From 2013 Progress to the WIP2 Scenario, the nitrogen decreased by 18 percent and the phosphorous decreased 11 percent, and the nonattainment rate decreased 7 percent. The EASMH attains water quality standard both at E3 and All Forest scenarios.

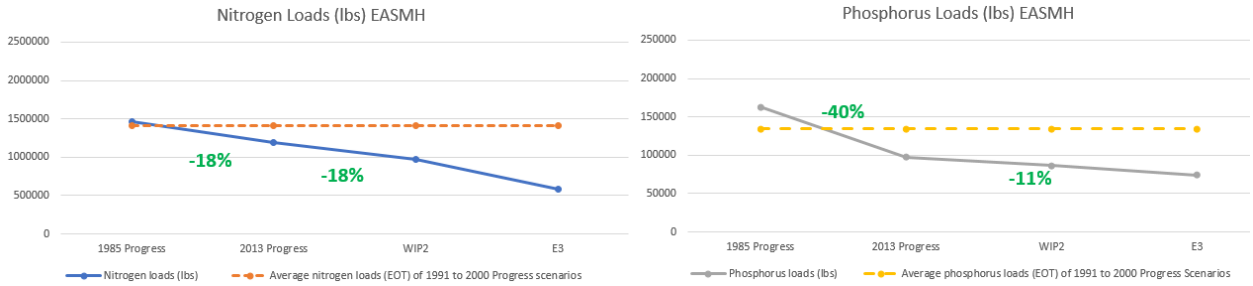


Figure 97: Nutrient loads (EOT) – EASMH

Table 29: DC EASMH criteria assessment

	1985Progress	2013Progress	WIP2	E3	All_Forest
CBSeg	347TN	253TN	195TN	133TN	40TN
	30.4TP	15.9TP	13.7TP	8.6TP	3.9TP
EASMH	21%	13%	6%	0%	0%

At the base scenario, three out of the twenty-four summer months sampling events in the 1993-1995 period attain the criterion (Figure 98). At the WIP2 Scenario, there are six sampling events have attained violation rates. Table 30 shows the months and years associated with those violations rates. The scenario-modified response in DO varies in time and space (Figure 99). For the June 1994 simulations, WQSTM estimates the slope of cell 55563 in CB4.1E to be 0.42. For the July 1995 simulations, WQSTM estimates the slope of cell 33723 in EE1.1 to be 147.

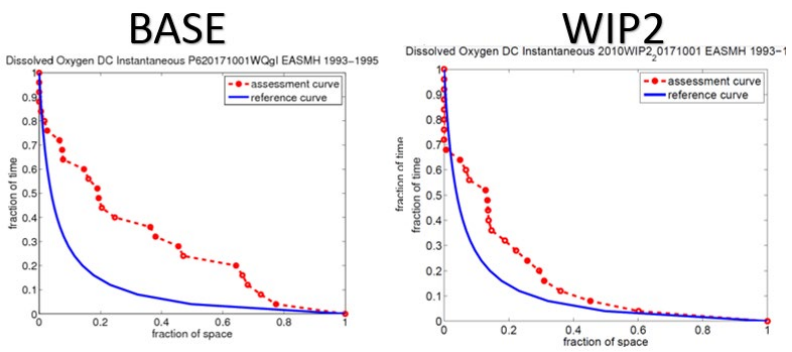


Figure 98: CFD curves for the Base scenario and WIP2 Scenario – EASMH

Table 30: Monthly Open Water DO criterion nonattainment percentages for EASMH in the 1993-1995 critical period

Year	Month	Violation Rate	
		Calibration	WIP2
1993	6	72%	22%
1993	6	38%	15%
1993	7	64%	29%
1993	7	77%	60%
1993	8	46%	26%
1993	8	68%	45%
1993	9	0%	0%
1993	9	0%	0%
1994	6	3%	1%
1994	6	2%	0%
1994	7	36%	8%
1994	7	7%	0%
1994	8	8%	13%
1994	8	19%	7%
1994	9	66%	19%
1994	9	0%	0%
1995	6	15%	0%
1995	6	8%	0%
1995	7	19%	13%
1995	7	25%	5%
1995	8	16%	31%
1995	8	47%	14%
1995	9	20%	14%
1995	9	1%	36%

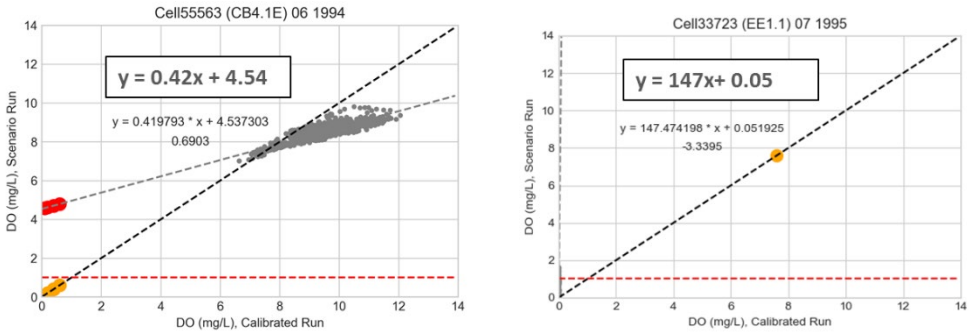


Figure 99: Scenario simulated response of June 1994 and July 1995 in at various cells of the monitoring stations in EASMH

The violin plot (Figure 100) compares the distributions of the observed DO concentrations at the monitoring stations CB4.1E and EE1.1 and the WIP2 scenario-modified observations from 1993 to 1995.

For CB4.1E, there are improvement in the all three quantiles of WIP2 scenario-modified DO concentrations. For EE1.1, there is minimal improvement in the all three quantiles except the third quantile. The ranges of the WIP2 scenario-modified observations for both stations have been larger than the distributions of observed DO.

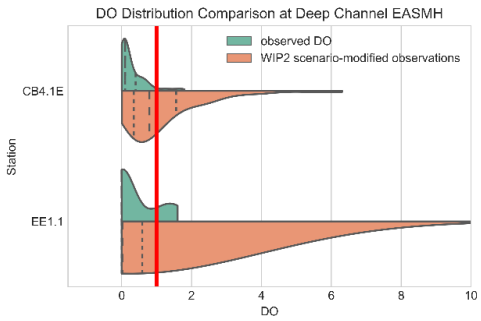


Figure 100: Comparison of the distributions of the observed DO at monitoring stations EE1.1 and CB4.1E from 1993 to 1995 and the WIP2 scenario-modified DO observations

In conclusion, the water quality is improving in EASMH but the scenario-modified DO is not simulating response to meet the water quality standards at the WIP2 level. Substantial violations of 1.0 mg/L deep-channel DO criterion were observed during the summer months in the Eastern Bay. The GAM trends of surface chlorophyll-*a* and total nitrogen and phosphorous are improving but there is no significant trend of summer bottom DO. The WQSTM simulates little improvement in low DO concentrations for this segment but there is substantial evidence that the WQSTM calibration of the EASMH segment overestimates the observed hypoxia in the Deep Channel as shown in Figure 101. Therefore, the WQSTM calibration of the EASMH segment is considered to be insufficient for the assessment of Deep Channel DO.

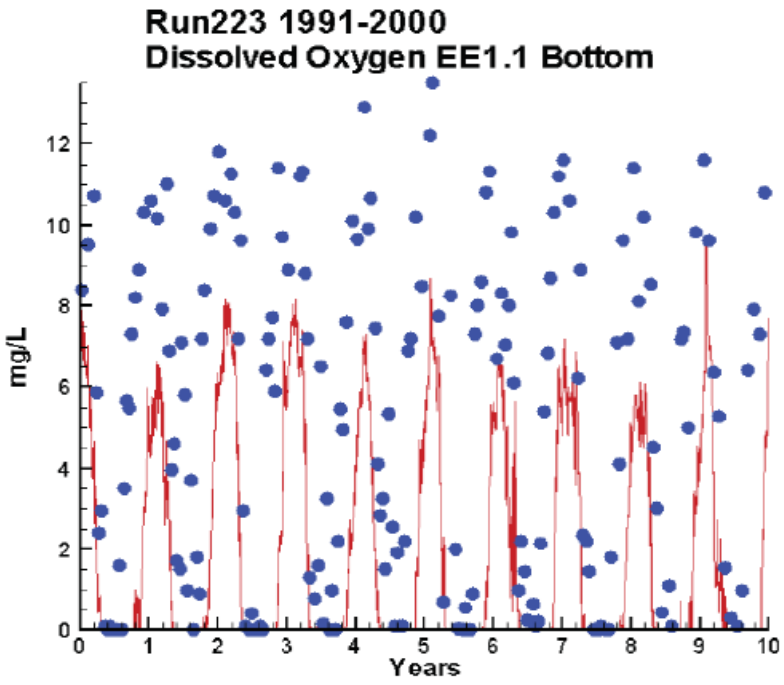


Figure 101: Time series of observed DO (blue dots) and WQSTM simulated DO (red line) for the Deep Channel DO monitoring station EE1.1 for the period 1991 to 2000.

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