Green City, Clean Waters

Tidal Waters Water Quality Model – Bacteria and Dissolved Oxygen

Consent Order & Agreement

Deliverable IX and X

City of Philadelphia Combined Sewer Overflow Long Term Control Plan Update

Submitted to

The Commonwealth of Pennsylvania

Department of Environmental Protection

By The Philadelphia Water Department

June 1, 2015

Notice of Intent to Produce an Addendum to this Report

Some errors and omissions identified by the authors after the publication of this report will be corrected by the publication of an addendum that will be posted to this location. Those changes are not expected to have a significant influence on the tidal water quality results described herein, and are not expected to lead to any alteration of the conclusions reached in this report. The corrections will address the inadvertent omission of the discharges from 12 combined sewer overflow points (of the 176) in the City (F04, F05, F06, F07, R18 in the Tacony-Frankford creeks basin; C19, C20, C21, C22 and C23 in the Cobbs Creek basin; and, P01 and P02 in the Pennypack Creek basin). In addition, some minor inadvertent anomalies occurred with respect to a small subset of municipal/industrial point source discharges, model boundary conditions, and minor stream/direct watershed inputs, as listed below. The addendum is expected to be completed and posted here by the summer of 2016.

Other model updates:

Repair Organic Nitrogen effluent estimates for subset of permitted dischargers
Repair DO effluent estimates for subset of permitted dischargers
Repair Organic Carbon effluent estimates for subset of permitted dischargers
Remove industrial discharger outfalls that are not treated wastewater
Repair Delaware City Refinery Outfall 601 effluent flow
Add Willingboro Twp. MUA
Add Assunpink Creek to model
Repair algae and particulate organic phosphorus loading at open boundary
Update gaged, ungaged and runoff polygon areas

Addendum to COA 9 and 10 Deliverable Report

In the process of pursuing continual improvement of the PWD Tidal Waters Bacteria and DO Models, a small number of errors and omissions were found following the June 2015 submittal of the COA 9 and 10 Deliverable Report (Table 1). Specifically, COA 9 and 10 Deliverable Report had an inadvertent omission of the discharges from 12 combined sewer overflow (CSO) points (of the 176) in the City (F04, F05, F06, F07, R18 in the Tacony-Frankford creeks basin; C19, C20, C21, C22 and C23 in the Cobbs Creek basin; and, P01 and P02 in the Pennypack Creek basin). In addition, some minor inadvertent anomalies occurred with respect to a small subset of municipal/industrial point source discharges, model boundary conditions, and minor stream/direct watershed inputs. The resolution status of these errors and omissions is shown in the right column of Table 1.

Table 1: Addendum Items

Addendum Item	Status
1. Include the discharges from 12 CSOs in the City that were omitted (F04, F05, F06, F07, R18, C19, C20, C21, C22, C23, P01, P02)	Completed
2. Repair Organic Nitrogen effluent estimates for subset of permitted dischargers	Updated tables A3-5 through A3-12. Next model version will contain updated permitted discharger boundary conditions.
3. Repair DO effluent estimates for subset of permitted dischargers	
4. Repair Organic Carbon effluent estimates for subset of permitted dischargers	
5. Remove industrial discharger outfalls that are not treated wastewater	
6. Repair Delaware City Refinery Outfall 601 effluent flow	
7. Add Willingboro Twp. MUA	
8. Add Assunpink Creek to model	Updated table A3-1 through A3-4. Next model will version will contain Assunpink Creek inflow and water quality.
9. Repair algae and particulate organic phosphorus loading at open boundary	Upon further investigation, particulate organic phosphorus was loaded correctly at open boundary in COA Deliverables 9 and 10. Repair for algae loading at open boundary has been identified and will be implemented in next model version.
10. Update gaged, ungaged and runoff polygon areas	Completed

With respect to Item 1, a comparison was made between a model simulation that included the 12 previously omitted CSOs, and a baseline simulation that excluded the 12 CSOs listed in Table 1.

The objective was to determine if the addition of the 12 previously omitted CSOs had a substantial influence on the tidal water quality results and conclusions described in the COA Deliverables 9 and 10 Report. For the Bacteria and DO Models, the addition of the 12 previously omitted CSOs had a negligible impact on simulated water quality output in the model domain (Figures 1 and 2), and the conclusions reported in 2015 regarding the Bacteria and DO Models are not impacted in any way.

In line with the Philadelphia Water Department's continued improvement of the Bacteria and DO Models, Items 2 through 9 in Table 1 will be implemented in the next model version. In addition, plans are underway to address the areas identified in Section 3.12 of the COA 9 and 10 Deliverable Report.

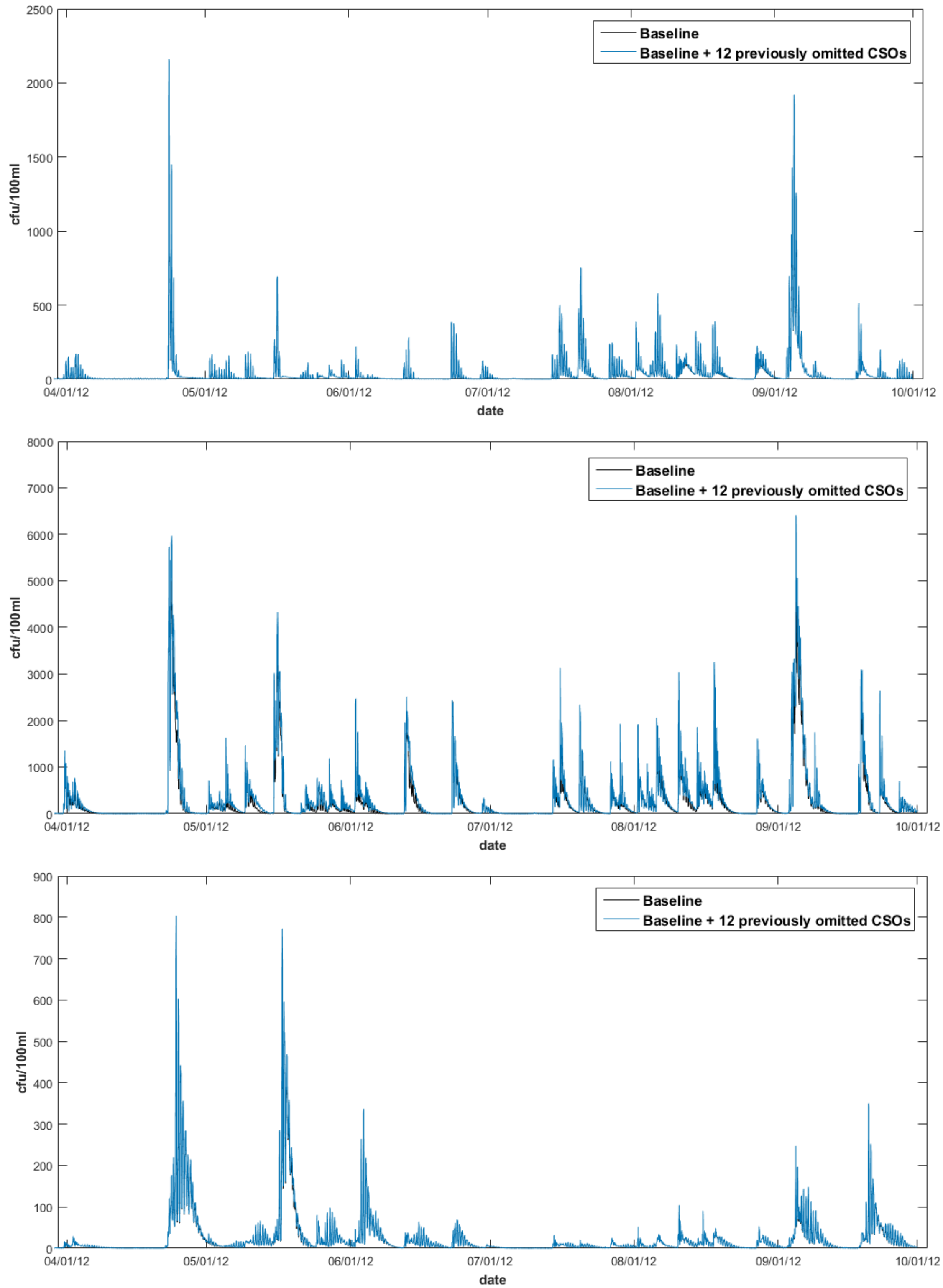

Figure 1. Simulated fecal coliform at USGS gages 014670261, 01467200, 01477050, shown top to bottom, in April-September 2012 validation period, at baseline condition and with all CSOs. 2013 results produced the same trend.

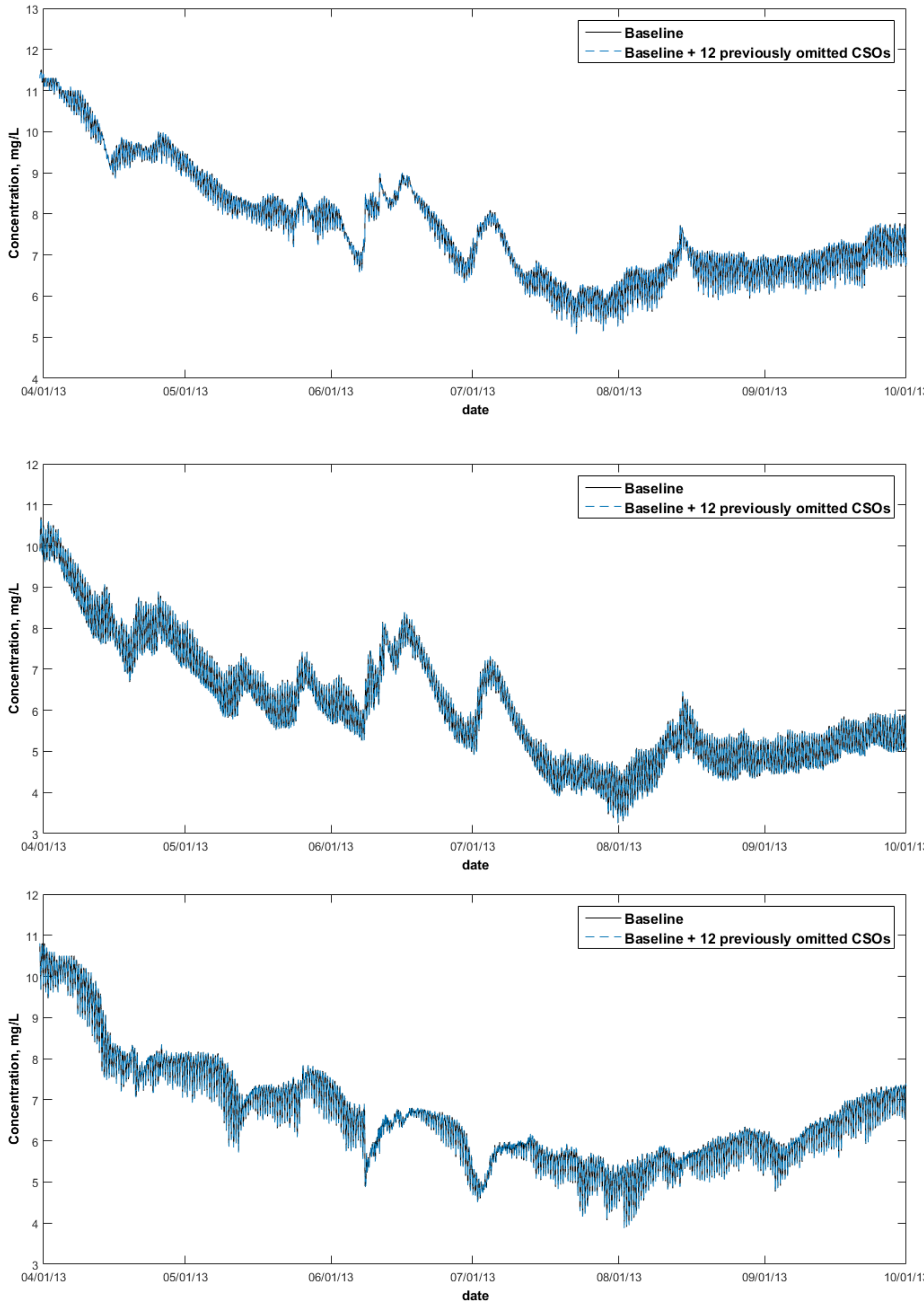

Figure 2. Simulated DO at USGS gages 014670261, 01467200, 01477050, shown top to bottom, in April-September 2013 validation period, at baseline condition and with all CSOs. 2012 results produced the same trend.

Table A3-1 through A3-4: Parameter concentrations for Assunpink Creek

Parameter	Spring	Summer	Winter
DOC (mg/L)	5	4.25	3.4
POC (mg/L)	1.3	0.8	0.68
NH4 (mg-N/L)	0.124117	0.094364	0.078212
NO3 (mg-N/L)	2.766359	3.932801	2.784265
DON (mg-N/L)	0.47	0.54	0.31
PON (mg-N/L)	0.245	0.09	0.05
PO4 (mg-P/L)	0.1425	0.2505	0.15
DOP (mg-P/L)	0.07125	0.12525	0.075
POP (mg-P/L)	0.07125	0.12525	0.075
DO (mg/L)	8.22	7.35	11.1
Fecal Coliform (CFU/100mL)	4450	12000	790
Chl-a	see Crosswicks		

Table A3-5 (corrected): Municipal WWTPS - Average flow and concentration, 2012

		2012 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
Ewing Lawrence Sewerage Authority	0.406	0.82[b]	7.36[b]	0.58[d]	0.58[d]	1.15[d]	0.01[a]	0.02[a]	0.10	17.25	9.69	4.0
Morrisville Boro Mun. Auth-STP	0.192	0.48[b]	4.31[b]	0.59[a]	0.59[a]	3.54[a]	1.28[a]	3.85[a]	9.19	4.90[a]	6.37	55.4
Trenton DPW Sewerage Authority	0.472	2.53[b]	22.77[b]	0.20[a]	0.20[a]	1.10[a]	0.38[a]	1.14[a]	6.64	6.90[a]	8.50[a]	1.0
Hamilton Twp WPCF	0.372	2.53[b]	22.80[b]	0.11[a]	0.11[a]	3.99[a]	0.26[a]	0.79[a]	23.93	5.26[a]	6.67	3.2
Bordentown Sewerage Authority	0.073	0.39[b]	3.53[b]	0.20[a]	0.20[a]	3.60[a]	0.88[a]	2.63[a]	0.16	28.30[a]	8.04	12.9
Lower Bucks County Joint MA	0.261	0.72[b]	6.51[b]	0.15[a]	0.15[a]	2.30[a]	1.32[a]	3.97[a]	23.00	7.00[a]	3.73	146.9
Florence Twp STP	0.076	0.57[b]	5.15[b]	0.86[d]	0.86[d]	1.73[d]	0.04[a]	0.12[a]	0.70	5.80[a]	6.95[a]	6.9
Bristol Boro WSA	0.052	0.57[b]	5.10[b]	0.06[a]	0.06[a]	0.11[a]	0.06[a]	0.17[a]	0.98	8.15[a]	6.95[a]	1.3
Burlington Twp DPW	0.091	0.34[b]	3.02[b]	0.57[d]	0.57[d]	1.14[d]	0.29[a]	0.86[a]	4.97	0.65[a]	6.95[a]	1.2
Burlington City STP	0.075	1.14[b]	10.29[b]	0.80[d]	0.80[d]	1.60[d]	0.04[a]	0.12[a]	0.69	5.73[a]	8.41	4.6
Bristol Twp WWTP	0.110	1.00[b]	8.97[b]	0.10[a]	0.10[a]	0.20[a]	0.17[a]	0.51[a]	2.95	24.45[a]	8.29	49.9
Willingboro Twp MUA	0.144	1.97[b]	17.75[b]	0.32[a]	0.32[a]	0.86[a]	0.71[a]	2.12[a]	7.13	15.50[a]	7.44	15.8
Delran Sewerage Authority	0.087	0.46[b]	4.15[b]	0.76[d]	0.76[d]	1.51[d]	0.02[a]	0.06[a]	0.34	14.52	6.23	14.5
Cinnaminson Sewerage Authority	0.050	2.40[b]	21.61[b]	0.21[a]	0.21[a]	2.04[a]	0.93[a]	2.80[a]	12.53	1.70[a]	0.90[a]	20.4
Moorestown WWTP	0.089	0.58[b]	5.19[b]	0.26[a]	0.26[a]	2.50[a]	0.10[a]	0.30[a]	1.73	17.15[a]	7.50[a]	16.3
Maple Shade POTW	0.095	0.30[b]	2.69[b]	0.05[d]	0.05[d]	0.09[d]	0.01[a]	0.04[a]	0.25	2.08[a]	8.64	4.5
Philadelphia - Northeast WPCP	7.003	0.52[b]	4.69[b]	0.10[d]	0.10[d]	0.23	0.58[e]	1.74[e]	6.80	2.43	5.67	14.1
Camden County MUA	1.937	0.66[b]	5.95[b]	0.25[a]	0.25[a]	1.64[a]	1.28[a]	3.83[a]	22.19	2.50[a]	3.50[a]	1.5
Philadelphia - Southeast WPCP	2.953	0.70[b]	6.32[b]	0.10[d]	0.10[d]	0.45	0.42[e]	1.26[e]	9.24	0.26	5.18	11.8
Philadelphia - Southwest WPCP	7.256	0.36[b]	3.24[b]	0.08[d]	0.08[d]	0.07	0.73[e]	2.18[e]	20.92	1.97	5.13	30.4
Gloucester County Utility Authority	0.732	1.07[b]	9.63[b]	0.27[a]	0.27[a]	2.54[a]	0.56[a]	1.69[a]	16.52	9.19[a]	6.16	2.4

Tinicum Twp WWTP	0.038	1.00[b]	9.03[b]	0.10[a]	0.10[a]	0.20[a]	0.53[a]	1.58[a]	2.11[a]	17.45[a]	8.19	55.2
Little Washington STP	0.065	0.75[b]	6.74[b]	0.07[a]	0.07[a]	0.15[a]	0.04[a]	0.11[a]	0.62	5.11[a]	6.77	9.1
DELCORA	1.270	2.00[b]	17.98[b]	0.10[a]	0.10[a]	0.70[a]	0.61[e]	1.82[e]	4.61	5.44	7.60[a]	70.9
Southwest Delaware County MUA	0.185	0.78[b]	6.99[b]	0.08[a]	0.08[a]	0.16[a]	0.12[a]	0.37[a]	2.15	17.80[a]	8.37	44.1
Logan Twp MUA	0.045	0.59[b]	5.35[b]	0.79[d]	0.79[d]	1.57[d]	0.15[a]	0.46[a]	2.65	21.91[a]	5.85	3.5
Carneys Point WWTP	0.038	1.52[b]	13.65[b]	1.08[d]	1.08[d]	2.15[d]	0.41[a]	1.24[a]	7.21	0.94[a]	6.95[a]	20.7
Pennsville Twp Sewerage Authority	0.055	0.91[b]	8.21[b]	0.39[d]	0.39[d]	0.78[d]	0.05[a]	0.15[a]	0.85	7.05[a]	6.95[a]	6.3
Wilmington WWTP	2.865	1.04[b]	9.36[b]	0.05[a]	0.05[a]	0.90[a]	0.03[a]	0.08[a]	16.20[a]	4.20[a]	4.50[a]	0.6

a) estimated b) based on reported BOD or CBOD c) based on reported TOC or DOC

d) based on reported TP e) based on reported TKN f) based on reported TON

Table A3-6 (corrected): Industrial Permitted Dischargers - Average flow and concentration, 2012

		2012 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
US Steel Fairless Hills Works (Outfall 103)	0.082	0.55[b]	0.55[b]	0.01[a]	0.01[a]	0.02[a]	0.12[a]	0.12[a]	0.23[a]	1.00[a]	6.95[a]	4.5[a]
Coastal Eagle Point Oil Co.	0.044	0.66[b]	0.66[b]	0.01[a]	0.01[a]	0.03[a]	0.04[a]	0.04[a]	0.33	1.00[a]	6.95[a]	0.8
Valero Refining Co. (Outfall 1)	0.345	0.96[b]	0.96[b]	0.13[a]	0.13[a]	0.77[a]	0.38[a]	0.38[a]	0.18	5.23[a]	8.00[a]	4.1
E I Dupont De Nemours & Co. Repauno Plant	0.044	0.80[b]	0.80[b]	0.02[a]	0.02[a]	0.03[a]	0.12[a]	0.12[a]	1.05	10.03	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 201)	0.059	0.33[b]	0.33[b]	0.15[a]	0.15[a]	0.40[a]	0.29[a]	0.29[a]	0.97	5.90[a]	6.20[a]	4.5[a]
Dupont Edgemoor (Outfall 1)	0.110	1.16[b]	1.16[b]	0.02[a]	0.02[a]	0.05[a]	0.24[a]	0.24[a]	0.49[a]	1.00[a]	6.95[a]	4.5[a]
Ferro Corp.	0.037	6.75[b]	6.75[b]	0.14[a]	0.14[a]	0.27[a]	1.46[f]	1.46[f]	1.71	1.00[a]	6.95[a]	8.8
E I Dupont De Nemours & Co. (Outfall 662)	0.369	5.67[c]	5.67	0.15[a]	0.15[a]	0.10[a]	0.78[a]	0.78[a]	0.33	14.90[a]	8.90[a]	4.1
Delaware City Refinery (Outfall 601)	0.452	7.38[c]	7.38[c]	0.05[a]	0.05[a]	0.10[a]	0.64[a]	0.64[a]	0.64	21.4[a]	6.20[a]	4.5[a]

a) estimated

b) based on reported BOD or CBOD

c) based on reported TOC or DOC

d) based on reported TP

e) based on reported TKN

f) based on reported TON

Table A3-7 (corrected): Municipal WWTPS - Average flow and concentration, 2013

		2013 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
Ewing Lawrence Sewerage Authority	0.458	0.97[b]	8.69[b]	0.60[d]	0.60[d]	1.20[d]	0.01[a]	0.03[a]	0.20	12.92	9.97	2.5
Morrisville Boro Mun. Auth-STP	0.221	0.71[b]	6.42[b]	0.30[a]	0.30[a]	1.80[a]	1.97[a]	5.91[a]	14.10	4.90[a]	6.15	53.7
Trenton DPW Sewerage Authority	0.503	2.35[b]	21.18[b]	0.20[a]	0.20[a]	1.10[a]	0.45[a]	1.36[a]	7.87	6.90[a]	8.50[a]	1.3
Hamilton Twp WPCF	0.355	2.42[b]	21.75[b]	0.10[a]	0.10[a]	3.71[a]	0.27[a]	0.82[a]	24.77	6.27[a]	6.53	3.2
Bordentown Sewerage Authority	0.078	0.42[b]	3.75[b]	0.20[a]	0.20[a]	3.60[a]	1.17[a]	3.52[a]	0.21	26.78[a]	8.25	5.7
Lower Bucks County Joint MA	0.295	0.82[b]	7.36[b]	0.15[a]	0.15[a]	2.30[a]	0.95[a]	2.84[a]	16.46	7.00[a]	3.53	137.8
Florence Twp STP	0.061	0.67[b]	6.02[b]	0.73[d]	0.73[d]	1.46[d]	0.04[a]	0.12[a]	0.67	5.56[a]	6.95[a]	9.2
Bristol Boro WSA	0.055	0.64[b]	5.74[b]	0.06[a]	0.06[a]	0.13[a]	0.07[a]	0.20[a]	1.15	9.52[a]	8.88	1.5
Burlington Twp DPW	0.092	0.35[b]	3.16[b]	0.43[d]	0.43[d]	0.85[d]	0.23[a]	0.68[a]	3.97	0.52[a]	6.95[a]	0.8
Burlington City STP	0.076	1.24[b]	11.14[b]	0.72[d]	0.72[d]	1.44[d]	0.05[a]	0.14[a]	0.81	6.69[a]	8.70	1.4
Bristol Twp WWTP	0.114	1.01[b]	9.06[b]	0.10[a]	0.10[a]	0.20[a]	0.21[a]	0.62[a]	3.59	0.47[a]	8.02	37.3
Willingboro Twp MUA	0.154	1.86[b]	16.71[b]	0.30[d]	0.30[d]	0.81[a]	0.54[a]	1.62[a]	5.44	15.50[a]	7.51	11.0
Delran Sewerage Authority	0.087	0.50[b]	4.53[b]	0.58[d]	0.58[d]	1.17[d]	0.05[a]	0.16[a]	0.95	7.89[a]	6.11	10.2
Cinnaminson Sewerage Authority	0.054	1.76[b]	15.85[b]	0.16[d]	0.16[d]	1.56[a]	1.58[a]	4.73[a]	21.19	1.70[a]	0.90[a]	21.4
Moorestown WWTP	0.104	0.52[b]	4.72[b]	0.24[a]	0.24[a]	2.31[a]	0.07[a]	0.21[a]	1.19	19.62[a]	7.50[a]	14.0
Maple Shade POTW	0.110	0.42[b]	3.79[b]	0.05[d]	0.05[d]	0.10[d]	0.14[a]	0.41[a]	2.36	19.51[a]	8.44	5.0
Philadelphia - Northeast WPCP	7.077	0.70[b]	6.26[b]	0.11[d]	0.11[d]	0.10	0.45[e]	1.36[e]	7.20	2.24	5.70	31.6
Camden County MUA	2.342	0.34[b]	3.02[b]	0.16[a]	0.16[a]	1.05[a]	1.15[a]	3.44[a]	19.92	2.50[a]	3.50[a]	1.1
Philadelphia - Southeast WPCP	3.447	0.67[b]	6.06[b]	0.06[d]	0.06[d]	0.06	0.30[e]	0.89[e]	8.66	0.32	5.20	16.8
Philadelphia - Southwest WPCP	7.089	0.58[b]	5.23[b]	0.10[d]	0.10[d]	0.13	0.63[e]	1.90[e]	18.55	2.08	5.43	22.2
Gloucester County Utility Authority	0.797	1.59[b]	14.28[b]	0.25[a]	0.25[a]	2.41[a]	0.59[a]	1.76[a]	17.25	8.84[a]	6.16	2.2

Tinicum Twp WWTP	0.044	0.94[b]	8.50[b]	0.09[a]	0.09[a]	0.19[a]	0.50[a]	1.49[a]	1.98[a]	16.43[a]	8.63	70.0
Little Washington STP	0.058	0.80[b]	7.20[b]	0.08[a]	0.08[a]	0.16[a]	0.03[a]	0.08[a]	0.47	3.86[a]	7.13	5.8
DELCORA	1.329	1.98[b]	17.78[b]	0.10[a]	0.10[a]	0.70[a]	0.65[e]	1.95[e]	2.30	5.72	7.60[a]	17.4
Southwest Delaware County MUA	0.188	0.69[b]	6.18[b]	0.07[a]	0.07[a]	0.14[a]	0.12[a]	0.35[a]	2.05	16.97[a]	8.91	46.2
Logan Twp MUA	0.052	1.28[b]	11.51[b]	0.62[d]	0.62[d]	1.25[d]	0.62[a]	1.87[a]	10.85	1.41[a]	6.27	5.7
Carneys Point WWTP	0.044	1.43[b]	12.86[b]	0.80[d]	0.80[d]	1.60[d]	0.45[a]	1.34[a]	7.77	1.01[a]	6.95[a]	11.2
Pennsville Twp Sewerage Authority	0.063	1.36[b]	12.27[b]	0.40[d]	0.40[d]	0.79[d]	0.02[a]	0.07[a]	0.39	3.19[a]	6.95[a]	7.5
Wilmington WWTP	3.165	1.42[b]	12.77[b]	0.05[a]	0.05[a]	0.90[a]	0.025[a]	0.075[a]	16.20[a]	4.20[a]	4.50[a]	0.7

a) estimated b) based on reported BOD or CBOD c) based on reported TOC or DOC

d) based on reported TP e) based on reported TKN f) based on reported TON

Table A3-8 (corrected): Industrial Permitted Dischargers - Average flow and concentration, 2012

		2013 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
US Steel Fairless Hills Works (Outfall 103)	0.071	0.56[b]	0.56[b]	0.01[a]	0.01[a]	0.02[a]	0.12[a]	0.12[a]	0.23[a]	1.00[a]	6.95[a]	4.5[a]
Coastal Eagle Point Oil Co.	0.039	0.76[b]	0.76[b]	0.02[a]	0.02[a]	0.03[a]	0.03[a]	0.03[a]	0.23	1.00[a]	6.95[a]	1.2
Valero Refining Co. (Outfall 1)	0.384	1.63[b]	1.63[b]	0.03[d]	0.03[d]	0.16[a]	0.65[a]	0.65[a]	0.30	5.23[a]	8.00[a]	1.3
E I Dupont De Nemours & Co. Repauno Plant	0.049	1.66[b]	1.66[b]	0.03[a]	0.03[a]	0.07[a]	0.15[a]	0.15[a]	1.32	7.88	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 201)	0.112	1.96[b]	1.96[b]	0.15[a]	0.15[a]	0.40[a]	2.54[a]	2.54[a]	8.48	5.90[a]	6.20[a]	4.5[a]
Dupont Edgemoor (Outfall 1)	0.110	1.95[b]	1.95[b]	0.04[a]	0.04[a]	0.08[a]	0.41[a]	0.41[a]	0.82[a]	1.00[a]	6.95[a]	4.5[a]
Ferro Corp.	0.037	4.75[b]	4.75[b]	0.10[a]	0.10[a]	0.19[a]	1.42[f]	1.42[f]	0.50	1.00[a]	6.95[a]	5.0
E I Dupont De Nemours & Co. (Outfall 662)	0.349	6.17[c]	6.17	0.15[a]	0.15[a]	0.10[a]	0.72[a]	0.72[a]	0.31	14.90[a]	8.90[a]	0.9
Delaware City Refinery (Outfall 601)	0.470	7.20[c]	7.20[c]	0.05[a]	0.05[a]	0.10[a]	0.93[a]	0.93[a]	0.93	21.40[a]	6.20[a]	4.5[a]

a) estimated

b) based on reported BOD or CBOD

c) based on reported TOC or DOC

d) based on reported TP

e) based on reported TKN

f) based on reported TON

Table A3-9 (corrected): Municipal WWTPs - Total Loads 2012

	2012 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	kg		kg P			kg N				kg	CFU
Ewing Lawrence Sewerage Authority	10,528	94,493	7,446	7,446	14,764	128	257	1,284	221,467	124,407	5.14E+09
Morrisville Boro Mun. Auth-STP	2,914	26,168	3,582	3,582	21,493	7,772	23,375	55,797	29,750	38,675	3.36E+10
Trenton DPW Sewerage Authority	37,762	339,860	2,985	2,985	16,418	5,672	17,015	99,107	102,988	126,869	1.49E+09
Hamilton Twp WPCF	29,762	268,209	1,294	1,294	46,936	3,059	9,293	281,501	61,876	78,463	3.76E+09
Bordentown Sewerage Authority	900	8,149	462	462	8,310	2,031	6,071	369	65,329	18,560	2.98E+09
Lower Bucks County Joint MA	5,942	53,730	1,238	1,238	18,983	10,895	32,766	189,829	57,774	30,785	1.21E+11
Florence Twp STP	1,370	12,377	2,067	2,067	4,158	96	288	1,682	13,939	16,703	1.66E+09
Bristol Boro WSA	937	8,386	99	99	181	99	280	1,611	13,402	11,428	2.14E+08
Burlington Twp DPW	978	8,690	1,640	1,640	3,281	835	2,475	14,302	1,870	20,000	3.45E+08
Burlington City STP	2,704	24,405	1,897	1,897	3,795	95	285	1,636	13,590	19,946	1.09E+09
Bristol Twp WWTP	3,478	31,202	348	348	696	591	1,774	10,261	85,048	28,836	1.74E+10
Willingboro Twp MUA	8,971	80,827	1,457	1,457	3,916	3,233	9,654	32,467	70,581	33,879	7.19E+09
Delran Sewerage Authority	1,266	11,417	2,091	2,091	4,154	55	165	935	39,947	17,140	3.99E+09
Cinnaminson Sewerage Authority	3,795	34,168	332	332	3,225	1,470	4,427	19,811	2,688	1,423	3.23E+09
Moorestown WWTP	1,632	14,607	732	732	7,036	281	844	4,869	48,267	21,108	4.59E+09
Maple Shade POTW	901	8,081	150	150	270	30	120	751	6,249	25,956	1.35E+09
Philadelphia - Northeast WPCP	115,155	1,038,608	22,145	22,145	50,934	128,442	385,326	1,505,871	538,128	1,255,631	3.12E+11
Camden County MUA	40,427	364,453	15,313	15,313	100,454	78,403	234,597	1,359,195	153,131	214,384	9.19E+09
Philadelphia - Southeast WPCP	65,367	590,168	9,338	9,338	42,021	39,220	117,660	862,840	24,279	483,713	1.10E+11
Philadelphia - Southwest WPCP	82,603	743,425	18,356	18,356	16,062	167,500	500,206	4,800,139	452,021	1,177,089	6.98E+11
Gloucester County Utility Authority	24,768	222,911	6,250	6,250	58,795	12,963	39,119	382,398	212,726	142,589	5.56E+09
Tinicum Twp WWTP	1,202	10,851	120	120	240	637	1,899	2,535	20,969	9,842	6.63E+09
Little Washington STP	1,542	13,854	144	144	308	82	226	1,274	10,503	13,915	1.87E+09

DELCORA	80,321	722,085	4,016	4,016	28,112	24,498	73,092	185,140	218,473	305,219	2.85E+11
Southwest Delaware County MUA	4,563	40,893	468	468	936	702	2,165	12,578	104,133	48,966	2.58E+10
Logan Twp MUA	840	7,613	1,124	1,124	2,234	213	655	3,771	31,178	8,325	4.98E+08
Carneys Point WWTP	1,827	16,403	1,298	1,298	2,584	493	1,490	8,664	1,130	8,351	2.49E+09
Pennsville Twp Sewerage Authority	1,583	14,279	678	678	1,357	87	261	1,478	12,262	12,088	1.10E+09
Wilmington WWTP	94,222	847,999	4,530	4,530	81,538	2,718	7,248	1,467,690	380,512	407,692	5.44E+09

Table A3-10 (corrected): Industrial Permitted Dischargers - Total loads 2012

	2012 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	kg		kg P			kg N				kg	CFU
US Steel Fairless Hills Works (Outfall 103)	1,426	1,426	26	26	52	311	311	596	2,593	18,022	1.17E+09
Coastal Eagle Point Oil Co.	918	918	14	14	42	56	56	459	1,391	9,670	1.11E+08
Valero Refining Co. (Outfall 1)	10,473	10,473	1,418	1,418	8,400	4,146	4,146	1,964	57,058	87,278	4.47E+09
E I Dupont De Nemours & Co. Repauno Plant	1,113	1,113	28	28	42	167	167	1,461	13,956	9,670	6.26E+08
Conoco Phillips Refinery (Outfall 201)	616	616	280	280	746	541	541	1,810	11,008	11,567	8.40E+08
Dupont Edgemoor (Outfall 1)	4,035	4,035	70	70	174	835	835	1,704	3,478	24,175	1.57E+09
Ferro Corp.	7,898	7,898	164	164	316	1,708	1,708	2,001	1,170	8,132	1.03E+09
E I Dupont De Nemours & Co. (Outfall 662)	66,161	66,161	1,750	1,750	1,167	9,102	9,102	3,851	173,863	103,851	4.78E+09
Delaware City Refinery (Outfall 601)	105,485	105,485	715	715	1,429	9,148	9,148	9,148	305,877	88,619	6.43E+09

Table A3-11 (corrected): Municipal WWTPs - Total Loads 2013

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	kg		kg P			kg N				kg	CFU
Ewing Lawrence Sewerage Authority	14,010	125,514	8,666	8,666	17,332	144	433	2,889	186,610	144,002	3.61E+09
Morrisville Boro Mun. Auth-STP	4,948	44,744	2,091	2,091	12,545	13,730	41,189	98,269	34,150	42,862	3.74E+10
Trenton DPW Sewerage Authority	37,277	335,970	3,173	3,173	17,449	7,138	21,573	124,839	109,452	134,832	2.06E+09
Hamilton Twp WPCF	27,093	243,497	1,120	1,120	41,534	3,023	9,180	277,307	70,194	73,105	3.58E+09
Bordentown Sewerage Authority	1,033	9,224	492	492	8,855	2,878	8,659	517	65,874	20,293	1.40E+09
Lower Bucks County Joint MA	7,629	68,471	1,395	1,395	21,397	8,838	26,421	153,129	65,122	32,840	1.28E+11
Florence Twp STP	1,289	11,581	1,404	1,404	2,809	77	231	1,289	10,696	13,370	1.77E+09
Bristol Boro WSA	1,110	9,956	104	104	225	121	347	1,995	16,512	15,402	2.60E+08
Burlington Twp DPW	1,015	9,168	1,248	1,248	2,466	667	1,973	11,518	1,509	20,164	2.32E+08
Burlington City STP	2,972	26,700	1,726	1,726	3,451	120	336	1,941	16,034	20,852	3.36E+08
Bristol Twp WWTP	3,631	32,572	360	360	719	755	2,229	12,906	1,690	28,833	1.34E+10
Willingboro Twp MUA	9,033	81,153	1,457	1,457	3,934	2,623	7,868	26,420	75,276	36,473	5.34E+09
Delran Sewerage Authority	1,372	12,429	1,591	1,591	3,210	137	439	2,606	21,647	16,764	2.80E+09
Cinnaminson Sewerage Authority	2,997	26,992	272	272	2,657	2,691	8,055	36,085	2,895	1,533	3.64E+09
Moorestown WWTP	1,705	15,480	787	787	7,576	230	689	3,903	64,349	24,598	4.59E+09
Maple Shade POTW	1,457	13,147	173	173	347	486	1,422	8,187	67,679	29,278	1.73E+09
Philadelphia - Northeast WPCP	156,226	1,397,109	24,550	24,550	22,318	100,431	303,525	1,606,898	499,924	1,272,128	7.05E+11
Camden County MUA	25,111	223,049	11,817	11,817	77,550	84,936	254,069	1,471,238	184,643	258,501	8.12E+09
Philadelphia - Southeast WPCP	72,832	658,750	6,522	6,522	6,522	32,611	96,747	941,382	34,785	565,264	1.83E+11
Philadelphia - Southwest WPCP	129,664	1,169,212	22,356	22,356	29,063	140,842	424,762	4,147,014	465,002	1,213,924	4.96E+11
Gloucester County Utility Authority	39,963	358,916	6,284	6,284	60,573	14,829	44,236	433,565	222,186	154,827	5.53E+09
Tinicum Twp WWTP	1,304	11,794	125	125	264	694	2,068	2,747	22,798	11,975	9.71E+09
Little Washington STP	1,463	13,169	146	146	293	55	146	860	7,060	13,041	1.06E+09

DELCORA	82,984	745,184	4,191	4,191	29,338	27,242	81,727	96,396	239,733	318,526	7.29E+10
Southwest Delaware County MUA	4,091	36,640	415	415	830	711	2,075	12,154	100,611	52,825	2.74E+10
Logan Twp MUA	2,099	18,875	1,017	1,017	2,050	1,017	3,067	17,793	2,312	10,282	9.35E+08
Carneys Point WWTP	1,984	17,844	1,110	1,110	2,220	624	1,859	10,782	1,401	9,644	1.55E+09
Pennsville Twp Sewerage Authority	2,702	24,378	795	795	1,570	40	139	775	6,338	13,808	1.49E+09
Wilmington WWTP	141,732	1,274,592	4,991	4,991	89,830	2,495	7,486	1,616,945	419,208	449,151	6.99E+09

Table A3-12 (corrected): Industrial Permitted Dischargers - Total loads 2013

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	kg		kg P			kg N				kg	CFU
US Steel Fairless Hills Works (Outfall 103)	1,254	1,254	22	22	45	269	269	515	2,239	15,561	1.01E+09
Coastal Eagle Point Oil Co.	935	935	25	25	37	37	37	283	1,230	8,548	1.48E+08
Valero Refining Co. (Outfall 1)	19,739	19,739	363	363	1,938	7,871	7,871	3,633	63,334	96,879	1.57E+09
E I Dupont De Nemours & Co. Repauno Plant	2,565	2,565	46	46	108	232	232	2,040	12,177	10,740	6.95E+08
Conoco Phillips Refinery (Outfall 201)	6,923	6,923	530	530	1,413	8,971	8,971	29,952	20,839	21,899	1.59E+09
Dupont Edgemoor (Outfall 1)	6,764	6,764	139	139	278	1,422	1,422	2,845	3,469	24,109	1.56E+09
Ferro Corp.	5,542	5,542	117	117	222	1,657	1,657	583	1,167	8,109	5.83E+08
E I Dupont De Nemours & Co. (Outfall 662)	67,907	67,907	1,651	1,651	1,101	7,924	7,924	3,412	163,990	97,954	9.91E+08
Delaware City Refinery (Outfall 601)	106,718	106,718	741	741	1,482	13,784	13,784	13,784	317,189	91,896	6.67E+09

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1.0 Introduction

This report describes the methods, and provides the results, of a project to model the receiving water quality in the tidal Delaware River and the tidal Schuylkill River. A multidimensional hydrodynamic and water quality modeling system was developed for tidal portions of the Delaware River from Trenton New Jersey to Delaware City Delaware, tidal portions of the Schuylkill River, and tidal portions of other major tributaries within the model domain (Figure 1-1). The mainstem model extent spans 72.6 statute miles.

The model system was developed in response to requirements included in the 2011 Consent Order and Agreement (COA) between the Pennsylvania Department of Environmental Protection (PADEP) and the Philadelphia Water Department (Water Department). Specifically, this report is intended to provide PADEP with both Deliverable Item 9, a report on the Tidal waters Water Quality Model developed for Bacteria in the tidal Delaware River and tidal Schuylkill River, and Deliverable item 10, a report on the Tidal waters Water Quality Model developed for Dissolved Oxygen in the tidal Delaware River and tidal Schuylkill River, of the COA. (COA, Paragraph 3a, items ix and x, and Appendix G page 4 of 4). In addition, this report is intended to supplement the submitted Deliverable Items 6 and 7 of the COA, which focused on the non-tidal portions of the Cobbs and Tookany/Tacony-Frankford (TTF) Creeks. (COA, Paragraph 3a, items vi and vii, and Appendix G page 3 of 4). This report addresses the model development of the tidal portions of the Cobbs and Tookany/Tacony-Frankford Creeks, which were included in the model system. Also, the portion of the tidal Pennypack Creek directly receiving combined sewer overflow (CSO) discharge was included in the model system.

The model system includes tidal waters that receive and respond to discharges from the areas of the City of Philadelphia (City) served by combined sewers (Figure 1-2). These combined sewer areas and their associated watersheds are described extensively in the Water Department's 2009 Long Term Control Plan Update and its supplements, and in the 2004, 2005 and 2009 Comprehensive Characterization Reports (CCRs), respectively. (Philadelphia Water Department, 2004, 2005 and 2009) These documents can be referenced for more detailed information on watershed and sewer-shed physical, hydrologic, and hydraulic characteristics, and for summaries of physical, chemical, and biological water quality monitoring results.

The Tidal waters Water Quality Models for bacteria and dissolved oxygen (DO) are collectively referred to as the Water Quality Models in this report, or separately as the Bacteria Model or the DO Model where needed for clarity and differentiation. In addition, report section 2 addresses an earlier stage of model development before water quality constituents were modeled, which is referred to as the Hydrodynamic Model in this report.

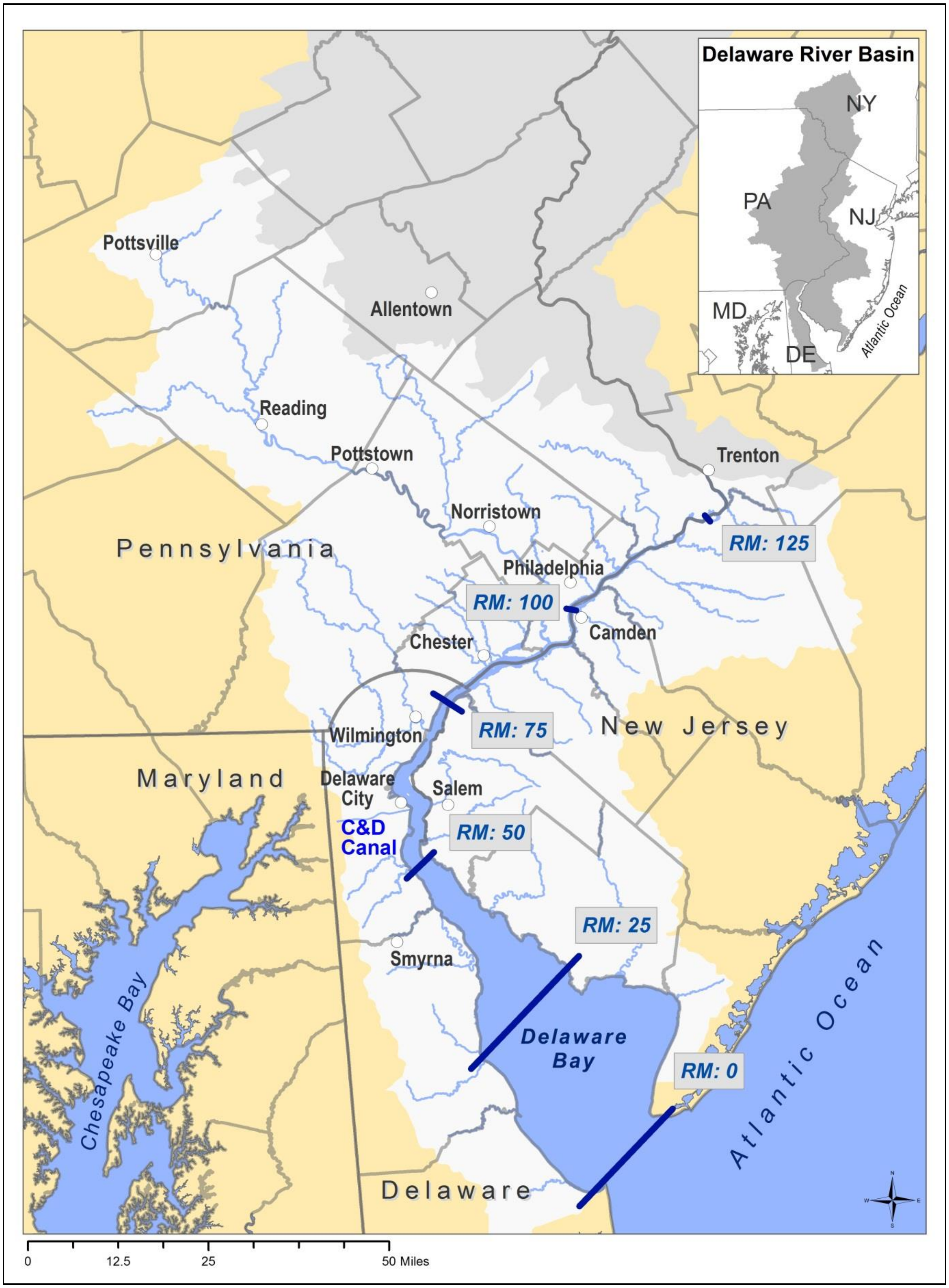


Figure 1-1: Study Area - Model Domain Extends from Trenton to Delaware City

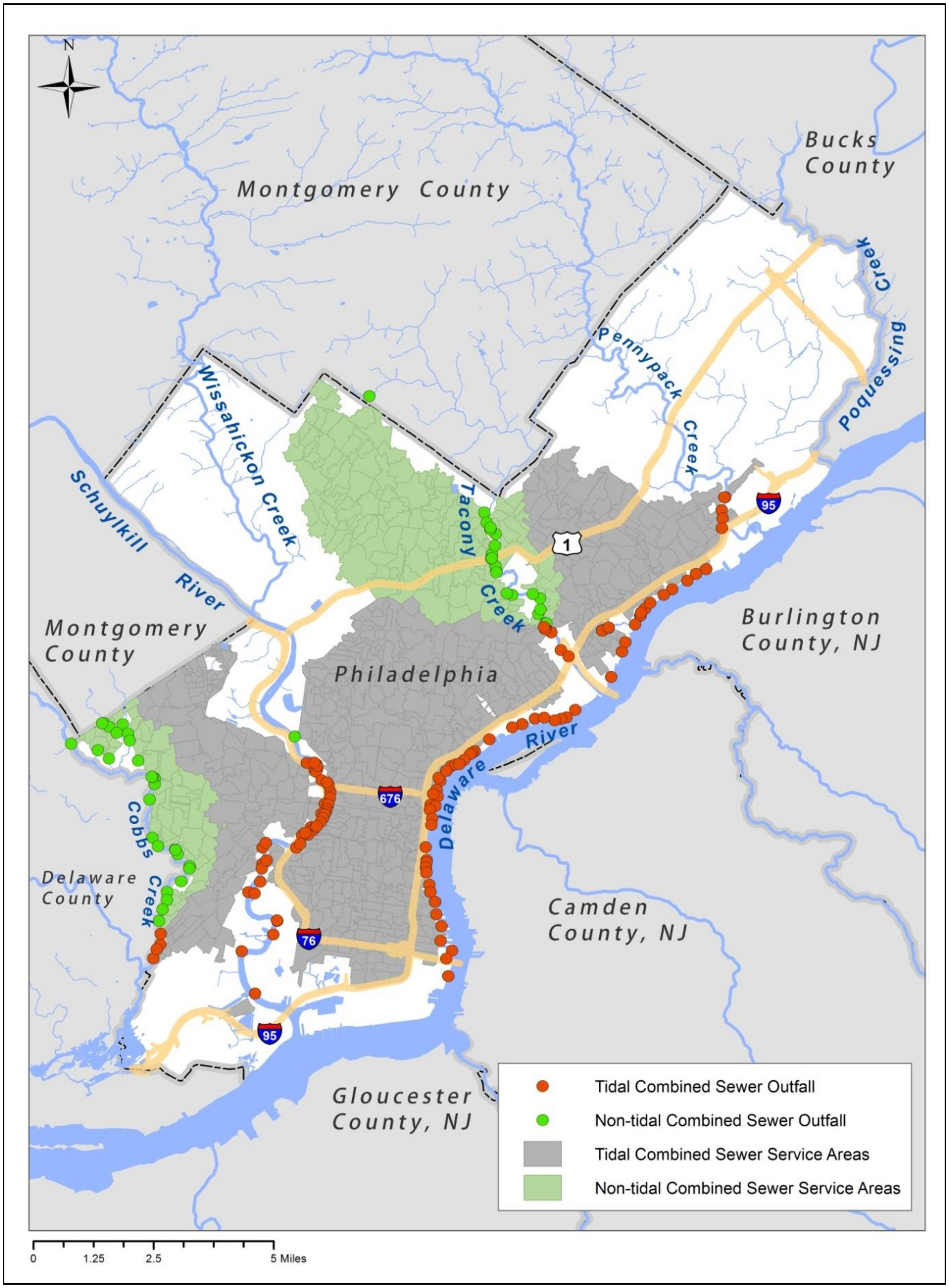


Figure 1-2: Combined-Sewered Areas in the City of Philadelphia

1.1 Tidal Waters Water Quality Models for Bacteria and Dissolved Oxygen Model Extent

The Water Quality Models simulate in-stream bacteria and DO conditions in the tidal reaches of the waters receiving and responding to the discharges of the combined sewer overflows (CSOs) from the City of Philadelphia. The principal domain of the model, also referred to as the mainstem, stretches along the tidal Delaware River from the head of tide at Trenton, New Jersey, to a point near Delaware City, Delaware, a distance of about 72.6 statute miles. The areal extent of the models include tidal portions of 28 streams and creeks that are tributary to the main stem of the Delaware, including the eight miles of tidal waters of the Schuylkill River in Philadelphia. Overall, discharge and loadings are included from 43 tributaries to the tidal Delaware River.

The upstream boundary of the model extent is the head of tidal influence on the Delaware River at River Mile (RM) 134.4 (*i.e.,* 134.4 miles upstream of the mouth of the Delaware Bay at Cape Henlopen - Lewes, Delaware, using the Delaware River Basin Commission (DRBC) River Mile designation system for the Delaware River, near the site of the United States Geological Survey (USGS) stream monitoring gage 01463500 at Trenton, New Jersey. The downstream boundary of the model is at RM 61.8, at a 2.6 mile-wide Delaware River transect just upstream of Pea Patch Island, about 1.5 miles upstream of Delaware City, and over 3 miles above the confluence of the Chesapeake and Delaware Canal with the Delaware River.

1.2 Model Objectives

The objectives of the model development were to represent existing bacteria and DO conditions and the underlying hydrodynamic and water quality processes in the tidal receiving waters, through comparison of predicted and observed bacteria and DO concentrations overlying benthic conditions during the recent past. In particular for this report, spring and summer bacteria, benthic, nutrient, algal, and DO conditions are simulated during 2012 and 2013. Meteorological, hydrodynamic and water quality monitoring, and biogeochemical sampling data, collected from numerous locations, were used to validate the model results. These data include continuous atmospheric wind, air temperature and pressure, and continuous tidal water column velocity, temperature, conductivity, and DO monitoring, as well as chemical and biological water column and benthic samples acquired during numerous sampling cruises.

1.3 Modeling Approach

The COA requires the Water Department to develop bacteria and DO models appropriate for characterizing bacteria and dissolved oxygen quality concentrations in the tidal receiving waters affected by the CSO discharges from the City. Flow and loadings of various water quality constituents discharge to the receiving waters from:

- Tributary rivers and creeks
- Overflows from sewer systems
- Stormwater runoff through storm sewer systems
- Municipal and industrial point sources
- Agricultural and other nonpoint sources
- Baseflow (interflow and groundwater; not explicitly modeled in this project)
- Atmospheric deposition (not explicitly modeled in this project)

As described in Section 3.4 of this report, a three-dimensional hydrodynamic and water quality model was considered necessary and appropriate to adequately represent the complexity of the physical and biogeochemical processes of the tidal receiving waters. The US EPA Environmental Fluid Dynamics Code (EFDC) was selected to model the bacteria and DO kinetics. The Water Quality Models were coupled to the Hydrodynamic Model to form one model system, which was simulated simultaneously.

An array of inputs were needed to drive the model system. Figure 1-3 and Figure 1-4 present flow charts, including summary input sources and model parameters, for the modeling approach used to develop the Water Quality Models, the major elements of which are described below and throughout this report.

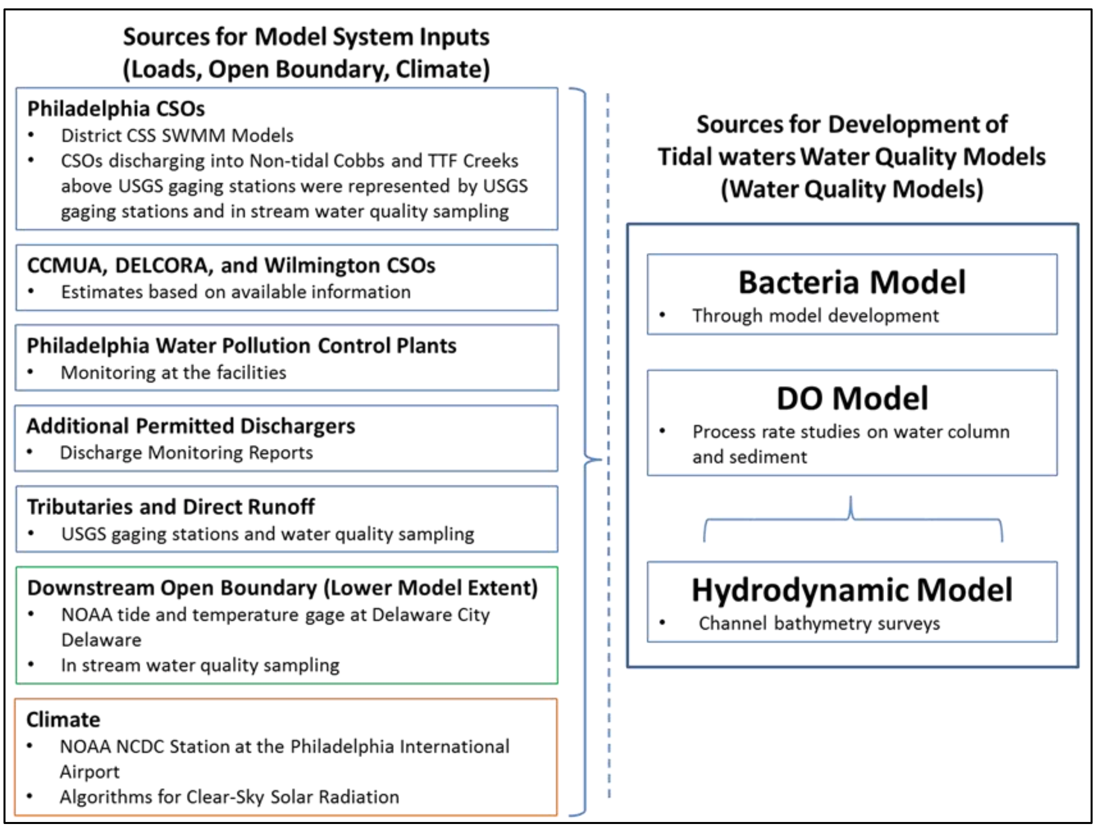


Figure 1-3: Summary Water Quality Modeling Approach Sources

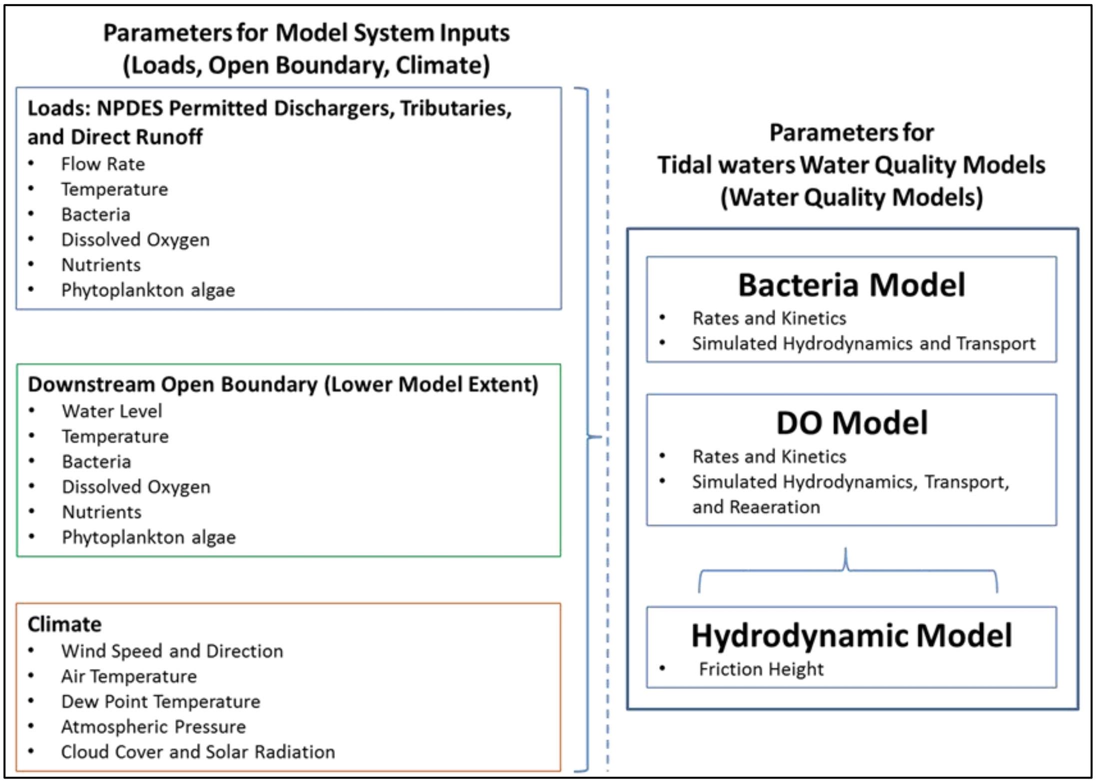


Figure 1-4: Summary Water Quality Modeling Approach Parameters

The model system inputs are described in detail in Sections 3.7 and 3.8 of this report. The Water Department Combined Sewer System (CSS) Models, as described in Section 3.8.4, were used to generate water quality constituent loading time series from the City collection systems to the receiving waters. Portions of the non-tidal Cobbs and TTF Creeks were tributary to and represented by USGS gaging stations and in-stream water quality sampling. More elementary approaches were used to estimate contributions from the three other municipal systems that discharge CSO to the tidal Delaware River in the model domain.

Discharge and water quality parameter loading estimates were developed for all tributary and direct runoff areas discharging to the model domain, based on available streamflow monitoring information and water quality sampling data. Discharges of municipal and industrial permitted dischargers contributing directly to the tidal waters in the model domain were estimated using records obtained from state agencies.

2.0 Hydrodynamic Model

This section of the report describes the development of a mathematical model of the hydrodynamics of the upper portions of the tidal Delaware River. The model is intended to resolve the complex hydrodynamics of the primary and secondary circulation that influences the water quality processes. For brevity, the 'tidal Delaware River' is hereafter referred to as the 'Delaware River', unless otherwise noted.

2.1 Study Area

The main sources of freshwater to the estuary are the Delaware and Schuylkill Rivers. Between the head of tide on the Delaware River at Trenton, and Delaware City, the Schuylkill River and forty-one other tributaries contribute freshwater to the upper estuarine system. This study is limited to the estuary's tidal freshwater region and includes tidal reaches of the Delaware River from a point 3 miles above the confluence with the Chesapeake and Delaware Canal to the head of tide at Trenton, stretching from River Mile 61.8 to 134.4.

The estuary commonly is regarded as well-mixed and weakly stratified. Circulation in the upper estuary is driven primarily by astronomical tides, freshwater inputs, and meteorological influences. The principal interface between fresh and salt water generally is located between River Miles 31 and 75 (km 50 and 120). The City of Philadelphia is situated at River Mile 91-111 (km 147-180), well north of the typical landward extent of significant salt intrusion (Figure 2-1).

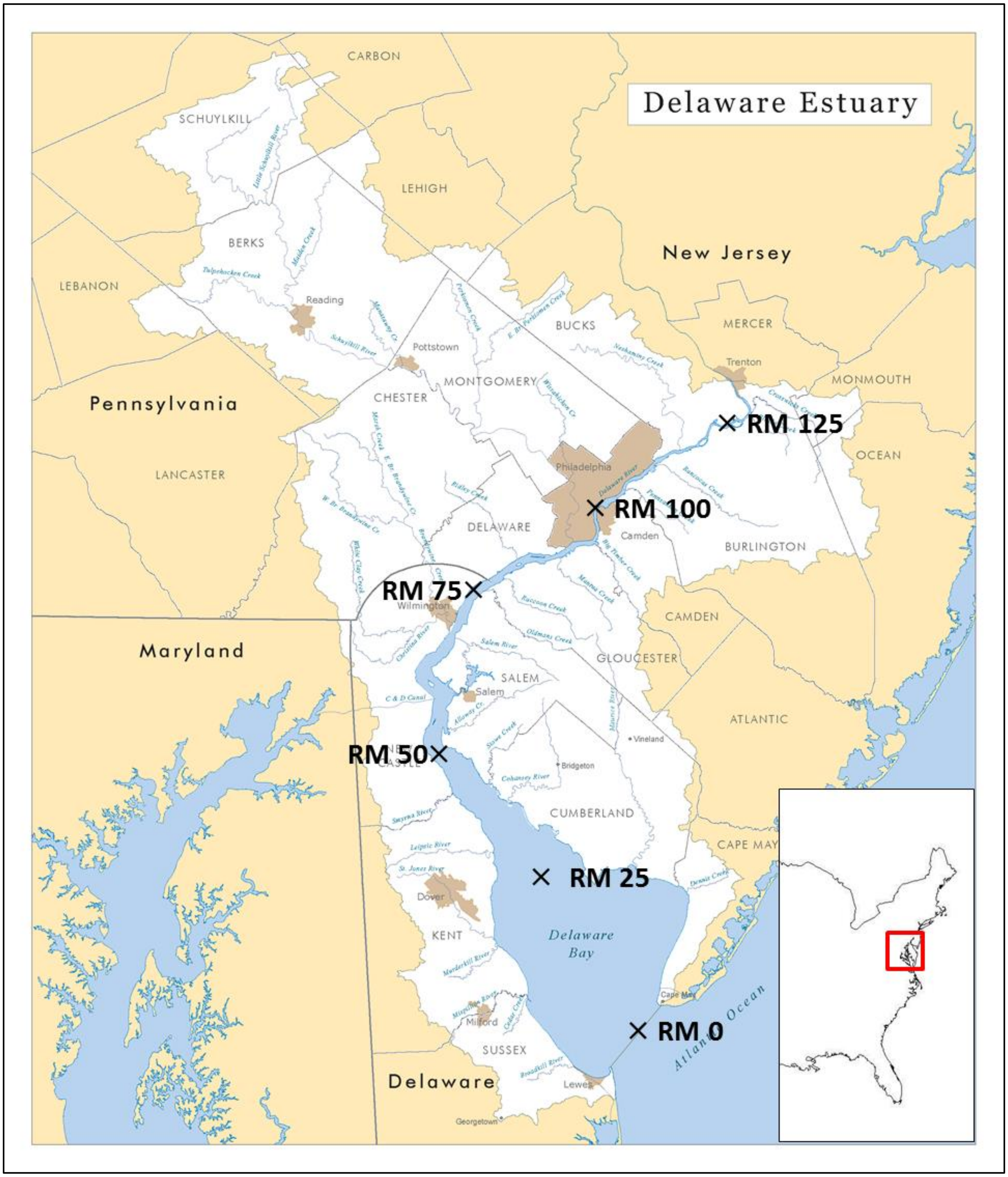


Figure 2-1: Map of Delaware Estuary with Along-Channel River Mile Reference Locations

2.2 Key Processes

The propagation of astronomical tides in the study area exhibits many characteristics of a progressive wave (DRBA, 1983). The tide wave enters the estuary at the mouth near Cape Henlopen and Cape May, and progresses upstream to the head of tide at Trenton. The incoming tide wave interacts with the fairly uniform convergence of the estuarine width as it travels up-estuary, and side wall reflection along with reflection from the head of tide result in a reflected progressive wave propagating down the estuary towards the ocean. The incoming tide wave amplitude increases in response to convergence and decreases because of frictional losses. The reflected wave decreases in amplitude with increasing sectional divergence and by friction losses. The net amplitude of the co-oscillating astronomical tidal wave increases steadily after entering the estuary to a point about 37 miles (153 km) from the mouth, and then decreases steadily to a local minimum at a point about 72 miles (116 km) from the mouth, and thereafter increases steadily to the head of tides. The tidal amplitude at the mouth of the estuary is about 4 feet (1.3 m), increases to a local maximum of almost 6 feet (1.8 m) at the 37-mile point, reduces to about 5 feet (1.6 m) by river mile 72, and increases thereafter to a maximum in excess of 6.5 feet (2 m) at Trenton. The amplitude of seven of the astronomical tidal constituents at three points along the tidal river (see map in Figure 2-4) are shown in Table 2-1. The principal lunar semidiurnal (M2, 12.42 hour period) is the dominant tidal constituent throughout the estuary.

Table 2-1: Tidal Amplitudes at NOAA gages in the Delaware River

Constituent	Amplitude at Marcus Hook/RM 79.5 [m]	Amplitude at Philadelphia/RM 89.5 [m]	Amplitude at Newbold/RM 126 [m]
M2	0.78	0.84	1.07
S2	0.10	0.09	0.13
N2	0.14	0.15	0.19
K1	0.10	0.10	0.11
M4	0.10	0.08	0.14
O1	0.08	0.08	0.07
M6	0.04	0.05	0.07

Influx of oceanic waters from the coastal ocean reach the study area only when river discharges are low during drought conditions, and therefore oceanic-derived salinity intrusion has little hydrodynamic influence in the domain of the model. The water column in these tidal fresh water regions of the upper estuary generally is well mixed vertically. Circulation within the study area is not influenced significantly by gravitational convection.

Key hydrodynamic processes that should be represented in a numerical model include the following processes:

- Energy dissipation,
- Propagation along estuary, and
- Conversion to turbulent kinetic energy available for mixing.

Tidal energy dissipation and along channel propagation influence tidal fluctuations in velocity and water level. These fluctuations drive transport and enhance mixing within the estuary, and are important processes for water quality studies. For model validation, it is important to simulate both the along-river tidal amplitude, water level and velocity records for comparison with data collected at individual monitoring stations. Modeling the tidal amplification process and individual signals indicates effective simulation of along channel tidal energy dissipation and transport. Adequately modeled tidal energy dissipation also implies effective tidal energy conversion to turbulent kinetic energy, a major factor in affecting mixing in the estuary.

Net non-tidal transport from freshwater inflows is also a key hydrodynamic process that must be represented in the hydrodynamic model to adequately support a water quality model. While strong wind conditions potentially assert an influence on surface transport, wind is expected to have a secondary influence on the longer term circulation relative to tidal signals and freshwater flushing. Non-tidal transport can be evaluated by an overall comparison between modeled and observed water level and velocities at monitoring stations.

2.3 Model Selection and Description

The Environmental Fluid Dynamincs Computer Code (EFDC; Tetra Tech, 2007; Hamrick, 1992) was selected for hydrodynamic modeling in this study. EFDC has a water quality model component that couples with the hydrodynamic model, simplifying water quality applications. EFDC is also widely used for water quality modeling applications throughout the world, and is part of the USEPA Total Maximum Daily Load (TMDL) toolbox.

The EFDC hydrodynamic model uses a curvilinear, orthogonal grid with sigma vertical layers that follow the bathymetry to represent the physical characteristics of a water body. EFDC uses Mellor-Yamada 2.5 level turbulence closure (Mellor & Yamada 1982) with a Galperin correction scheme (Galperin, 1988). The EFDC model application to the Delaware River uses a spatial upwind difference scheme, with a two-time level integration. Anti-numerical diffusion (AND) and flux limiting (FL) is also activated for all transported state variables in the present study. The AND and FL corrections limit numerical (and therefore non-physical) diffusion and spurious oscillations.

The developers of EFDC were instrumental in this study, and provided significant technical support in both the hydrodynamic and water quality applications of EFDC.

2.4 Data Acquisition

2.4.1 Shoreline Profile

The Delaware Bay Model Evaluation Environment (MEE), developed by the Office of Coast Survey's Coast Survey Development Laboratory (CSDL) within the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS), provides shoreline profiles, bathymetry data, current and water level observational data for the Delaware Estuary (Patchen 2007). Because the MEE dataset does not include all tributaries to the Delaware River, additional tributaries were added to the shoreline profile by smoothing NOAA Medium-Resolution Digital Vector Coastline for the survey area (obtained via Sommerfield and Madsen, 2003).

2.4.2 Bathymetry

Individual sounding datasets obtained from the NOAA National Geophysical Data Center, Digital Elevation Model Discovery Portal (NOAA 2013) characterize most of the estuary within the study area. PWD conducted additional soundings of Delaware River tributaries between 2011 and 2013 using a Sontek Sonarmite single beam sonar in combination with a Leica Real Time Kinematic (RTK) GPS receiver. Data provided by NOAA and PWD were integrated and used as a basis for Hydrodynamic Model grid development.

2.4.3 Direct Discharges

The City of Philadelphia contains 4800km of sewer pipe, 455 storm water outfalls and 164 combined sewer outfalls (Figure 2-2). Most outfalls discharge directly into the Delaware and Schuylkill Rivers. Some CSOs are located along smaller non-tidal tributaries in the city area, mainly the Cobbs, Frankford and Pennypack Creeks, and their discharges were captured in the boundary flows at the respective tributary.

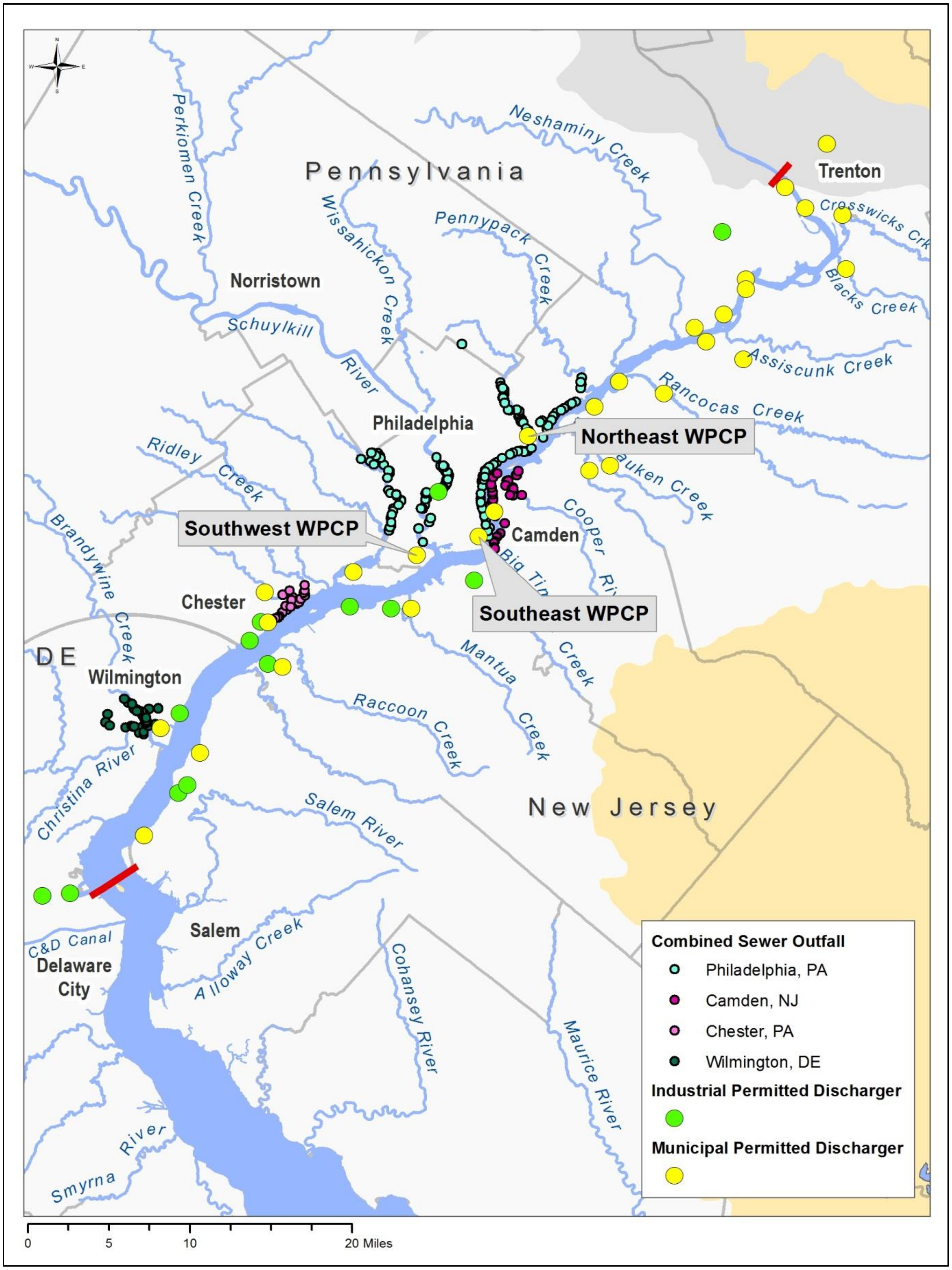


Figure 2-2: Watershed and Point Source Overview

Hydraulic models of each of the three CSS drainage districts in the City of Philadelphia were applied to calculate flows at the 113 CSOs in the tidal portion of the City CSS area during the validation period. The CSS Models are discussed further in Section 3.8.4. Flows from non-Philadelphia CSOs were not included in the Hydrodynamic Model for hydrodynamic validation, but were included for water quality validation. These flows are also discussed further in Section 3.8.4.

2.4.4 Tidal Data

Water Level

NOAA maintains several water level monitoring sites within the study area:

- Delaware City (NOAA 8551762),
- Marcus Hook (8540433),
- Philadelphia (8545240),
- Burlington (8539094), and
- Newbold (8548989).

Figure 2-4 shows the locations of these gages. Water level observations are available at these stations on a 6-minute time interval from the NOAA Tides and Currents web service. To illustrate the general range of amplitude, Figure 2-3 contains recorded water levels at Philadelphia between March and May, 2013.

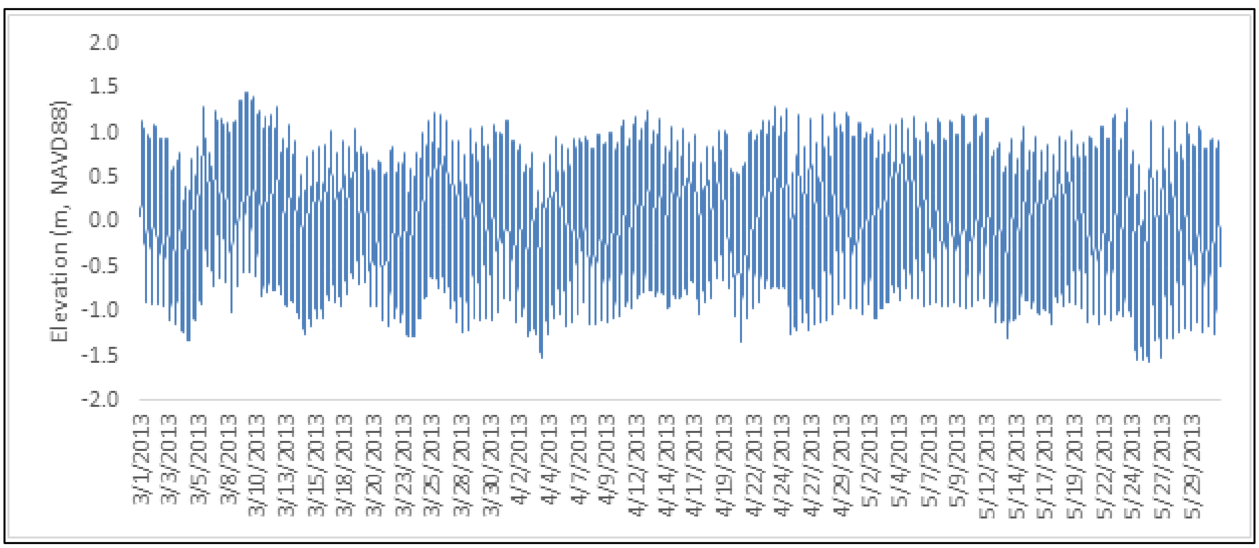


Figure 2-3: Philadelphia NOAA Water Level Observations between March and May, 2013

Current

NOAA maintains an Acoustic Doppler Current Profiler (ADCP) sidelooker station at Penns Landing in Philadelphia (db0301), as shown in Figure 2-4. Observations span 160 m across channel from the Philadelphia shore, and are divided into 40 bins of 4 m each. The data was obtained using CMIST, an interface provided by NOAA to download current data (NOAA, 2013).

PWD installed three buoys equipped with downlooking ADCPs at Burlington (referred to as Buoy A at RM 117.4), Philadelphia Eagle Point (Buoy B at RM 93.7), and Marcus Hook (Buoy C at RM 77.1) in May 2012. After initial calibration issues, these ADCPs collected data starting in August 2012. Buoy C was replaced by an uplooking ADCP in March 2013, after persistent issues with the downlooking compass calibration. Direction data collected from the downlooker at Buoy C before March 2013 were adjusted using compass information from the meteorological sensors that were installed on Buoy C. Each buoy provides data in 0.5 m vertical bins covering the full water column depth.

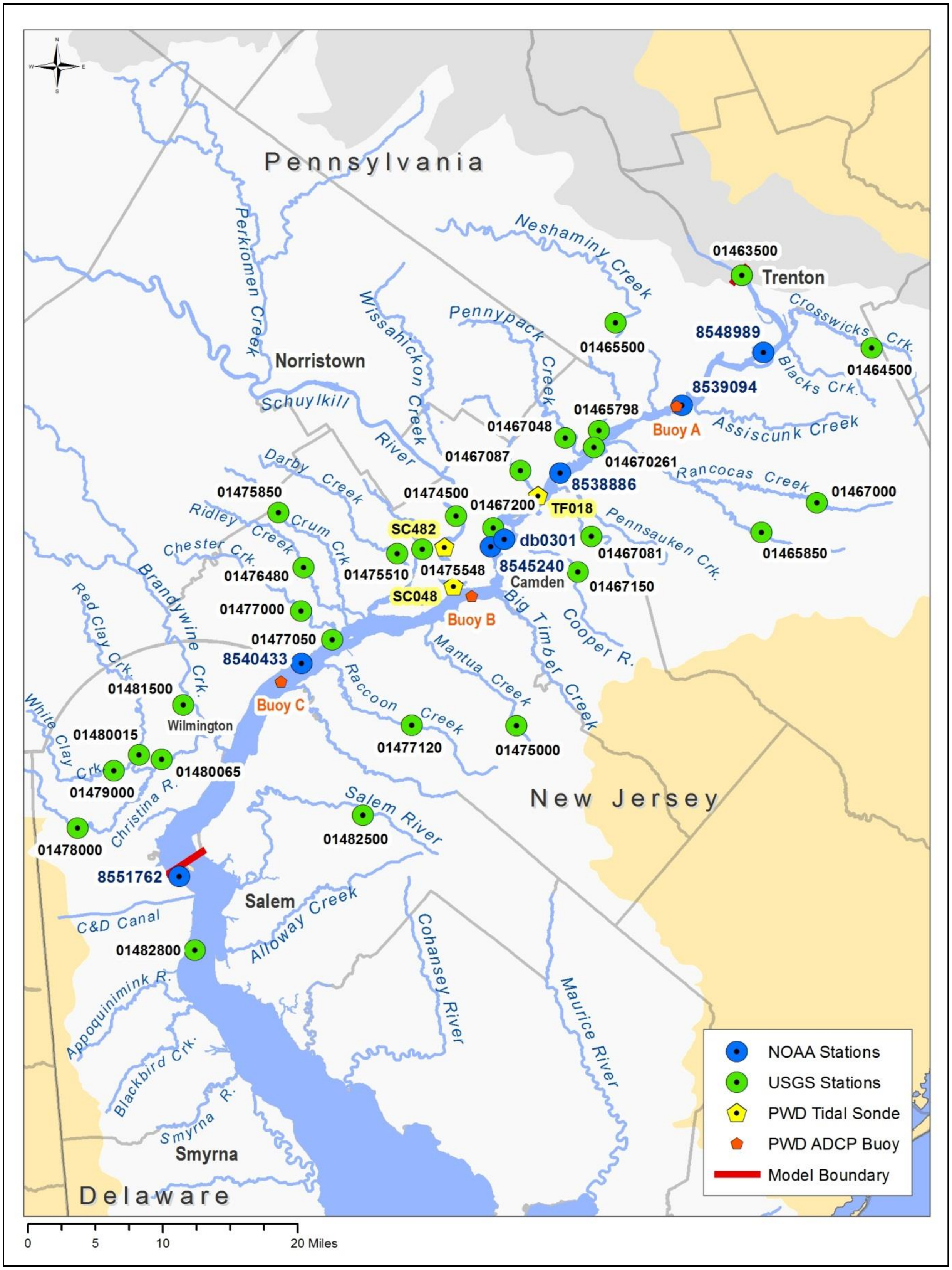


Figure 2-4: Water Level and Current Observation Meters in the Model Domain

2.4.5 Freshwater Flow Data

Of the 43 tributaries included in this study, observed sub-hourly time series discharge data (Figure 2-5) for 23 tributaries and daily discharge data for Darby Creek were obtained from the USGS National Water Information System (USGS, 2013). For the remaining 20 tributaries without available discharge data, a drainage area ratio was applied to the time series of a neighboring tributary with discharge data. Table 2-2 contains an overview of data availability for the tributaries included in this study, and shows which tributaries were used to provide data for gap filling and ungaged tributaries.

Table 2-2: Tributaries included in the Model Domain

River/Tributary	USGS Gage	Fill missing discharge data with	River Mile
Delaware River	01463500	NA	134.25
Blacks Creek	None	Crosswicks Creek	128.0
Crosswicks Creek	01464500	NA	128.0
Stream @ Crystal Lake	None	Crosswicks Creek	126.0
Crafts Creek	None	Crosswicks Creek	124.0
Bustleton Creek	None	Crosswicks Creek	119.75
Assiscunk Creek	None	Rancocas Creek	118.0
Stream @ Burlington	None	Rancocas Creek	117.75
Neshaminy Creek	01465500	NA	115.0
Poquessing Creek	01465798	NA	111.25
Swede Run	None	Cooper River	110.75
Rancocas Creek north	01467000	NA	110.5
Rancocas Creek south	01465850	NA	110.5
Pennypack Creek	01467048	NA	109.0
Pompeston Creek	None	Cooper River	108.5
Pennsauken Creek	01467081	NA	104.75
Frankford Creek	01467087	NA	104.0
Cooper River	01467150	NA	100.5
Newton Creek	None	Cooper River	96.75
Big Timber Creek	None	Cooper River	95.5
Schuylkill River	01474500	NA	92.25
Woodbury Creek	None	Cooper River	91.5
Little Mantua Creek	None	Mantua Creek	90.5

River/Tributary	USGS Gage	Fill missing discharge data with	River Mile
Mantua Creek	01475000	Raccoon Creek, Salem River	89.75
Clonmell Creek	None	Mantua Creek	87.0
Cobbs Creek	01475548	NA	85.0
Darby Creek	01475510	Crum Creek	85.0
Crum Creek	01475850	NA	84.8
Ridley Creek	01476480	Crum Creek	84.0
Chester Creek	01477000	NA	82.5
Little Timber Creek	None	Raccoon Creek	82.5
Still Run	None	Raccoon Creek	82.0
Raccoon Creek	01477120	Salem Creek	80.0
Stoney Creek	None	Chester Creek	80.0
Marcus Hook Creek	None	Chester Creek	79.5
Namaan Creek	None	Chester Creek	77.75
Oldmans Creek	None	Raccoon Creek	76.0
Brandywine River	01481500	NA	70.5
Christina River	01478000	NA	70.5
Red Clay Creek	01480015	White Clay Creek	70.5
White Clay Creek	01479000	NA	70.5
Salem River	01482500	Raccoon Creek	68.75
Army Creek	None	Christina River	64.0

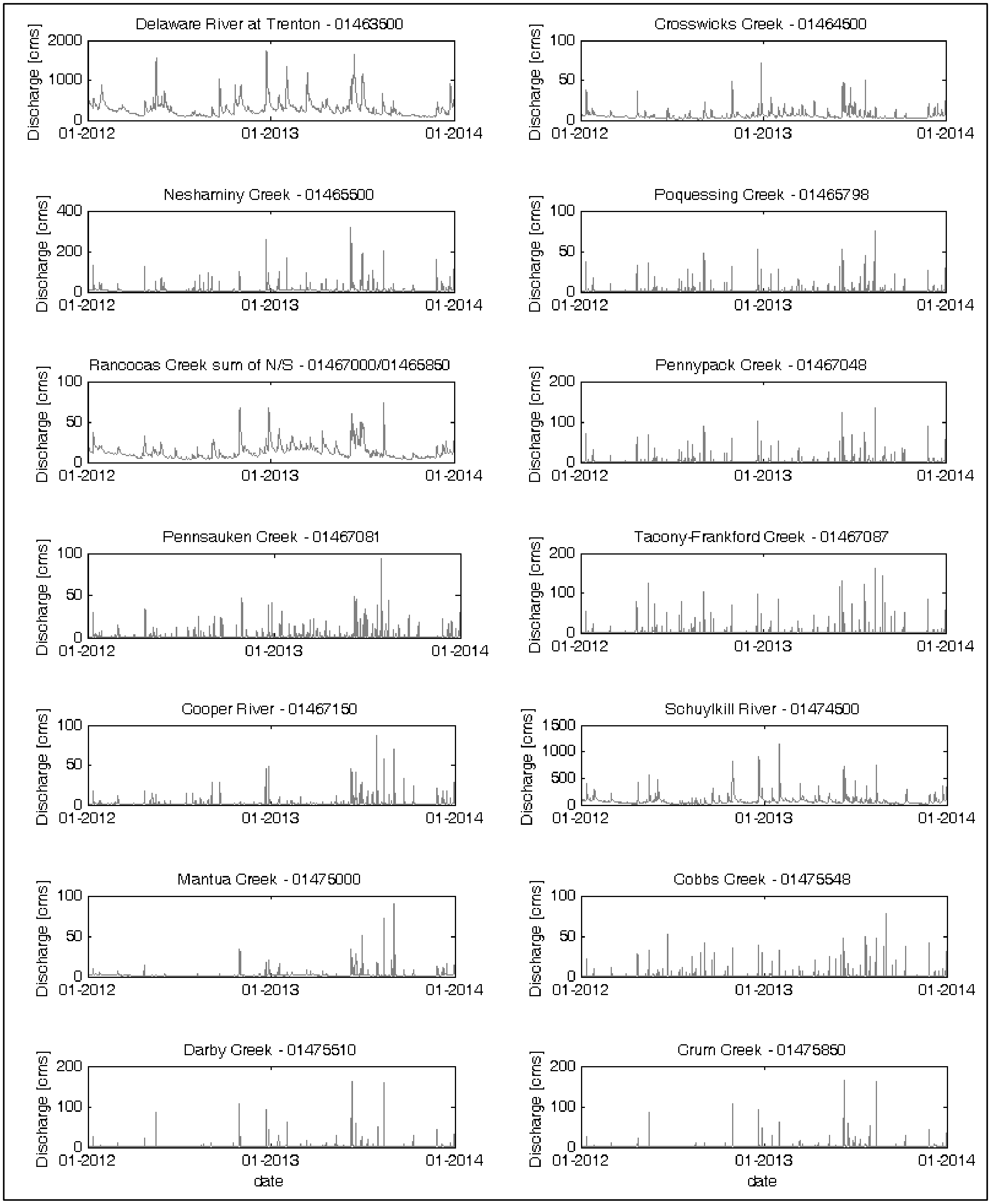


Figure 2-5: Tributary Discharge Time series

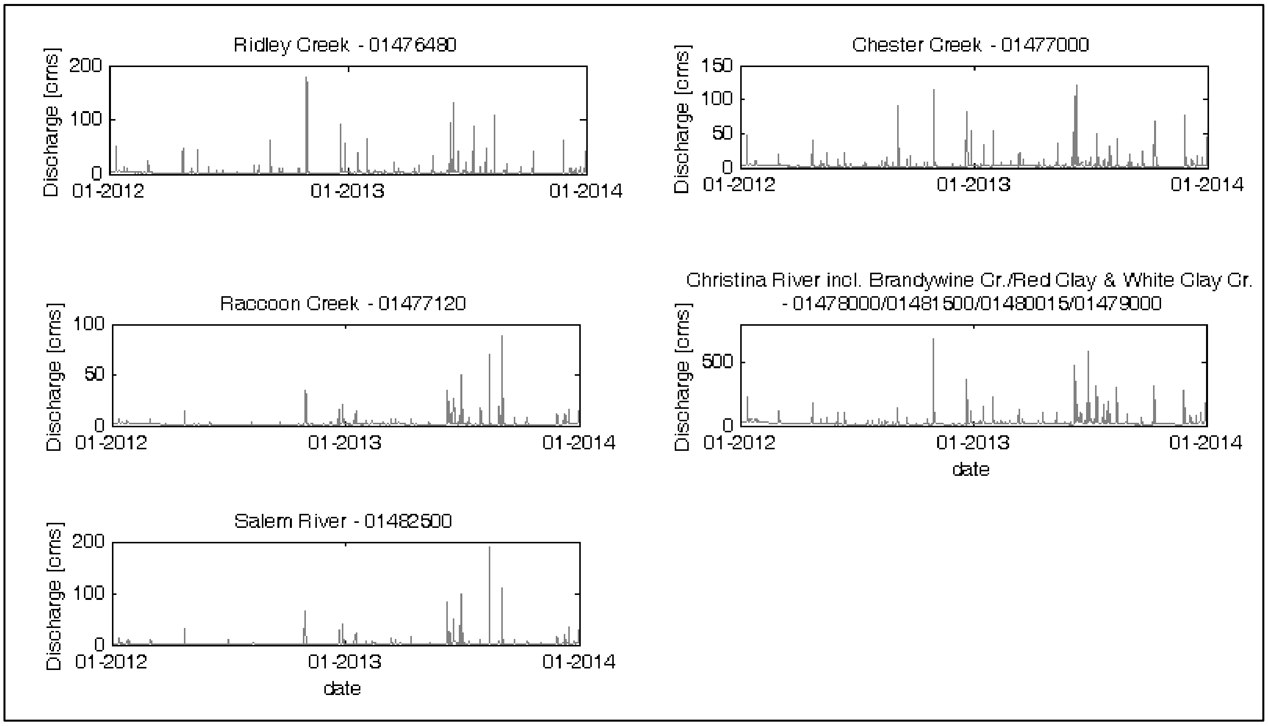


Figure 2-5: Tributary Discharge Time series (continued)

2.4.6 Wind

Five wind time series were obtained within the study area:

- National Climatic Data Center (NCDC) station Trenton-Mercer - USAF 724095, WBAN 14792;
- National Climatic Data Center (NCDC) station Philadelphia Airport - USAF 724080, WBAN 13739;
- National Climatic Data Center (NCDC) station Wilmington - Airport - USAF 724180, WBAN 13781;
- Wind data from Buoy C, and NOAA Station at Burlington (8539094).

Data collected from these stations between May 2012 and August 2013 are shown in Figure 2-6. The wind records show a spatial variation over the study area. At Trenton, winds from the Northwest are predominant; at Wilmington winds originate mostly from either the South-southeast or from the Northwest. Throughout the study area, there is a pattern of winds originating from the Northwest.

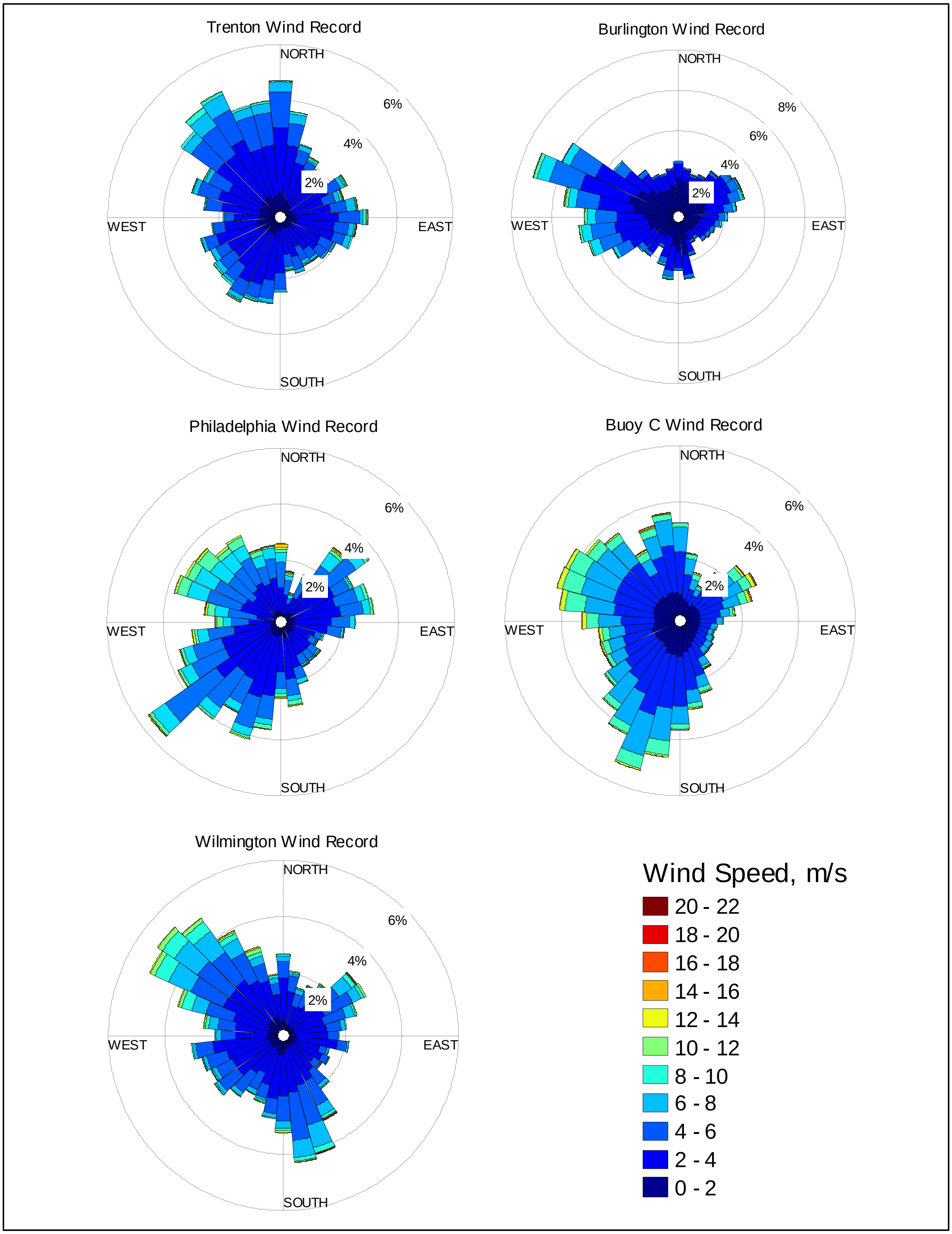


Figure 2-6: Wind Speed and Direction data for five NOAA Weather Stations in Study Area, May 2012 - August 2013

2.5 Model Domain Description

2.5.1 Domain Extent

The model domain includes the Delaware River from River Mile (RM) 61-134 (km 99 – 215) and the tidal Schuylkill River to its head of tide at Fairmount Dam. The model domain's southern extent lies north of the Chesapeake & Delaware Canal confluence and includes a small portion of the turbidity maximum's northern extent.

A curvilinear grid of the Delaware Estuary provided by NOAA (Schmaltz, 2008) served as a template to generate the Delaware River model grid. The grid was modified for this study using the software package Delft3D-RGFGRID (Deltares 2011), part of the Delft3D modeling suite. Modifications included removal of grid sections outside of the study area, addition of grid sections needed to encompass the full study area, and grid resolution refinement in the area of interest around the City of Philadelphia. The resulting model grid contains 75 miles (120 km) of the Delaware River, 8 miles (13 km) of the Schuylkill River (from the Delaware River confluence to the head of tide at Fairmount Dam), the full tidal extents of Cobbs Creek (5.6 miles or 9 km), Frankford Creek (1.85 miles or 3 km) and Pennypack Creek (1.85mi or 3km), all of which receive CSO discharges. The grid contains 9,746 horizontal elements with edge lengths ranging from 17 m to 650 m, and 5 vertical layers. Figure 2-7 shows the fine grid.

Coarse Grid

While the grid described above is configured for hydrodynamic validation, the hydrodynamic grid's fine resolution proves computationally inefficient for water quality applications. A coarse grid to be used for water quality applications was developed based on the fine grid, and hydrodynamic validation results for both the fine and coarse grids are presented in this document. The coarse grid has a roughly 4:1 grid cell area ratio with the fine grid. It contains 2,860 grid cells. Figure 2-8 shows the coarse grid layout. The coarse grid is also discussed in Section 3.

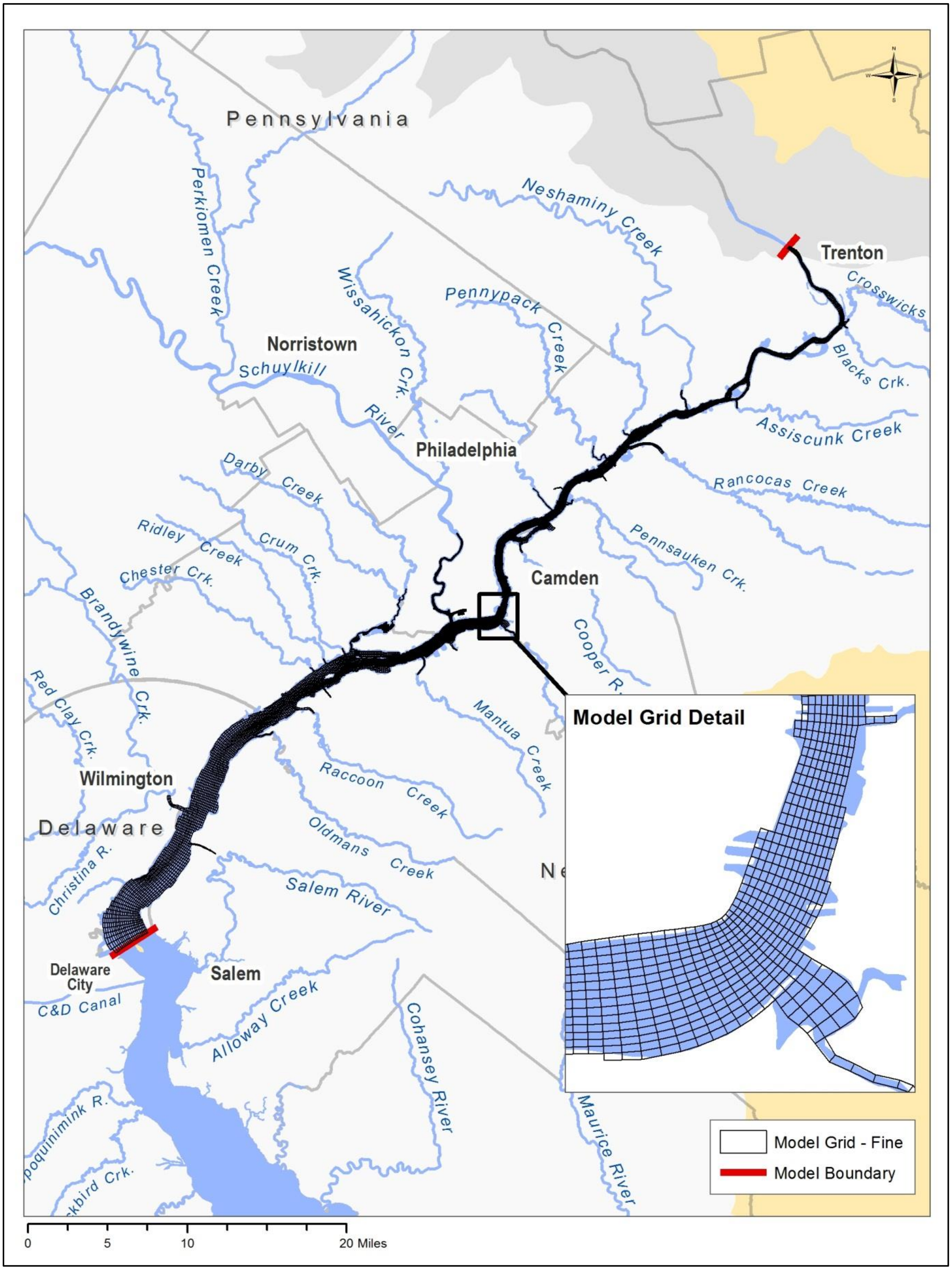


Figure 2-7: Hydrodynamic Model Fine Grid

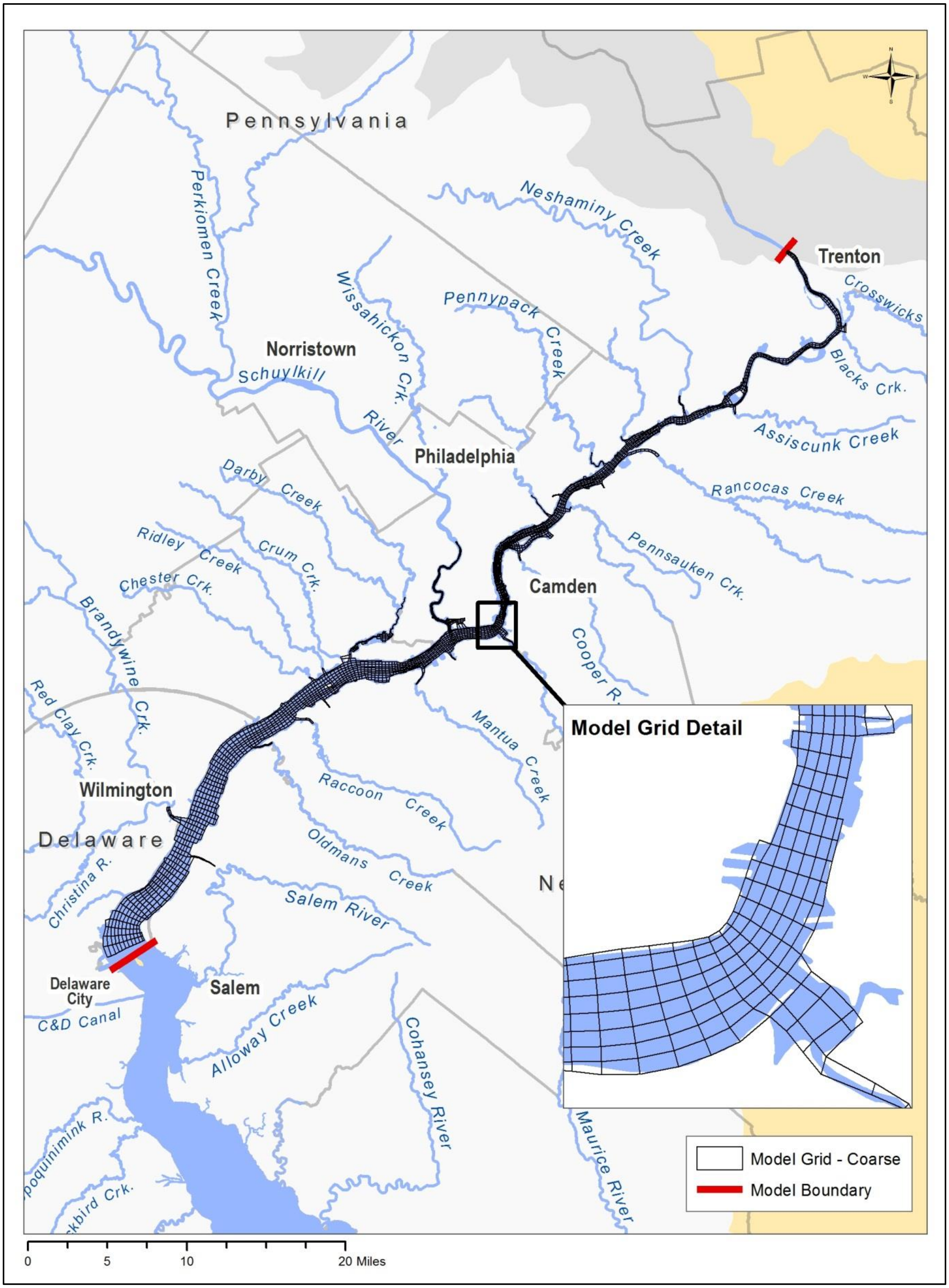


Figure 2-8: Hydrodynamic Model Coarse Grid

Raw bathymetric sounding data was integrated into the fine grid by averaging the depth of all available soundings within each grid cell. To avoid potential cumulative data processing errors associated with translating model features from the fine grid to the coarse grid, the same processing of raw data was done for the coarse grid.

2.5.2 Boundary Configuration

Several model boundaries exist in the model domain:

- The southern edge of the model domain near Delaware City;
- All tributaries entering the model domain, including the Delaware River at Trenton

The southern boundary is treated as an open boundary with a forced elevation based on reported water levels at the Delaware City tidal gage. All other boundaries are treated as volumetric inflows, or point discharges. At these point discharge locations, the Hydrodynamic Model applies a time series volumetric flow rate.

Tidal Head

Special treatment of the tidal head in Trenton is needed to ensure realistic flows through the Delaware River inlet in the Hydrodynamic Model. At the tidal head, water depths are mostly very shallow with a water depth of less than two feet; in both the coarse and fine grid, the deep shipping channel is centered towards the New Jersey shore. In order to distribute the Delaware River dicharge correctly over the full cross section, an artificial extension of six rows was added upstream of the falls. The cells of the extension are deep enough to receive the evenly distributed non-tidal Delaware River discharge, from where it distributes according to the downstream bathymetry.

2.6 Hydrodynamic Model Validation

The validation time period is a nine-month interval from August 2012 through May 2013. This long time period was analyzed to resolve all tidal constituents and prevent the bleeding of energy from unresolved constituents into M2, M4 and M6 amplitudes.

2.6.1 Validation Configuration

River Discharges

As discussed in Section 2.4.5, USGS stream gage data was only available for approximately half of the tributaries included in the model domain. Time series for the ungaged extents of tributaries, fully ungaged tributaries, and direct runoff areas were developed using the watershed area ratio and discharge time series of a gaged adjacent or similar watershed, as described in Table 2-2.

Water Level

The NOAA tide gage at Delaware City, DE, provides observed water levels to drive the southern boundary. Figure 2-9 shows the water level applied.

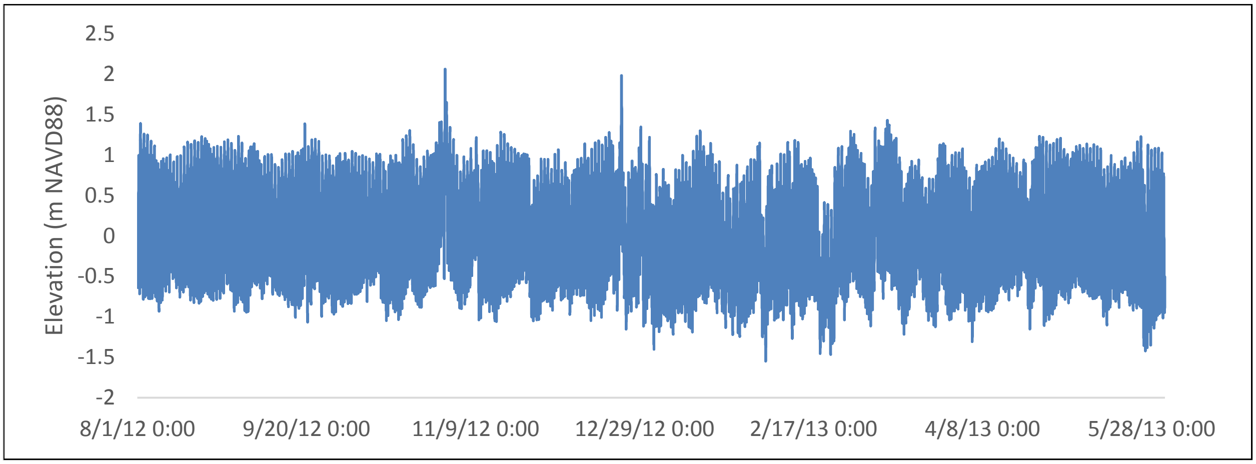


Figure 2-9: Delaware City Observed Water Level during Validation Time Period

Wind

All five wind records described in Section 2.4.6 were incorporated into the fine grid validation configuration. A distance weighted averaged wind was assigned to cells located between two stations. At the upstream and downstream ends, the full unweighted wind data from Trenton and Wilmington wind were assigned, respectively.

Sensitivity tests (not documented) comparing simulations using all five wind records with simulations using a single station uniformly over the model domain showed undetectable differences in Hydrodynamic Model results. Because of this finding, the coarse grid applied the Philadelphia Airport wind record uniformly across the model domain for hydrodynamic validation.

Bottom Roughness

Fine Grid

Bottom sediments of the Delaware River in the model area range from fine sediment and mud at the lower boundary close to the estuarine turbidity maximum (ETM) to coarse sediment and bed rock in the upper model extent. In order to determine if a spatially variable roughness distribution is necessary to match realistic hydrodynamic conditions in all areas a roughness sensitivity study was performed. The results confirmed that the variability in bottom conditions made a spatially variable roughness distribution necessary.

Validation data available to inform roughness coefficients included findings from a 2003 sediment inventory study of the upper Delaware River (Sommerfield & Madsen 2003), local knowledge of the River's bed composition, and Tetra Tech industry experience.

Due to the uncertainties inherent in bottom roughness treatment in hydrodynamic models, an attempt was made to use as simple a treatment of bottom roughness as possible. A uniform roughness height of 0.004 m was used throughout the model domain with the exception of the Trenton area near the head of tide where a higher roughness was applied, and the downstream area near the model's open boundary where a lower roughness was applied. The shipping channel was also assigned a different roughness than the shallower portions of the River. These areas were assigned a roughness value specific to surveys and local knowledge, and were deemed necessary to maintain realistic tidal energy transport within the model domain.

The final roughness distribution is shown in Figure 2-10. The figure shows that modeled roughness increases with distance upstream. This measure ensures tidal energy dissipation reflective of observations. The figure also shows higher roughness in the shipping channel than in the shallows, which reflects likely sedimentation of fines in the shallows.

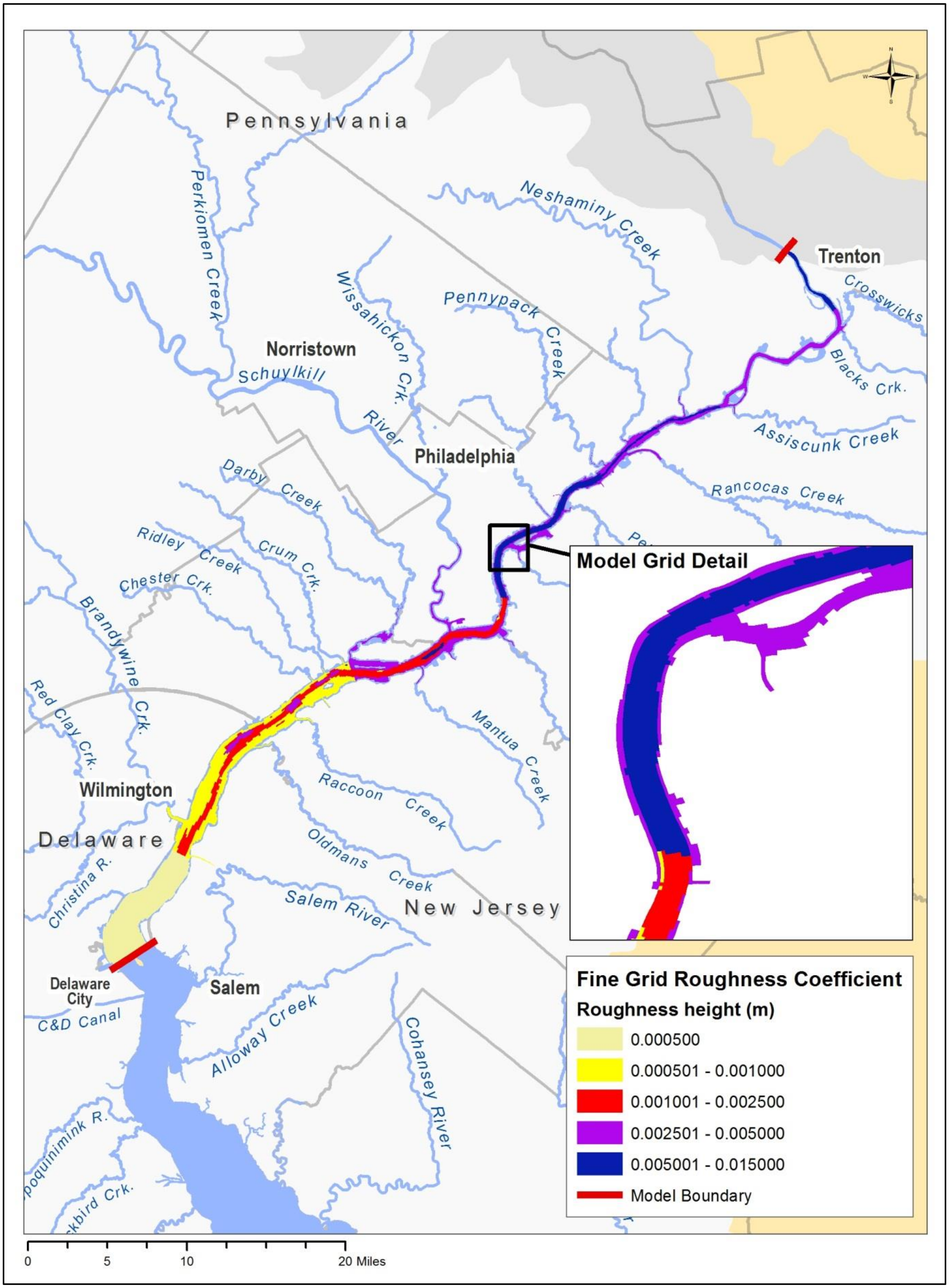


Figure 2-10: Validated Roughness Distribution – Fine Grid

Coarse Grid

While the cross-section of the river was still well resolved in the relatively wide downstream section, the effect of decreased grid resolution was magnified as the river narrowed going upstream. In the upper section, the cross-section was represented by only three cells in the coarse grid, compared to five to six cells in the fine grid, resulting in the loss of correct representation of the cross-channel shape. When a tidal wave travels upstream into shallower water the friction effects of bottom roughness and shape of the river cross section on the tide increase and energy is transferred from the M2 tide into the shallow water harmonics M4 and M6. It is possible that in the coarse grid the change in cross sectional shape leads to more energy being transferred from the M2 than in the fine grid. To balance this, the bottom roughness was decreased overall, and more significantly in the upstream section. Scaling factors were applied to the upstream and downstream regions to adjust their ratios to the mid-estuary roughness coefficients until optimal roughness values were achieved. The final roughness coefficients for the coarse grid are shown in Figure 2-11.

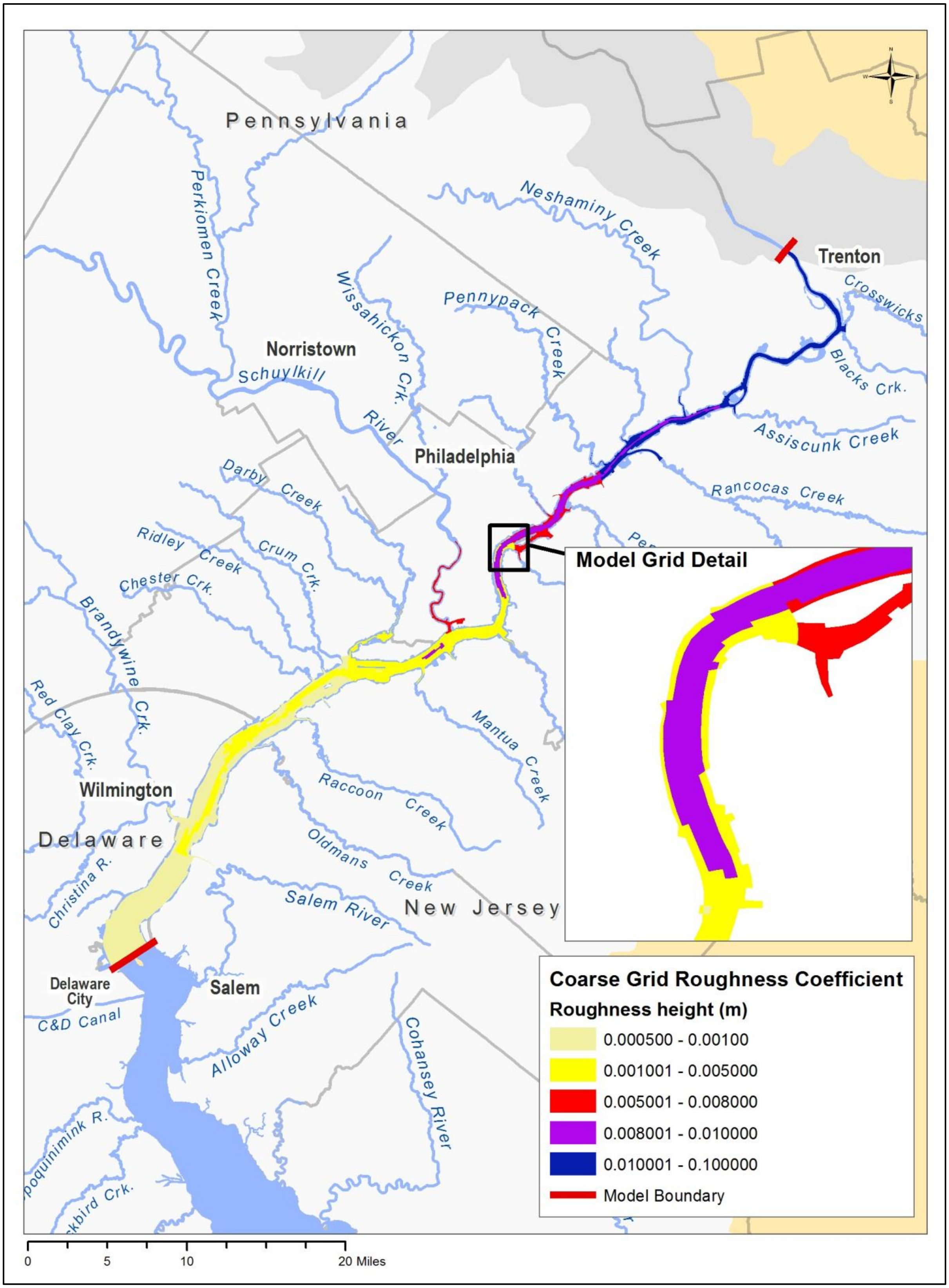


Figure 2-11: Validated Roughness Distribution – Coarse Grid

2.6.2 Validation Criteria

Qualitative and quantitative metrics used to evaluate model validation include direct model-observation comparison statistics such as the root mean square error (RMSE) and Skill factor, direct model-observation harmonics evaluation, along-channel harmonics evaluation, tidal asymmetry, and subtidal analysis. Each of these metrics is detailed below.

RMSE and Skill Factor

The results were analyzed with respect to RMSE (Eq.1) and Skill factor by Willmott (1981) (Eq. 2):

Root Mean Square Error $$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2} \quad \text{with } e = y_m - y_o \qquad \text{Eq. 1}$$

Skill Factor $$Skill = 1 - \frac{\sum \left| y_m - y_o \right|^2}{\sum \left(\left| y_m - \bar{y}_o \right| + \left| y_o - \bar{y}_o \right| \right)^2} \qquad \text{Eq. 2}$$

with m=modeled and o=observed values.

A perfect model would have RMSE and Skill factor results of zero and one, respectively. There is no specific recommended threshold for acceptable error or skill, but they are nonetheless informative in the validation process.

Harmonics

The technique of isolating tidal constituents and evaluating modeled tidal amplitude and phase is common practice in oceanographic model evaluation. A modeled tidal signature is broken into various tidal components, and the amplitude and phase of each tidal constituent is compared with an observed tidal signature. Zhang *et al.* (2006) uses an acceptable error of 15 cm for tidal amplitude, and 26 cm/s for tidal velocity amplitude, when evaluating model harmonic performance.

Progressive Wave Representation

Using the harmonic components of modeled results, it is useful to plot modeled and observed tidal constituents along channel, in order to assess along-channel representation of a progressive wave within the model domain. This assessment provides a qualitative spatial evaluation of model performance.

Tidal Asymmetry Analysis

Because the hydrodynamic model developed in this study is meant for water quality model support, assessing overtides is a useful analysis. Overtide amplitude ratios M4/M2 and M6/M2, are a measure of tidal asymmetry due to friction and nonlinear effects that determines part of the net transport. Comparing modeled and observed overtides informs modeled tidal transport.

Subtidal Analysis

Model representation of subtidal signals demonstrates the model's ability to simulate currents and water level changes that reflect net non-tidal transport. A sensitivity study was performed to test the influence of local wind within the model area on subtidal signals. Most subtidal events develop due to forcing in the bay (strong along bay wind) or the ocean (Ekman) and are already contained in the water level boundary condition of the model forcing. Subtidal water level time series were produced for this analysis by applying a Lanczos filter to model water level results (Emery & Thomson 2001). For time series with a 6 min interval, a cut off period of 34 hours was used. The cutoff frequency was calculated as 2*π*0.1/34, where 0.1 is the sampling frequency (6/60), and the half window width was calculated as 2*10*34, where 10 is the sampling period (10/hour). Subtidal analysis was only performed for the fine grid simulations.

2.6.3 Fine Grid Results

Water Level

RMSE and Skill Factor

Table 2-3 shows RMSEs and Skill Factors for stations where observed data was available for the full validation period. These stations include Marcus Hook, Philadelphia, Burlington, and Newbold. The water level RMSE ranges from 3.8cm at the most downstream location to 10.2cm upstream at Newbold, where model resolution decreases. All stations are well below the acceptable error of ±15cm, especially in the area of interest in the vicinity of the City of Philadelphia. Skill factors range from 0.999 to 0.996, with 1.0 being a perfect result.

Table 2-3: RMSE and Skill Factors for Fine Grid Water Level

Station	RMSE [m]	Skill Factor [-]
Marcus Hook	0.038	0.999
Philadelphia	0.050	0.999
Burlington	0.081	0.997
Newbold	0.102	0.996

Harmonics Comparison

Tidal analysis was performed using the MATLAB tool T_TIDE (Pawlowicz *et al.* 2002). T_TIDE identifies harmonic signals in a dataset with regular time intervals, including both water level and current data sets.

Figure 2-12 and Figure 2-13 show the amplitude and phase error between the modeled and observed water level constituents M2, S2, N2, K1, M4, O1, and M6. Negative (positive) amplitude errors are underpredictions of the observed amplitude, and positive errors are overpredictions. A negative phase lag shows that the Hydrodynamic Model is leading the observed data, meaning the respective high water occurs earlier than observed. A positive phase error therefore indicates that the Hydrodynamic Model is lagging behind. Results are shown for stations Buoy C, Marcus Hook, Philadelphia, Tacony Palmyra Bridge, Burlington, and Newbold.

Figure 2-12 and Figure 2-13 show the amplitude and phase errors of the fine grid validated Hydrodynamic Model. Most amplitude errors were below 2 cm. Only the M2 amplitude error in the downstream section was under predicted by 2.5-3.0 cm, which is still well within accepted error margins (Zhang 2006). The majority of phase errors fell below 6 minutes. Larger phase errors of up to 24 min occurred for the K1 and O1 amplitudes, which are still relatively small in comparison to their period close to 24 hours.

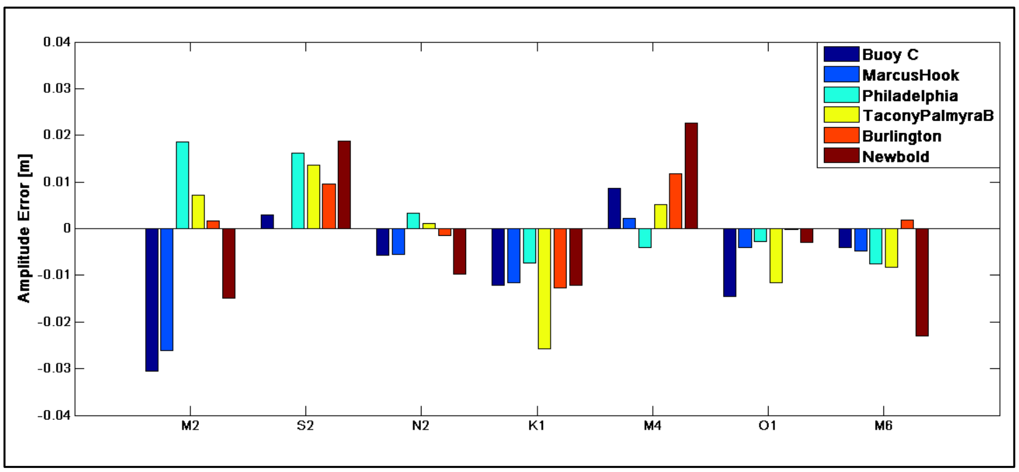


Figure 2-12: Fine Grid Water Level Amplitude Error

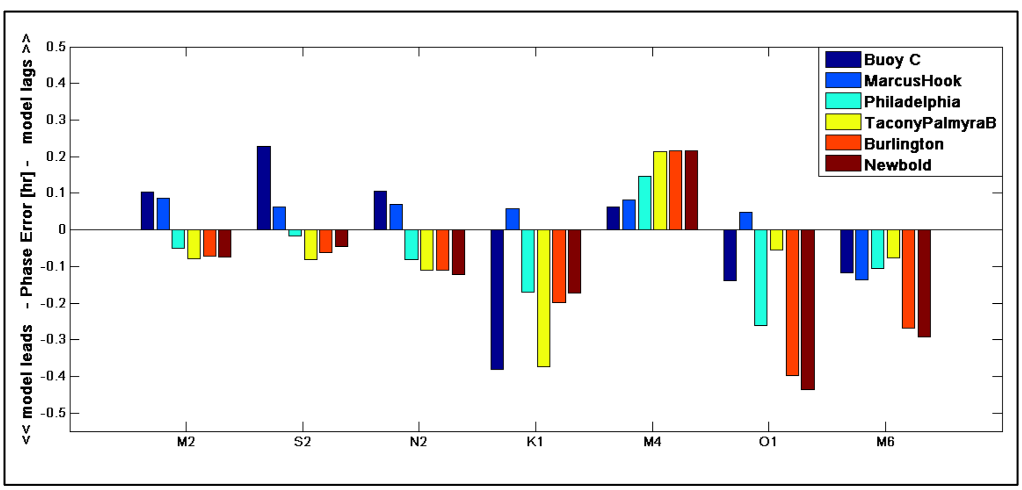


Figure 2-13: Fine Grid Water Level Phase Error

Progressive Wave

Figure 2-14 shows the tidal amplitude plotted along channel, along with observed data. The figure demonstrates the amplitude increase in observed and modeled tidal constituents, particularly M2, moving upstream. Modeled tidal amplitudes qualitatively represent the progressive wave present in observational data.

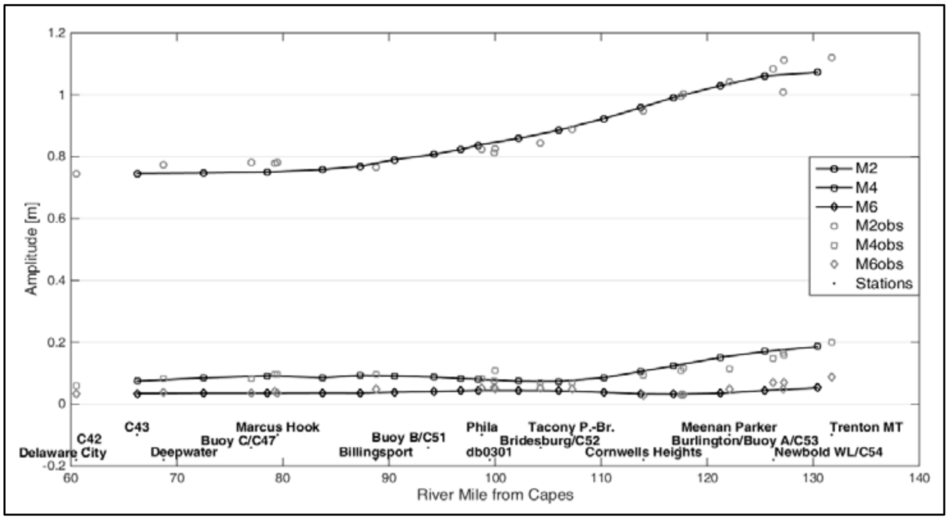


Figure 2-14: Along Channel M2, M4, and M6 Water Level Amplitudes

Tidal Asymmetry

Figure 2-15 shows the overtide amplitude ratios M4/M2 and M6/M2. The fine grid Hydrodynamic Model compares relatively well to both observed ratios, though a larger deviation is apparent in the upstream regions.

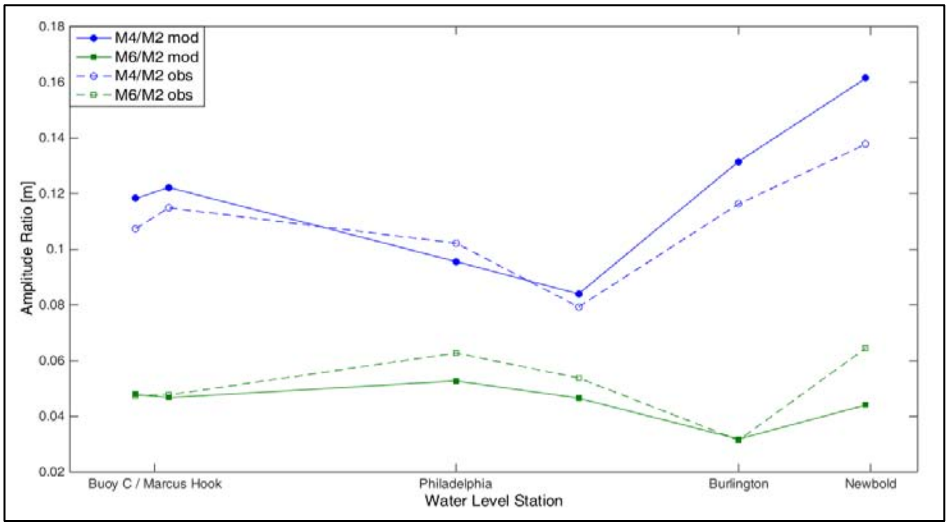


Figure 2-15: Water Level Overtide Ratios

Subtidal Analysis

The subtidal results of a model simulation that included a local wind field (Figure 2-17) compared to a simulation that did not use wind (Figure 2-16) showed that when a sufficiently strong wind is blowing aligned with the river within the model area, a subtidal effect was induced. The red circles in Figure 2-16 and Figure 2-17 mark cases where the model results did not reach peaks visible in the observed data unless the local wind field was turned on, confirming the importance of considering local wind fields in the numerical model. Overall the modeled subtidal signal compares qualitatively well to the observed signal (Figure 2-17).

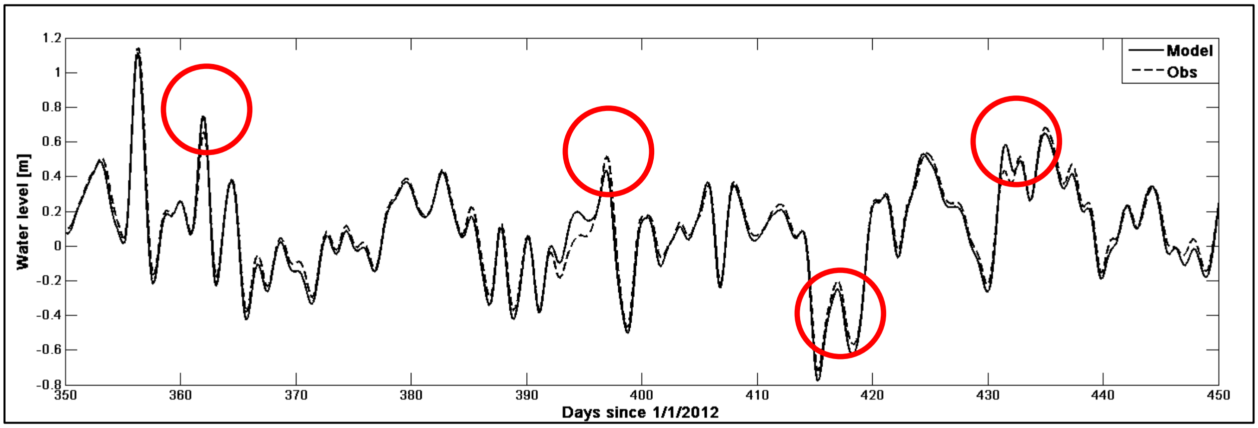


Figure 2-16: Observed vs. Modeled Subtidal Signal @ Philadelphia – No Local Wind

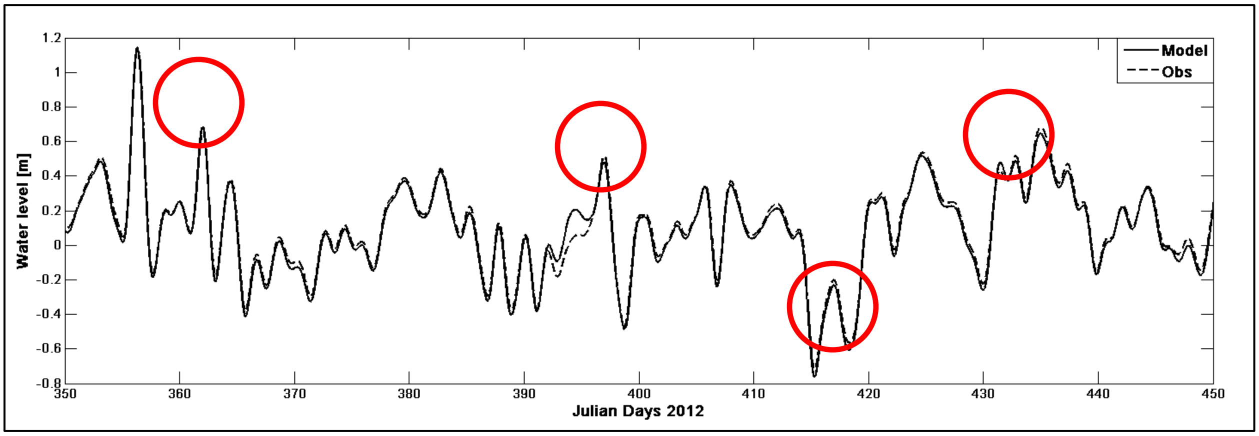


Figure 2-17: Observed vs. Modeled Subtidal Signal @ Philadelphia – with Local Wind

Current

To generate a single time series that can be compared to each vertical cell layer output of the model, a dynamic average of each bin within a vertical model layer per time step was calculated.

RMSE and Skill Factor

Table 2-4 shows RMSEs and Skill Factors for stations where observed data was available for the full validation period. These stations include Buoys A, B and C, and Philadelphia station db0301. RMSEs range from 7.3 cm/s downstream to 9.4 cm/s upstream, well within the acceptable error of ±25 cm/s. All skill factors are close to 1, ranging from 0.997 to 0.988.

Table 2-4: RMSE and Skill Factors for Modeled Current

Station	RMSE (m/s)	Skill Factor
Buoy C	0.073	0.997
Buoy B	0.059	0.993
db0301	0.093	0.993
Buoy A	0.094	0.988

Harmonic Comparison

Figure 2-18 and Figure 2-19 show amplitude and phase error at Philadelphia, and Buoys A, B and C. The largest amplitude error is present at Buoy A, at 15cm/s. This error is within the threshold discussed in Zhang *et al.* (2006). As demonstrated in the along-channel comparison, there is also significant variation in observed amplitudes of velocity tidal signatures.

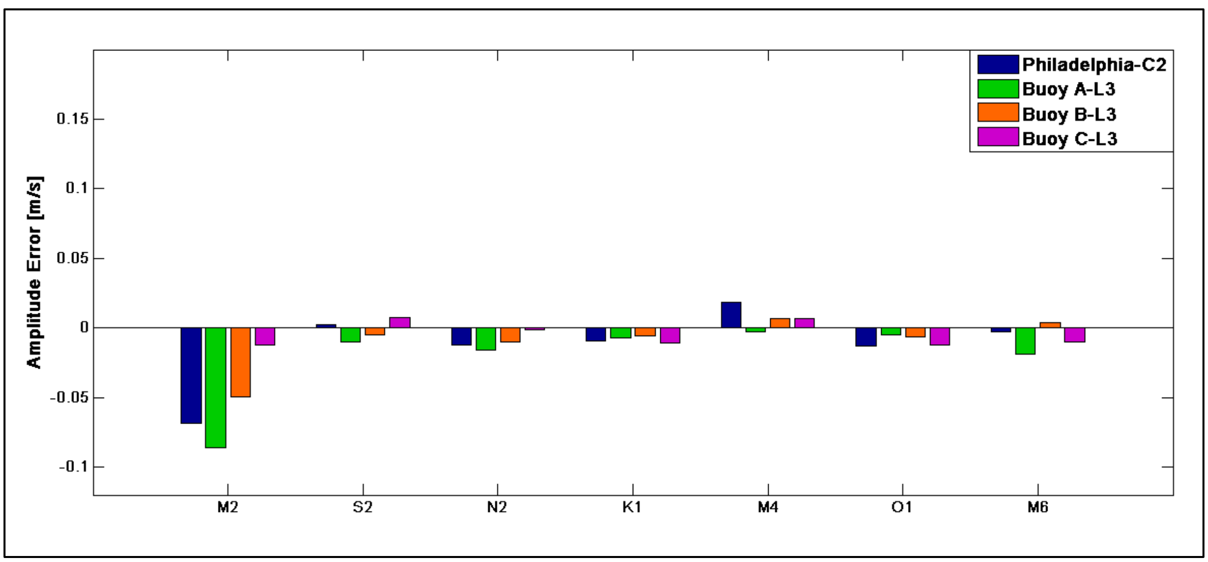


Figure 2-18: Velocity Amplitude Error in Fine Grid

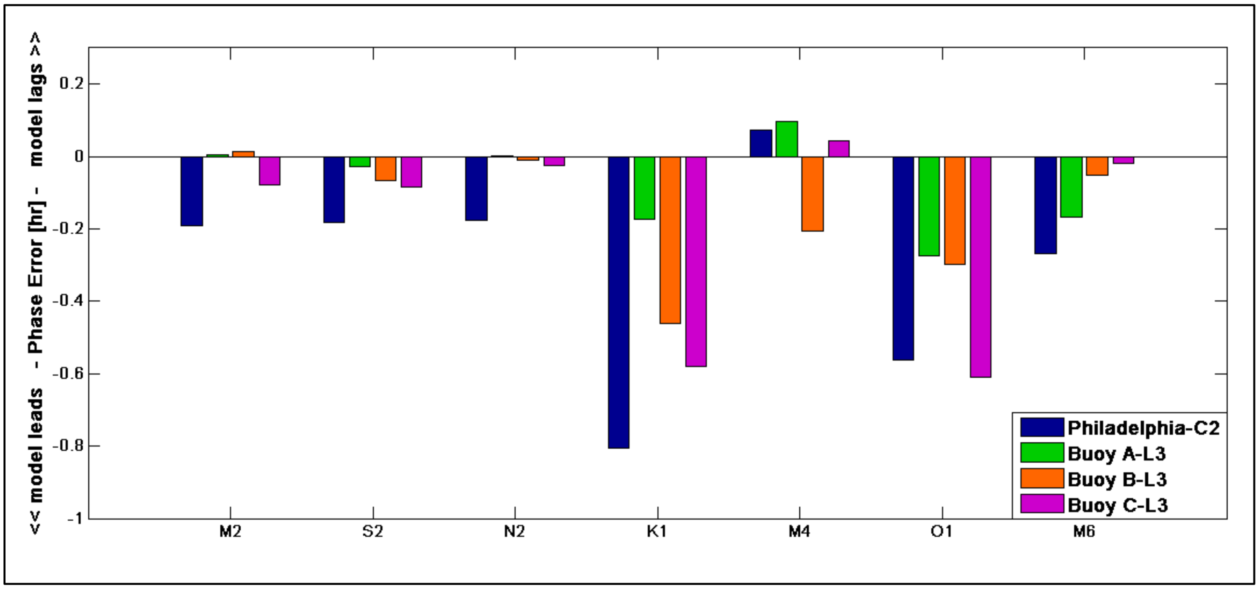


Figure 2-19: Velocity Phase Error in Fine Grid

Progressive Wave

Figure 2-20 shows tidal velocities plotted along channel. The figure shows the large variability in observed tidal velocities. Modeled velocities are within the range of observations. The figure also demonstrates a general decrease in velocity amplitude moving upstream.

The M2 amplitudes peak upstream of Marcus Hook at RM 85 results from the flow being constricted by Chester Island which leads to an increased velocity at this location. The figures also demonstrate a high variability in observed amplitudes; observed M2 velocity amplitudes vary in some locations by as much as 100%.

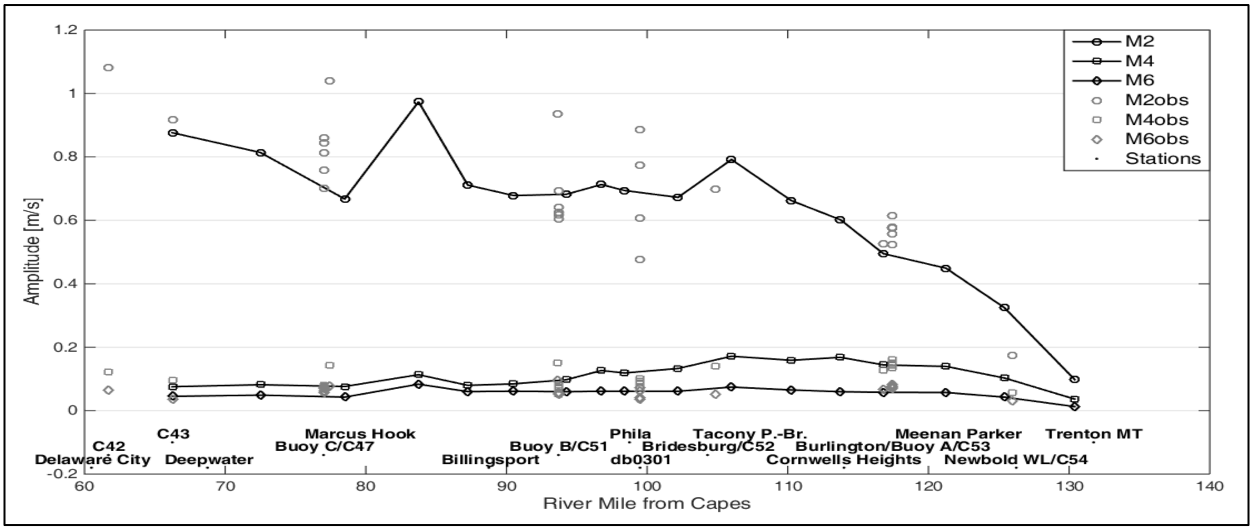


Figure 2-20: Along-channel M2, M4, and M6 Current Amplitudes

Tidal Asymmetry

Figure 2-21 shows the overtides for modeled and observed velocity harmonics. The Hydrodynamic Model results show good agreement compared to observations in overtide ratios at Buoy C, and the model performed similarly well at upstream stations. The overall M6/M2 ratios compared well to observed values. The M4/M2 ratio is over estimated at upstream stations.

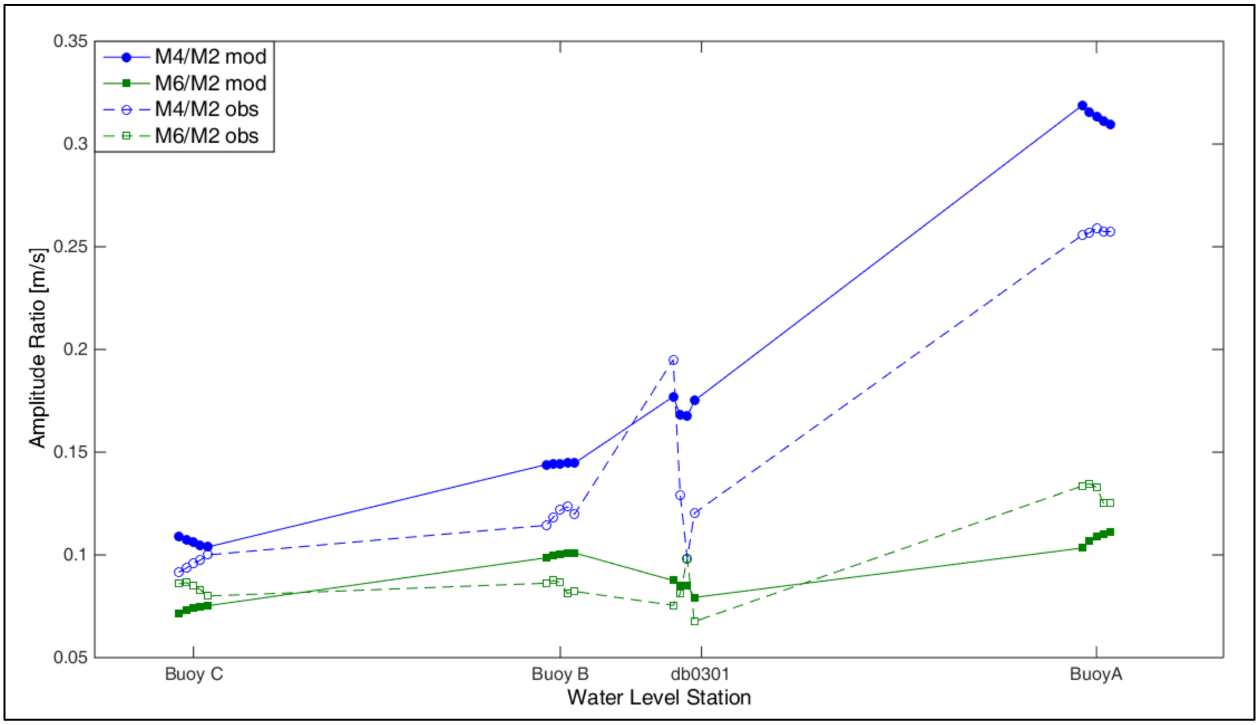


Figure 2-21: Observed and Modeled Overtides for Current Harmonics

2.6.4 Coarse Grid Results

Water Level

RMSE and Skill Factor

Table 2-5 shows RMSEs and Skill factors for stations where observed data was available for the full validation period. These stations include Marcus Hook, Philadelphia, Burlington, and Newbold.

Table 2-5: Water Level Model Statistics for Coarse Grid

Station	RMSE (m)	Skill Factor
Marcus Hook	0.060	0.998
Philadelphia	0.043	0.999
Burlington	0.090	0.997
Newbold	0.105	0.996

Harmonic Comparison

Comparison of water level amplitudes and phase between the coarse and fine grids in Figure 2-22 and Figure 2-23 show that the coarse grid model performs well within acceptable margins for hydrodynamics. An increase of 1.5 cm in the M2 amplitude error beyond the fine grid results at Marcus Hook and an increase of 2 cm in the M4 amplitude error at Burlington were the most noticeable differences. With a total of 5 cm and 4 cm respectively, both errors lie well within the maximum acceptable error for models of +/- 15 cm according to NOAA (Zhang 2006). Phase errors did not change considerably when compared to fine grid results.

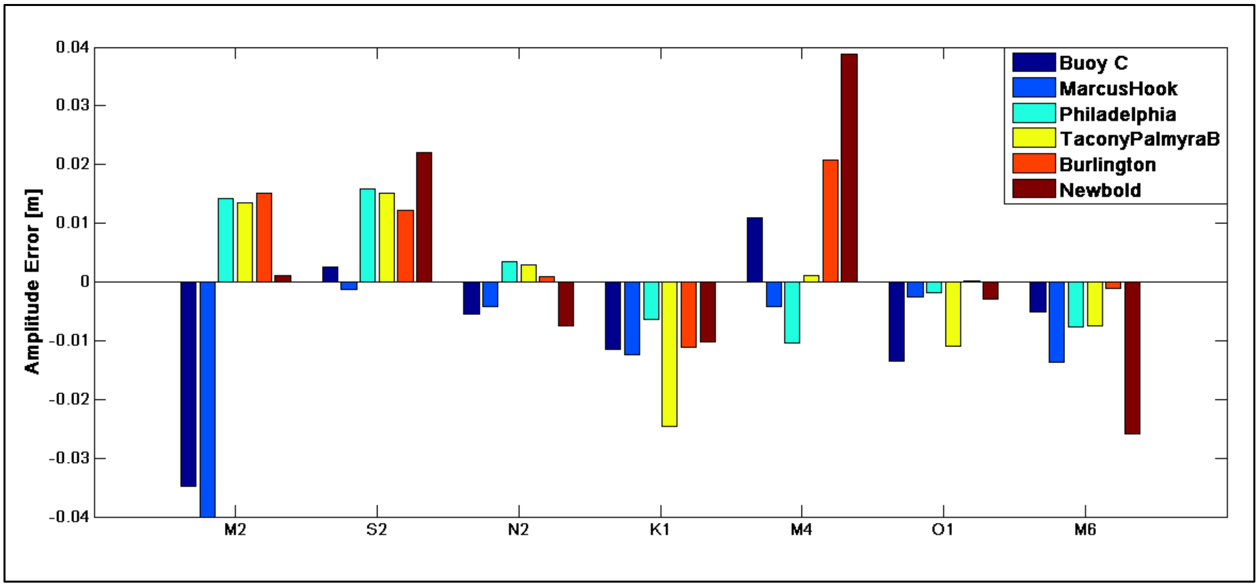


Figure 2-22: Water Level Amplitude Error in Coarse Grid

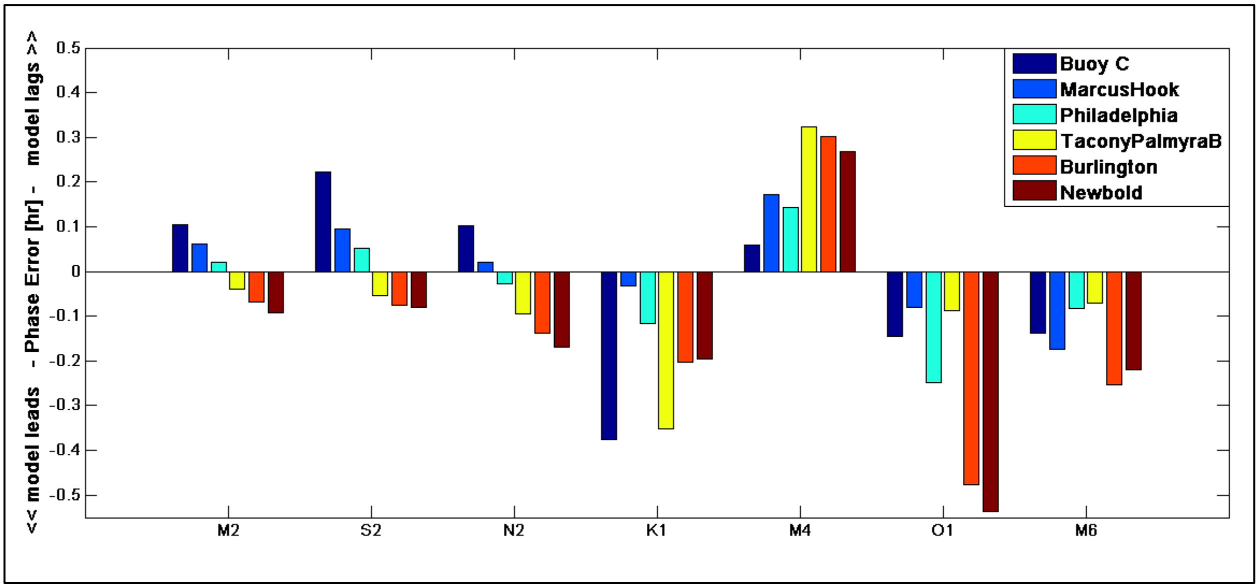


Figure 2-23: Water Level Phase Error in Coarse Grid

Progressive Wave

Figure 2-24 shows the along channel change in M2, M4, and M6 amplitudes for the coarse gird in comparison to its respective 4 cells in the fine grid. The coarse grid results match those from the fine grid qualitatively well throughout the model domain. Between Tacony-Palmyra Bridge and the head of tide, the coarse grid M2 and M4 amplitudes exceed the fine grid results by up to 2 cm. Modeled along-channel tidal wave progression in the coarse grid model qualitatively correspond to observed wave progressions.

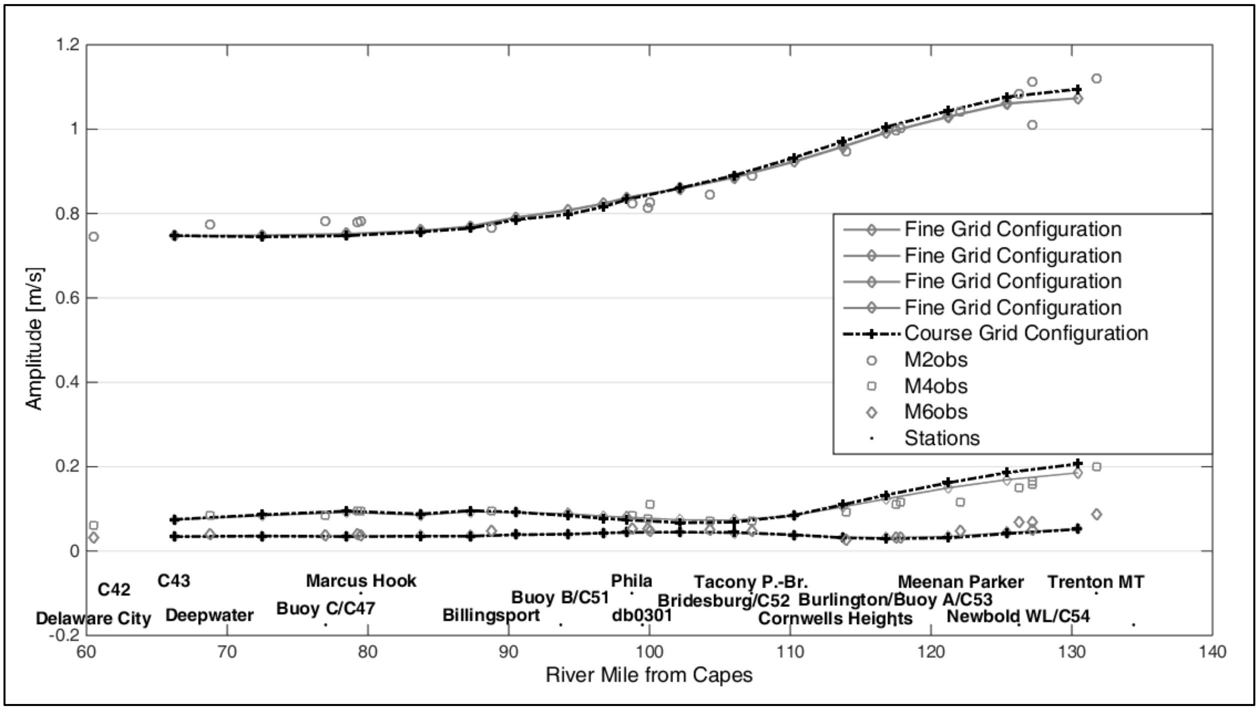


Figure 2-24: Along-channel M2, M4, and M6 Water Level Amplitudes

Tidal Asymmetry

Figure 2-25 shows the overtides for the coarse grid. The M4/M2 ratio increases beyond observed data in the upstream section, possibly as a result of more energy being transferred into the M4 in the coarse grid simulations. The M6/M2 ratio is below the ratio in observations throughout the model domain. While these ratios show differences between Hydrodynamic Model results and observations, they are still qualitatively close.

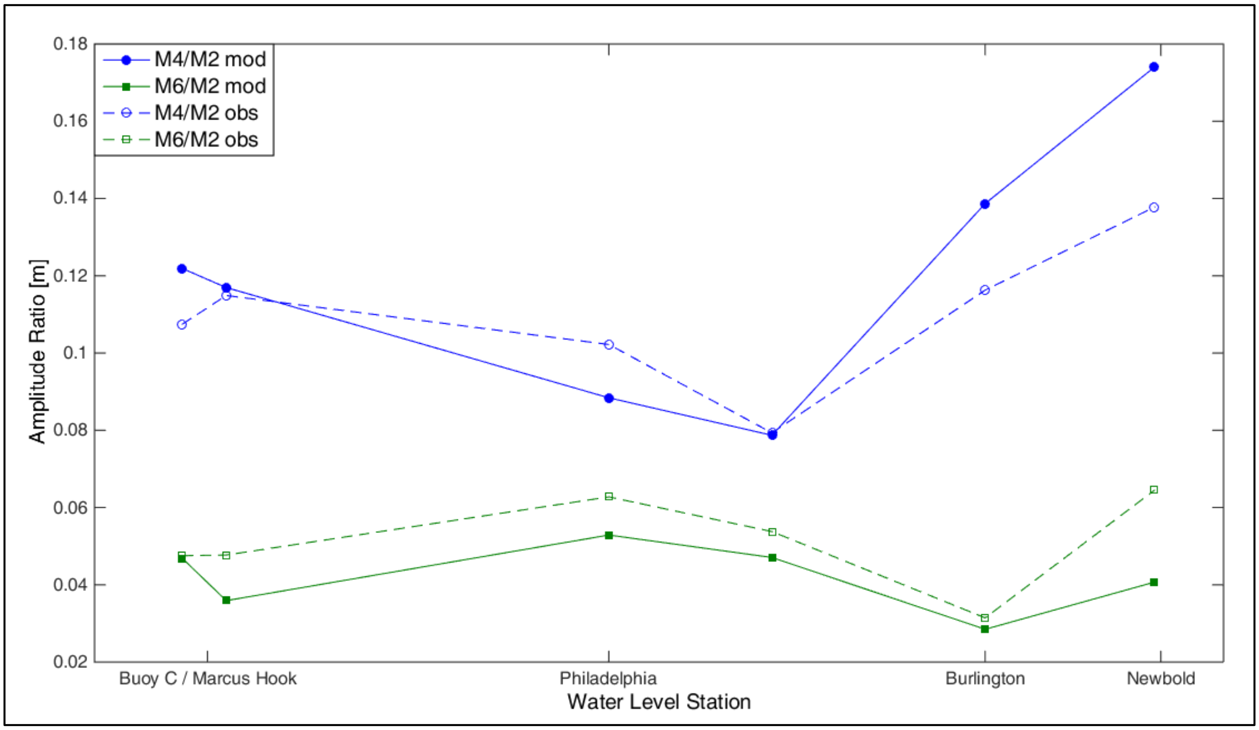


Figure 2-25: Water Level Overtide Ratios

Subtidal Signal

The subtidal signal produced by the coarse grid hydrodynamic model is shown in Figure 2-26. The figure shows a qualitatively good agreement between modeled and observed subtidal signal. A wind sensitivity analysis for subtidal signals was not performed on the coarse grid.

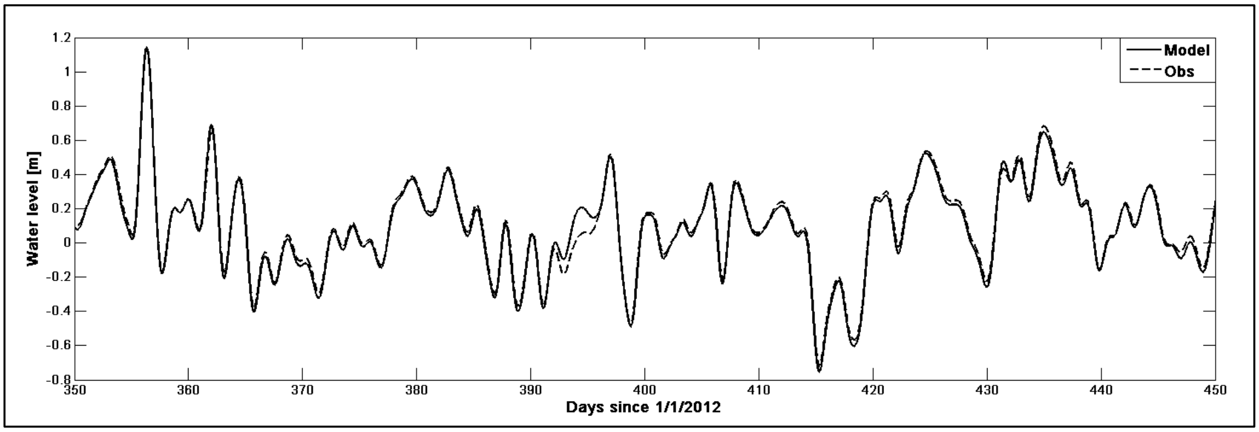


Figure 2-26: Coarse Grid Subtidal Signal

Current

RMSE and Skill Factor

Table 2-6 shows RMSEs and Skill factors for stations where observed data was available for the full validation period. These stations include Buoys A, B and C, and Philadelphia station db0301. RMSE increases slightly in an upstream direction, and similarly the Skill factor decreases slightly from downstream to upstream. The maximum RMSE is 10 cm/s.

Table 2-6: RMSE and Skill Factors for Modeled Current

Station	RMSE (m/s)	Skill Factor
Buoy C	0.038	0.999
Buoy B	0.050	0.999
db0301	0.081	0.997
Buoy A	0.102	0.996

Harmonic Comparison

Figure 2-27 and Figure 2-28 show tidal velocity amplitude and phase errors. The maximum amplitude error is well below the NOAA threshold of 26 cm/s. Phase errors are also similar to those in the fine grid (Figure 2-19).

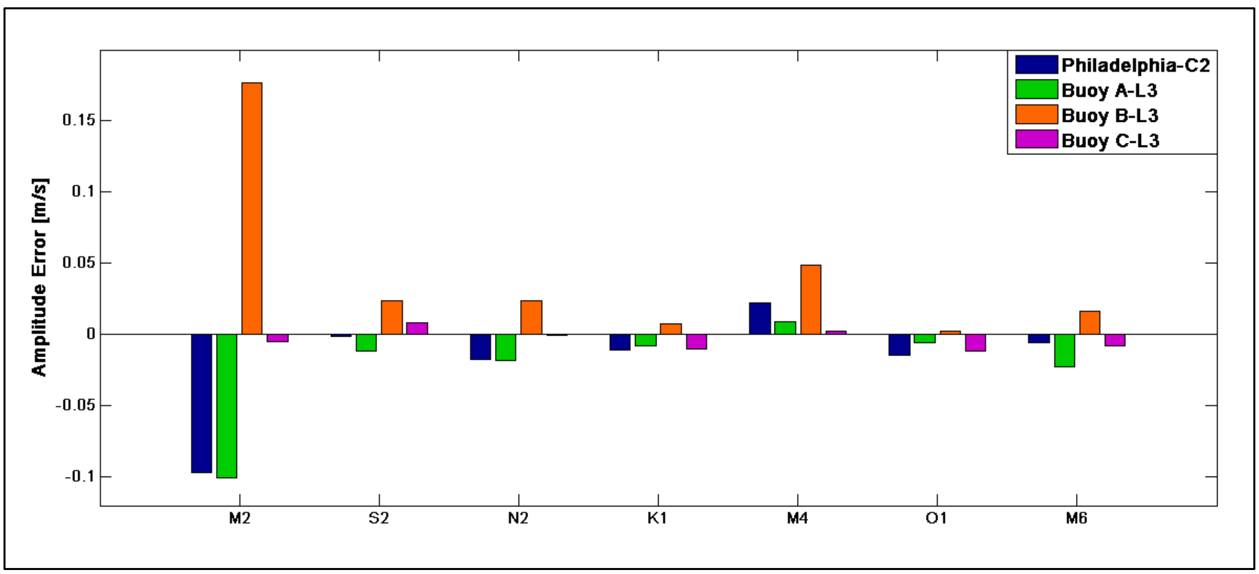


Figure 2-27: Velocity Amplitude Error in Coarse Grid

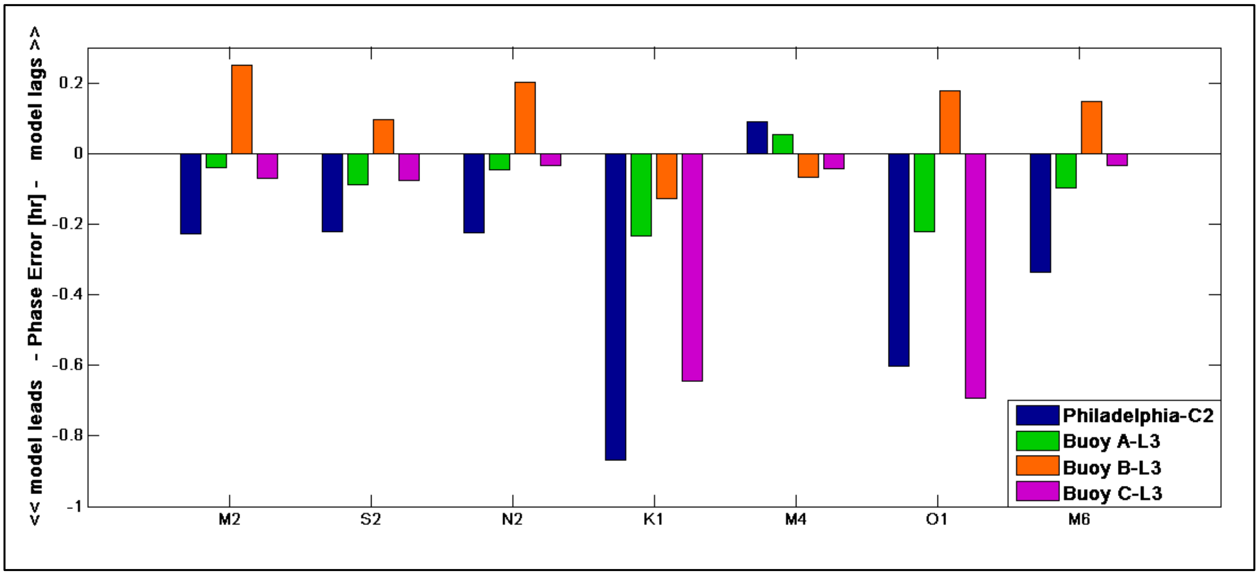


Figure 2-28: Velocity Phase Error in Coarse Grid

Progressive Wave

In Figure 2-29 the along-channel velocity results of coarse grid cells are plotted against the respective 4 cells of the fine grid, and observed data. The figure demonstrates the dependence of velocities on water depths; Hydrodynamic Model results from the four fine grid cells that make up one coarse cell can span a significant range of velocities. For example, velocities from fine cells surrounding Buoy B ranged from 0.60 to 0.67m/s. Overall, coarse grid velocities along the river channel matched the fine grid results where cells had comparable depths and were within the range of observed velocities (circles). M4 amplitudes were slightly higher than in the fine grid results in the upstream section starting at Buoy B (RM 93).

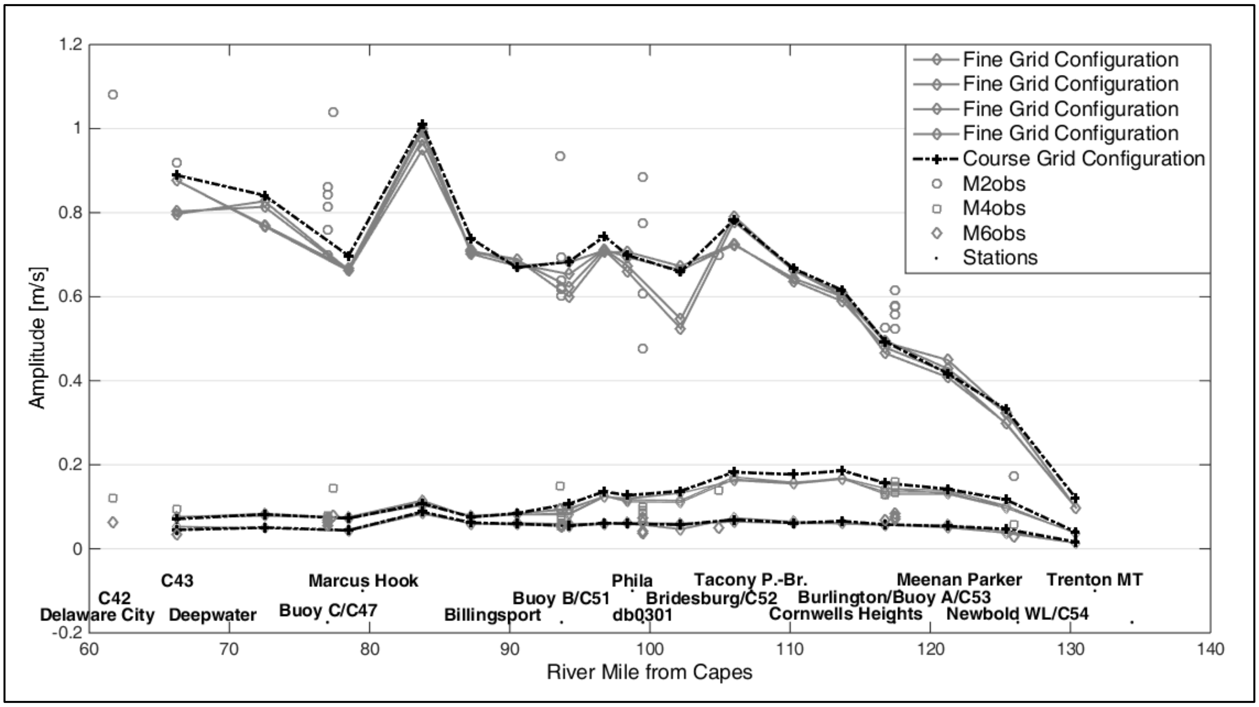


Figure 2-29: Along Channel M2, M4, and M6 Current Amplitudes

Tidal Asymmetry

Figure 2-30 shows overtide ratios for the coarse grid tidal velocities. Similar to water level results, an increase in M4 current amplitudes was observed in the upstream section, and is reflected in the M4/M2 ratio throughout the model domain.

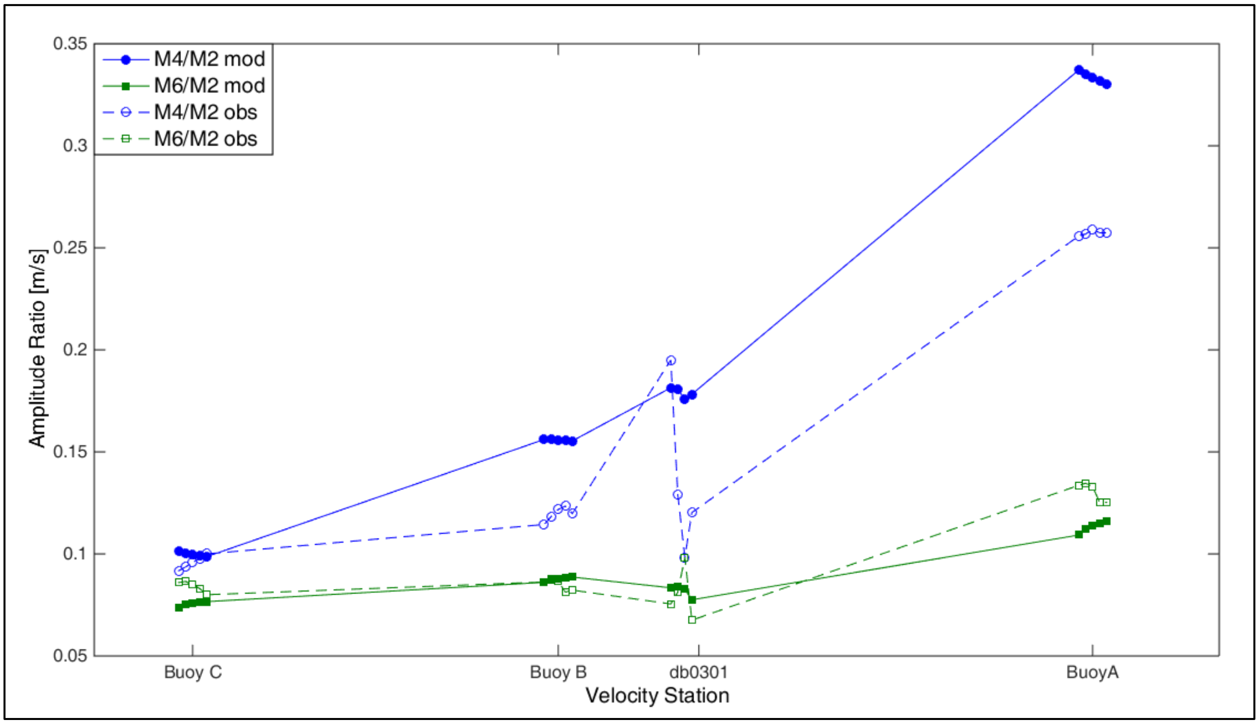


Figure 2-30: Velocity Overtide Ratios

2.7 Summary

A hydrodynamic model of the tidal Delaware River was developed and successfully validated against observed data. The model was developed for the purpose of supporting water quality simulations, and for that purpose accurate representation of tidal transport and mixing are essential features.

This study demonstrates adequate representation of physical transport processes in the EFDC model applied to the tidal Delaware River, using both a fine grid designed for high resolution of hydrodynamic conditions, and also a coarser grid modified to increase computational efficiency without losing hydrodynamic processes resolution adequate for water quality simulations.

3.0 Water Quality Model

This section of the report describes the development of a mathematical model of the water quality of the tidal Delaware River. The goal of this effort, as stipulated in the Water Department's Consent order and Agreement with the Pennsylvania Department of Environmental Protection, was to develop models of the bacteria and dissolved oxygen conditions in the regional receiving waters. As described in this report, that goal has essentially been accomplished.

3.1 Factors Influencing Bacteria in the Model Domain

Pathogen indicating bacteria (*e.g.,* fecal coliform) can enter the receiving waters from

- Tributary rivers and creeks
- Overflows from sewer systems
- Stormwater runoff through storm sewer systems
- Municipal and industrial point sources
- Agricultural and other nonpoint sources

Wet weather concentrations are typically higher than those observed during dry weather, reflecting the contributions from sewer system overflows, stormwater runoff via storm sewer systems and tributaries, and nonpoint sources.

In the water column, bacteria are partitioned into dissolved and particulate fractions. Regrowth and resuspension are phenomena that have been described in the general literature (Uchrin and Weber, 1981; Crabill *et al.*, 1999; Davies *et al.*, 1999; Steets and Holden, 2003; Muirhead *et al.*, 2004; Characklis *et al.*, 2005; Jeng *et al.*, 2005; Bai and Lung, 2005; Jamieson *et al.*, 2005), however the common practice in bacteria water quality modeling is to represent bacteria entirely as dissolved, and not account for regrowth or resuspension. Although multiple processes affect the decay rate, such as temperature, salinity, predation, photolysis, settling, resuspension, and regrowth (USEPA, 2001), in this project bacteria is modeled through a temperature-corrected first order decay term applied in a spatially uniform manner.

Validation of bacteria water quality models is generally limited in objectivity due to the scarcity of observed data and the uncertainties inherent to both observed (Gronewold and Borsuk, 2009) and simulated concentrations. Absolute thresholds or statistical criteria for model performance are not in place to evaluate bacteria water quality models. Instead model validation is generally conducted through qualitative comparison of simulated and observed time series plots for periods of wet and/or dry weather until a determination is made that the model adequately represents the system of interest.

3.2 Factors Influencing Dissolved Oxygen in the Model Domain

3.2.1 Biogeochemical Summary of the Delaware Estuary

A brief overview of Delaware Estuary biogeochemical processes follows. For simplification, the system was divided into five regions as proposed by Sharp *et al.* (2009): the upper river (River Mile 109 to Trenton; ~175-210km), the urban river (RM 71-109; ~115-175km), the turbidity maximum zone (RM 43-71; ~70-115km), the mid-Delaware Bay (RM 15-43; ~25-70km), and the lower Delaware Bay (RM 0- 15; ~0-25km; Sharp *et al.*, 2009). For detailed information regarding biogeochemical processes throughout the Delaware Estuary, refer to Sharp *et al.* (2009) and references therein. Dynamics of the regions included in the Tidal waters Water Quality Model domain are detailed in section 3.2.2.

The Upper River

The upper river receives nutrient loadings due to runoff from large upstream areas of agriculture and from numerous municipal sources discharging to the Delaware River. Nutrient loadings vary with river discharge (Sharp *et al.*, 2009), and algal productivity, controlled by temperature and ambient light levels, peaks in the summer and early fall (*e.g.,* Yoshiyama and Sharp, 2006; Marshall and Alden, 1993).

The Urban River

The urban river is dominated by nutrient inputs from urban discharges. Nitrate, phosphorus, and ammonia peak between River Miles 62 and 93 (100-150 km). Instream nitrification results in a spatial and temporal lag in nitrate and ammonia peak concentrations, with the highest nitrate concentrations down-stream of the ammonia inputs and during summer months (*e.g.,* Cifuentes *et al.*, 1989; Lipschultz *et al.*, 1986; Sharp *et al.*, 2009). Phytoplankton productivity in this region of the estuary is further discussed in section 3.2.2.

The Turbidity Maximum Zone

Sommerfield and Wong (2011) characterize the estuarine turbidity maximum (ETM) zone as a region of persistent elevated suspended sediment concentrations generated from a combination of tidal pumping and gravitational circulation, which results in continual particle settling, deposition, and resuspension. The ETM typically extends from River Miles 30 to 75 (50-120 km), with peak suspended sediment concentrations often at or near the estuarine null point (where tidally averaged bottom currents are near zero; Sommerfield and Wong, 2011). Typically, the landward limit of this upper ETM is centered near waters with salinities between 1-3 PSU (Biggs *et al.*, 1983), though the landward limit has been measured between 0.1-1 PSU (Cook *et al.*, 2007). The ETM has highly variable suspended sediment concentrations, and oftentimes a bimodal sediment distribution is observed in the ETM (*e.g.,* Biggs *et al.*, 1983; Cook *et al.*, 2007).

High suspended sediments limit light in the ETM, and therefore, despite high nutrient concentrations, algal production is characteristically low in this region (*e.g.,* Sharp *et al.*, 1994; Sharp, 2010). Productivity is also limited because freshwater phytoplankton become stressed by brackish conditions and *vice versa* for estuarine species (Pennock and Sharp, 1986).

The ETM acts as a biogeochemical filter between the upper tidal freshwater Delaware River and Delaware Bay, spatially decoupling the zone of high nutrient loads from the zone of light penetration and productivity (Church, 1986). Most dissolved nutrients pass through this filter and are diluted in proportion to rising levels of salinity into the lower estuary. However, excess phosphorus is adsorbed by iron and manganese oxides onto particulates and then is slowly released back into the dissolved phase mid-estuary (Sharp *et al.*, 1982; Biggs *et al.*, 1983; Sharp *et al.*, 1994).

The Mid-Delaware Bay

Biogeochemistry of the mid-Delaware Bay is dominated by a spring phytoplankton bloom. Nutrient concentrations in Delaware Bay are influenced by transport from the tidal freshwater river, and therefore, vary with river discharge and seasonal nitrification processes (Pennock, 1987). Prolonged vertical stratification over the main channel of the estuary during the spring freshet period of increased river discharge suppresses sediment resuspension, which increases the average light availability in the surface mixed layer (Pennock, 1985). During this time, a spring diatom bloom develops dominated by *Skeletonema costatum*, which draws down ammonia and silica (Pennock, 1987; Sharp *et al.*, 2009). Spring chlorophyll-a maxima in Delaware Bay average 50-60 µg/L (Pennock, 1985; Sharp, 2006; Sharp *et al.*, 2009). The spring bloom terminates when phosphorus is exhausted and grazing by zooplankton becomes dominant (Pennock, 1985; Pennock and Sharp, 1994).

The Lower Delaware Bay

The lower Delaware Bay is characterized by high salinity, relatively diluted nutrients, low turbidity, and seasonal phytoplankton production. Nutrients are exported from the estuary primarily as dissolved nitrate and particulate phosphorus (Lebo and Sharp, 1992). Marine phytoplankton production is often evident near the mouth of the estuary in September, and is supported by nitrate (Pennock, 1985, 1987).

3.2.2 Physical and Chemical Controls on Phytoplankton Production and Dissolved Oxygen in the Water Quality Model Domain

The PWD water quality model domain encompasses the upper river, the urban river, and the upper extent of the turbidity maximum zone, as defined in section 3.2.1. In this section, controls on phytoplankton production and dissolved oxygen in the water quality model domain are examined in more detail to account for the dissolved oxygen concentration sag typically observed between RM 71 and 103 (115 - 165 km upriver; Sharp *et al.*, 2009).

Despite high nutrient inputs from urban sources, the Delaware Estuary is not considered "eutrophic," because the zone of maximum phytoplankton productivity is decoupled from the zone of high nutrients and low dissolved oxygen concentrations, with the turbidity maximum in between (Sharp *et al.*, 1994; Sharp, 2010). Consequently, the Delaware Estuary has been characterized as "high nutrient - low growth" (Yoshiyama and Sharp, 2006). In contrast to a typical eutrophication scenario, oxygen depletion in the urban river is primarily caused by primary biochemical oxygen demand from wastewater effluent inputs of reduced carbon and nitrogen (Sharp, 2010; Lipschultz *et al.,* 1986). Sediment oxygen demand has been found to be low in this region, suggesting that water column processes dominate oxygen demand (Lipschultz *et al.*, 1986).

Nitrification and phytoplankton production compete for nutrients in the water column of the water quality domain. The balance between nitrification and production in the water column is affected by light and seasonal temperatures. Nitrification is enhanced during summer months (August – September) with increased water temperatures (*e.g.,* Cifuentes *et al.*, 1989; Sharp, 1994), and rates have been measured as high as ~340 ng N l^{-1} h^{-1} (Lipshultz *et al.*, 1986). This, in combination with decreased oxygen saturation in warmer water, results in greater oxygen depletion during this time. The biogeochemical effect of increased nitrification during summer is manifested as a change in the nitrogen speciation of dissolved inorganic nitrogen in the urban river from primarily ammonia to nitrate (*e.g.,* Sharp *et al.*, 2009).

Light inversely influences nitrification and productivity rates in that nitrification is favored in low light conditions, whereas phytoplankton productivity is enhanced in high light conditions (Lipschultz *et al.*, 1985). Experimental evidence suggested that the optimal light level for phytoplankton production is approximately 300 μE m^{-2} s^{-1}, at which production is maximal and nitrification is inhibited (Lipschultz *et al.*, 1985). Competition for nutrients occurs between nitrifiers and phytoplankton when light conditions are less than 300 μE m^{-2} s^{-1}.

Despite the high nutrient inputs in the urban river, phytoplankton productivity is relatively low except during summer months (~ June through August), and at this time, production primarily peaks up-river from maximum nutrient concentrations (RM 100 and up; *e.g.,* Sharp *et al.*, 1994). There are several hypotheses as to why productivity is limited in the high nutrient zone, including: light limitation, micro- and/or macro-nutrient limitation, and/or toxicants effects. Wofsy (1983) compared results of a light-limitation growth model to observed chlorophyll, suspended sediments, mixed layer depth, and extinction coefficients, and suggested that production is primarily regulated by light. Lipschultz *et al.* (1985, 1986) also suggested that production is light-limited. Yoshiyama and Sharp (2006) and Sharp *et al.* (1994) further suggested that productivity is suppressed by toxicants (*e.g.,* polychlorinated biphenyls, polycyclic aromatic hydrocarbons, or others). Sanders and Riedel (1992) conducted mesocosm studies to determine the limiting factors for productivity, testing phosphorus, nitrogen, silicon, micronutrients, light, chlorinated organics, trace metals, and other organics. They found that light limited productivity in spring and summer, and iron or manganese potentially contributed to limitation as well. The experiments testing the effects of toxicants were inconclusive. It has also been suggested that though phosphorus (P) loads to the urban Delaware River are high, reactive phosphorus may be a limiting nutrient as phosphorus flocculates out with iron and manganese oxides (Sanders and Riedel, 1992; Pennock and Sharp, 1994; Sharp *et al.*, 1994). In summary, phytoplankton production is likely limited by a combination of factors.

There is some evidence that phytoplankton nitrate assimilation is inhibited when ambient ammonium concentrations are greater than ~1-5 μM (28 - 70 μg N/L; Dortch, 1990; McCarthy, 1981; Syrett, 1981; Dugdale *et al.*, 2007; Parker *et al.*, 2012; Wilkerson *et al.*, 2006; Pennock, 1987; Lipschultz *et al.*, 1986), while both nitrate and ammonium assimilation seems to be limited when the ammonium concentration is greater than about 10μM (140 μg N/L; Yoshiyama and Sharp, 2006; Sharp, 2010). The limitation of nitrate assimilation in the presence of the lower range of ammonium concentrations has been widely recognized as some form of suppression of the formation of the nitrate reductase enzyme in algal cells, and often is referred to as preferential utilization. The limitation of algal uptake of both nutrients at the higher concentrations of ammonium appears not to be well understood. Nitrate uptake suppression with high ammonium concentrations has been observed in the San Francisco Estuary (Parker, 2012) and the Guadiana Estuary, Spain (Domingues *et al.*, 2011). In the tidal freshwater Delaware River, only in summer when nitrification increases with warmer temperatures does the concentration of ammonium decrease to low enough levels to allow algal production using nitrate. This could be one controlling factor regulating phytoplankton production in the water quality modeling domain.

When phytoplankton production does occur within the Delaware River in the area covered by the PWD model domain, phytoplankton speciation is related to nutrient distributions. Diatoms dominate summer blooms throughout the region. Freshwater and benthic diatoms dominate blooms above Philadelphia with higher silica concentrations, and chlorophytes and cyanobacteria increase in abundance from Philadelphia to the ETM with limited silica (Pennock, 1985; Pennock and Sharp, 1986, *e.g.,* Sharp *et al.*, 2009). Areal production peaks above RM 80 during summer with rates of ~1.2 gC $m^{-2}d^{-1}$ (Yoshiyama and Sharp, 2006).

In summary, regions of the Delaware River within the PWD water quality model domain generally do not experience dissolved oxygen depletion from classic estuarine eutrophication. Seasonal production occurs in the urban corridor when nitrate uptake is no longer inhibited by high ammonium concentrations, but dissolved oxygen depletion is primarily caused by water column nitrification.

3.2.3 Relevant Stable Isotope and Biomarker Biogeochemistry in the Water Quality Model Domain

Stable isotope and biomarker studies assist in characterizing sources of organic matter and biogeochemical processes in a system. Several studies have examined the stable isotope and biomarker geochemistry of the Delaware Estuary (*e.g.,* Cifuentes *et al.*, 1988; Fogel *et al.*, 1992; Mannino and Harvey, 1999; Harvey and Mannino, 2001; Hermes, 2013; McIntosh *et al.*, 2015), but generally emphasis has been on processes in Delaware Bay. Spatial resolution of these studies has been limited within PWD's water quality model domain, often including only 1-4 stations within this region. Nevertheless, these methods elucidate and/or validate sources and processes derived from nutrient profiles and incubation experiments.

The stable carbon isotopic signature of dissolved and particulate organic carbon reflects the average carbon source in a given sample, primarily differentiating between allochthonous inputs (*e.g.,* riverine detritus and wastewater) and autochthonous production (*e.g.,* phytoplankton blooms). The stable carbon isotopic signature of organic carbon in the upper tidal freshwater river suggests that organic carbon in this region is primarily derived from riverine detritus and wastewater inputs (Cifuentes *et al.*, 1988; Mannino and Harvey, 1999; Harvey and Mannino, 2001; Hermes, 2013). In the summertime, freshwater algal production is evidenced by strong depletion in the carbon isotopic signature of particulate organic carbon (Fogel *et al.*, 1988; Mannino and Harvey, 1999; Hermes, 2013). Cifuentes *et al.* (1989) evaluated the stable nitrogen isotopic signature of dissolved ammonium, which reflects bacterial nitrification, assimilation of ammonium by primary producers, and microbial regeneration of ammonium. The study demonstrated the importance of nitrification in the late summer and early fall in the upper tidal freshwater river. The enriched ammonium pool leftover after nitrification throughout the summer is transported to Delaware Bay in the winter. The nitrogen isotopic composition of ammonium demonstrated the connections between nutrient inputs in the upper estuary and phytoplankton productivity in Delaware Bay.

Stable isotopes represent the average of sources of organic matter in a particular sample, but biomarker compounds act as tracers of sources through environmental systems. A host of biomarker compounds can be assessed for source information, but lipid and lignin compounds have been used most informatively in the Delaware Estuary (*e.g.,* Cifuentes, 1991; Mannino and Harvey, 1999; Harvey and Mannino, 2001; Hermes, 2013; McIntosh, 2015). Again, however, sampling resolution in the water quality modeling domain is limited. Biomarker studies reinforce that the upper tidal freshwater river is predominated by terrestrial-derived riverine-delivered organic matter, with seasonal inputs of autochthonous production. The estuarine turbidity maximum traps riverine-delivered organic matter and received algal organic matter from both the upper and lower estuary. Anthropogenic biomarkers have not been assessed in spatial detail, but some have been detected in the ETM (Mannino and Harvey, 1999).

3.2.4 Summary

In combination, stable isotope and biomarker results support biogeochemical processes inferred from nutrient distributions. Organic matter in the water quality modeling domain transitions from riverine detritus from Trenton to Philadelphia to a mixture of riverine detritus and wastewater from Philadelphia to the ETM. Algal productivity provides 'fresh' organic matter seasonally, with diatom production dominating the model domain and chlorophytes and cyanobacteria seasonally somewhat more prevalent downstream than upstream. It is likely that a substantial proportion of the algal material produced *in situ* during summer months is respired in the water column, since sediment oxygen demand does not significantly increase at this time.

Biogeochemistry of the water quality modeling domain in the zone of wastewater inputs is dominated by primary carbonaceous and nitrogenous biochemical oxygen demand, which are responsible for the oxygen depletion of this zone. This suggests that CBOD decay and nitrification are very important for the water quality model, and additionally, that the biogeochemistry of the tidal freshwater Delaware River is not driven by algal material, but is instead driven by anthropogenic inputs and less 'labile' riverine detritus.

3.3 Findings of Previous Water Quality Models of the Delaware River

The last major dissolved oxygen water quality modeling effort of the Delaware River was conducted by Hydroqual (1998), in which a 3D model was applied based on ECOM for hydrodynamics, and a framework similar to EUTRO-WASP for water quality. The Hydroqual model improved upon the 1970s Dynamic Estuary Model (DEM) of the Delaware Estuary in four key aspects. The DEM was only applied at steady state conditions to assess dry weather DO impacts. Neither time-variable conditions, nor CSOs were simulated. The DEM simulated CBOD and NBOD effects on DO, but not algal-nutrient dynamics. Lastly, the DEM was a 2D model.

In contrast, the Hydroqual model was a 3D, time-variable eutrophication model that simulated algal-nutrient dynamics in addition to the effects of CBOD and NBOD on DO. It utilized time-varying forcing functions such as tidal stage data, flow inputs, and wind. However, it was not applied to simulate pathogen indicator bacteria such as fecal coliform.

Both the DEM and Hydroqual models simulated the spatial extent from the head of tide at Trenton (RM 133) to Liston Point (RM 48.5), *i.e.,* Water Quality Zones 2 through 5 of the Delaware River Basin Commission (DRBC). The Hydroqual model grid was 84 cells in length, up to five cells in width, and had four vertical layers. The model accounted for nine tributaries, the Chesapeake and Delaware (C&D) Canal, 72 municipal and industrial wastewater loadings, and CSO loadings from Philadelphia and Camden.

The Hydroqual water quality model was parameterized with global kinetic rate constants, except for spatially-varying light extinction, nitrification, and algal loss rates. A uniform rate for sediment oxygen demand (SOD) (0.5 g/m2/d) was based on a local study by Owens and Cornwell (1997). An ultimate CBOD study performed in the river was referenced to derive the CBOD decay rate. The main source of observed data for model output comparison was the set of grab samples from DRBC monthly boat runs. The water quality model was validated over two periods - June to October 1991 and July to October 1995. Primary sources of uncertainty were listed as inputs from the Schuylkill River, and CSO inputs from major urban areas.

Hydroqual concluded that the oxidation of ammonium is the main factor depleting DO and produces a maximum decrease of 2 mg/L during summer low flow. Oxidation of CBOD reduces DO by a maximum of 1 mg/L during summer low flow. SOD decreases DO by an average 0.6 mg/L during summer. CSOs result in a maximum decrease of DO of a few tenths of 1 mg/L. Algae effects are highly variable spatially and temporally, and generally increase DO by 0.5 to 2.0 mg/L; algal production contributes an indirect counter-effect through deposited organic matter exerting SOD, although the model does not apply sediment diagenesis. It was proposed that in order to explain the high algal loss rate parameterized in the upper reach of the model domain, benthic bivalves are consuming algae in the upper estuary.

Finally, the Hydroqual modeling study concluded that algal production is light-limited and not nutrient limited, so point source nutrient control would not be adequate to control algal growth. The study concluded that light-limited algal effects may be the most important single contribution to variability in river DO levels.

3.4 Water Quality Model Selection and Description

3.4.1 EFDC Water Quality Model

The EFDC water quality eutrophication model was selected for this water quality modeling study of the Delaware River. The EFDC model is part of the EPA TMDL Toolbox and has been applied in numerous settings across the U.S. and abroad. It is capable of simulating water quality processes in a wide variety of environments such as rivers, estuaries, lakes, and coasts. The Water Quality Model runs concurrently with the Hydrodynamic Model on the same model grid.

The kinetic processes included in the EFDC water quality eutrophication model are derived from the CE-QUAL-ICM water quality model (Cerco and Cole, 1995) as described in Park *et al.* (1995). In contrast with other water quality models such as WASP (Ambrose *et al.*, 1993), which use biochemical oxygen demand to represent oxygen-depleting organic material, the EFDC water quality model is carbon-based.

As described in the EFDC Water Quality Module documentation (Hamrick, 2007), major model compartments include dissolved and particulate organic matter (carbon, nitrogen, and phosphorus), inorganic nitrogen and phosphorus, phytoplanktonic algae and dissolved oxygen. Particulate organics settle out of the water column or are converted into dissolved organic form via hydrolysis. Dissolved organic carbon, nitrogen, and phosphorus are converted into inorganic forms by mineralization. Utilization of dissolved organic carbon by heterotrophic bacteria consumes dissolved oxygen. Similarly, dissolved organic nitrogen and phosphorus are converted by bacterial activity to ammonium (NH_4) and orthophosphate (PO_4), respectively.

Ammonium is subsequently oxidized by bacteria to nitrate (NO_3) in the nitrification process which consumes dissolved oxygen. Under conditions of very low dissolved oxygen, NO_3 may be reduced by bacteria to dissolved nitrogen gas, which may subsequently be lost to the atmosphere at the air-water interface. This process, known as denitrification, consumes dissolved organic carbon.

Growth, respiration, and predation of algae are affected in the model by optimal water temperature specifications. Algae uptake inorganic nitrogen (NH_4 and NO_3) and phosphorus (dissolved PO_4) during growth, according to Michaelis-Menton kinetics with user-defined half-saturation constants. Similarly, algae release dissolved and particulate organic matter due to respiration(*i.e.*, basal metabolism), and predation. Algae are growth-limited in a multiplicative manner by ambient levels of light, water temperature, and concentrations of inorganic nitrogen (NH_4 and NO_3) and phosphorus (dissolved PO_4). Algae take up dissolved oxygen during respiration, and release dissolved oxygen during photosynthetic activity. Algae also settle out of the water column.

The complete EFDC water quality eutrophication model simulates sediment diagenesis and 21 state variables in the water column, including 3 phytoplankton groups, macrophytes, a generalized total active metal that adsorbs dissolved PO_4, total suspended solids that dynamically affects light extinction, two classes of particulate organic matter, and silica. The EFDC water quality eutrophication model described in this report uses 12 state variables (Table

3-1) in order to accelerate run time, in a manner that maintains sufficient representation of key water quality processes in the system(Figure 3-1). Instead of sediment diagenesis, spatially variable zero-order rates for SOD and benthic nutrient fluxes are applied, with a Monod adjustment to the latter to prevent negative nutrient concentrations in water column. The Monod adjustment is applied to the case when a negative flux is specified, indicating a net loss of nutrient from the water column. The negative flux is adjusted based on the water column concentration, such that the negative flux decreases in magnitude and approaches zero as the water column concentration approaches zero. This formulation provides a more accurate representation of the system and prevents the output of negative concentrations.

Other simplifications in the 12 state variable approach included: a) one class of particulate organics; b) no total active metal; c) no silica; d) one phytoplankton group; e) no macrophytes; f) constant TSS concentration; and g) no atmospheric deposition. These features could be included in future iterations of the Water Quality Model, but in this initial stage they were excluded. Validation, as described in Section 3.11, indicated that the simplified model performed to a satisfactory level.

Table 3-1: EFDC State Variables Applied in Tidal Waters Water Quality Model

EFDC state variable (name in model)	
Particulate organic carbon (LPOC)	Dissolved organic carbon (DOC)
Particulate organic nitrogen (LPON)	Dissolved organic nitrogen (DON)
Particulate organic phosphorus (LPOP)	Dissolved organic phosphorus (DOP)
Ammonium (NH_4)	Nitrate (NO_3)
Total phosphate (PO_4)	Dissolved oxygen (DO)
Phytoplankton algae (CHC)	Fecal coliform bacteria (FCB)

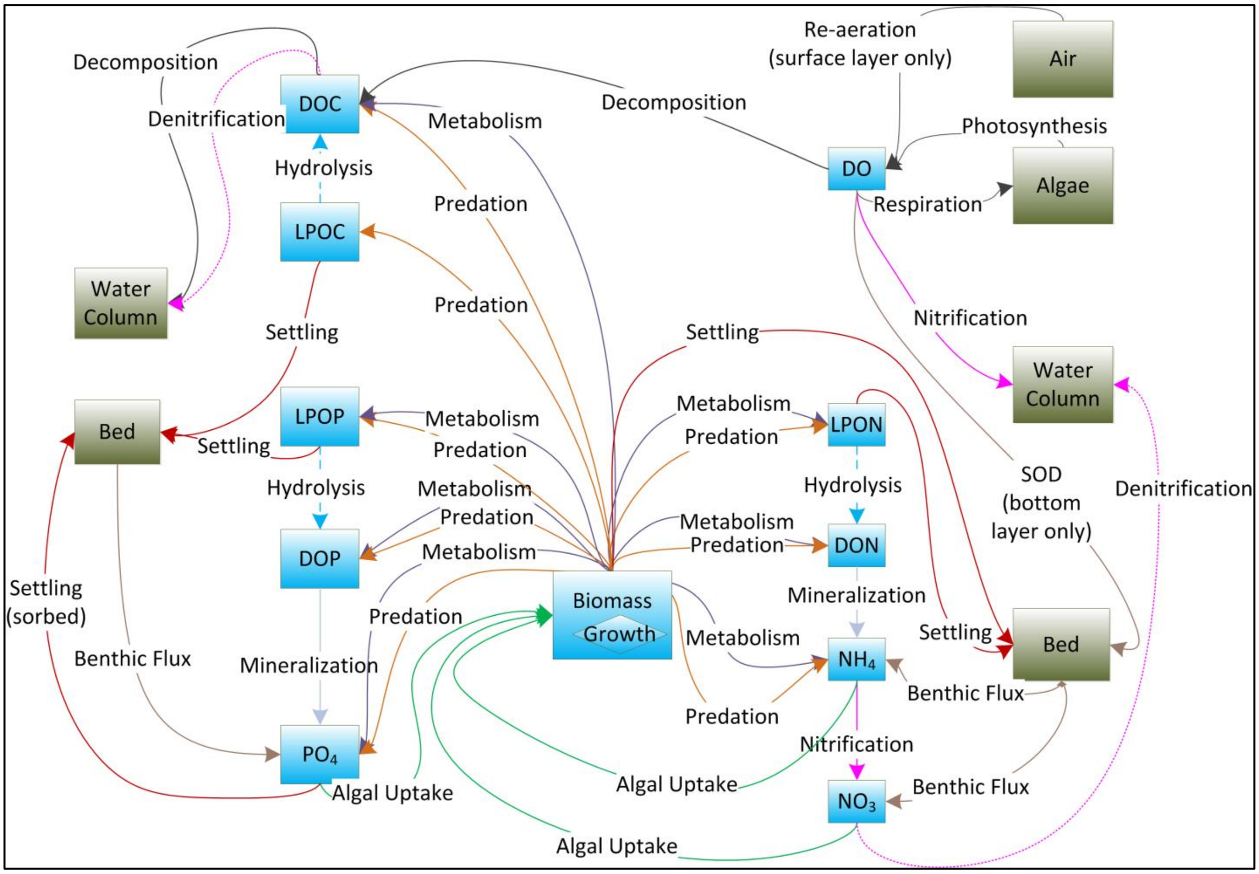


Figure 3-1: EFDC Water Quality Model Schematic with Eleven State Variables (FCB Not Shown)

3.4.2 Water Quality Model Grid and Relation to Hydrodynamic Model Grid

The Water Quality Model is run simultaneously with the Hydrodynamic Model in EFDC using the same model grid. Since the Water Quality Model significantly increases computational requirements, it therefore runs on the coarse grid discussed in Section 2.5.1, rather than the fine grid. The coarse grid was developed for the purpose of improving computational efficiency in the Water Quality Model. Where possible, the coarse grid encompasses four fine grid cells for every coarse grid cell.

Because the coarse grid is generated from the fine grid, hydrodynamic results are very similar to the fine grid. As mentioned in Section 2.6.1, roughness coefficients were adjusted to account for changes in grid resolution. Wind is also applied to the coarse grid from a single weather station at Philadelphia, rather than using the five weather stations throughout the model domain that are applied to the fine grid model configuration. Aside from these modifications, the design of the Hydrodynamic Model that supports the Water Quality Model is identical to the fine grid.

Hydrodynamic performance evaluations discussed in Sections 2.6.3 and 2.6.4 show that the coarse grid's hydrodynamics are not compromised by using the coarse resolution.

3.4.3 Customized Aspects of Water Department EFDC Water Quality Application

The Water Department worked directly with Tetra Tech, Inc. in order to tailor the EFDC water quality model to the Delaware River system. The public release version of EFDC available via USEPA (Tetra Tech, 2007) differs significantly from the version of the model used for this study. Modifications include changes to model processes, and also modifications to model outputs. Changes to modeled processes include:

- Allowing for spatially-varying background light attenuation coefficient and maximum nitrification rate;
- Ensuring that light attenuation occurs when the sediment model is not activated. Typical applications of the EFDC water quality model include sediment transport. However, the Delaware River application of the EFDC water quality model does not include sediment transport; rather, it applies a temporally constant and spatially uniform TSS concentration to the water column. In EFDC's public release version, certain parameters related to light penetration bypass user-input values when the sediment transport model is turned off;
- Improving model precision. PWD noticed a cumulative numerical error that resulted in a loss of mass within the modeled system over long simulation times. Tetra Tech switched the EFDC model to a precise floating point precision, which rounds calculated variables up or down rather than the default truncation associated with traditional single precision. This change lowered the numerical loss of mass to undetectable levels;
- Developing an output file to include algae process rates. PWD requested that the EFDC model produce output with additional variables to aid in validation. Tetra Tech developed an output file to include algae production, metabolism, and predation;
- Improving shading factors that impact light penetration. Tetra Tech ensured that shading factors are properly initialized in the model code;
- Adjusting benthic flux calculation algorithms. The Delaware River is characterized by negative benthic fluxes of dissolved oxygen and nutrients in some places. Tetra Tech took measures to ensure that negative flux values did not result in negative water quality constituent concentrations. These measures included:
    - Bypassing kinetic calculations for dry cells; and
    - Incorporating a capped Monod-type continuous transitional function to relate a negative flux to the bottom water concentration. This is a more realistic representation of actual flux than the previously applied specified constant flux;
- Ensuring that kinetics for inactive variables are bypassed. This measure improves model efficiency and prevents negative concentrations from developing;
- Increasing memory allocation for boundary condition time series. The Hydrodynamic and Water Quality Models employ high frequency data at the southern boundary and numerous tributaries and point source locations, which exceeded memory allocation in

the public release EFDC version. Tetra Tech increased memory allocation to accommodate long time series input data; and

- Increasing flexibility in spatially-varying water quality parameters. The Delaware River is characterized by heterogeneous benthic fluxes. To enable the DO Model to represent the complex nature of benthic processes in the River, Tetra Tech increased the number of zones defining benthic flux in the model domain.

Modifications related to model outputs include:

- Making adjustments to enhance results plotting in TECPLOT. Tetra Tech made several model modifications to improve the interface between EFDC and TECPLOT, a computational fluid dynamics environment for post-processing model results. These modifications enabled vertical contour plots, among other enhancements;
- Adjusting output file formatting. Tetra Tech ensured that output files generated by the water quality model included headers that indicated which constituents were included;
- Developing a wetting/drying log to track cells as they become wet or dry during a simulation; and
- Increasing memory allocation for water quality model output. To enhance water quality model validation, Tetra Tech increased the number of possible output locations in the water quality model.

These model modifications and enhancements greatly facilitated successful hydrodynamic and water quality validation. However, these modifications may prevent the reproduction of the results reported in this study using the public release EFDC model.

3.5 Water Quality Model Validation Period

The periods of April 1 to October 1 in both 2012 and 2013 were chosen for water quality model validation. April to October captures the main period of primary productivity observed in the model domain, as well as the summer season when lowest DO conditions are typically observed. The years 2012 and 2013 were selected because of the wide array of observed data sources available. Numerous hydrodynamic and water quality studies were undertaken in 2012 and 2013 by the Water Department to supplement the existing network of continuous and grab sample monitoring stations. These data sources are detailed in the next section. Contrasting precipitation patterns also characterized 2012 and 2013 (Figure 3-2), which further enhanced the selected validation period.

Hydroynamic Model performance during the 2012 and 2013 Water Quality Model validation periods are presented in Table 3- 3 and Table 3-4. In addition to April to October data, February and March data were also used where available, to correspond with the Water Quality Model spin-up period. All stations are well below the acceptable error for water level of ±15cm, and within the acceptable error for current of ±25 cm/s.

Table 3- 2: Hydrodynamic Model Performance during 2012 Water Quality Model Validation Period

Water level Station†	RMSE (m)	Skill Factor	M2 amplitude error (m)	M4 amplitude error (m)	M6 amplitude error (m)
Marcus Hook	0.038	0.999	0.004	0.009	0.000
Philadelphia	0.046	0.999	0.042	-0.006	-0.006
Burlington	0.081	0.997	0.056	0.026	0.001
Newbold	0.092	0.997	0.047	0.043	-0.023
Velocity Station	**RMSE (m/s)**	**Skill Factor**	**M2 amplitude error (m)**	**M4 amplitude error (m)**	**M6 amplitude error (m)**
Buoy C*	0.079	0.996	0.020	0.01	-0.005
Buoy B*	0.168	0.977	0.205	0.047	0.021
db0301**	0.119	0.989	-0.062	0.021	0.007

† Water level analysis period: February-October 2012; Velocity analysis period: * mid August-October 2012, ** June-October because of limited observed data availability

Table 3- 3: Hydrodynamic Model Performance during 2013 Water Quality Model Validation Period

Water level Station†	RMSE (m)	Skill Factor	M2 error (m)	M4 error (m)	M6 error (m)
Marcus Hook	0.036	0.999	0.005	0.011	-0.001
Philadelphia	0.039	0.999	0.042	-0.004	-0.005
Burlington	0.078	0.998	0.048	0.032	0.000
Newbold	0.094	0.997	0.035	0.050	-0.023
Velocity Station†	**RMSE (m/s)**	**Skill Factor**	**M2 error (m/s)**	**M4 error (m/s)**	**M6 error (m/s)**
Buoy C	0.074	0.997	0.028	0.011	-0.004
Buoy B	0.181	0.974	0.205	0.057	0.020
db0301	0.117	0.989	-0.077	0.028	-0.002

† Water level and velocity analysis period: February-October 2013

3.6 Monitoring Data

3.6.1 Atmospheric Data

Atmospheric data are essential inputs in EFDC for both hydrodynamic and water quality processes. Atmospheric data affect hydrodynamics with respect to advection and dispersion resulting from wind shear, and water temperature from solar radiation and air temperature. Water quality effects include dependency of the algal growth cycle on solar radiation and temperature, and resultant photosynthesis/respiration processes on dissolved oxygen.

EFDC implements a data assimilation algorithm to correct water temperature and adjust solar radiation. This solar radiation/water temperature loop then impacts most other water quality processes such as bacteria decay, nitrification, hydrolysis, mineralization, and algal dynamics which are each temperature-dependent.

NCDC

The primary source of meteorological data for atmospheric forcing was the NOAA National Climatic Data Center (NCDC). Parameters used as inputs included wind speed and direction, air temperature, dew point temperature, atmospheric pressure, sky cover, and precipitation (NCDC, 2014).

Sky cover codes were converted to numeric values and dew point temperatures were converted to relative humidity using appropriate algorithms. Wind data was converted from mi/hr to m/s. Details of these Hydrodynamic Model input parameters are discussed in sections 3.7.1 – 3.7.3.

Wind data was applied as one zone using Philadelphia International Airport data. All other meteorological parameters including precipitation were applied as one zone also using Philadelphia International Airport data. These data are complete for the simulation years of 2012 and 2013 and were provided as quality assured NCDC datasets.

A plot of monthly precipitation values for the validation years of 2012 and 2013 and the monthly means for the 1981 – 2010 period at Philadelphia International Airport appears below (Figure 3-2). Total annual precipitation for 2012, 2013 and the 1981 – 2010 period were 35.96 in, 55.82 in, and 41.53 in respectively. The total precipitation for the validation period of April 1 to October 1 for 2012, 2013 and the 1981 – 2010 period were 21.17 in, 37.62 in, and 22.33 in respectively. These values show that on average 2012 was dryer and 2013 was wetter than the 1981 – 2010 period.

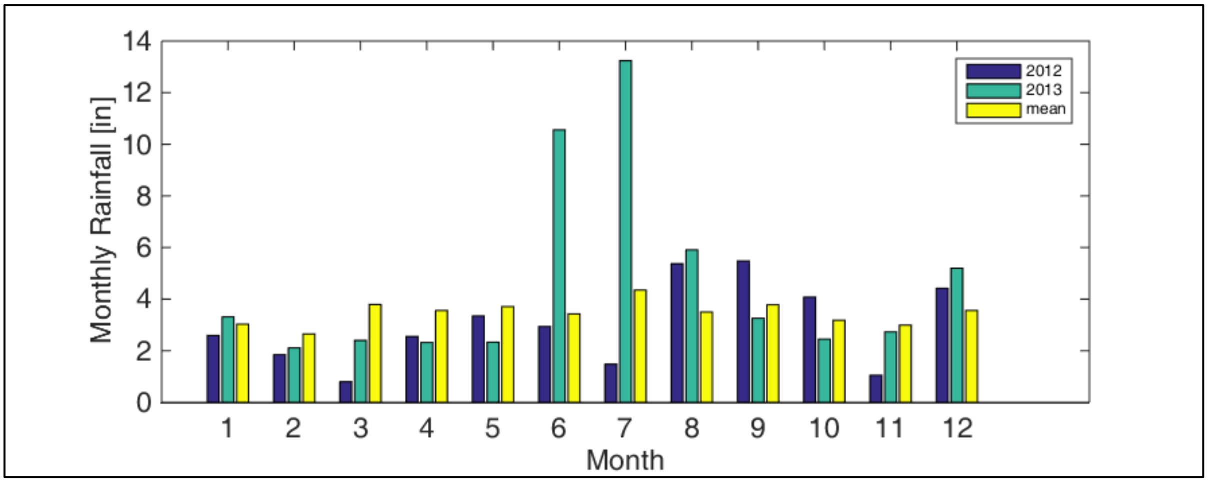


Figure 3-2: Mean monthly precipitation for 2012, 2013 and 1981-2010 period at Philadelphia International Airport (WBAN 13739)

3.6.2 Continuous Water Quality Data Sources

Several USGS gages in the model domain, and along tributaries that are boundaries to the model, are equipped to record continuous water quality data (*i.e.,* DO, temperature, pH, specific conductance, and turbidity), typically at a 30 minute frequency from March-November. USGS gages located on tributaries and near the open boundary were used to provide DO and temperature input time series to the model.

Three USGS gages with continuous water quality instruments are within the model domain on the mainstem Delaware River (Figure 2-4, Table 3-4). They are located at Pennypack Woods near the Water Department Baxter Water Treatment Plant (RM 110.11), Ben Franklin Bridge (RM 100.20), and at the Kimberly-Clark Paper Company, Chester PA, 0.5 mi downstream of the confluence with Chester Creek (RM 83.10). (For brevity, the Pennypack Woods gage is hereafter referred to as the Baxter gage). These gages were invaluable in model validation, and in comparing simulated to observed DO concentrations. Water quality instruments at the Ben Franklin Bridge and Chester gages are maintained exclusively by USGS, while the Baxter gage water quality instrumentation is maintained by the Water Department as part of a cooperative agreement with USGS. Water quality data quality assurance (QA) for all USGS gages in Philadelphia, including the City tributaries, is performed jointly by USGS and the Water Department, while the remainder have QA review solely by USGS. Any observations that did not pass QA were excluded from the model validation process.

The Water Department also deployed two continuous water quality instruments (sondes) in the tidal Schuylkill River, at River Miles 4.82 and 0.48 from the Schuylkill confluence with the Delaware River, and a third sonde in the tidal Frankford Creek, 0.18 river miles from its confluence with the Delaware River (Figure 2-4, Table 3-4). Similar to the USGS gages, the Water Department tidal sondes recorded DO, temperature, pH, specific conductance, and turbidity. Water quality data QA for the three tidal sondes was performed by the Water

Department. Any observations that did not pass QA were excluded from the DO Model validation process.

Table 3-4: Continuous Monitoring Stations Used for DO Model Validation

Station	4/1/2012-10/1/2012: number of accepted DO observations	4/1/2013-10/1/2013: number of accepted DO observations
USGS 01467200 (Ben Franklin Bridge)	8675	8708
USGS 01477050 (Chester)	8608	8496
USGS 014670261 (Pennypack Woods)	8705	8722
SC048 (PWD)	250	7481
SC482 (PWD)	8272	7481
TF018 (PWD)	7269	7383

3.6.3 In-Stream Water Quality Grab Sample Data

Long term datasets of grab samples for water quality parameters have been collected by the Water Department, regulatory agencies, and academic institutions with many sampling programs exceeding several decades in duration. While less frequent than continuous data, grab sample data can provide single point reference comparisons that are key to EFDC Water Quality model validation. They also serve as the basis for setting model parameterizations resulting from statistical model analysis. An example of this would be selecting a range of appropriate light extinction coefficients from linear regression analysis of TSS and Secchi depth data.

Parameters collected by these agencies include those that can be directly incorporated into the Water Quality model for reference or input and those that need either conversion from like species or conversion from different units. Analytical methods equivalency between agency parameters was determined using the USEPA document "Methods and Guidance for the Analysis of Water" (USEPA, 1997). In order to assemble these diverse sets of data, a database was prepared using the Water Resources Database (WRDB), one of the USEPA sponsored TMDL Modeling Toolbox packages (USEPA, 2005). This relational database front-end creates a uniform organization structure based on supplementary tables according to parameter, station, and quality code. WRDB also enforces a data validation scheme to ensure that QA evaluation is performed on all input parameters. Once the WRDB was populated with all agency data, a QA process was performed for each parameter using available quality codes from dataset metadata, outlier analysis and best scientific judgment to determine whether result values were ultimately transferred to the validated master table. Using this approach, it was ensured that each agency dataset underwent QA review.

Data assembled in WRDB begins with year 1990 to more closely represent the Delaware River following the establishment of secondary treatment among major municipal dischargers. A threshold of 10 miles from the confluence with the mainstem Delaware River was used to select appropriate stations in modeled tributaries. At present, WRDB has been updated through 2013. The Water Department intends to update the WRDB for 2014 and on an ongoing basis thereafter as staff and budget resources allow. The total number of records currently in WRDB is 175,370. The parameter list by agency is detailed below (Table 3-5).

Table 3-5: Distribution of Grab Sample Data by Agency

Parameter	DRBC	DNREC	NJDEP	POWR	PWD	Rutgers	U Delaware	USGS
Total Count	105,907	11,059	4,699	1,414	6,899	688	3,747	36,248
Ammonia-nitrogen as N	✓		✓			✓	✓	✓
Ammonia-nitrogen as N (Total)	✓	✓	✓		✓			✓
Biochem. Oxygen Demand 5 day	✓		✓		✓			✓
Carbon	✓							
Carbonaceous BOD20		✓			✓			✓
Carbonaceous BOD5		✓			✓			✓
Chlorophyll a	✓	✓	✓		✓		✓	✓
Depth, Secchi disk depth	✓	✓						
Dissolved Inorganic Carbon							✓	
Dissolved Kjeldahl Nitrogen			✓					✓
Dissolved organic carbon	✓	✓	✓		✓		✓	✓
Dissolved oxygen (DO)	✓	✓	✓	✓	✓	✓	✓	✓
Dissolved oxygen saturation	✓	✓	✓				✓	✓
E.coli/Enterolert					✓			
Enterococci/Enterolert					✓			
Enterococcus	✓	✓	✓		✓			✓
Escherichia coli	✓		✓		✓	✓		
Fecal Coliform	✓		✓		✓	✓		✓
Fecal Coliform-colilert					✓			
Nitrate and nitrite as N	✓							✓
Nitrate and nitrite as N (Total)	✓	✓	✓					✓
Light Attenuation							✓	
Nitrate as N	✓			✓	✓	✓	✓	✓
Nitrate as N (Total)	✓			✓				✓
Nitrite as N	✓		✓		✓	✓	✓	✓
Nitrite as N (Total)	✓		✓					✓
Nitrogen								✓
Nutrient Nitrogen as N (Particulate)	✓							
Nutrient-nitrogen as N	✓							
Nutrient-nitrogen as N (Total)	✓	✓						
Orthophosphate as P (total)	✓		✓	✓				
Orthophosphate as P	✓	✓	✓		✓	✓		✓
Particulate Carbon	✓						✓	
Particulate Nitrogen							✓	✓
Phosphate-phosphorus as P	✓						✓	✓
Phosphate-Phosphorus as P (Particulate)	✓							
Phosphate-phosphorus as P (Total)	✓	✓	✓					✓

Parameter	DRBC	DNREC	NJDEP	POWR	PWD	Rutgers	U Delaware	USGS
Seston							✓	
Total Chlorophyll	✓				✓			
Total dissolved Phosphorus					✓			
Total dissolved solids	✓		✓		✓			✓
Total Kjeldahl Nitrogen as N	✓	✓	✓		✓	✓		✓
Total organic carbon	✓	✓	✓		✓			✓
Total Phosphorus	✓		✓		✓	✓		✓
Total suspended solids	✓	✓	✓		✓	✓		✓

Water Department

Monitoring by the Water Department in support of the Water Quality Modeling program began in June of 2011 and concluded in October 2014. USEPA Region 3 supported this monitoring effort by providing the vessel and crew. Grab samples were collected in the center of the navigation channel on the ebb slack tide on a year-round, monthly basis at 7 locations (Figure 3-3). Parameter groups collected include nutrients, DO, as well as dissolved and total organic carbon; biochemical oxygen demand (BOD) and carbonaceous BOD; solids; enterococcus, E. coli, and fecal coliform bacteria; chlorophyll a and total chlorophyll, along with additional parameters not applicable to the Bacteria and DO Models. These monitoring locations extend from the Commodore Barry Bridge (RM 81.90) through the vicinity of the Baxter Water Treatment Plant intake (RM 110.11) with finer spacing of stations around the City of Philadelphia. Data were downloaded from the Water Department Laboratory Information Management System (LIMS).

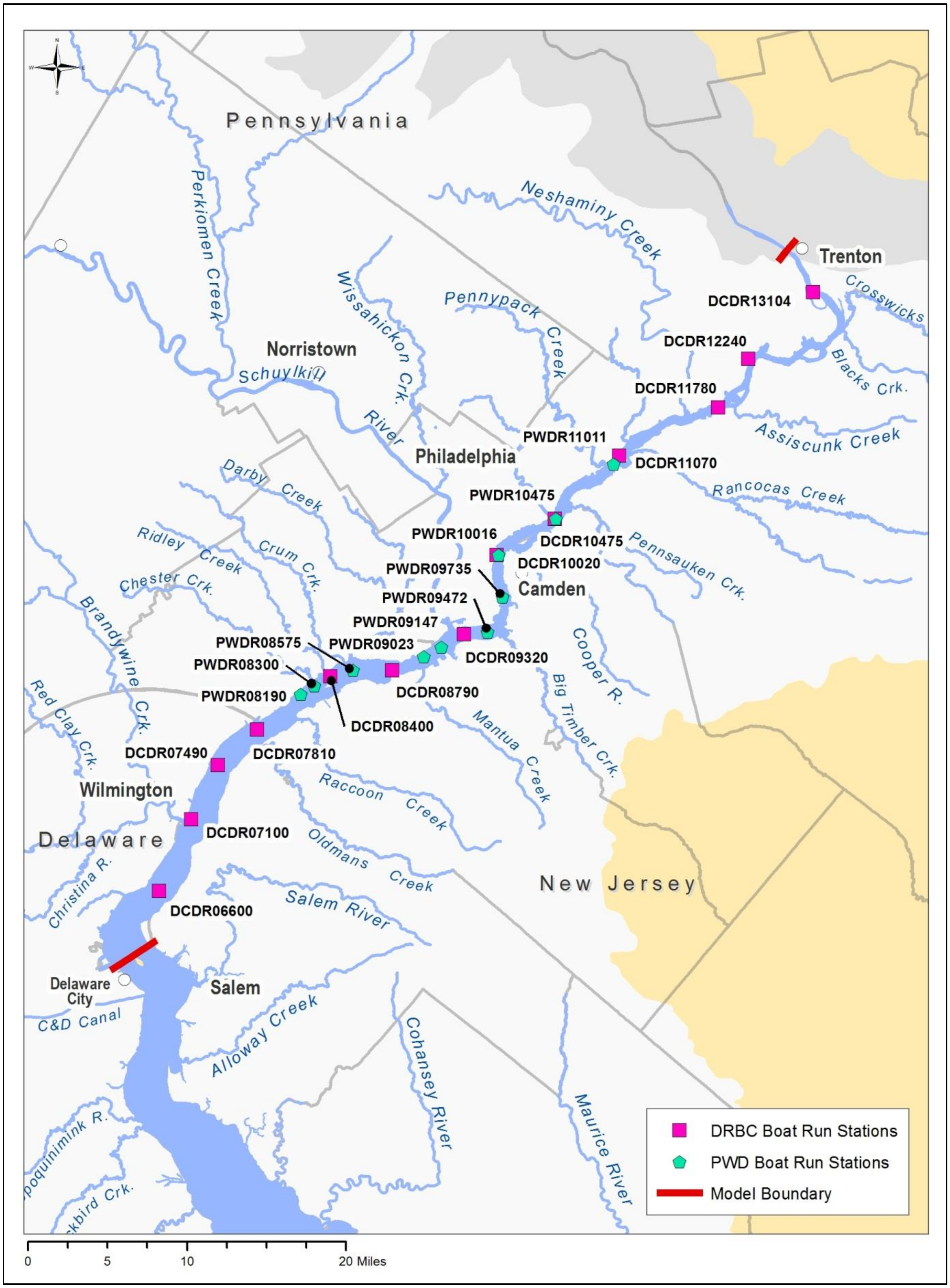


Figure 3- 3: DRBC and Water Department Boat Run Monitoring Stations.

Stations are identified by River Mile (*e.g.*, PWDR09023 is at RM 90.23)

DRBC

The DRBC Estuary Boat Run monitoring program began in 1962 and is presently conducted in agreement with Delaware Department of Natural Resources and Environmental Control (DNREC). At present, 8 grab samples are collected per year in the center of the navigation channel from April to October. Sampling is scheduled to target ebb slack and flood slack tides on alternating months. Water quality data for 13 of the 35 DRBC boat run sampling sites in the Water Quality model domain were included in WRDB (Figure 3-4). Parameter groups include nutrients, DO, as well as solids, enterococcus, fecal coliform, Secchi depth, and chlorophyll-a (Fikslin, 2011). These data were downloaded from USEPA STORET.

USGS

Water quality data from 45 USGS stations in the Delaware River and its tributaries were selected for inclusion in WRDB. The stations include those with continuous monitoring of temperature, pH, conductivity and DO, as well as sites that are monitored only as field samples collected monthly or less frequently. Data were downloaded using the USGS National Water Information System Water-Quality Web Services (USGS, 2012) along with the Water Quality Data Portal, a cooperative service sponsored by USGS, EPA, and the National Water Quality Monitoring Council (WQP, 2014). Parameter groups downloaded include nutrients, DO, as well as dissolved and total organic carbon, BOD and carbonaceous BOD, solids, enterococcus, E. coli, fecal coliform, and chlorophyll-a.

State Agencies

State agencies include DNREC and the New Jersey Department of Environmental Protection (NJDEP). DNREC collected DO, dissolved and total organic carbon, carbonaceous BOD, salinity, solids, enterococcus, and chlorophyll-a in the Brandywine Creek and Christina River. NJDEP collected nutrients, DO, dissolved and total organic carbon; BOD; solids; enterococcus, E. coli, and fecal coliform bacteria; and chlorophyll-a in 12 tributaries including the Cooper River and the Big Timber, Mantua, Newton, and Pennsauken Creeks.

Also included in this category are two auxiliary organizations that collected grab samples within the model domain. The Pennsylvania Organization of Watersheds and Rivers (POWR) collected nutrient and DO data in the Darby and Poquessing Creeks and the Schuylkill River (KWMN, 2014) and the Rutgers Cooperative Extension Water Resource Program (WRP, 2015) collected nutrient, DO and bacteria data in the Salem River. Data from the above agencies were downloaded from USEPA STORET.

University of Delaware

The research cruises of Jonathan Sharp of the University of Delaware have produced a valuable dataset starting in 1978 from the head of tide in Trenton to the mouth of Delaware Bay using mostly the same stations as DRBC (Sharp *et al.*, 2009). While less frequent than the DRBC Estuary Boat Run program, Sharp's database provides a comparable dataset of ambient concentrations with consistent sampling and analytical methods over the three decade history of this program. Data from the 16 main Sharp stations within our model domain were included in WRDB from 1990 to the project's termination in 2003. Parameter groups included in the

University of Delaware data set nutrients and DO as well as dissolved and total organic carbon, Secchi depth, solids, and chlorophyll.

3.6.4 Process Data

Nitrification Rate

Nitrification rates in the Delaware and Schuylkill Rivers were measured by the University of Maryland Center for Environmental Science Horn Point Laboratory using the stable isotope method described in Santoro *et al.* (2010). The method consists of adding the isotope tracer $^{15}NH_4^+$ to the water column sample, and then measuring the change in $^{15}NO_2^-$ and $^{15}NO_3^-$ concentrations to quantify a nitrification rate.

Eleven Delaware River Estuary sites and one Schuylkill River site were sampled on August 19 and 20, 2013 (Figure 3-4). The summer season was chosen because the high water temperature facilitates high nitrification rates and low DO concentrations characteristic of the critical period. During sample collection, the mean water temperature measured at the Ben Franklin Bridge (USGS Gage 01467200) was 24.1°C. River flow at Trenton (USGS gage 01463500) averaged 178.7 cms, and the 7 day average flow at USGS gage 01463500 prior to sampling was 298.3 cms. This flow was somewhat greater than the historic August mean Q of 177.8 cms based on the 1913-2013 period of record. Due to logistical constraints, sample collection was not scheduled to follow a particular portion of the tidal cycle.

At each site, three 250 mL samples were collected, one of which was a control bottle with no stable isotope. Reported nitrification rates were the average of duplicate rate determinations at each site. Nitrification was not detected in any control bottles. Results were reported in units of Molarity/hour, and then converted by the Water Department to a first order rate constant (in units of per day) through division by the corresponding water column sample NH_4^+ concentration. First order rate constants were then normalized to 20°C via an Arrhenius calculation for Water Quality model input (Table 3-6).

The nitrification rates measured in August 2013 showed a similar spatial pattern to August 1983 results reported by Lipshultz (1986), with lower rates at the upper and lower bounds of the study area, and elevated rates in the lower Philadelphia to Chester area (approximately River Miles 100 to 85). The reach of elevated rates does appear to have narrowed in August 2013 to a 12 mile span, compared to 26 miles in August 1983. The location of the peak rate was observed further upstream in 2013. A decrease was seen in the immediate vicinity of the Schuylkill River in both studies, suggesting some degree of dilution effect from the Schuylkill River. Overall, the magnitudes of the nitrification rates are smaller in August 2013 compared to August 1983. The peak rate in August 2013 was 142 nM/hr at River Mile 94.72, and was 275 nM/hr at RM 85.65 in August 1983. It should be noted that the August 1983 study did not sample the Schuylkill River, whereas one Schuylkill River site 0.47 miles from its confluence with the Delaware River was sampled in August 2013. NH_4^+ concentrations on August 19-20, 2013 ranged from 0.0042 to 0.084 mg-N/L at the twelve sites.

Given the spatial variability of the August 2013 results, the model domain was divided into five river mile-based zones for setting zone-specific constant nitrification rates in the DO Model. The zone locations and DO Model nitrification rates (at 20°C) range from 0.01 per day near Trenton to 1.9 per day from the Schuylkill River confluence to the lower boundary. The DO Model nitrification rates in the two most urban zones are high (*i.e.*, 0.7 and 1.9 per day, respectively) but not outside the range cited in Bowie *et al.* (1985). The high nitrification rates observed in the Philadelphia to Chester area (Table 3-6) also explain the low ammonium concentrations typically observed in that segment of the river during summer despite relatively high ammonium loadings from point source discharges.

Table 3-6: Observed Nitrification Rates (August 2013)

Station	Delaware River mile	Mean nitrification rate (µM/day)	NH4 conc (mg-N/L)	Nitrification rate (kn [per day])	Nitrification rate at 20°C (kn [per day])
DR6221	62.21	0.69	0.0042	2.42	1.78
DR8300	83.00	1.94	0.0084	2.71	1.99
DR9023	90.23	3.26	0.0224	2.28	1.68
DR9147	91.47	2.13	0.0140	2.99	2.20
SC047	92.50	1.54	0.0840	0.27	0.20
DR9472	94.72	3.41	0.0490	0.95	0.70
DR9735	97.35	1.95	0.0294	0.91	0.67
DR10016	100.16	0.81	0.0140	1.14	0.83
DR10307	103.07	0.52	0.0126	0.73	0.54
DR10475	104.75	0.28	0.0126	0.39	0.29
DR11011	110.11	0.62	0.0224	0.43	0.32
DR13013	130.13	0.04	0.0588	0.01	0.01

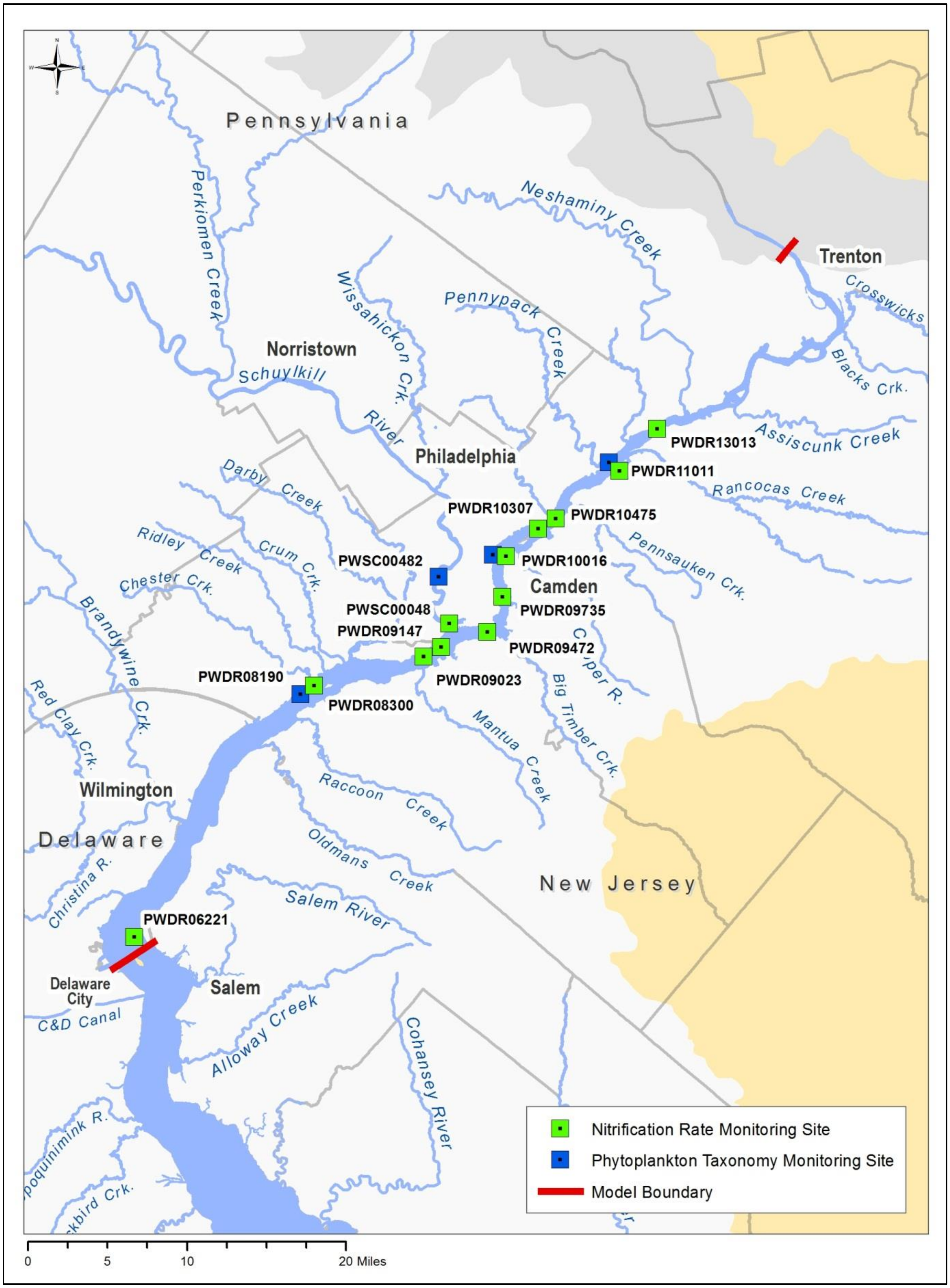


Figure 3-4: Monitoring Sites for Nitrification Rate, CBOD$_{ultimate}$, and Phytoplankton Taxonomy and CNP Sampling

CBOD Decay Rate

120 day CBOD (or $CBOD_{120}$) concentrations were measured by the Academy of Natural Sciences of Drexel University (ANSDU) at each of the twelve nitrification rate sampling sites, plus two replicate samples, in the August 2013 study. As part of their analysis, $CBOD_5$ and $CBOD_{20}$ concentrations of each sample were also measured. Under the assumption that $CBOD_{120}$ approximated $CBOD_{ultimate}$, CBOD decay rate was calculated from paired sample $CBOD_5$ and $CBOD_{120}$ concentrations for each site using the following equation:

$$BOD_u = \frac{BOD_t}{(1-e^{-kt})} \qquad \text{Eq. 3-1}$$

$CBOD_{120}$ concentrations on August 19-20, 2013 ranged from 1.83 to 4.78 mg/L at the twelve study sites. The resulting CBOD decay rates, or k values, decay rates ranged from 0.029 to 0.068 per day (Table 3-7). In the Philadelphia area, from River Miles 110.11 to 90.23, the decay rates had a narrower range from 0.041 to 0.050 per day, excluding a 0.062 rate in the lone Schuylkill River site. Since the CBOD decay rates displayed less spatial variance than the nitrification rates, and in order to reduce model complexity, a global CBOD decay rate value of 0.045 per day was used for the DO Model KDC rate (*i.e.*, minimum dissolution rate of DOC).

Table 3-7: Observed CBOD Concentrations and Decay Rates (August 2013)

Station	Delaware River mile	CBOD5 (mg/L)	CBOD120 (mg/L)	kd (per day)
DR6221	62.21	0.38	2.81	0.029
DR8300	83.00	0.81	3.48	0.053
DR9023	90.23	0.6	2.76	0.049
DR9147-A	91.47	0.53	2.83	0.042
DR9147-B	91.47	0.63	2.97	0.048
SC047	92.50	0.88	3.29	0.062
DR9472	94.72	0.7	3.15	0.050
DR9735	97.35	0.85	4.17	0.046
DR10016	100.16	0.99	4.77	0.047
DR10307	103.07	0.95	4.75	0.045
DR10475	104.75	1	4.78	0.047
DR11011	110.11	0.83	4.33	0.043
DR13013-A	130.13	0.48	1.83	0.061
DR13013-B	130.13	0.75	2.59	0.068

Sediment Oxygen Demand

The basis for developing a SOD input field for the validation phase of DO Model development relied upon an understanding that, among other factors, the SOD flux term is a representation of the net respiration by benthic biotic communities, chemosynthetic oxygen uptake, and chemical oxidation. Contributing sources of organic matter to the sediment typically are considered to derive from loadings of allochthonous material to the estuary, and from the settling of in-situ produced autochthonous material. The SOD is regarded as a function of the accumulation of the organic material accumulating from these sources, as mediated by the nature of the benthic environment. Based on this hypothesis, the project team consisting of the Water Department, Woods Hole Group, The Academy of Natural Sciences of Drexel University, and the Chesapeake Biogeochemical Associates, designed a field data collection program to measure SOD throughout the water quality model domain.

Initially, since direct measurements of SOD are complex and costly to perform over a large spatial area, the project team decided to sample for specific surface sediment parameters that possibly could be used to correlate with SOD. The concept was that, as a more cost effective approach, these parameters could be used to infer SOD, allowing the collection and processing of fewer SOD samples, and enabling the less costly collection and analysis of many more of these surface sediment, or SOD-surrogate parameters. The use of the surrogate parameters would allow the modelers to confidently extend SOD estimates to more areas of the model domain without having the expense of making direct measurements. Furthermore, in the Delaware Estuary there is a wealth of existing surface sediment data that are available for incorporation in derivations of model input parameters, potentially increasing their spatial data density for little to no additional cost. The surrogate parameters chosen for collection and analysis included sediment chlorophyll a, organic carbon, total nitrogen, total phosphorus, grain size (%< 63µm), total organic matter (loss on ignition), and percent water/solids.

A field data collection program, based on the approach of using surrogate parameters with SOD measurements, was developed by the project team and included five field surveys: Cruise No. 1) summer 2012 surrogate sample collection; Cruise No. 2) summer 2012 SOD and nutrient flux measurements; Cruise No. 3) fall 2012 SOD measurements; Cruise No. 4) spring 2013 SOD and nutrient flux measurements; and, Cruise No. 5) summer 2013 SOD and nutrient flux measurements (Figure 3-5). Seasonal SOD surveys were scheduled based on a season's representative water temperature, which indirectly drives biological productivity, and thus SOD. Following the analysis and review of data from the first three surveys, the project team determined that the surrogate approach was not providing a robust correlation with SOD. Analysis also revealed that, although SOD measurements were of high quality, rates were unexpectedly low compared to the dissolved oxygen inventory of the estuary's waters, and the spatial variance was more limited (smaller) than was originally expected. This finding led the project team to consider the water column as a larger contributor to oxygen consumption, and required further investigation. At this point, the project team decided to change the field data collection approach, electing to forgo a correlation between the surrogates and SOD, and instead focus on the collection of more SOD samples. Additionally, water column profiles of biogeochemically sensitive parameters were collected, and all SOD samples included nutrient flux measurements. The spring 2013 and summer 2013 SOD surveys were performed using this refocused approach.

The SOD determinations were performed using gas analyses via membrane inlet mass spectrometry. Measurement included N_2:Ar and O_2:Ar ratios; these ratios were converted to gas concentrations using the saturation value of Ar for the temperature of incubation. The membrane inlet mass spectrometer is used for analysis of the elemental composition of gas samples obtained from the continuous flow for nutrient and gas fluxes (see below). The mass spectrometer was fitted with a high pressure centrifugal pump that drew gas out of a water sample flowing through a gas-permeable tube.

The field efforts yielded 127 station-estimates of SOD rates, from samples collected during the one spring and two summer cruises. For the purposes of model input, SOD flux rate estimates were not corrected to a standard temperature using van't Hoff form of the Arrenius relationship because the initial model validation simulations were performed for spring and summer periods, and the model methodology applies SOD fluxes at simulated ambient temperatures (*i.e.*, uncorrected for temperature).

The mean of all SOD determinations used for DO Model input is 1.00 g O_2 m^{-2} day^{-1} (2,2625 µg-at O m^{-2} h^{-1}), with a standard deviation of 0.61 g O_2 m^{-2} day^{-1} (1,600 µg-at O m^{-2} h^{-1}). However for input to the DO Model, the SOD estimates were stratified into 8 segments along the main stem of the tidal Delaware River, as listed in Table 3-8.

Table 3-8: Sediment Oxygen Demand Rates (Measured and Modeled)

Segment Number	Delaware River Mile range	Number of samples	Measured Values (Average ± Standard Deviation) (g m^{-2} d^{-1})	Measured Values (Average ± Standard Deviation) (µg-at O m^{-2} h^{-1})	Validated DO Model rates (g m^{-2} d^{-1})
1	Upstream 117	13	1.50 ± 1.09	3916 ± 2827	1.50
2	104.75 – 117	18	0.88 ± 0.38	2293 ± 990	0.88
3	100.1 – 104.75	15	1.33 ± 0.53	3474 ± 1383	1.60
4	92.5 – 100.1	19	0.93 ± 0.50	2418 ± 1311	1.43
6	85.5 – 92.5	15	0.91 ± 0.43	2380 ± 1129	1.35
8	79 – 85.5	11	0.75 ± 0.18	1960 ± 481	0.94
9	68.8 – 79	14	0.70 ± 0.37	1821 ± 966	0.70
10	60 – 68.8	12	0.57 ± 0.34	1484 ± 888	0.57
5	Schuylkill River	7	1.79 ± 0.57	4665 ± 1495	1.79
7	Darby Creek	3	1.27 ± 0.34	3299 ± 897	1.27

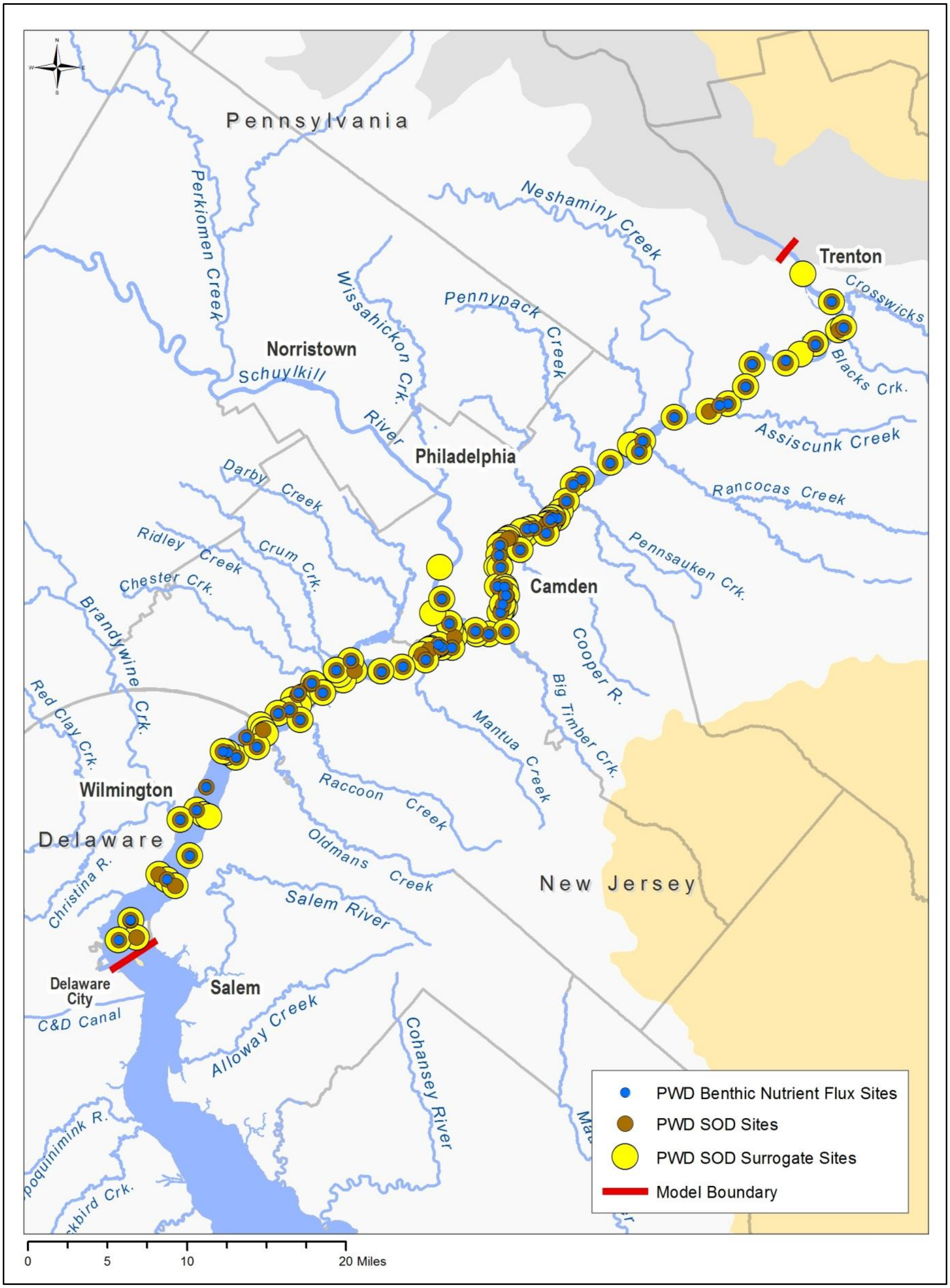


Figure 3-5: Sediment Monitoring Sites

Benthic Nutrient Fluxes

The DO Model requires estimates for zero-order rate benthic nutrient fluxes as a proxy for sediment diagenesis processes. Benthic nutrient fluxes affect water column nutrient concentrations, and thereby can influence oxygen concentrations and algal uptake in the water column. Benthic nutrient fluxes were measured alongside SOD on three field surveys to provide spatial and temporal empirical benthic flux values for the modeled water column: Cruise No. 2, summer 2012, 12 sites; Cruise No. 4, spring 2013, 36 sites; and Cruise No. 5, summer 2013, 36 sites. Benthic nutrient flux measurements included ammonium (NH_4), nitrate plus nitrite (NO_x), nitrogen (N_2-N), and soluble reactive phosphorus (SRP).

Nutrient flux measurements followed protocols used at the University of Maryland Center for Environmental Science (*e.g.,* Kana *et al.*, 2006; Cornwell and Owens, 2011; Gao *et al.*, 2012). Briefly, sediment cores collected from the field were incubated with a heating/refrigerating circulator to maintain ambient water temperatures. Cores were pre-incubated overnight with an air lift pump to prevent anoxia and to recirculate the water overlying the sediment core. Incubations initiated the day after core collection. Control chambers without sediment were used to account for water-column-only effects.

Benthic nutrient fluxes were calculated from the slope of the change of chemical constituent concentrations in the overlying water. Water above each core was sampled three times at ~1.5 hr intervals after an initial sampling for flux calculations. Water samples were filtered through a 0.4 µm pore size 25 mm syringe filter and analyzed for dissolved nutrient parameters (NH_4, NO_x, SRP) as per USEPA (1983) ANSP Standard Operating Procedures on a SmartChem 200 Discrete Analyzer (Alpkem 300). As with SOD, N_2 flux was determined by gas analyses via membrane inlet mass spectrometry. Ratios of N_2:Ar and O_2:Ar were converted to gas concentrations using the saturation value of Ar for the temperature of sediment core incubation.

For all three cruises for which nutrient fluxes were assessed, the flux of N_2 was positive, or out of the sediments, and ranged from 1.60 to 186.60 mg N m^{-2} d^{-1} (n = 84; mean 57.98 ± 27.03 mg N m^{-2} d^{-1}). The August 2012 samples had higher N_2 fluxes than the May or August 2013 samples (72.87± 27.26 mg N m^{-2} d^{-1} compared to 59.32 ± 31.90 mg N m^{-2} d^{-1} and 51.68 ± 19.05 mg N m^{-2} d^{-1}, respectively). The Schuylkill River had on average higher N_2 flux than the Delaware River, but was also more variable (101.08 ± 61.17 mg N m^{-2} d^{-1} and 55.82 ± 22.96 mg N m^{-2} d^{-1}, respectively).

All other nitrogen fluxes had larger variation than N_2, with fluxes both into and out of the sediments. NO_x was mostly negative (n = 78; -27.70 ± 65.94 mg N m^{-2} d^{-1}), however, NO_x was generally positive upstream of RM 103.1 in August 2013 and downstream of RM 94.1 in May 2013. Only one core had positive NO_x flux in August 2012, which also happened to be the largest efflux of NO_x observed (119.78 mg N m^{-2} d^{-1}).

NH_4^+ was positive on average (n = 83; 23.67 ± 78.43 mg N m^{-2} d^{-1}), with an outlier from May 2013 which had 418 mg N m^{-2} d^{-1}. While positive fluxes and large variation were measured in the Schuylkill River and upstream of the Schuylkill confluence in the Delaware River (> RM 92.5;

45.74 ± 97.74 mg N m^{-2} d^{-1}), downstream of the Schuylkill River (< RM 92.5), NH4+ fluxes were lower and had less variation (-3.76 ± 25.91 mg N m^{-2} d^{-1}).

SRP was generally positive (n = 84; 2.04 ± 7.77 mg P m^{-2} d^{-1}), although several cores sampled between RM 92-106 had negative fluxes in August 2012, and fluxes were generally negative upstream of RM 110 in August 2013. One core had a large influx of SRP in August 2012, -43.21 mg P m^{-2} d^{-1}. Somewhat elevated SRP efflux was measured between RM 92 – 104.75 and within the Schuylkill River compared to the rest of the Delaware River (3.96 ± 7.81 mg P m^{-2} d^{-1} and 1.13 ± 7.65 mg P m^{-2} d^{-1}, respectively), but the difference was not significant.

N_2 gas emission from sediment cores and water samples is a commonly used assay for denitrification. As N_2 fluxes were always positive, denitrification is likely an important biogeochemical process in sediments throughout the model domain. Denitrification rates are driven by the supply of nitrate from the overlying water column and nitrification-denitrification coupling within the sediments. NO_x was generally inversely related to N_2, further supporting the predominance of denitrification in sediments. Since denitrification, as measured by N_2 fluxes, was generally greater than or equal to NH_4^+ fluxes (n = 83; 23.67 ± 78.43 mg N m^{-2} d^{-1}), denitrification in the sediments is an important sink for nitrogen in the Delaware River. Denitrification rates measured for this study were quite high for estuarine sediments (*e.g.,* Joye and Anderson 2008), likely a result of elevated NO_x concentrations in the overlying water.

In some cases, nitrification seemed to dominate sediments, or at least coupling of denitrification and nitrification occurred. For example, during the May 2013 cruise, positive NO_x flux observed in samples collected around Delaware RM 83 was associated with low N_2 flux, negative NH_3 flux, and moderate SOD (~1 g m^{-2} d^{-1}). A similar pattern was measured between RM 110-117 in August 2013. Overall, the spring 2013 cruise had larger variability than the summer cruises for all nitrogen fluxes.

Benthic nutrient fluxes measured in the model domain can be roughly compared to other measurements of low salinity estuarine sediment fluxes. Relatively few studies have been conducted with comparable methodologies in low salinity estuarine waters, but the Delaware River measurements can be compared to sites in the Potomac River (*e.g.,* Cornwell *et al.*, *in prep*), the upper Chesapeake Estuary (Susquehanna River; *e.g.,* Cowan and Boynton, 1996; Testa *et al.*, 2013; Francis *et al.*, 2013), and the Elbe River Estuary (Germany; *e.g.,* Deek *et al.*, 2013). All of these sites have seasonally elevated or generally high NO_3 in the water column.

Since sediment biogeochemical processes often have strong seasonality, data sets were compared as a function of time (Figure 3-6). Warm-season denitrification rates, as indicated by N_2 fluxes, were similar in the upper Chesapeake, Potomac, Elbe, and Delaware Rivers. The Delaware denitrification rates were highest on average, but had large variability. Nitrate fluxes were generally negative in the Delaware, the Potomac River, and in the upper Chesapeake (Cowan and Boynton, 1996), but the Delaware River measurements had the greatest variability. Interestingly, Elbe river nitrate fluxes were very negative. Delaware River NH_4 fluxes were very similar to measurements in the upper Chesapeake and Potomac Rivers in spring, but the Potomac had substantially higher ammonium fluxes in summer months. Delaware River SRP fluxes were compared to Boynton's Still Pond data from the upper Chesapeake Estuary (Cowan and Boynton, 1996). The mean exchange of SRP was indistinguishable from zero for most sites, including the Delaware River. Average values masked considerable spatial variability in fluxes; high mid-estuary effluxes suggest release from redox-related processes or perhaps changing character of P binding. Bottom water SRP concentrations do not suggest, however, important sediment sources of P to the water column, though water column mixing and P assimilation may mask sediment inputs.

It is remarkable that nutrient flux measurements are comparable between locations since the source of sediment organic matter fueling sediment metabolism is mixed and variable. However, high turbidity at all of the tidal freshwater sites likely limits algal primary production, suggesting metabolism is primarily fueled by fluvial/terrestrial and urban runoff/wastewater organic matter.

For input to the DO Model, as with the SOD estimates, benthic nutrient fluxes were stratified into 8 segments along the main stem of the tidal Delaware River and estimates for the Schuylkill River and Darby Creek. Averages and flux standard deviations per segment were determined for observations from all three cruises. Through DO Model validation, average values were adjusted by one standard deviation, with PO_4 and NO_3 fluxes decreased and NH_4 fluxes increased. In some cases, the adjustment by one standard deviation resulted in a value outside of the range of observations in that segment, in which case the value was adjusted by one-half of a standard deviation (Table 3-9).

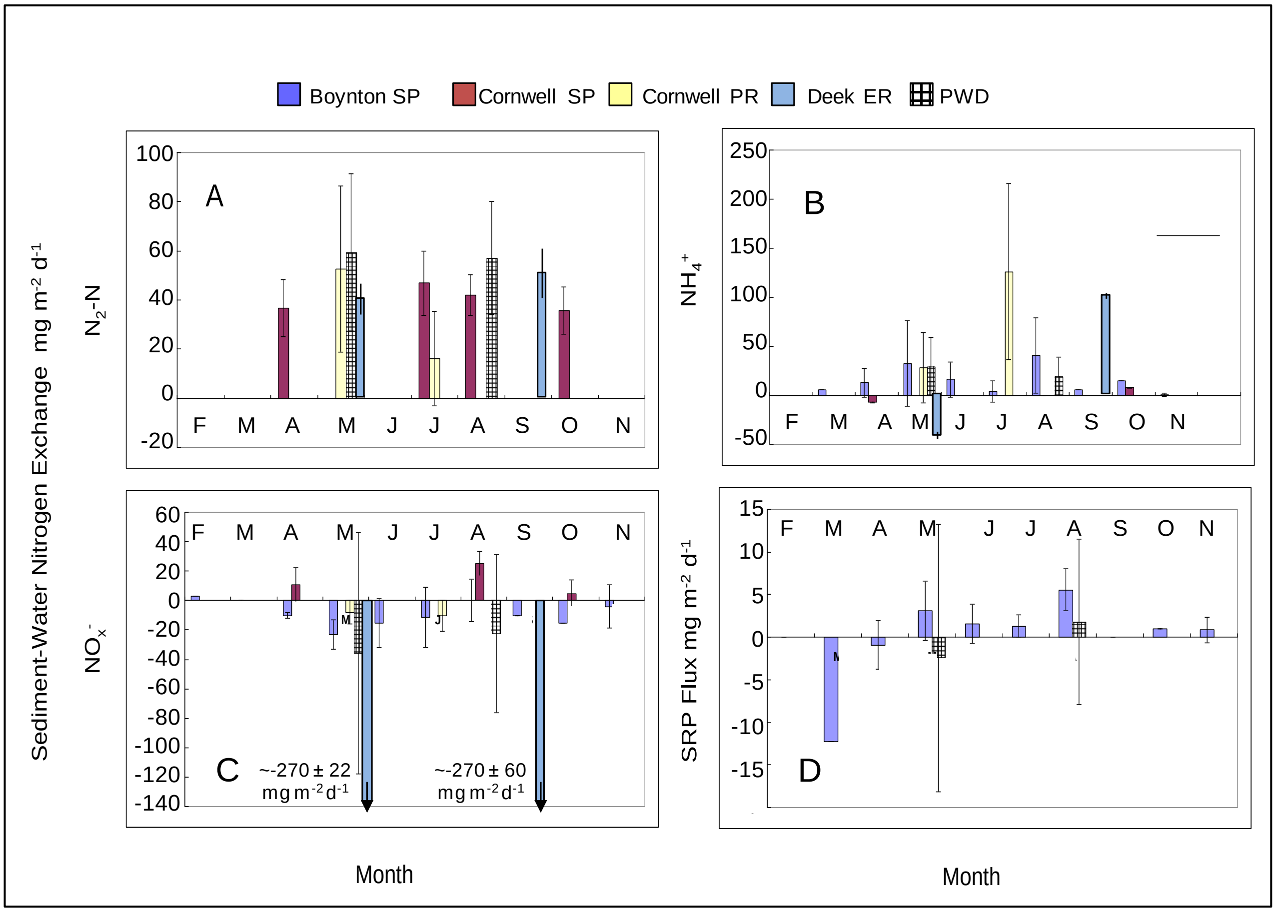


Figure 3-6. Average (± S.D.) rates of A) N_2-N (di-nitrogen); B) NH_4^+; C) NO_x (nitrate + nitrite); and D) SRP flux in the Delaware (PWD; checkered) and representative tidal freshwater/oligohaline sediments.

Cornwell SP (magenta) and Boynton SP (purple) are upper Chesapeake Bay data sets from a low salinity site (Still Pond; Cowan and Boynton 1996; Testa *et al.*, 2013; Francis *et al.*, 2013) and the Potomac River data (Cornwell PR; white) are unpublished (Cornwell *et al.*, in preparation). Deek ER (blue) is from the Elbe River Station "ML" which had salinity <0.5 and was sampled in March and September 2009 (Deek *et al.*, 2013). Sediment-water SRP exchange (mean ± S.D.) is in the upper Chesapeake Bay (Cowan and Boynton 1996) and in the Delaware River (PWD).

Table 3-9: Benthic Nutrient Flux Rates (Measured and Modeled)

		Measured Values (Average ± Standard Deviation) ($g\ m^{-2}\ d^{-1}$)			Validated DO Model rates ($g\ m^{-2}\ d^{-1}$)		
Segment Number	Delaware River Mile range	SRP (n = 84)	NH4 (n = 83)	NOx (n = 78)	PO4 (-1σ)	NH4 (+1σ)	NOx (-1σ)
1	Upstream 117	-0.00185 ± 0.003313	0.064786 ± 0.110686	-0.03989 ± 0.057325	-0.005159648	0.17547217	-0.097216591
2	104.75 – 117	-0.00233 ± 0.012412	0.018373 ± 0.046462	-0.00731 ± 0.05333	-0.014737845	0.064834895	-0.060644034
3	100.1 – 104.75	0.004612 ± 0.007098	0.095716 ± 0.140545	-0.05451 ± 0.08828	-0.002485854	0.236260496	-0.14278721
4	92.5 – 100.1	0.005153 ± 0.007754	0.002365 ± 0.055651	-0.0396 ± 0.05037	-0.002600429	0.058016342	-0.08997242
6	85.5 – 92.5	0.00355 ± 0.006398	-0.00684 ± 0.02962	-0.01544 ± 0.071038	-0.002848294	0.022780821	-0.086481463
8	79 – 85.5	0.003231 ± 0.003671	-0.00506 ± 0.027549	-0.0146 ± 0.09184	-0.0004406	0.022487068	-0.106435263
9	68.8 – 79	0.001658 ± 0.005504	-0.00482 ± 0.01295	-0.02375 ± 0.052223	-0.003845642	0.008128008	-0.075970599
10	60 – 68.8	0.001879 ± 0.006691	0.007435 ± 0.02842	-0.00376 ± 0.052539	-0.004812234	0.035854801	-0.03002754*
5	Schuylkill River	0.004447 ± 0.008095	0.149243 ± 0.13242	-0.10963 ± 0.083992	-0.003648584	0.281662442	-0.151625631*
7	Darby Creek	0.0019 ± 0.002687	-0.0233 ± 0.05176	0.0378 ± 0	0.000556497*	0.002580108*	0.0378

* Indicates the modeled rate was outside the range of observed values (*e.g.*, minimum value is greater than the average value minus one sigma) and so the mean was adjusted by one-half the standard deviation.

Phytoplankton Taxonomy and CNP Analyses

A sampling program was initiated in 2012 with the Academy of Natural Sciences of Drexel University (ANS-DU) to analyze the taxonomy and carbon, nitrogen, phosphorus content of phytoplankton samples. Three of the PWD boat run stations on the Delaware River at River Miles 81.90, 100.16, and 110.11 (*i.e.*, Commodore Barry Bridge, Ben Franklin Bridge and Baxter WTP, respectively) were sampled from 2012-2014, and one Schuylkill River site (Schuylkill RM 4.70 by Bartrams Garden) was sampled in 2013-2014 (Figure 3-7). Chl-*a* and total chlorophyll concentrations of the samples were analyzed by the Water Department Bureau of Laboratory Services (BLS).

Taxonomic analyses have been completed for samples collected in March 2012 – June 2013 (n=115). Samples collected in July 2013 –June 2014 have not yet completed taxonomic analysis (n=29). Samples were typically collected monthly at the four sites, with gaps in the summer of 2012 and winter of 2012-2013. The method applied by the Phycology Section of the Patrick

Center for Environmental Research at ANS-DU to analyze algae samples was the same as in their work with the USGS National Water Quality Assessment (NAWQA) program to evaluate water quality using data on algae samples collected from rivers nationwide.

Cell density [cells/mL] of each algal taxon per sample was reported by ANS-DU. The Water Department grouped taxa into the classes Chlorophyceae (green algae), Bacillariophyceae (diatoms) and Myxophyceae (cyanobacteria or blue-green algae). The proportional abundance of each algal class was calculated for each sample. Results indicated that diatoms were the dominant class at all sites, in all samples. Chlorophytes exhibited greater prevalence in spring, while cyanobacteria (blue-green algae) were somewhat more prevalent at downstream stations compared to upstream stations (Figure 3-7). These findings are broadly consistent with previous studies of the tidal freshwater Delaware River, as summarized in Sections 3.2.2 and 3.2.4. Considering that diatoms prefer nitrate to ammonium (Paerl, 2008), and that NO_3 dominates the DIN pool in summer along the urban tidal freshwater river (Sharp, 2010), it is not surprising that diatoms are dominant in this system. Chlorophytes prefer higher levels of NH_4; this condition tends to occur in the tidal freshwater Delaware River in spring, when nitrification has not yet reached summer levels, and may explain the greater prevalence of chlorophytes in spring.

The taxonomic analysis aided selection of kinetic rate constants for the simplified single algal class water quality model. Values that approximated published diatom rate constants were chosen, but such that they were also within the range of published chlorophyte and cyanobacteria rate constants.

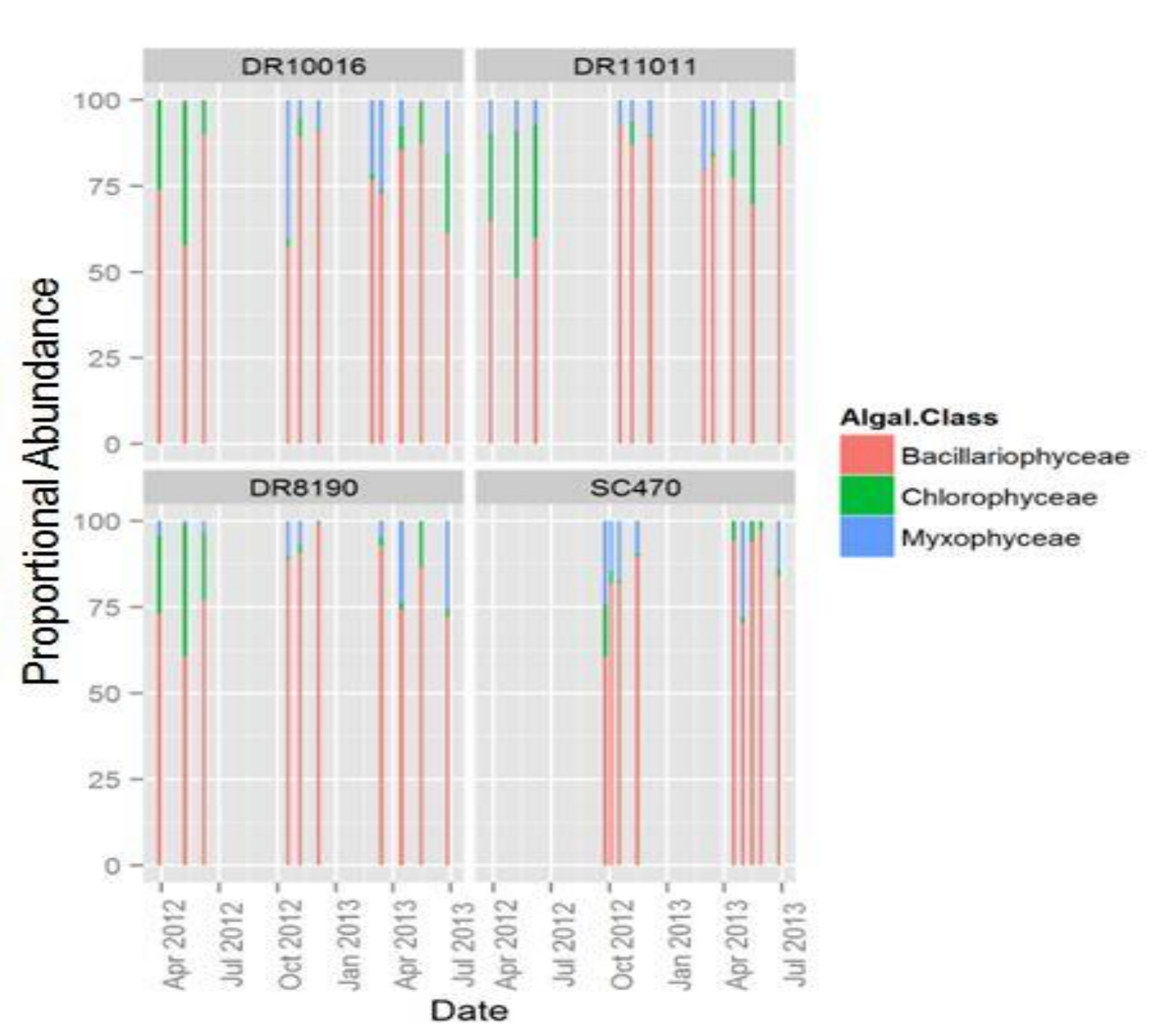


Figure 3-7: Proportional Abundance of Diatoms (Red), Chlorophytes (Green), and Cyanobacteria (Blue) at Delaware RM110.11, RM100.16, RM81.90, and Schuylkill RM4.70 (Counterclockwise from Top Right)

The Patrick Center of ANS-DU analyzed seston samples for total carbon, total nitrogen, and total phosphorus to determine %C, %N, %P (CNP) in each phytoplankton sample. 57 samples were collected across four sites (Figure 3-4) from September 2012 – June 2014 in conjunction with sample collection for taxonomic analyses. ANS-DU reported concentrations for C, N, and P in each sample. The Water Department calculated mass ratios of C:N, C:P, and C:chl-a for each sample (Table 3-9).

The Redfield ratio is a measure of the relative proportions of carbon, nitrogen, and phosphorus based on research of oceanic phytoplankton described in (Redfield, 1934). The Redfield ratio is 400 mgC: 72 mgN: 10 mgP. In general, the carbon to chlorophyll ratio ranges from 20 to 100 mgC/mg chl-a (Chapra, 1997). The average stoichiometric ratio measured in all mainstem

Delaware River samples was 400 mgC: 53.2 mgN: 21.3 mgP: 1.6 mg chl-*a*. When limited to March-September growing season samples, the ratio measured in mainstem Delaware River samples was 400 mgC: 52.7 mgN: 19.7 mgP: 5.3 mg chl-*a*. The latter set indicated that compared to the Redfield ratio, Delaware River samples had twice as much phosphorus and 30% less nitrogen, while chl-*a* was within the range described in Chapra (1997) .

Observed C/N and C/P results of the Mar-Sep subset were applied in the DO Model (Table 3-10). The carbon: chlorophyll ratio was set at 20 through model validation, which is also the ratio stated in Sharp (2006) for the Delaware Estuary.

Table 3-10: Observed CNP Results Compared to Literature Values

	C/chl-*a*	C/N	C/P
Average of Delaware River mainstem, all samples	252.8	7.7	18.8
Average of Delaware River mainstem, Mar-Sep subset	76.0	7.6	20.3
Literature	20 to 100 (Chapra, 1997) 20 (Sharp, 2006)	5.6 (Redfield, 1934)	40.0 (Redfield, 1934)

Light Attenuation

Data for the estimation of the diffuse light attenuation coefficient for the DO Model is derived from two sources. The first is from the data collected by University of Delaware, including results of 101 research cruises conducted between May 1978 and October 2003 along the length of the Delaware Estuary (see Section 3.6.3). Information was also obtained from the DRBC "Boat Run" monitoring data, described in Section 3.6.3. Data acquired by the DRBC Boat Run monitoring program from March 2000 through June 2004 were used for this analysis.

The University of Delaware light data was acquired using electronic meters recording photosynthetically active radiation, which was used with the Beer-Lambert law to estimate a diffuse light attenuation coefficient. The DRBC Boat Run program collected light information using a Secchi disk, and light attenuation was estimated using the convention that the 1% light extinction level is reached at three times the Secchi depth. Both the University of Delaware and the DRBC "Boat Run" programs determined total suspended sediment concentrations by traditional gravimetric analysis. The data from these two sources were combined for all stations located within the domain of the Water Quality Model (approximately River Mile 60 to Trenton, NJ). The resultant data set yielded 621 estimations of light attenuation paired with seston, or total suspended solids observations, collected between 1978 and 2004 within the model domain.

Using these diffuse light attenuation and total suspended solids data, linear regressions were performed with the diffuse light attenuation coefficient as the endogenous variable, and total suspended solids as the exogenous variable. For these regressions, the data were stratified geographically into two regions within the model domain. The upper region extends from

Trenton to River Mile 85, and the lower region extends below River Mile 85 to the lower model boundary. The form of the regression equation is:

$$Ke_{Total} = Ke_{TSS}\,[TSS] + Ke_b \qquad \text{Eq. 3-2}$$

Where:

Ke_{TOTAL} is the total diffuse light extinction coefficient

Ke_{TSS} is the partial diffuse light extinction coefficient dependent upon Seston

Ke_b is the background diffuse light extinction coefficient

In practice, the results of these regressions were used to estimate a global Ke_{TSS} by first applying the regression results to the average total suspended solids concentrations within each zone, then averaging those results across both regions and dividing by the global average of the total suspended solids observations to yield a revised global Ke_{TSS}. The Ke_b then was adjusted for each zone to maintain the total diffuse light extinction that was estimated from the data set for each region. The results of these calculations yielded estimates of Ke_{TSS} = 0.055 (m^{-1}) globally, Ke_b for the upper region = 0.20 (m^{-1}), and Ke_b for the lower region = 2.15 (m^{-1}).

3.6.5 Discharge Monitoring Reports Overview

Discharge Monitoring Reports (DMRs) were another key source of model input data. DMRs are monthly reports required under the National Pollutant Discharge Elimination System (NPDES) regulations that contain the measured effluent concentrations of target constituents in permitted discharges. Parameters varied by discharger but generally included bacteria, BOD, temperature, dissolved oxygen, nitrogen, phosphorus, discharge flow and TSS among others.

The regulated parties among dischargers in Pennsylvania, New Jersey and Delaware include municipal wastewater treatment, industrial and power generating plants. Together these include 53 individual inputs (Figure 3-8). When appropriate, the reported data from each source was converted to EFDC model state variables using stoichiometric and other relationships that are detailed in Section 3.8.3.

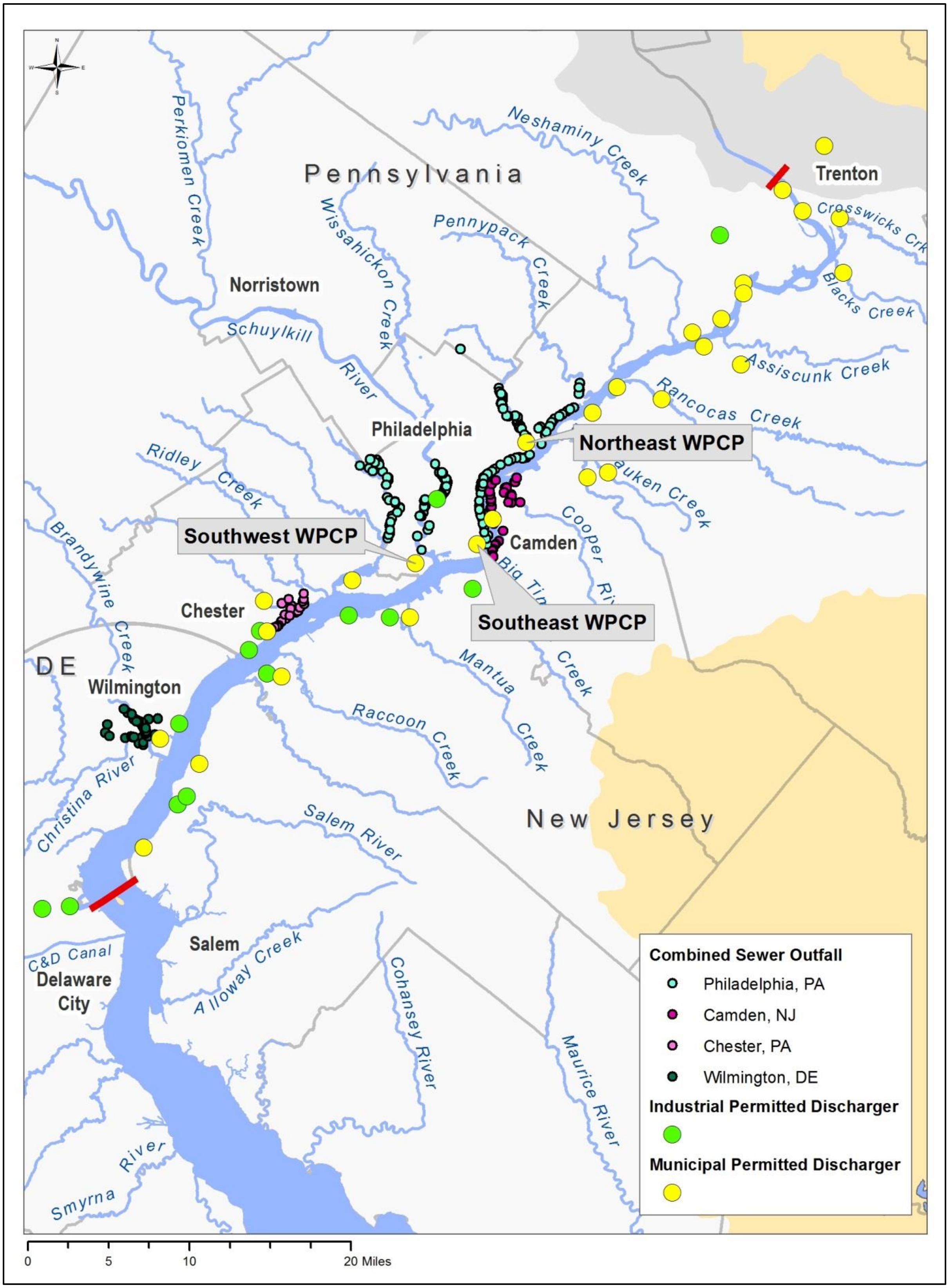


Figure 3-8: CSO and WWTP Direct Inputs to the Water Quality Model

3.6.6 CSOs Overview

Discharges of CSO volume and water quality constituents were needed as boundary conditions to the Delaware River EFDC Model for the model period 2012 through 2013. Flow and water quality loads were estimated for the cities with CSO systems within the model domain, which include Philadelphia, Camden, Chester and Wilmington. These loads were estimated from existing models, and/or modeling reports provided by the following utilities: Philadelphia Water Department, Camden County Municipal Utilities Authority (CCMUA), Delaware County Regional Water Quality Control Authority (DELCORA), and the City of Wilmington. The methods used to estimate the CSO loads for the validation periods for each system are described in Section 3.8.4. Where information was not available for a water quality parameter for a system, the data gap was filled using a value estimated from a composite of the other systems.

EFDC accounts for a more comprehensive set of water quality parameters than sampled and reported in most stormwater and wastewater studies. Values for these parameters were derived from the available data to develop loading boundary conditions for the required parameters. Organic nitrogen was calculated by subtracting ammonia from total Kjeldhal nitrogen (TKN). It was assumed that the total organic nitrogen was 50 percent dissolved and 50 percent particulate. Organic phosphorus was estimated by subtracting inorganic phosphate from total phosphorus. Similar to organic nitrogen, a 50/50 fraction of dissolved organic phosphorus to particulate phosphorus was assumed. EFDC requires values of organic carbon, which can be estimated from ultimate CBOD. If ultimate CBOD is not available, it can be estimated from BOD5 by applying a decay rate of 0.2/day (Chapra, 1997) to Eq. 3-1. Total organic carbon was then calculated from CBOD via an assumed 2.67 Oxygen: Carbon stoichiometric ratio. Half of the total organic carbon was assumed to be dissolved and the other half was assumed to be particulate.

3.6.7 Stormwater Runoff Overview

Concentrations of chemical constituents in stormwater runoff were estimated for the stormwater component of the CSO discharges that were loaded into the Water Quality Model. In the CSO systems that discharge to the Delaware River, stormwater and sanitary wastewater physical and chemical constituents are carried through the collection system and discharged from the outfalls to the receiving waters during wet weather periods. Event mean concentrations (EMCs) were applied to stormwater runoff to estimate runoff constituent loads. An EMC is defined as the mass load of a pollutant parameter yielded from a site during a storm divided by the total runoff volume discharged during the storm (Smullen and Cave, 2003). Estimates of EMCs derived from published national databases (Smullen *et al.*, 1999; Smullen and Cave, 2003; Pitt, 2004) that were applicable to the Water Quality Models are listed in Table 3-11**.** Since the EMCs are pooled from a number of studies nationwide, and by definition represent averages, the same urban runoff EMC for each water quality parameter was assigned to all stormwater areas. Organic nitrogen and organic phosphorus constituents were derived in the same manner as in Section 3.6.6.

Table 3-11: National EMCs Derived from Published Sources

Parameter	EMC (mg/L)
Ammonia (NH_3)	0.44
Nitrite + Nitrate (NO_2 + NO_3)	0.60
Total Kjeldhal Nitrogen (TKN)	1.43
Inorganic Phosphate (PO_4)	0.10
Total Phosphorus (TP)	0.27
5 - day Biochemical Oxygen Demand (BOD_5)	9.50

3.7 Atmospheric boundary conditions

3.7.1 Air temperature

Air temperature is one of the meteorological parameters available from NCDC (see section 3.5.1) that was applied through the EFDC Water Quality Model ASER.inp input file. These hourly data were applied at the modeled air-water interface for the validation years of 2012 and 2013 from February 1 through October1.

Air temperature affects heat transfer at the water surface and thus water temperature. An additional parameter, relative humidity, is related to heat transfer and is derived from air temperature in combination with dew point data from NCDC (Tetra Tech, personal communication, 2015). Data from WBAN 13739 at Philadelphia International Airport were utilized for this parameter group. Monthly mean air temperatures in 2012 were warmer than 2013 from January through September except for June of 2013 which was warmer by only 0.1 °C. Both years were warmer than the1981 – 2010 monthly means from April through October except for August and September of 2013, which were cooler (Figure 3-9).

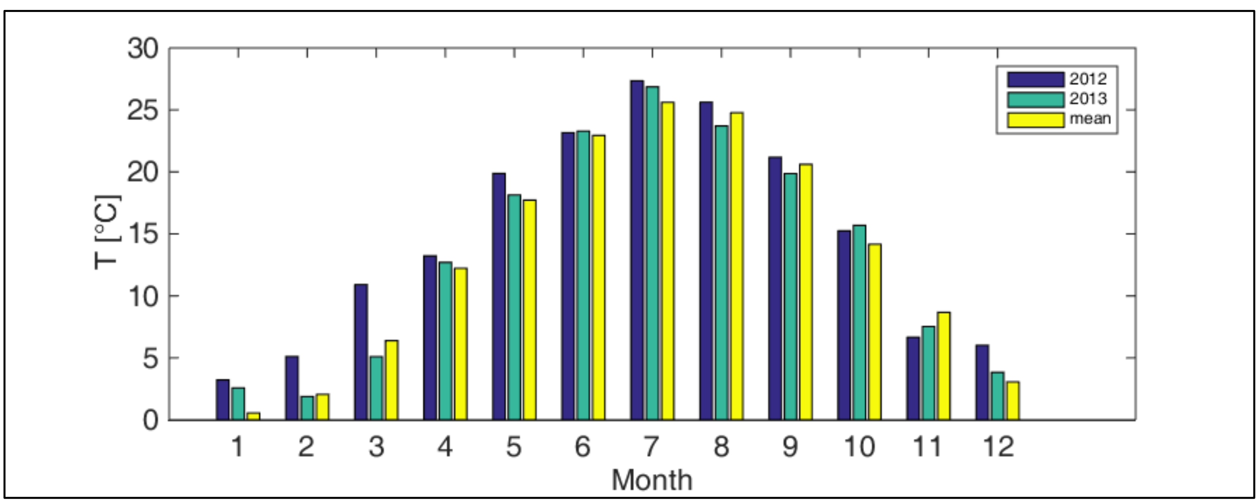


Figure 3-9: Mean Monthly Air Temperature for 2012, 2013 and 1981-2010 Period at Philadelphia International Airport (WBAN 13739)

3.7.2 Solar radiation

Solar radiation was computed using the algorithms in the CE-QUAL-W2 Water Quality Model (Cole, 2006). NCDC sky cover descriptive information data were converted to cloud cover fraction as follows: "CLR" = 0.05, "FEW" = 0.25, "SCT" = 0.50, "BKN" = 0.75, "VV" = 0.9 and "OVC" = 0.95 (TetraTech, personal communication, 2015). Together they were applied at the air-water interface as an effective solar radiation input that impacted both water temperature and modeled photosynthetically active radiation (PAR). Data from WBAN 13739 at Philadelphia International Airport were utilized for cloud cover and solar short wave radiation was calculated based on latitude/longitude for that same location. Mean monthly values of effective incident solar short-wave radiation as corrected by cloud cover show a normal seasonal trend for 2012 and 2013 (Figure 3-10).

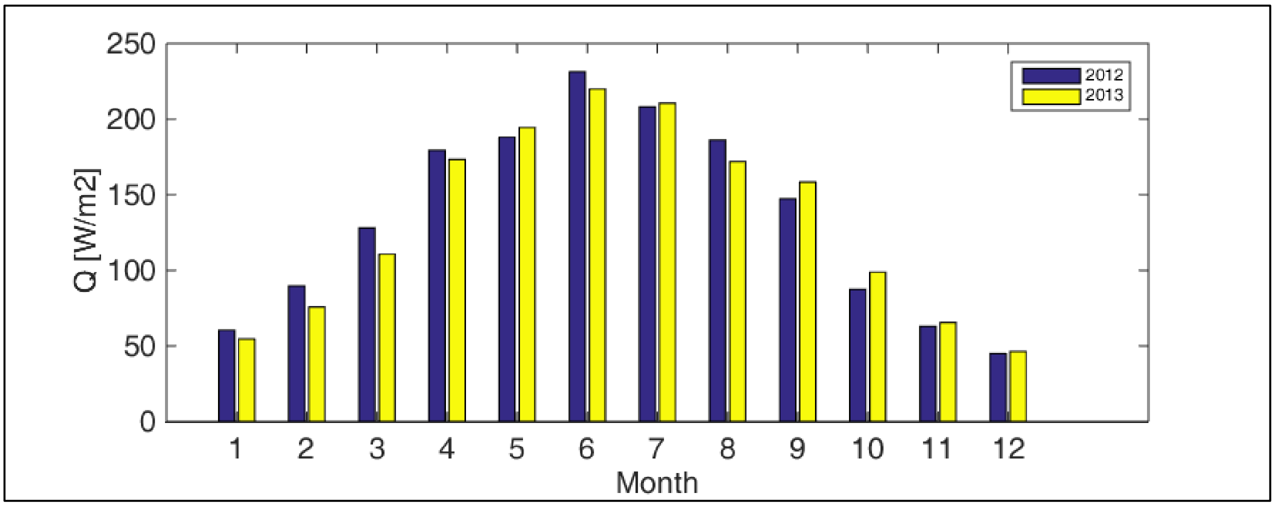


Figure 3-10: Mean Monthly Solar Short-Wave Radiation for 2012 and 2013 at Philadelphia International Airport (WBAN 13739)

3.7.3 Wind

Wind speed and direction data from Philadelphia International Airport are applied as a homogenous wind field over the model domain. This input is applied to the air-water interface as wind stress, which drives the DO Model representation of surface oxygen reaeration (TetraTech-Inc., 2007). Reaeration is implemented using the O'Connor-Dobbins method (O'Connor, 1958). Wind Rose plots for validation years of 2012 and 2013 are below (Figure 3-11 and Figure 3-12).

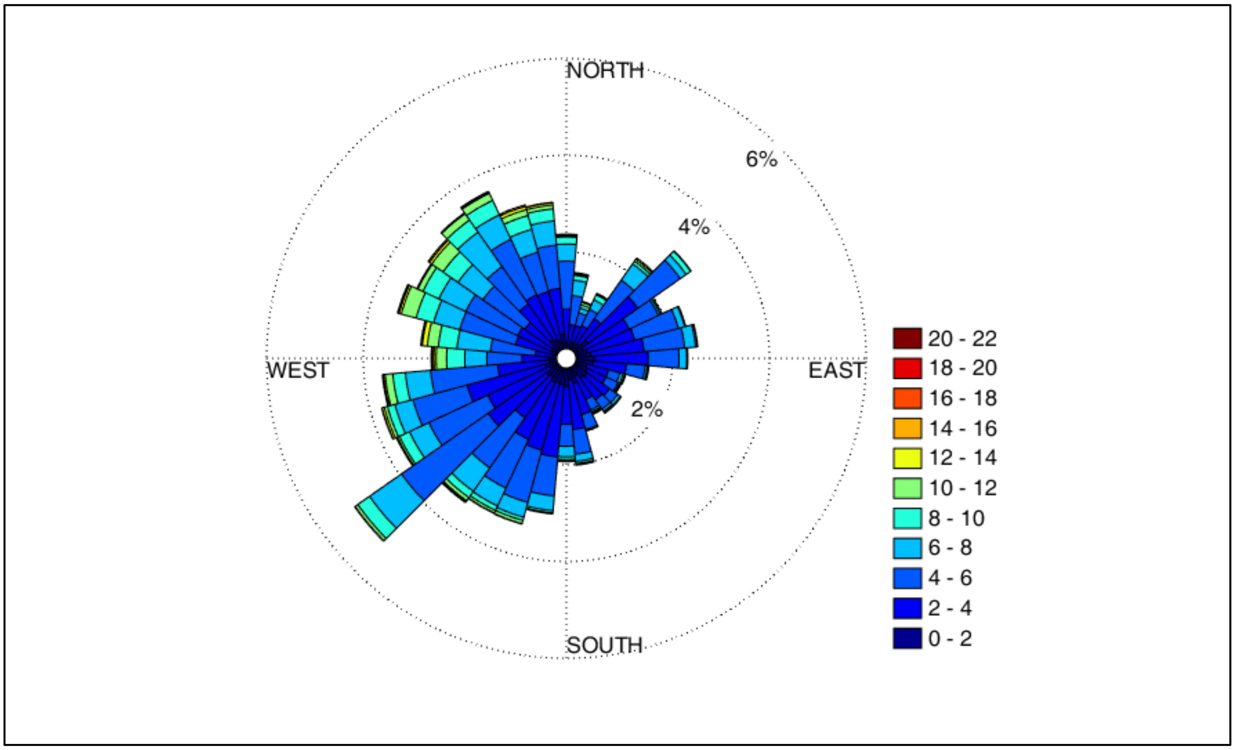


Figure 3-11: 2012 Wind Rose for Philadelphia International Airport (WBAN 13739) showing wind speed [m/s] and compass direction, blowing from [° M].

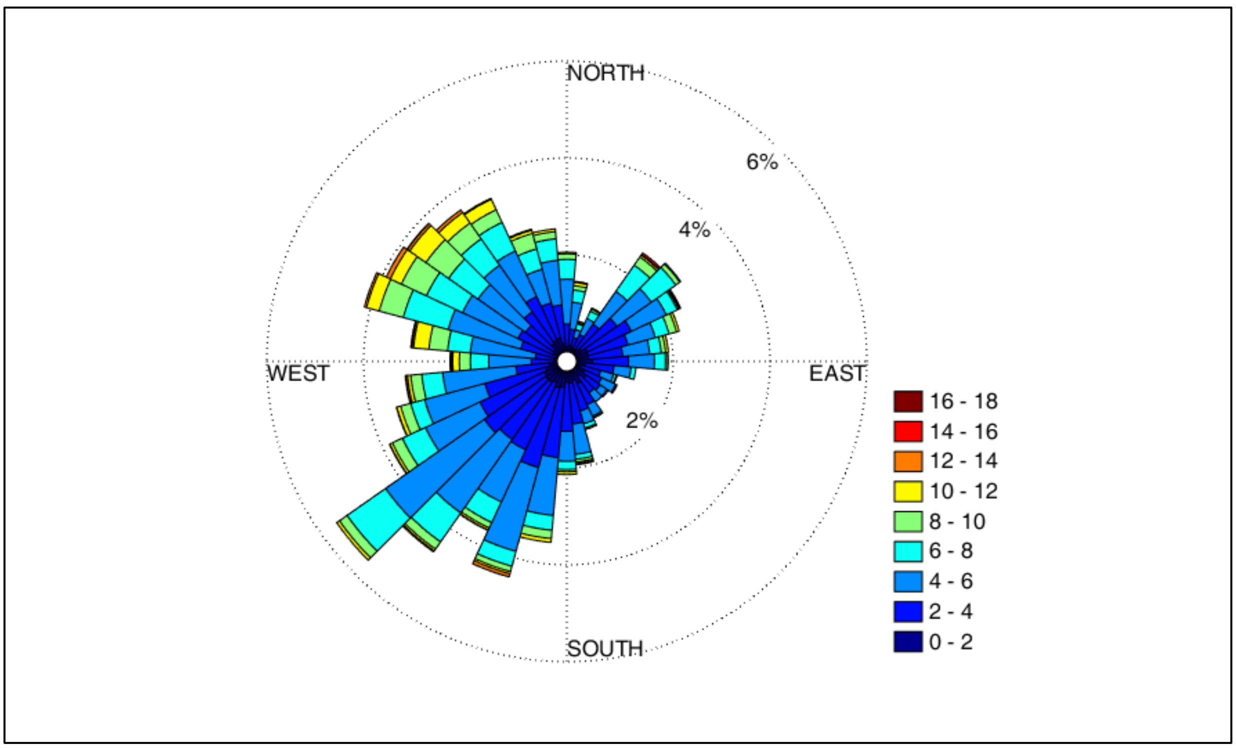


Figure 3-12: 2013 Wind Rose for Philadelphia International Airport (WBAN 13739) showing wind speed [m/s] and compass direction, blowing from [° M].

3.8 Inflow Boundary Conditions

3.8.1 Water Level Open Boundary

In order to establish WQ state variable concentrations for the open boundary near Delaware City, the database (WRDB) was queried for stations in the vicinity of the lower boundary. For the period 1990-2013, water quality data was retrieved from DRBC boat run monitoring station Pea Patch Island at RM 60.60 (1.6 miles downstream of the model boundary), and University Delaware monitoring station at RM 62.67 (0.5 miles upstream of the model boundary). Non-detect samples were converted to half the detection limit. Median concentrations were calculated for ammonium and fecal coliform. Sensitivity analysis confirmed that the effect of representing ammonium and fecal coliform as steady state concentrations at the open boundary does not propagate into the area of influence of Philadelphia discharges.

In contrast with the constant boundary concentrations assumed for ammonium and fecal coliform, a time series of DO during the validation period was taken directly from USGS gage 01482800 at Reedy Island Jetty (RM 54.10, 8.1 miles downstream of the model boundary). Deployment of a continuous DO sensor at RM 62.2 in May-Oct 2014 confirmed that the DO at USGS gage 01482800 is representative of the lower model boundary. Time series of chl-a, DOC, POC, nitrate, orthophosphate, DOP, and POP were developed based on interpolation between monthly grab samples during the validation period at DRBC boat run monitoring station New Castle at River Mile 66.00.

3.8.2 Tributaries

Observed continuous DO data were available at USGS stations for seven tributaries along the study area: Christina River, Brandywine Creek, Cobbs Creek, the Delaware River at Trenton (for upstream boundary), Frankford Creek, Pennypack Creek, Poquessing Creek, and Schuylkill River. Additionally, grab samples from 1990-2013 were used to determine input values for the following parameters: DOC, POC, NH4, NO3, DON, PON, PO4, DOP, POP, algae, and fecal coliform bacteria. In addition to the tributaries listed above, grab samples were available for Brandywine River, Chester Creek, Cooper River, Crosswicks Creek, Crum Creek, Neshaminy Creek, Pennsauken Creek, Raccoon Creek, and Rancocas Creek. Based on these observations input time series for all parameters and tributaries were generated using the following methodology.

Data from all available stations were assembled in one spreadsheet and checked for parameter availability. Not all parameters were necessarily available at each station and some had to be calculated based on existing parameters:

$$POC = TOC - DOC \qquad \text{Eq. 3-3}$$

$$PON = (TKN - NH4T)-(DKN - NH4) \qquad \text{Eq. 3-4}$$

$$DON = DKN - NH4 \qquad \text{Eq. 3-5}$$

$$DON = N - IN \qquad \text{Eq. 3-6}$$

POP = (TP – PO4T)-(TDP – PO4) Eq. 3-7

POP = (TP – OPO4T)-(TDP – OPO4T) Eq. 3-8

DOP = TDP – PO4 Eq. 3-9

DOP = TDP – OPO4 Eq. 3-10

TPO4 = OPO4 + PO4P Eq. 3-11

TPO4 = PO4 + PO4P Eq. 3-12

Most water quality parameter concentrations were dependent on wet/dry weather, season or both. In order to use the best parameter values possible, time series were generated with appropriate parameter values during wet or dry weather, according to season, according to season and wet or dry weather, or as a constant. Seasonal discharge limits were determined for each tributary to indicate whether a grab samples were collected under dry or wet conditions. Cumulative Distribution Functions (CDF) of discharge since 1990 during seasons of distinct biological activity (spring (3/1 – 6/15), summer (6/16 – 9/30), winter (10/1 – 2/28)) were prepared for each tributary. The seasonal wet/dry discharge limit was defined as the percentile discharge at which the CDF curve increases asymptotically. The example of Delaware River in Figure 3-13 shows a discharge limit of 475 cms in spring, 180 cms in summer, and 450 cms in winter. Samples collected during discharge conditions below these seasonal limits were categorized as dry and samples collected when discharge was greater than the seasonal limit were considered wet.

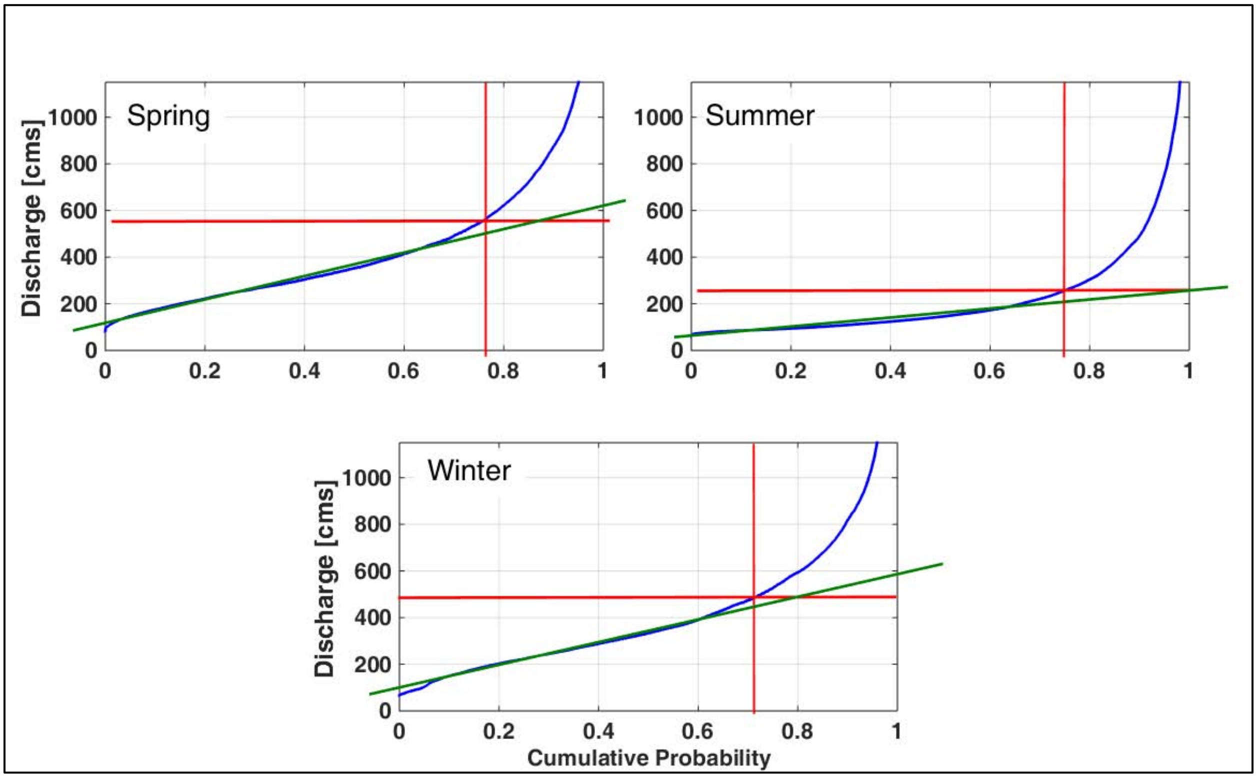


Figure 3-13: CDFs of Delaware River During Biological Seasons

Once the grab sample data were categorized as wet/dry and by season, box plots of all parameters were generated for several subsets of data: box plots including all survey points per parameter, box plots categorized by season, box plots categorized by wet and dry conditions, and box plots categorized by season and wet/dry conditions. The examples in Figure 3-14 to Figure 3-17 show box plots for all cases in Cooper River. The central mark is the median and the edges of the box are the 25th and 75th percentiles. The whiskers extend to 1.5 times the interquartile range, and points plotted beyond the whiskers (+) are considered outliers. The notches signify the 95% confidence interval about the median; the medians of two datasets are significantly different when their notches do not overlap. When sample sizes are small notches may extend beyond the end of the box, as can be seen for the case of wet summer in Figure 3-17. The label below each boxplot shows parameter, case, and number of data points included.

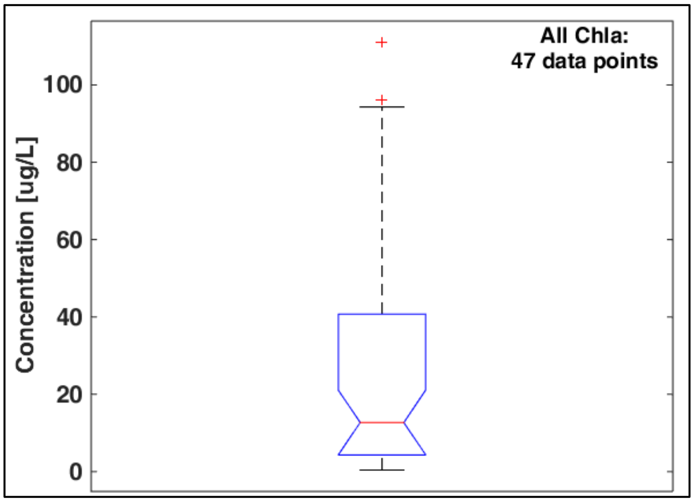


Figure 3-14: Box Plot of Cooper River Chl-A Including All Available Data

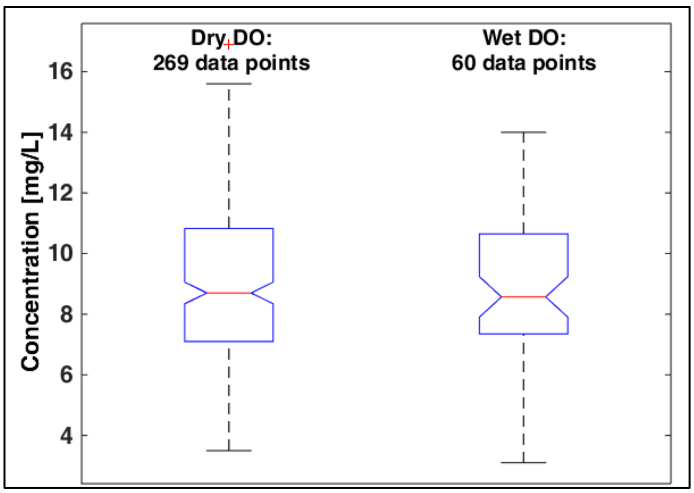


Figure 3-15: Box Plot of Cooper River DO During Wet/Dry Periods

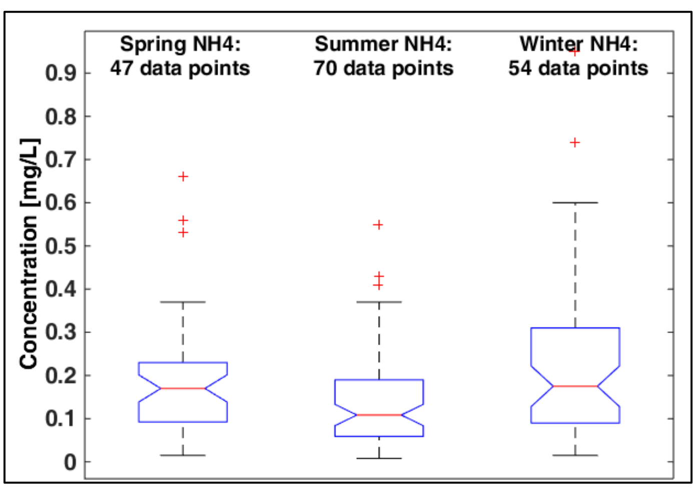


Figure 3-16: Box Plot of Cooper River NH4 Subsetted by Season

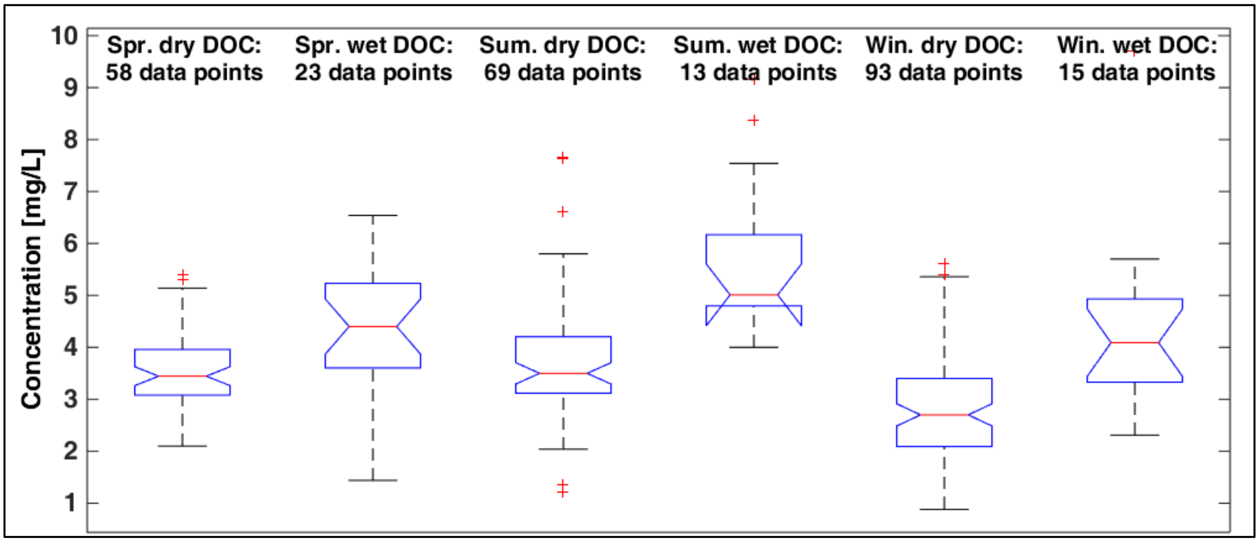


Figure 3-17: Box Plot of Cooper River DOC Subsetted by Weather and Season

Depending on the number of sample observations in each case and the variability between subsets, either a constant value was chosen for the parameter, or time series were constructed based on specific values chosen for the parameter

- during wet and dry periods,
- during different seasons, or
- during wet and dry weather and in different seasons

Sufficient algae data was often not available for tributaries, and in these cases a constant of 2 μg/L chl-*a* was applied season.

The water quality parameter concentrations applied to each tributary are listed in Table A3-1 through Table A3-4. In contrast with other state variables, DO was the only continuously monitored parameter measured in several tributaries (Table A3-4). Time series for DO were developed based on available continuous DO data.

In this fashion input time series of all parameters for all tributaries that had grab sample or continuous data were created. These time series were also assigned to similar tributaries for which no observed data existed (through Table A3-4).

3.8.3 Municipal and Industrial Permitted Dischargers

Boundary condition information for municipal (Table 3-12) and industrial (Table 3-13) permitted dischargers was available from DMRs (see Section 3.6.5). All municipal and industrial point sources permitted for discharge of more than 1 MGD within a 10 mile radius from the model area shoreline were included in the Water Quality Model. DMRs from 2007-2013 were available from PA DEP, NJDEP, DNREC, and USEPA. Some DMRs were only available as paper copies that needed to be scanned and digitized. Depending on the sources

(Pennsylvania, New Jersey or Delaware) data were presented indifferent formats and units, requiring conversion to a consistent format prior to analysis.

For a given permitted discharger, monthly average effluent flow data were applied at the boundary for each entire month, and then stepped to the next monthly value (*i.e.*, no interpolation was applied between monthly values). For each of the three Water Department Water Pollution Control Plants (WPCPs), daily average effluent flow values were applied at the boundaries for each entire day, and then stepped to the next daily value.

Table 3-12: Location and NPDES Permit Number for Municipal Wastewater Treatment Plants in Model Domain

Municipal wastewater treatment plants	River Mile	NPDES
Ewing Lawrence Sewerage Authority	133.8	NJ0024759
Morrisville Boro Mun. Auth-STP	133.0	PA0026701
Trenton DPW Sewerage Authority	131.8	NJ0020923
Hamilton Twp WPCF	128.5	NJ0026301
Bordentown Sewerage Authority	128.3	NJ0024678
Lower Bucks County Joint MA	122.0	PA0026468
Florence Twp STP	121.3	NJ0023701
Bristol Boro WSA	119.3	PA0027294
Burlington Twp DPW	118.5	NJ0021709
Burlington City STP	117.3	NJ0024660
Bristol Twp WWTP	116.8	PA0026450
Willingboro Twp MUA	111.3	NJ0023361
Delran Sewerage Authority	111.0	NJ0023507
Cinnaminson Sewerage Authority	108.8	NJ0024007
Moorestown WWTP	105.5	NJ0024996
Maple Shade POTW	105.5	NJ0069167
Philadelphia - Northeast WPCP	104.0	PA0026689
Camden County MUA	98.0	NJ0026182
Philadelphia - Southeast WPCP	96.8	PA0026662
Philadelphia - Southwest WPCP	90.8	PA0026671
Gloucester County Utility Authority	89.5	NJ0024686
Tinicum Twp WWTP	85.5	PA0028380
Little Washington STP	84.0	PA0024121
DELCORA	80.5	PA0027103
Southwest Delaware County MUA	80.5	PA0027383
Logan Twp MUA	79.5	NJ0027545
Wilmington WWTP	72.0	DE0020320
Carneys Point WWTP	71.3	NJ0021601
Pennsville Twp Sewerage Authority	65.0	NJ0021598

Table 3-13: Location and NPDES Number for Industrial Permitted Dischargers in Model Domain

Industrial permitted discharger	River Mile	NPDES
US Steel Fairless Hills Works (Outfall 103)	122.0	PA0013463
Coastal Eagle Point Oil Co.	93.5	NJ0005401
Valero Refining Co. (Outfall 1)	87.0	NJ0005029
E I Dupont De Nemours & Co. Repauno Plant	85.5	NJ0004219
Conoco Phillips Refinery (Outfall 2)	80.5	PA0012637
Conoco Phillips Refinery (Outfall 101)	80.5	PA0012637
Conoco Phillips Refinery (Outfall 201)	80.5	PA0012637
Sunoco, Inc. Marcus Hook Refinery	79.3	PA0011096
Dupont Edgemoor (Outfall 1)	72.8	DE0000051
Dupont Edgemoor (Outfall 3)	72.8	DE0000051
Ferro Corp.	68.8	NJ0005045
E I Dupont De Nemours & Co. (Outfall 1)	68.8	NJ0005100
E I Dupont De Nemours & Co. (Outfall 2)	68.8	NJ0005100
E I Dupont De Nemours & Co. (Outfall 13)	68.8	NJ0005100
E I Dupont De Nemours & Co. (Outfall 662)	68.8	NJ0005100
Deepwater Energy Center (Outfall 3)	68.5	NJ0005363
Deepwater Energy Center (Outfall 10)	68.5	NJ0005363
Delaware City Refinery (Outfall 1)	62.0	DE0000256
Delaware City Refinery (Outfall 201)	62.0	DE0000256
Delaware City Refinery (Outfall 601)	62.0	DE0000256
Delaware City Refinery (Outfall 701)	62.0	DE0000256
Conectiv Delaware City Power Plant	62.0	DE0050601
Exelon Corp. Schuylkill Generating Station (Outfall 1)	Schuylkill 6.2	PA0011657
Exelon Corp. Schuylkill Generating Station (Outfall 301)	Schuylkill 6.2	PA0011657

When available, the water quality parameter effluent data were applied at the boundary for each discharge for the entire corresponding month (or at a finer temporal resolution in the case of the three Water Department WPCPs) in the validation period. Non-detect concentrations were estimated to be half the detection limit. Water Quality Model input parameters were not always available in DMRs and some estimates and simplifications were needed to complete the boundary conditions. If parameter data for a facility was missing for a validation year but had been reported in previous years (*e.g.*, 2007-2011), the average of all available data for that parameter was applied to the validation year that had missing data for that parameter. The derivation method for unreported parameters is described below.

Carbon

When necessary, DOC and POC time series for municipal and industrial permitted dischargers were derived from DMR data as follows:

- If DOC and TOC data were reported, POC was calculated to be the difference.
- If only TOC data were reported, a partition coefficient was applied to derive DOC and POC. The ratio of DOC:TOC was assumed to be 0.9 and 0.5 for municipal and industrial permitted dischargers, respectively.
- If paired $CBOD_5$ and $CBOD_{20}$ data were reported, the decay coefficient 'kd' was calculated to determine ultimate CBOD, as described in section 3.6.4. Ultimate CBOD was then converted to TOC via an assumed stoichiometric ratio. TOC was then partitioned to DOC and POC as described in the bullet above.
- If paired $CBOD_5$ and $CBOD_{20}$ data were not reported, decay coefficients of 0.07 and 0.2 per day were assumed for municipal and industrial permitted dischargers, respectively. Ultimate CBOD and TOC were then determined as described in the bullet above.

Phosphorus

When necessary, PO_4, particulate organic phosphorus (POP), and dissolved organic phosphorus (DOP) time series for municipal and industrial permitted dischargers were derived from DMR data as follows:

- If paired total phosphorus (TP) and PO_4 data were reported, total organic phosphorus (TOP) was calculated to be the difference, and partitioned equally into DOP and POP.
- If only TP data were reported, PO_4 fractions of 0.5 were assumed for municipal and industrial permitted dischargers, respectively. TOP, DOP, and POP were then derived as described in the bullet above.
- If no phosphorus data were reported, a carbon:phosphorus mass ratio based on bacteria cells (Rittmann and McCarty, 2001) was applied to derive TP from the facility's associated TOC value. PO_4, DOP, and POP were then derived as described in the bullet above.

Nitrogen

When necessary, nitrate, ammonium, DON and PON time series for municipal and industrial permitted dischargers were derived from DMR data as follows:

- If paired NH_4 and TKN data were reported, total organic nitrogen (TON) was calculated to be the difference, and partitioned into DON and PON. The ratio of DON:TON was assumed to be 0.75 and 0.5 for municipal and industrial permitted dischargers, respectively.
- If only NH_4 data were reported for municipal treatment plants

- NO_3 was derived from the average ratio of NH_4: NO_3 associated with municipal treatment plants in the model domain with similar NH_4 effluent concentrations, to distinguish between treatment plants that are or are not applying nitrification.
- TON was derived from the average ratio of TKN: NH_4 from the three PWD treatment plants. DON and PON were then partitioned as 75% and 25% of TON, respectively.

- If only NH_4 data were reported for industrial plants, NO_3 was assumed to be 1 mg-N/L, and DON = PON = 0.5* NH_4.
- For a subset of industrial plants, only Total Nitrogen (TN) data were reported. In these cases, NO_3 was assumed to be 1 mg-N/L, so TKN = TN – 1. NH_4 was set equal to TON, with DON equal to PON.
- If no nitrogen data of any kind were reported for a municipal treatment plant, a carbon:nitrogen mass ratio based on bacteria cells (Rittmann and McCarty, 2001) was applied to translate DOC to DON, and POC to PON for the facility. Ratios of TKN:NH4 and NH_4: NO_3 were then applied as described above for municipal treatment plants to derive NH_4 and NO_3. This situation was not encountered for any industrial permitted dischargers.

Pathogen Indicating Bacteria

When necessary, fecal coliform bacteria time series for industrial permitted dischargers were derived from DMR data as follows:

- For industrial permitted dischargers that reported no pathogen indicating bacteria, an average concentration from other industrial permitted dischargers was applied.

Dissolved Oxygen

If no DO effluent data were reported, concentrations were assigned from the average of other municipal or industrial permitted dischargers in the model domain.

A zero concentration of phytoplankton algae chl-a was assigned to all treatment plant effluents.

Discharger flows, parameter concentrations, and mass loading inputs to the Water Quality Model are summarized on an annual basis in Table A3-5 through Table A3-12.

3.8.4 CSOs

Philadelphia

The City of Philadelphia has a total land area of 136 square miles, of which approximately 64 square miles are served by combined sewers. Three water pollution control plants (WPCPs) are operated by PWD: Northeast, Southeast, and Southwest. The department also operates the system of branch sewers, trunk sewers, regulator chambers, and interceptor sewers that convey the combined wastewater to the WPCPs. The PWD wastewater service area consists of the entire City of Philadelphia, as well as ten other outlying communities and authorities. There are 164 CSO outfalls within the City. Regulators control the flow from the combined sewers to the interceptors. During wet weather CSOs may discharge to the Delaware and Schuylkill Rivers, and to the Cobbs, Frankford, Old Frankford, Pennypack, Tacony, West Branch Indian, and East Branch Indian Creeks.

Discharge and loads from the CSOs in the City of Philadelphia that discharge to tidal waters were estimated from combined sewer system (CSS) district model simulations. The CSS Models were developed for each of the drainage districts contributing to the City's three Water Pollution Control Plants using the EPA Storm Water Management Model Version 5 (SWMM5). The CSS Models were originally developed for the Long Term Control Plan (Philadelphia Water Department, 1997). Additional refinement of the CSS Models occurred as part of the Long Term Control Plan Update (LTCPU) (Philadelphia Water Department, 2009). CSS Model development and validation methodology are discussed in the LTCPU Supplemental Documentation Volume 4 (Philadelphia Water Department, 2011).

The baseline SWMM5 CSS Models for the Northeast, Southeast, and Southwest Districts were simulated with water quality for the validation years 2012 through 2013. EMCs were applied to all subcatchments within the drainage area of each district to simulate the water quality of stormwater runoff. Median values of sampled dry weather wastewater flow at regulators throughout the system were assigned to the baseflow in the CSS Models to account for the water quality of sewage flow. The sewage water quality values are referred to as the base wastewater (BWW) parameters. These assigned water quality values are summarized in Table 3-14.

The EMC parameters in Table 3-14 that were used in the CSS Models were derived from the values listed in Table 3-14 and BWW sampling data with some additional information. The National Stormwater Quality Database (NSQD) included measured DO values for stormwater, although they were not published by Pitt (2004). A median value for DO in runoff was calculated from the data in the NSQD and used as the EMC for DO. A DO concentration of 2.0 mg/L was assumed for the BWW. An ultimate value of CBOD was required for both EMC and BWW, so the BOD_5 values were converted to CBOD by applying a decay rate of 0.2/day (Chapra, 1997) to Eq. 3-1. The EMC and BWW values used in the bacteria tributary models in Tributary Water Quality Model for Bacteria, CO&A Deliverable VI (Philadelphia Water Department, June 2013) were used for Fecal coliform.

Time series of CSO flows and water quality constituents were extracted from the CSS Model simulations for the years 2012 and 2013 at a 15 minute time step to be used as boundary conditions for the Hydrodynamic and Water Quality Models.

Table 3-14: EMC and Base Wastewater (BWW) Water Quality Values in SWMM

Parameter	EMC	BWW
Ammonia (NH_3) (mg/L)	0.44	8.45
Nitrate (NO_3) (mg/L)	0.6	0.88
Total Kjeldahl Nitrogen (TKN) (mg/L)	1.43	19.98
Orthophosphate (oPO_4) (mg/L)	0.126	1.69
Total Phosphorus (TP) (mg/L)	0.27	3.44

Parameter	EMC	BWW
Ultimate Carbonaceous Biochemical Oxygen Demand ($CBOD_u$) (mg/L)	15.03	182
Dissolved Oxygen (DO) (mg/L)	8.2	2
Fecal Coliform (#/100ml)	4776	3,000,000

Camden County Municipal Utilities Authority

The Camden County Municipal Utilities Authority is a regional wastewater management agency serving communities in Camden County, New Jersey. Part of the CCMUA system is served by combined sewers, with combined sewer overflow regulating structures located in the City of Camden, in Gloucester City, and a single structure operated by CCMUA. The Delaware River, Cooper River and the Newton Creek receive discharges in wet weather at 36 overflow locations draining 4,430 acres in the two municipalities served by combined sewers.

To provide estimates for sewage volume and water quality parameter loading from CCMUA overflow locations, the U.S. Army Corps of Engineers Storage, Overflow and Treatment model was employed (NetSTORM). The model application was developed using physical feature, flow and water quality data available from a series of planning study reports prepared between 1999 and 2001, in response to the New Jersey Sewage Infrastructure and Improvement Act, for the City of Camden, Gloucester City and the Camden County Municipal Utilities Authority. These reports provided information on the characteristics and extent of the tributary drainages, the trunk and interceptor sewers, the wastewater treatment plant, precipitation monitoring, sewer flow meter monitoring, and combined sewer overflow water quality sampling results. This information was used to develop the model hydrologic and conduit network, and to establish hydraulic capacities including wastewater plant and regulating structure wet weather treatment rates. Model validation was conducted for the period of available overflow data, June to August of 1997. The model then was used to provide overflow and water quality discharge loading estimates for 2012 and 2013, using precipitation inputs from the Philadelphia International Airport.

Delaware County Regional Water Quality Control Authority

The Delaware County Regional Water Quality Control Authority (DELCORA) owns and operates the Western Regional Wastewater Treatment Plant located in Chester, PA. The plant receives sanitary and combined sanitary and stormwater flow from the City of Chester, as well as sanitary flow from the neighboring municipalities. The City of Chester includes a total drainage area of approximately 5 square miles, with 25 overflow regulating structures that discharge in wet weather from 24 outfalls to the Delaware River, Chester Creek, and Ridley Creek.

Discharge volume and water quality constituent loads from CSOs in the City of Chester were estimated for input to the Water Department's Water Quality Model, using information obtained from the DELCORA Long-Term CSO Control Plan for the City of Chester Combined Sewer System (April 1999). This document included model-based estimates of flow and water quality load discharges from all CSO outfalls for a typical year, as determined from 95 years of precipitation records at the Philadelphia International Airport. The DELCORA report includes event-based discharge volumes for each outfall during the typical year simulation. Since the rainfall input data also is provided, the overall ratio of overflow volume to depth of precipitation was determined for each outfall. The event-based CSO discharge information was used to determine the threshold amount of precipitation expected to initiate overflows for each outfall. That rainfall threshold was applied to the storm events recorded at the Airport gage between 2012 and 2013, and for those events expected to trigger overflows, the precipitation event volume was multiplied by the CSO volume-to-precipitation amount ratio for each regulator, to generate an overflow volume time series. Applying a CSO event average concentration, determined from the DELCORA report for each water quality constituent at each outfall, to the estimated CSO discharge overflow volumes, CSO water quality constituent loadings were estimated for 2011 through 2013 for Water Quality Model input.

City of Wilmington

The City of Wilmington Delaware operates a wastewater collection and treatment system serving the City and surrounding areas. A portion of the Wilmington sewer system is served by combined sewers, with 4,600 acres of combined-sewered area tributary to 45 overflow regulating structures. Discharges in wet weather occur to the Brandywine Creek, Little Mill Creek, Christina River, and the Shellpot Creek, upstream of their confluence with the tidal Delaware River, about 20 miles downstream of Philadelphia.

A simplified loading approach was developed to estimate overflow loadings based on an application of a modified rational method for rainfall runoff. This application was developed using physical feature, flow, and water quality data available from reports prepared by the Wilmington Department of Public Works and the USEPA. In addition, geographic information system (GIS) files were provided by the City of Wilmington. Runoff flows from combined sewer sheds were estimated by applying a runoff coefficient to precipitation depth, and then multiplied by the sewer shed area, using precipitation records from the Wilmington-New Castle County Airport. Combined sewage volumes were estimated by adding the runoff flow to the dry weather sewer flow, and overflow discharges were estimated by subtracting a constant treatment flow rate from the total trunk flow at each time step. For combined sewer sheds tributary to one of the three combined sewer storage tanks in the system, storage and drain down were estimated and factored into the CSO discharge estimates. Water quality loadings were estimated based on water quality sampling results reported by USEPA. Validation of the application was accomplished by comparison with annual and monthly discharge estimates that were included in Department of Public works combined sewer overflow report. This approach was used to provide overflow and water quality discharge loading estimates to the tidal Delaware River for 2012 and 2013.

3.8.5 Direct Runoff

Direct runoff from the areas downstream of gages on gaged tributaries and for areas that contribute runoff directly to the Delaware River between tributaries were defined as boundary conditions. The runoff from these areas was estimated using a unit flow per area ratio approach based on either the upstream gaged portion of the tributary or a neighboring tributary (Table 2-2, Section 2.4.5). Water quality parameters were assigned to the direct runoff time series based on the water quality of either the respective upstream gaged portion of the tributary or a neighboring tributary.

3.9 Initial Conditions and Spin-Up Period

All state variables were given spatially uniform initial concentrations, and a spin-up period of two months was used to establish a semi-equilibrium before high spring productivity occurs. Initial concentrations were based on a model template provided by Tetra Tech and on local data analysis (**Table 3-15**).

Table 3-15: Initial Concentrations of Water Quality State Variables

Water Quality Constituent	EFDC Name	Initial Concentration	Units
Algae	CHC	0.08 or 4.0	mg-C/L or µg chl-*a*/L
Particulate Organic Carbon	LPOC	0.875	mg-C/L
Dissolved Organic Carbon	DOC	0.875	mg-C/L
Particulate Organic Phosphorus	LPOP	0.21	mg-P/L
Dissolved Organic Phosphorus	DOP	0.021	mg-P/L
Total Phosphate	PO_4t	0.05	mg-P/L
Particulate Organic Nitrogen	LPON	0.15	mg-N/L
Dissolved Organic Nitrogen	DON	0.15	mg-N/L
Ammonium	NH_4	0.1	mg-N/L
Nitrate	NO_3	0.1	mg-N/L
Dissolved Oxygen	DO	5	mg/L

Investigations showed that the model generally requires a month to reach equilibrium, and using a spin-up period of 2 months provides a buffer to ensure that a semi-steady state is reached. For water quality model validation purposes, simulations begin on February 1 and continue through October 1 in each validation year. In many cases, observational concentration data (used to drive the model) at the model's inflow boundaries were not available until March of either 2012 or 2013; however, data from March were repeated in February to extend the model spin-up period. Model results were used to evaluate model performance starting in April; February through March is considered a spin-up period.

3.10 Sensitivity Analysis

3.10.1 Methodology

To understand how the model responds to variations in various kinetic parameters, a sensitivity analysis was conducted. The sensitivity analysis consisted of several model simulations in which a single parameter was varied from a "Base" model configuration. For this analysis, parameter variations consisted of the maximum and minimum reasonable values for each parameter, as determined by literature review and local data analysis. This methodology "bracketed" the base configuration with maximum and minimum realistic parameter values.

A total of 17 model parameters were varied, resulting in 35 model simulations (the Base configuration and the maximum and minimum of each parameter assessed). Table 3-16 shows the parameters varied in the sensitivity analysis, including the maximum and minimum values used.

Table 3-16: Sensitivity Analysis Model Parameter Variations

EFDC name	Description	Units	Literature References	Base Value	Minimum Value	Maximum Value
PMc	Algae maximum growth rate under optimal conditions	per day	4 (Cerco *et al.*, 2000); see Table 6-5 in Bowie *et al.* 1985; 2.0 (Wool *et al.*, 2003); 0.1-0.5 (Wool *et al.*, 2003); 0.2-8.0 (Jia *et al.*, 2010); 2.0 (Tetra Tech, 2005)	2	0.5	6
BMc	Algae basal metabolism rate at reference temperature	per day	0.1 (Cerco *et al.*, 2000); See Table 6-18 in Bowie *et al.* 1985; 0.125 (Wool *et al.*, 2003); 0.03 (Wang *et al.*, 2013); 0.01 (Tetra Tech, 2005); Set to 10 to 20% of PMx (Pennock and Sharp, 1994)	0.05	0.0125	0.25
PRc	Algae predation rate at reference temperature	per day	0.02 (Cerco *et al.*, 2000); 0.02 (Wool *et al.*, 2003); 0.15 (Wang *et al.*, 2013); 0.215 (Tetra Tech, 2005)	0.0875	0.00875	0.875
KHN	Half-saturation constant for N uptake	gN/m^3	0.03 (Cerco *et al.*, 2000); see Table 6-10 in Bowie *et al.* 1985; 0.025 (Wool *et al.*, 2003); 0.0014-0.4 (Jia *et al.*, 2010); 0.01 (Tetra Tech, 2005)	0.021	0.0021	0.21

EFDC name	Description	Units	Literature References	Base Value	Minimum Value	Maximum Value
KHP	Half-saturation constant for P uptake	gP/m^3	0.005 (Cerco *et al.*, 2000); See Table 6-10 in Bowie *et al.* 1985; 0.001 (Wool *et al.*, 2003); 0.0005-0.08 (Jia *et al.*, 2010); 0.001 (Tetra Tech, 2005)	0.003	0.0003	0.03
CChlc	Carbon to chlorophyll ratio	gC/mg Chl	75 (Cerco *et al.*, 2000); 20-50 (Wool *et al.*, 2003); 0.045 (Wang *et al.*, 2013; 0.033 (Pennock and Sharp, 1994)	0.045	0.01125	0.135
KE-iss	Light extinction from total suspended solids	m^2/g	0.085 (Cerco *et al.*, 2000); 0.015 (Tetra Tech, 2005); 0.075 (Pennock and Sharp, 1994)	0.055	0.01375	0.165
KE-chl	Light extinction coefficient for algae chlorophyll	m^2/mg Chl	0.017 (WASP6); 0.017 (Tetra Tech, 2005); 0.02 (Pennock and Sharp, 1994)	0.01	0.0025	0.03
D-optc	Depth of max algal growth	m	1.0 (Wang *et al.*, 2013; Tetra Tech, 2005)	0.5	0.125	1.5
I-sxmin	Minimum optimum light intensity	W/m^2	see Table 6-8 in Bowie *et al.*, 1985; 200-500 Ly/d(Wool *et al.*, 2003); 40 (Tetra Tech, 2005); 27.3 W/m2 annual avg (Pennock and Sharp, 1986)	40	10	120
KHR-c	Half-saturation constant of DO for algal DOC excretion	gO_2/m^3	0 (Cerco *et al.*, 2000); 0.5 Tetra Tech, 2005)	0.5	0.125	1.5
KHOR-DO	Oxic respiration half-saturation constant for DO	gO_2/m^3	0.5 (Cerco *et al.*, 2000); 0.5 (Wool *et al.*, 2003); 0.5 (Tetra Tech, 2005)	0.5	0.125	1.5
KPO4p	Partition coefficient for sorbed/dissolved PO_4	none	0.2 (Cerco *et al.*, 2000); 2.0 (Tetra Tech, 2005)	0.2	0.01	0.5
KHNitDO	Nitrification half-saturation constant for dissolved oxygen	gO_2/m^3	3.0 (Cerco *et al.*, 2000); 0.5, 2.0 (Wool *et al.*, 2003); 1.0 (Tetra Tech, 2005)	1	0.25	3
KHNitN	Nitrification half-saturation constant for ammonium	gN/m^3	1.0 (Cerco *et al.*, 2000; Tetra Tech, 2005)	1	0.25	3

EFDC name	Description	Units	Literature References	Base Value	Minimum Value	Maximum Value
WSc	Algae settling velocity	m/d	0.01 (Cerco *et al.*, 2000); See Table 6-19 in Bowie et al., 1985; 0.11 (Wang *et al.*, 2013); 0.10-0.15 (Tetra Tech, 2005)	0.2	0.05	0.6
WS-LP	Settling velocity of labile POM	m/d	0.03 (Cerco *et al.*, 2000); 0.15 (Tetra Tech, 2005)	0.1	0.025	0.3

3.10.2 Base Model Configuration

Several sources contributed to the Base model configuration, including:

- A water quality model developed by Hydroqual (described in Section 3.3),
- Analysis of water quality data collected in the Delaware River,
- Interpretation of published studies of the Delaware River, and
- A template developed by Tetra Tech.

The Base model and all subsequent sensitivity analysis model simulations consisted of a 40-day model simulation from June 15, 2012 through July 25, 2012. Boundary conditions included actual time series of all modeled flows, atmospheric conditions and water quality constituent concentrations as described in Sections 3.7 and 3.8. Because model results were compared with other model results rather than observed data, no spin-up period was applied to the sensitivity analysis and the flux limiter and anti-numerical diffusion options were not used for computational efficiency.

3.10.3 Results

For each parameter, the maximum and minimum cases were compared with the base configuration model results. PWD Buoy locations A, B and C, and the USGS stream gages at Chester, Baxter, Delran and the Ben Franklin Bridge were used as locations for model result comparison (Figure 2-4).

For each parameter varied in the sensitivity analysis, time series plots were developed for all water quality state variables at each of the seven output locations. Each plot compared the model variable result produced by the Base, minimum and maximum scenario for the parameter being evaluated. For example, Figure 3-18 shows the modeled DOC at PWD Buoy B resulting from variations in algal predation rate (PR). As expected, the maximum and minimum PR test cases bracket modeled DOC in the Base scenario. Variations in PR can raise or lower modeled dissolved organic carbon (DOC) by more than 0.3 mg/L.

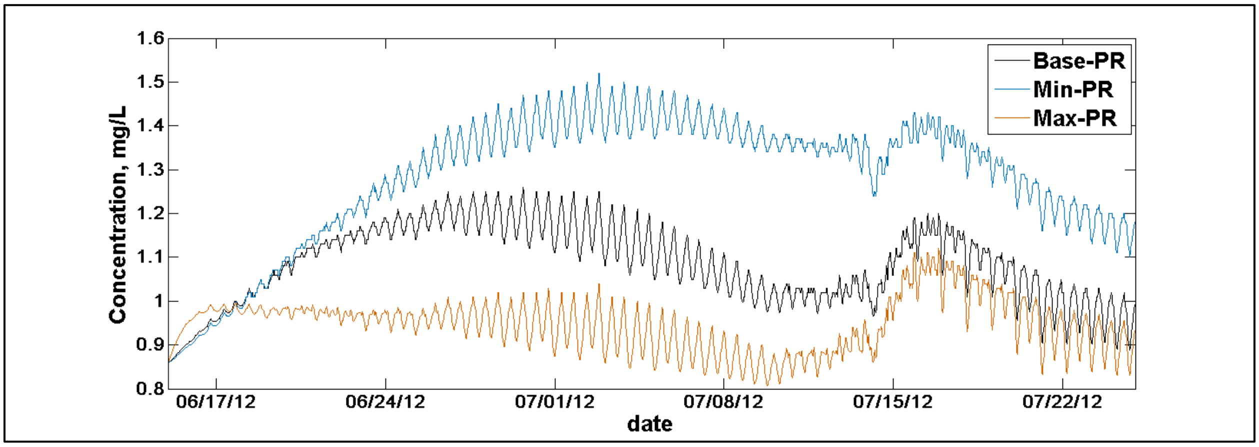


Figure 3-18: Time Series of Modeled DOC at PWD Buoy B, Model Simulations Varying Algal Predation Rate.

Sensitivity analysis evaluation also involved water quality constituent along-channel representations. In each model simulation, each state variable was evaluated for a median, maximum and minimum value during the final 10 days of the 40-day simulation period. These values were plotted along-channel at each river mile location of the seven USGS and PWD stations. Along-channel mean, minimum and maximum values were compared among the Base, Minimum and Maximum parameter scenarios for each parameter evaluated. For example, Figure 3-19 shows modeled nitrate/nitrite concentrations along-channel when the nitrification half-saturation concentration for ammonium is varied. As expected, a higher nitrification half-saturation concentration results in lower nitrate concentrations, while a lower half-saturation concentration results in higher nitrate concentrations.

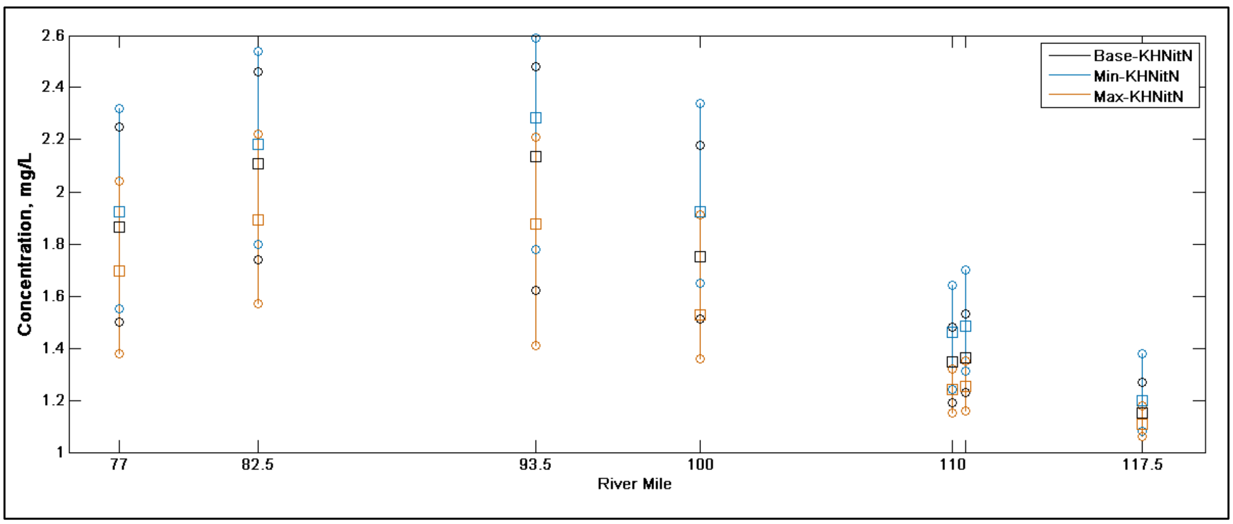


Figure 3-19: Modeled Along-Channel NOx Concentrations in Simulations Varying Nitrification Half Saturation Concentration for Ammonium

3.10.4 Conclusions

Time series and along-channel plots informed parameter classification as primary model validation parameters and secondary model validation parameters. Primary model validation parameters, defined as parameters that have an impact on several state variables beyond the variability observed in tidal fluctuations, include:

- Algae production rate,
- Algae basal metabolism rate,
- Algae predation rate,
- Algae settling velocity,
- Light attenuation related to suspended sediment,
- Nitrification half saturation constant for ammonium,
- Algal carbon to chlorophyll ratio, and
- Optimum depth for algal growth.

These very sensitive parameters were relied upon most heavily in the water quality model validation process. The less sensitive parameters include:

- Half-saturation constant for N uptake
- Half-saturation constant for P uptake
- Nitrification half-saturation constant for dissolved oxygen
- Oxic respiration half-saturation constant for DO
- Partition coefficient for sorbed/dissolved PO_4
- Particulate organic matter settling velocity

Parameters classified as insensitive include the half-saturation constant of DO for algal DOC excretion and the minimum optimum light intensity.

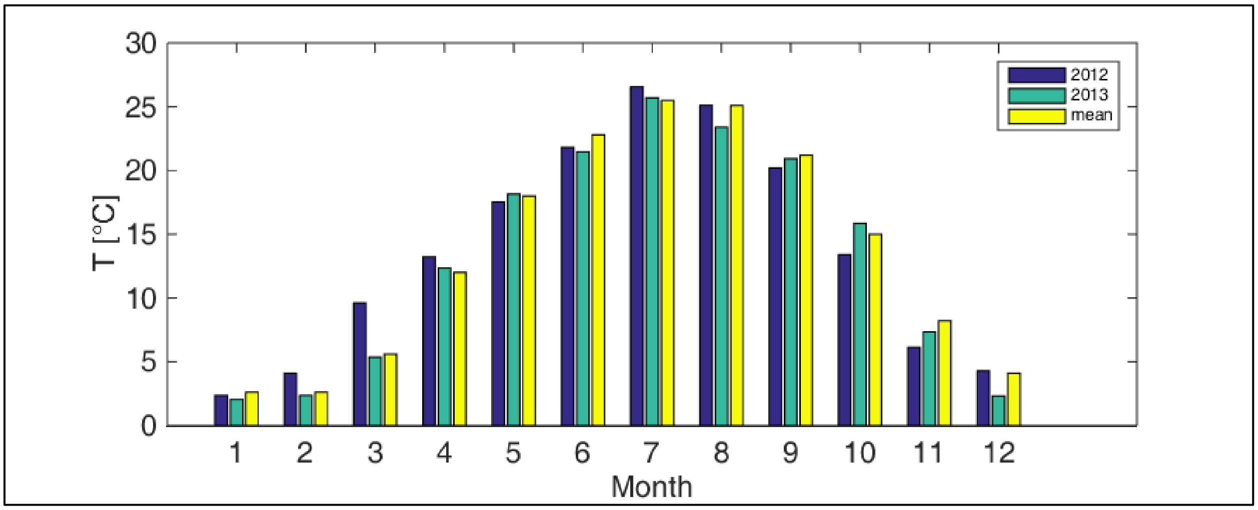
3.11 Water Quality Model Validation

Results are described below for specific parameters in the validation period. Monitoring data contained in the plots were acquired as described in Sections 3.6.2 and 3.6.3. Corresponding model results were extracted from each simulation from the model cell that most closely represents the specific sampling location.

Along-channel plots show the range of simulated values (minimum, maximum, and median) for each monitoring station plotted against river mile location, for a defined period. Station time series plots show a continuous model result time series on a 15 minute interval along with observed sample values represented as individual points.

3.11.1 Water temperature

Water temperature inputs included data from four USGS stations: Delaware River at Trenton (01463500), Schuylkill River at Fairmount Dam (01474500), Cobbs Creek at Mt. Moriah (01475548), and Delaware River at Reedy Island Jetty (01482800), which was applied at the model open boundary. Cobbs Creek was used as a proxy for all other tributaries, CSOs, and WWTP discharges. Watershed runoff water temperature for all streams used Cobbs Creek as a proxy except for the Schuylkill River, which used the Schuylkill River USGS station 01474500. A



plot of monthly mean water temperature for Delaware River at Trenton for 2012, 2013 and the 1995 – 2013 periods is below (Figure 3-20).

Figure 3-20: Mean Monthly Water Temperature of Delaware River at Trenton (USGS 01463500) for 2012, 2013 and 1995-2013 Period

Accuracy of water temperature simulation was improved by implementation of data assimilation algorithms internal to the EFDC model. The model's solution to the heat flux equations of state was supplemented by water temperature data from 6 stations. These include USGS stations Chester (01477050), Ben Franklin Bridge (01467200) and near Pennypack Woods (014670261), and NOAA stations Philadelphia (8545240), Burlington (8539094) and Newbold (8548989).

Model output indicates excellent agreement with observed water temperatures (Figure 3-21).

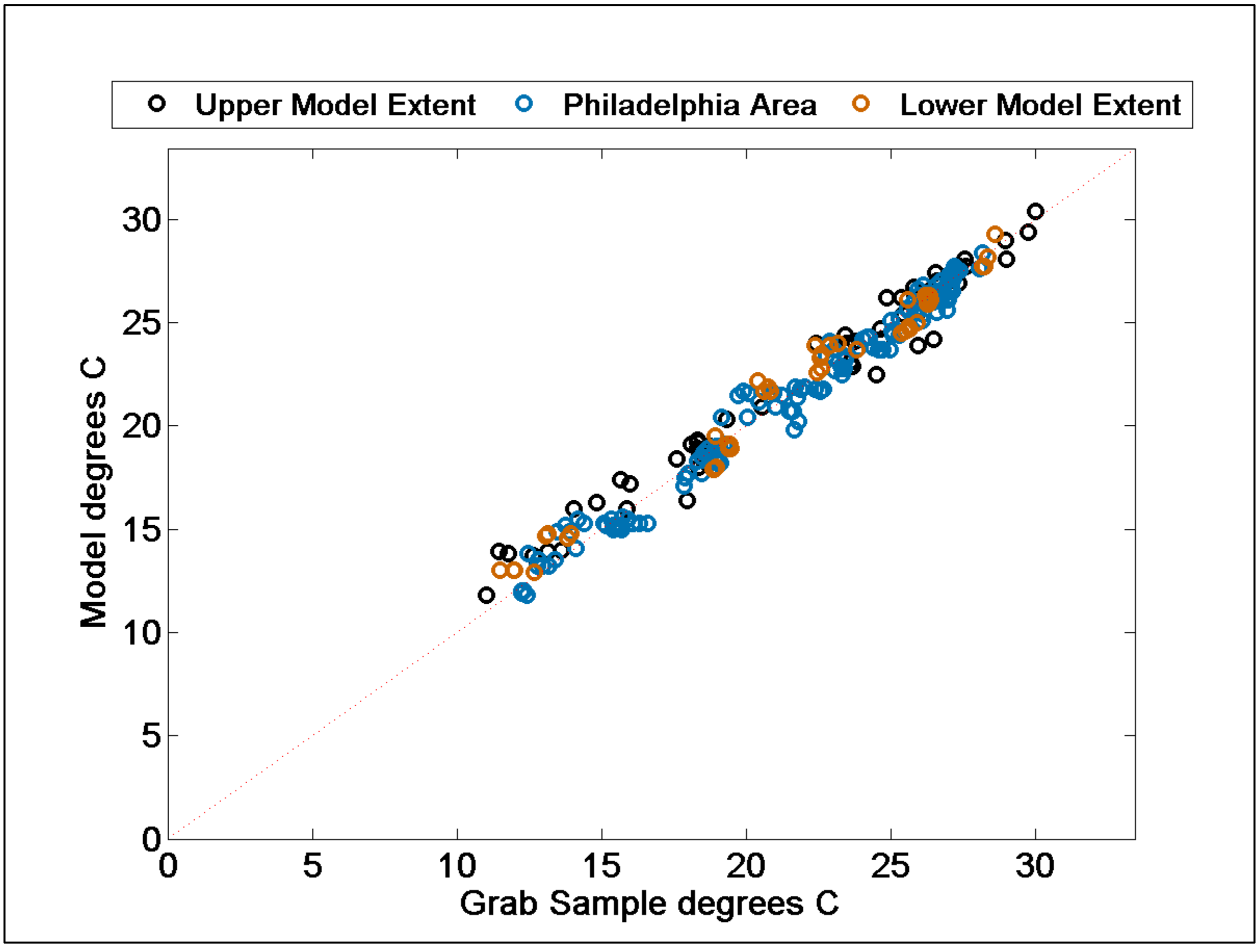


Figure 3-21: System-wide Modeled vs. Observed Water Temperature for 2012 and 2013 Validation Periods

3.11.2 Bacteria

Introduction

The EFDC water quality model was used to simulate the receiving waters' response to wet weather bacteria inputs resulting from CSOs, wastewater treatment plant discharges and direct stormwater runoff. The parameter of interest for these simulations was fecal coliform bacteria (FCB). The two validation years and seasonal period chosen for FCB model simulations were identical to those used in the previously described simulations. The 2012 and 2013 model validation years were considered dryer than average and wetter than average, respectively. The target simulation period was April 1 to October 1.

Bacteria Model configuration

The fate and transport of bacteria was simulated using the water quality parameter for fecal coliform bacteria in EFDC. While these processes are often simulated as transport of dye with first order decay in a hydrodynamics-only model, the EFDC water quality model provided the advantage of including temperature dependence along with first order decay. The formulation of this relationship in EFDC is written as:

$$\frac{\partial FCB}{\partial t} = -KFCB \times (TFCB^{(T-20)}) \times FCB + \frac{WFCB}{V} \qquad \text{Eq. 3-13}$$

where

FCB = bacteria concentration (MPN per 100 mL)
KFCB = first order die-off rate at 20°C (day^{-1})
TFCB = temperature correction factor
WFCB = external loads of fecal coliform bacteria (MPN day^{-1})
V = Volume (m^3)

For the validated Bacteria Model, KFCB = 0.8 day^{-1} and TFCB = 1.024. This first order decay rate is the equivalent of a 90% decay time of 2.88 days. The temperature term has the effect of increasing or decreasing the decay rate at water temperatures above or below 20°C, respectively.

As with other water quality model simulations, the EFDC "anti-numerical diffusion correction to standard donor cell scheme" (ISADAC) and "add flux limiting to anti-numerical diffusion correction" (ISFCT) options were activated for FCB model runs. Simulations were run with FCB as the only parameter for computational efficiency because modeled bacteria fate and transport depend only on temperature. No other water quality model state variables were included.

Review of Observed Data and Model Inputs

Bacteria data were collected in the mainstem Delaware River, center of navigation channel, by PWD starting in 2011 and by DRBC starting in 1962. These grab samples were used as reference values to measure the Bacteria Model's agreement with observed conditions in the 2 validation years. Timing of the sampling events for both PWD and DRBC were based on a planned monthly schedule and not on wet-weather event timing. Units of CFU per 100 ml (colony forming units) were treated as equivalent to MPN per 100 mL (most probable number) in performance analyses. Observations ranged from 5 to 3000 CFU/100 mL and from 8 to 2500 MPN/100 mL in 2012-2013.

As described in sections 3.8.1 through 3.8.5, bacteria loadings were applied as time series at boundary inputs representing the southern boundary, tributaries, municipal and industrial WWTPs, CSOs, and direct runoff.

Results

Bacteria Model results for the validation years of 2012 and 2013 are presented in the following pages as along-channel, station time series, and event box plot figures. Observed FCB grab sample data from the DRBC and PWD boat run monitoring programs were used as reference values, which were taken in the center of the navigation channel at regular monitoring locations for each agency. Bacteria Model results were extracted for each simulation from the model cell corresponding to grab sample locations. The time range for each figure is April 1 to October 1.

Along-channel plots display the minimum, maximum and median model results for each grab sample location plotted against river mile location (Figure 3-22 and Figure 3-25). Station time series plots display the Bacteria Model result time series on a 15 minute interval along with observed grab sample data (Figure 3-23- Figure 3-24, Figure 3-26, and Figure 3-27).

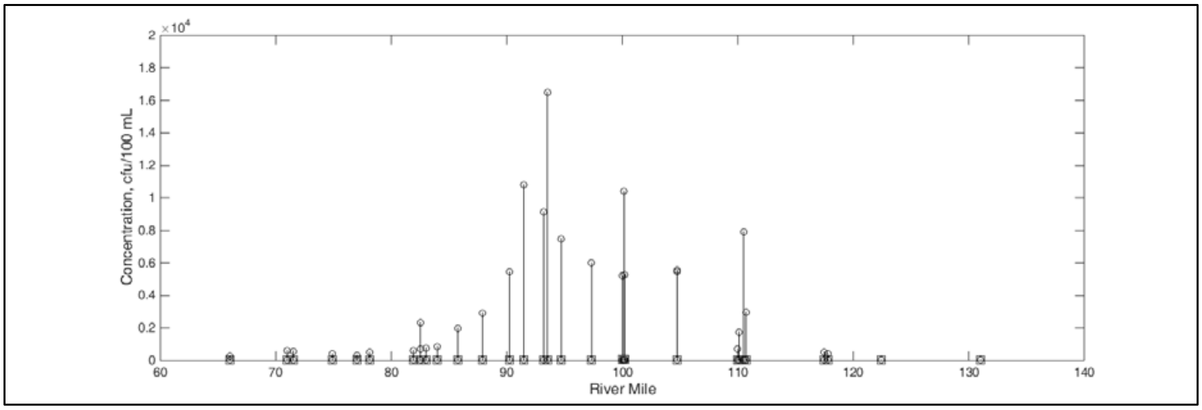


Figure 3-22: 2012 Simulation Period Modeled FCB Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

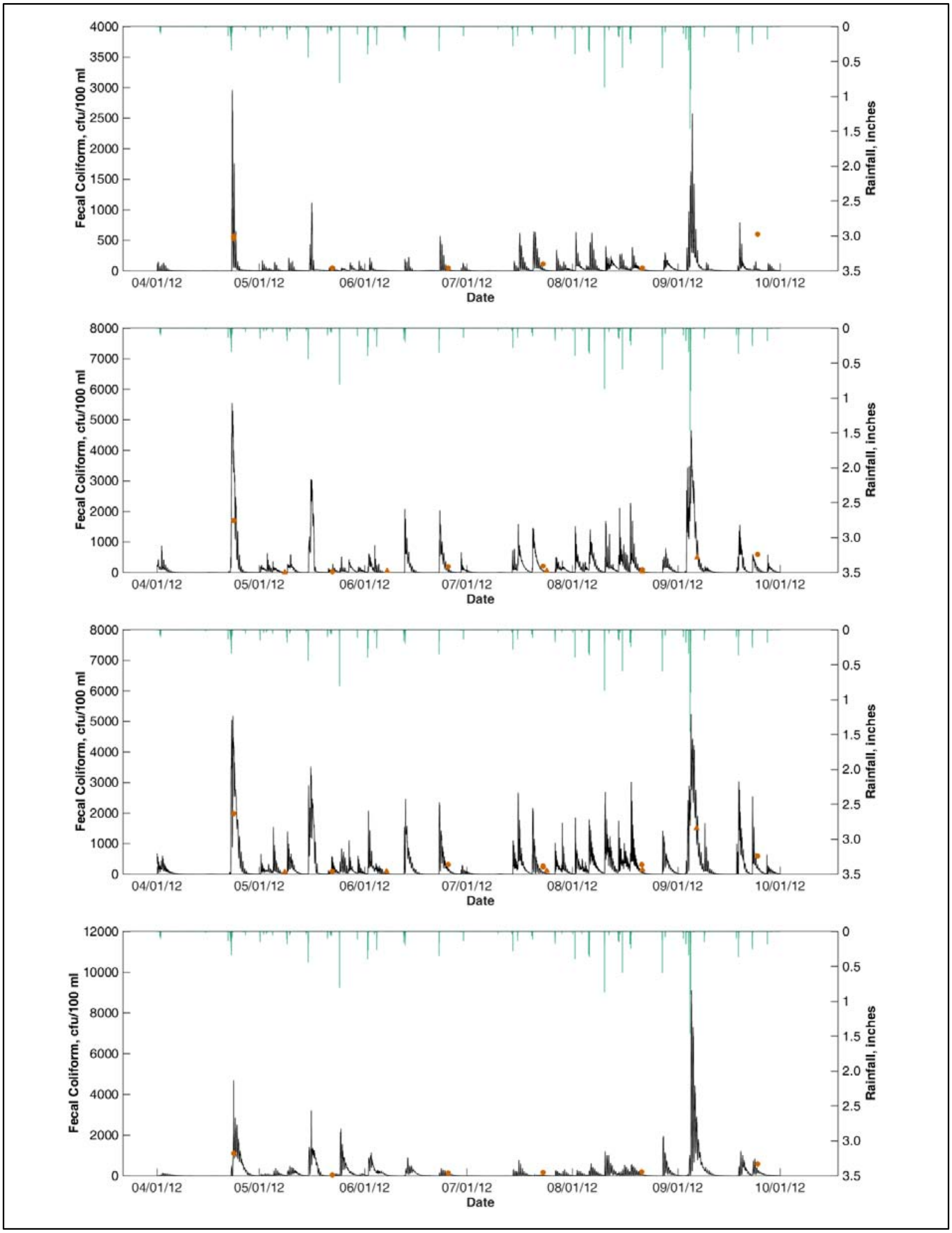


Figure 3- 23: 2012 Simulation Period Modeled and Observed FCB Concentrations, River Miles 110.7, 104.75, 100.2 and 93.2.

Both PWD and DRBC sampled at River Miles 100.2 and 93.2 (▲ = PWD, ●= DRBC)

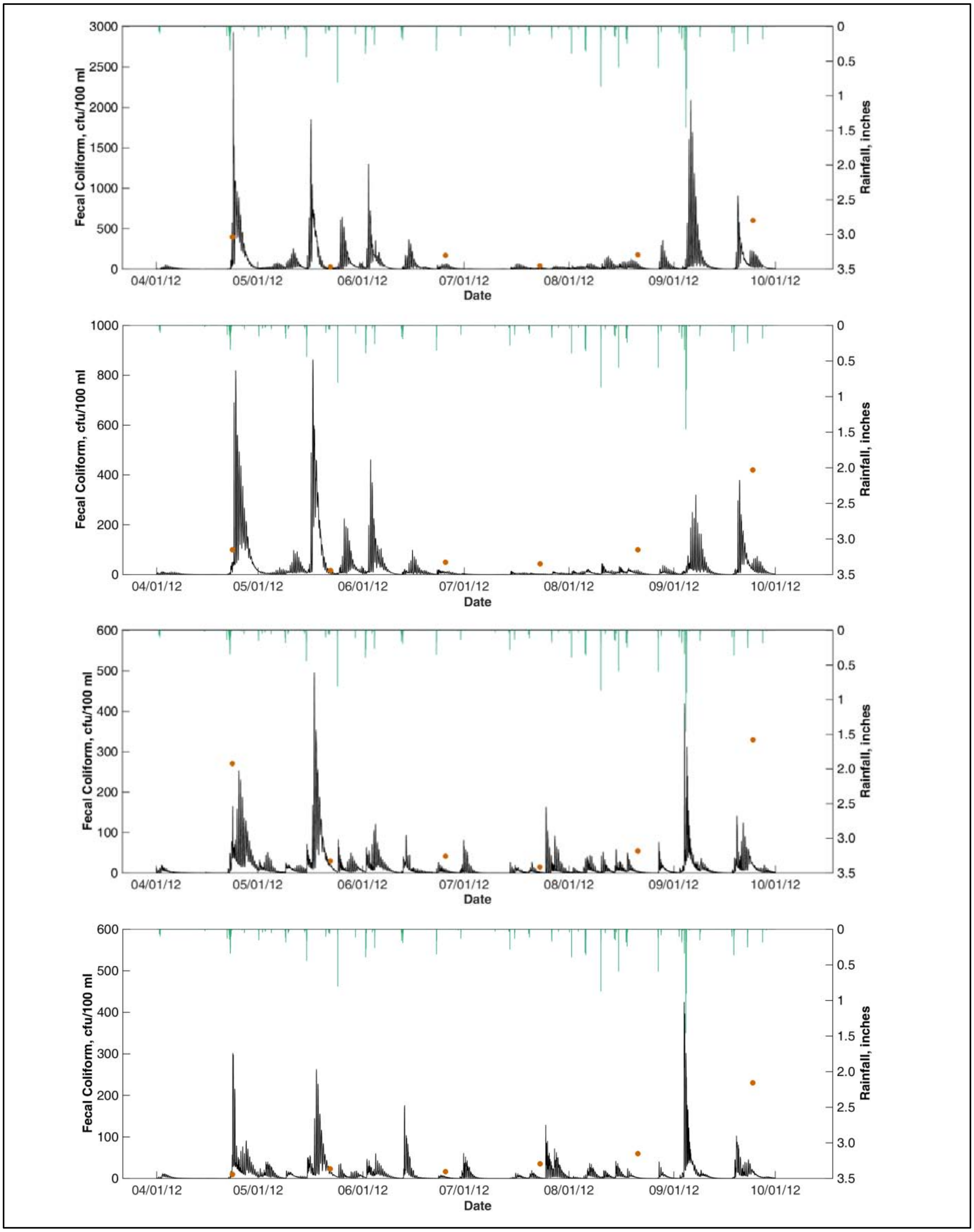


Figure 3-24: 2012 Simulation Period Modeled and Observed FCB Concentrations, River Miles 87.9, 84.0, 78.1, and 74.9 with rainfall from WBAN 13739

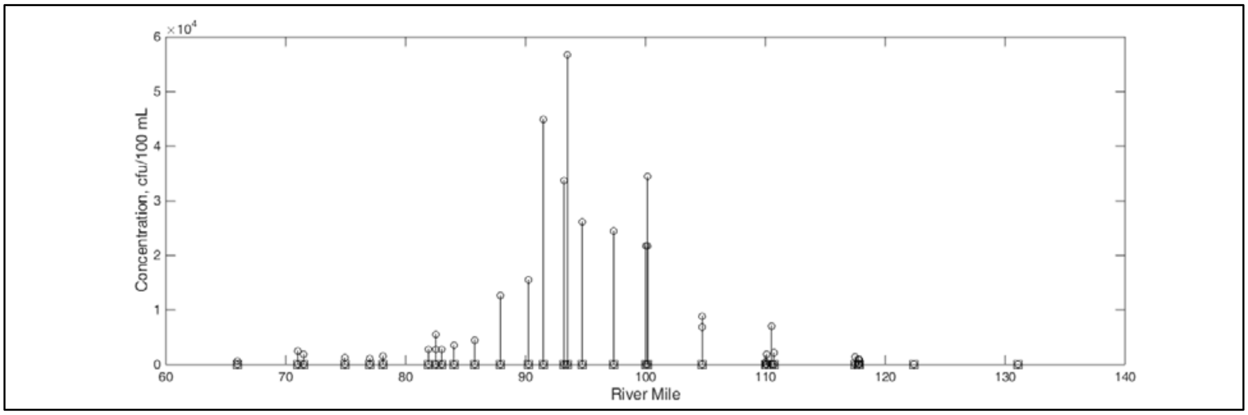


Figure 3-25: 2013 Simulation Period Modeled FCB Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

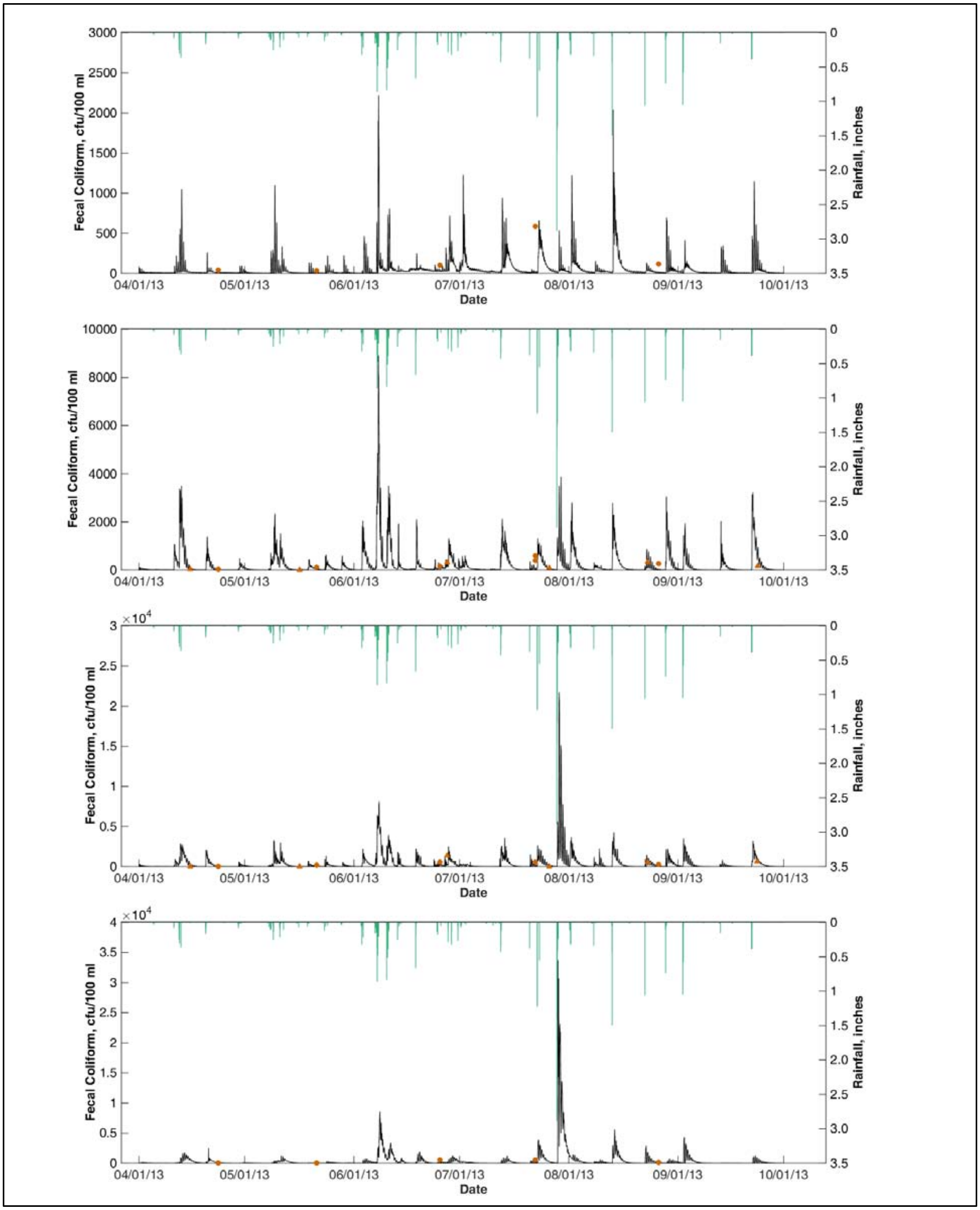


Figure 3-26: 2013 Simulation Period Modeled and Observed FCB Concentrations, River Miles 110.7, 104.75, 100.2 and 93.2 with rainfall from WBAN 13739.
Both PWD and DRBC sampled at River Miles 100.2 and 93.2 (▲ = PWD, ● = DRBC)

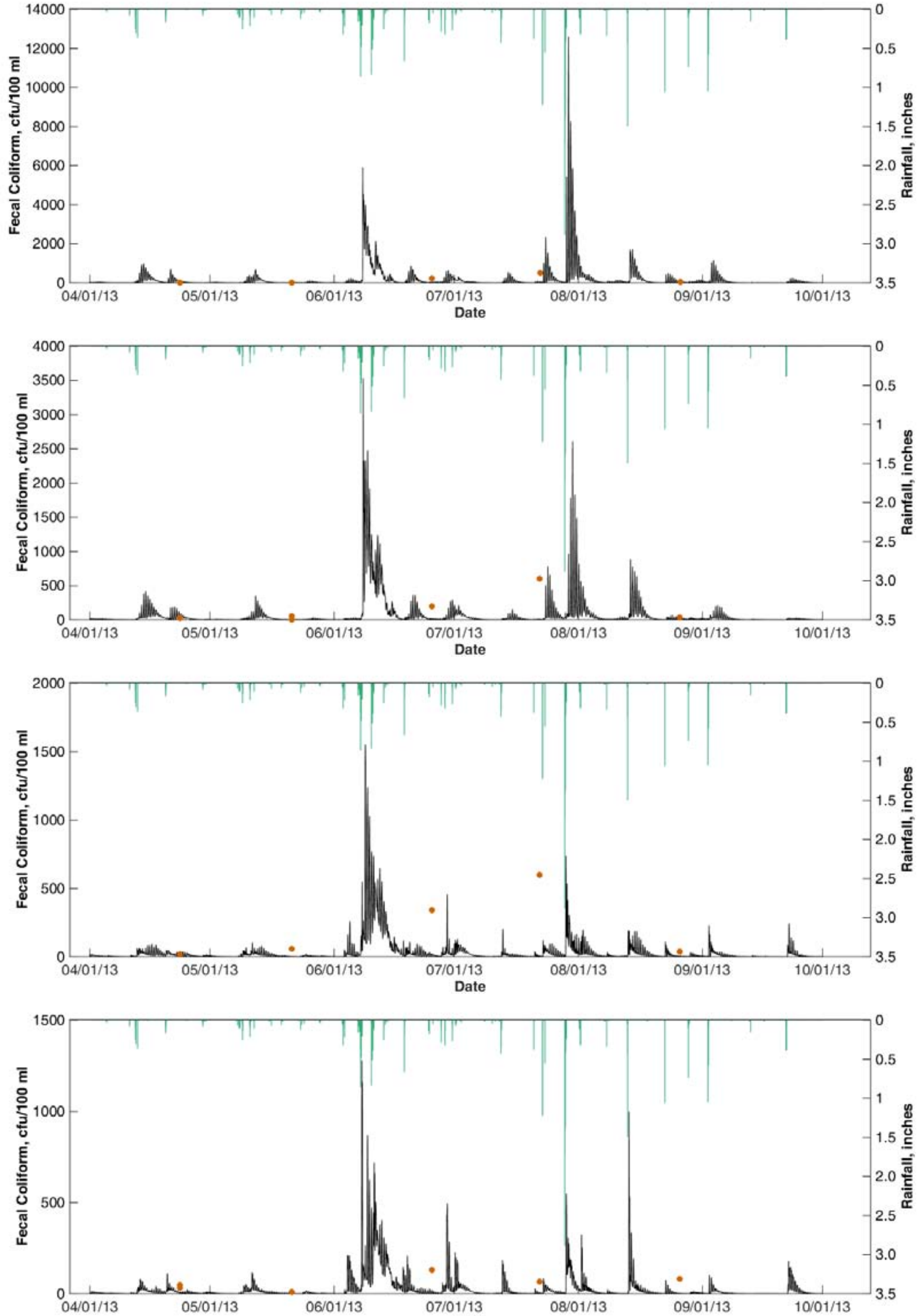


Figure 3-27: 2013 Simulation Period Modeled and Observed FCB Concentrations, River Miles 87.9, 84.0, 78.1, and 74.9

Discussion

Simulated FCB values at Chester Island (RM 84.00) and downstream (lower domain) are underpredicted in each of the validation period years (Figure 3-23 –Figure 3-24 and Figure 3-26-Figure 3-27). In contrast, Bacteria Model results at Tinicum Island (RM 87.90) and those along the Philadelphia shoreline (middle domain) demonstrate closer agreement with observations.

A likely source for the divergent model performance evident in the lower and middle domains is the difference in quality between the input data available for each. CSO inputs for FCB in the lower domain are comprised of overall mean concentration and hourly discharge values for the City of Wilmington and DELCORA as described in Section 3.8.4, and are therefore not fully representative of peak loadings associated with individual wet weather events. The middle domain inputs are comprised of FCB loadings for City of Philadelphia CSOs, which include 15 minute interval time series based on rainfall-driven validated CSS Models, along with daily FCB effluent loadings from the three Water Department WPCPs. Camden CSO inputs in the middle domain are represented in a similar manner as Wilmington and DELCORA, but are smaller in magnitude than the higher resolution Philadelphia CSO inputs.

FCB simulation performance improves in the middle domain of the model, but Bacteria Model results are often over or under predicted in comparison to the observed grab sample concentration at the stated monitoring time. It is likely that this error results from a combination of uncertainties related to rainfall data reporting and hydraulic model routing inherent in the various methods used to generate model FCB inputs.

A broader event-based approach was applied to evaluate model performance, as an alternative to a comparison based on discrete time steps implied by time series plots. At a given station, the range of simulated values during the entirety of an individual wet weather event was compared to any measurements during the event, in order to assess if the Bacteria Model reliably encompasses the range of event concentrations. At a given station, the minimum, maximum and median simulated values for specific wet weather events were extracted and compared to measurements during the related events. The results from multiple stations were aggregated into along-channel plots (Figure 3-28-Figure 3-31) that depict the range of simulated values and related measurements. Viewed from the event-based perspective, the lower domain is still underpredicted; however, the high quality of prediction in the middle domain demonstrates the Bacteria Model's ability to represent individual wet weather events in the Philadelphia area.

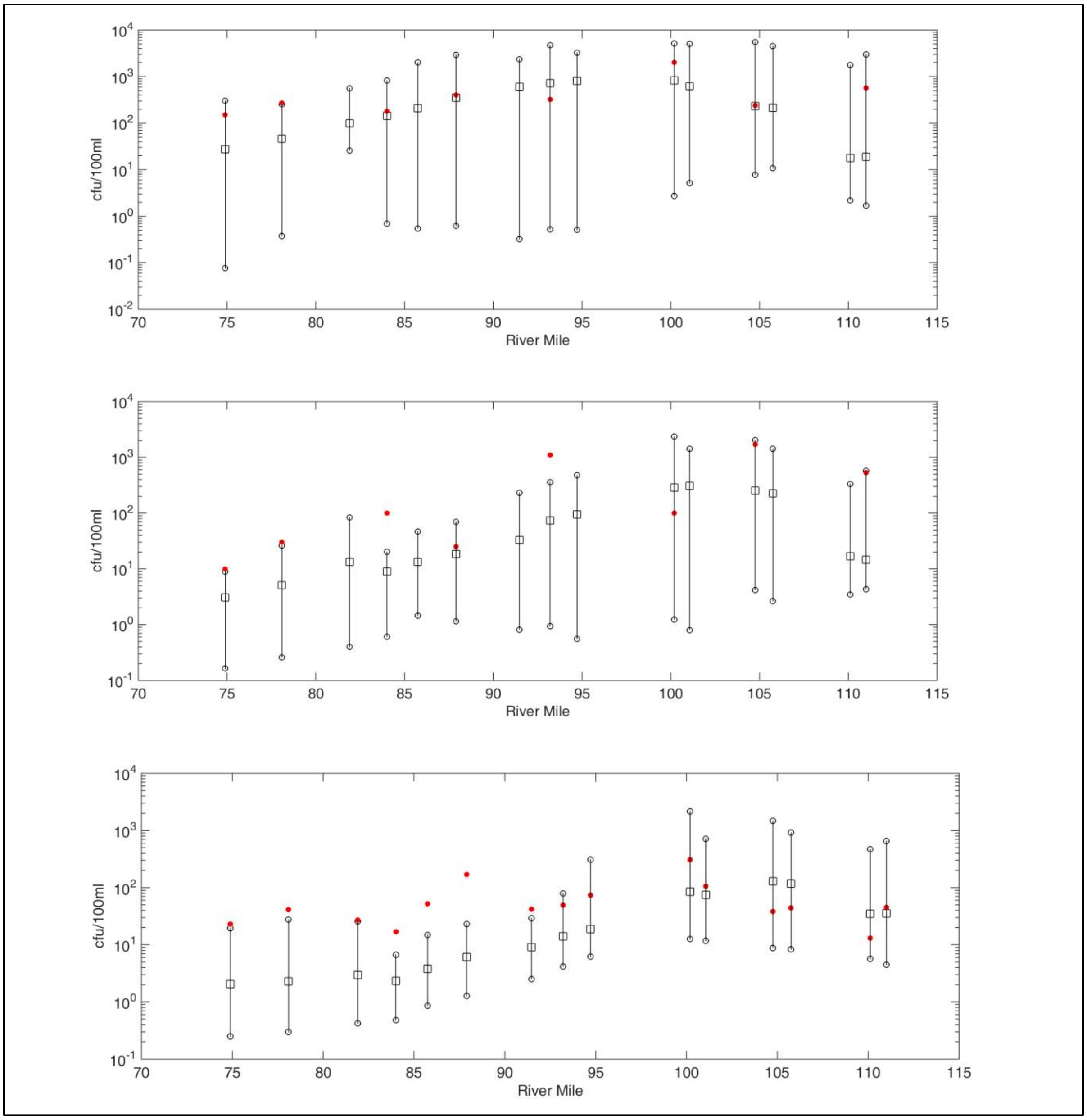


Figure 3-28: Wet-Weather Event Model Summary Statistics (○ = min, max; □ = median) and Observed Data (● = grab sample) Versus River Mile. Events represented are for April 22, June 22, and July 20 in 2012.

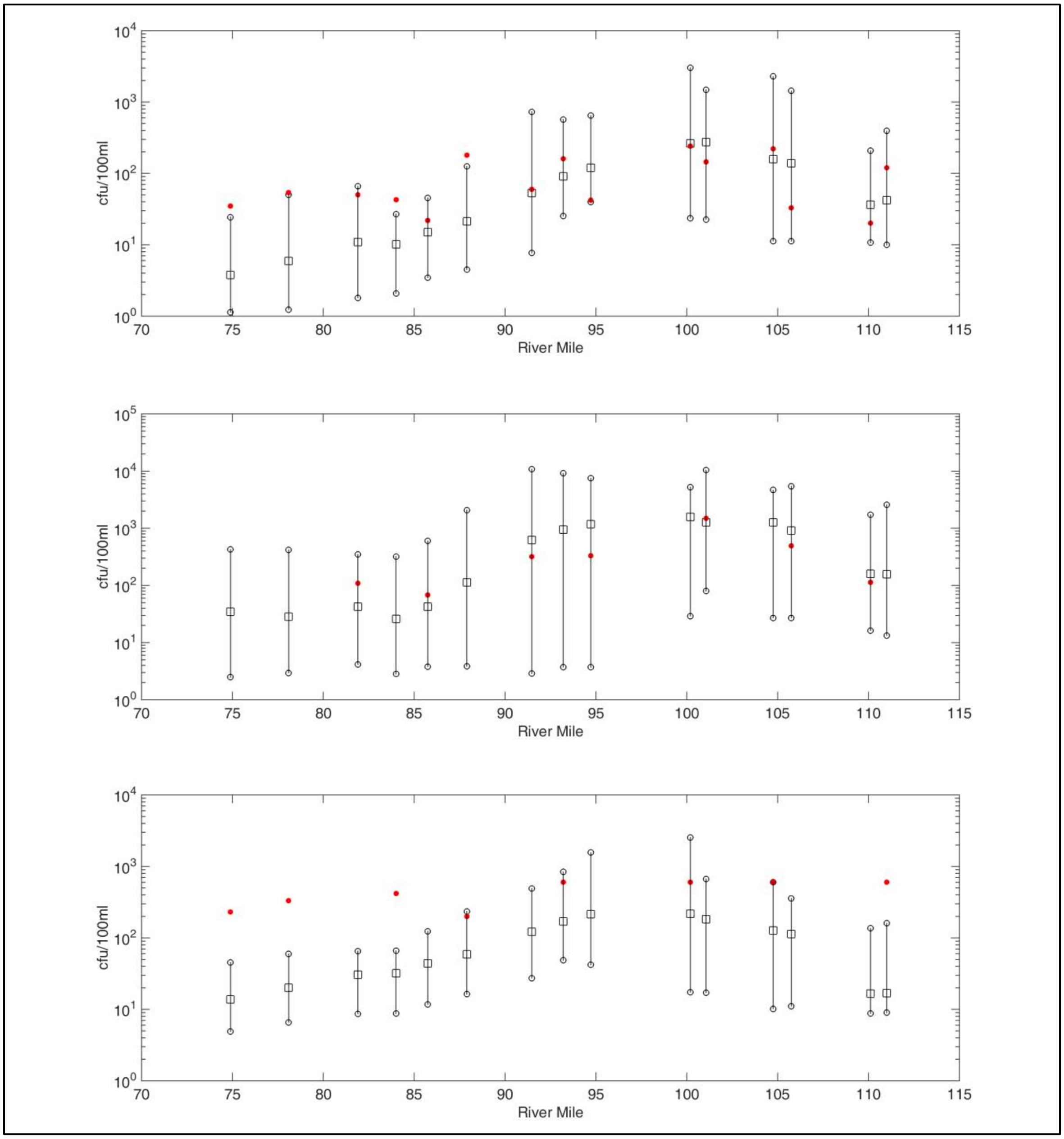


Figure 3-29: Wet-Weather Event Model Summary Statistics (○ = min, max; □ = median) and Observed Data (● = grab sample) Versus River Mile. Events represented are for August 17, September 3, and September 22 in 2012.

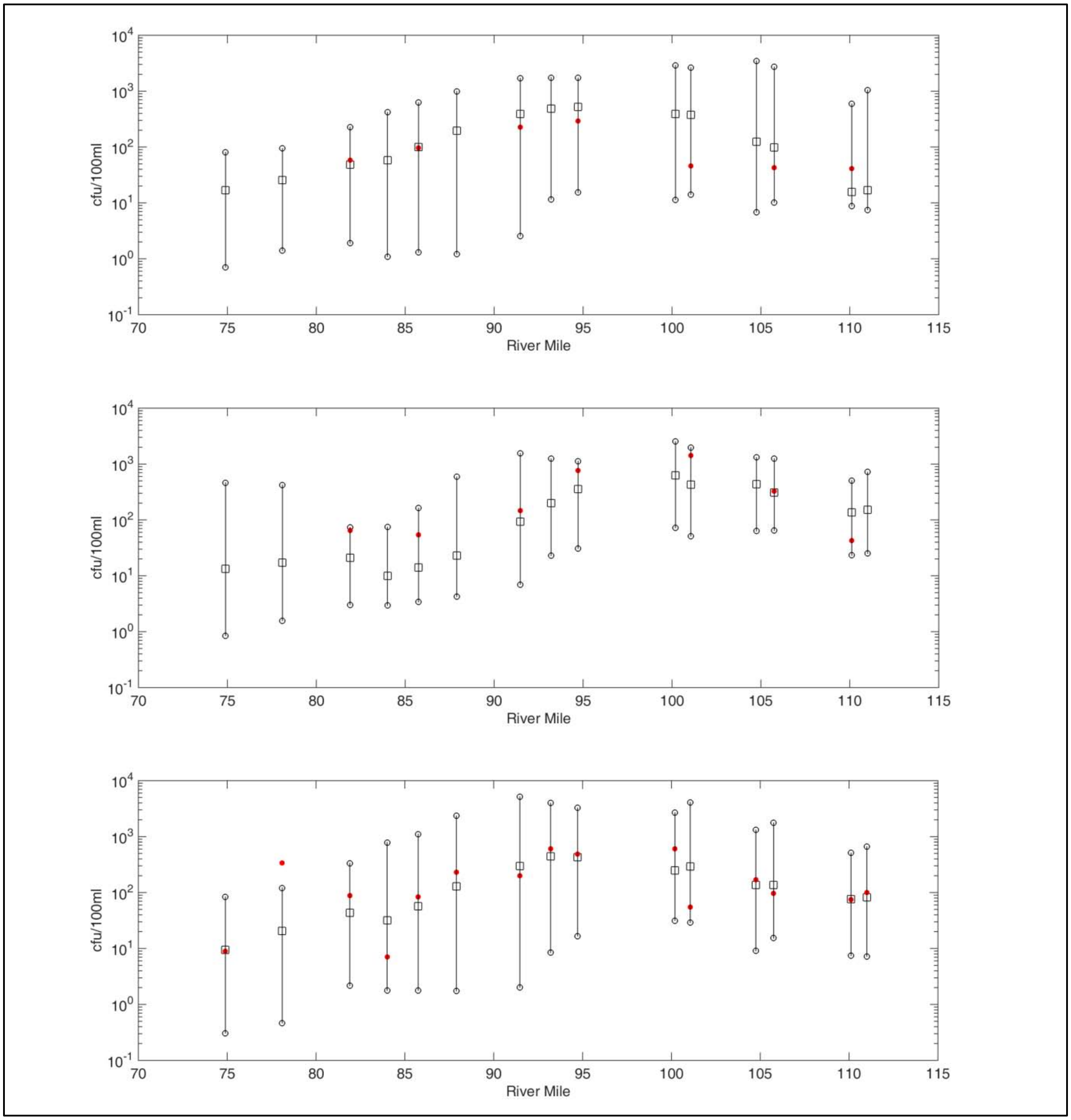


Figure 3-30: Wet-Weather Event Model Summary Statistics for (○ = min, max; □ = median) and Observed Data (● = grab sample) versus River Mile. Events represented are for April 12, June 27, and July 22 in 2013.

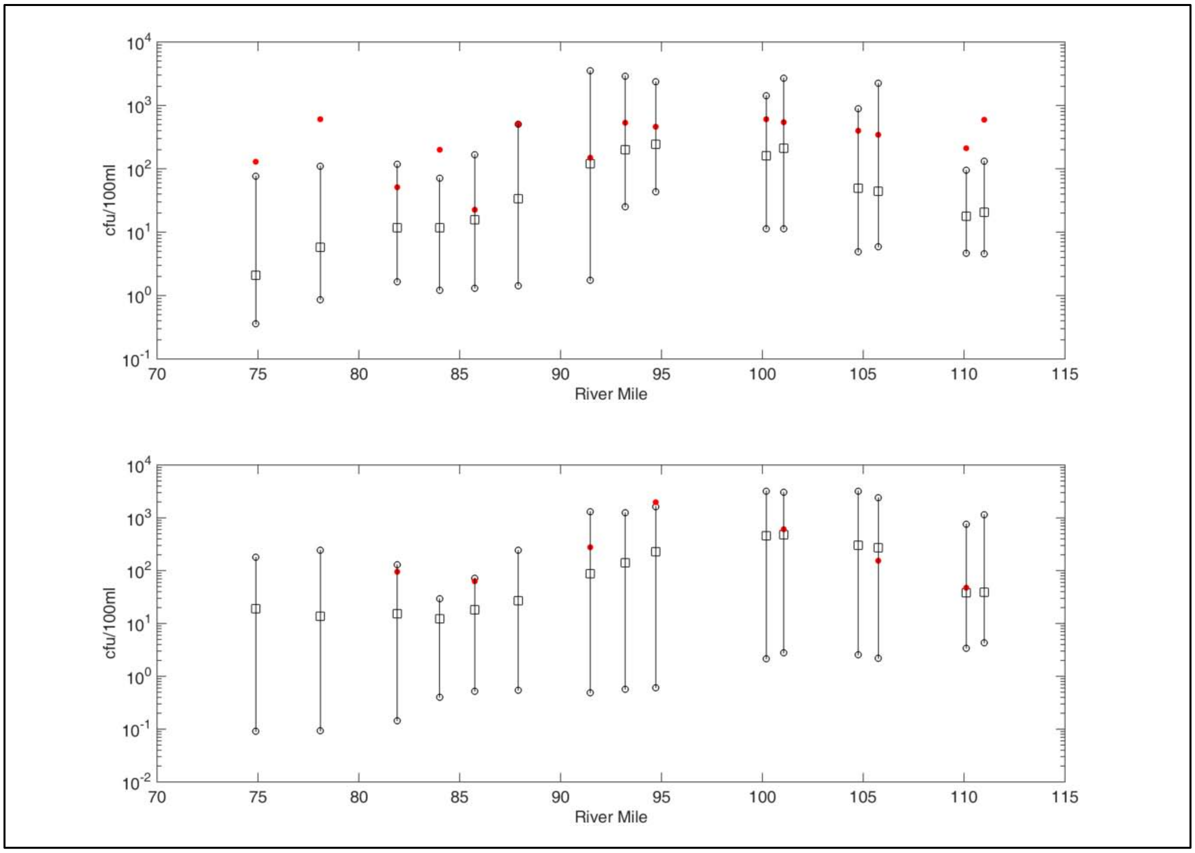


Figure 3-31: Wet-Weather Event Model Summary Statistics (○ = min, max; □ = median) and Observed Data (● = grab sample) Versus River Mile. Events represented are for August 22 and September 21 in 2013.

3.11.3 DO Model Kinetic Rate Constants

Water Column

Water column kinetic rate constants and other parameters applied globally in the validated DO Model are listed in Table 3-17.

Table 3-17: Kinetic Rate Constants Applied Globally in Validated DO Model

Parameter Name	Parameter	Global Value
KHNc	Nitrogen half-saturation for algae (mg/L)	0.021
KHPc	Phosphorus half-saturation for algae (mg/L)	0.003
CChlc	Carbon-to-chlorophyll ratio for algae (mg C / µg Chl)	0.02
DOPTc	Optimal depth for algae growth (m)	1
KeCHL	Light extinction for total suspended chlorophyll (1/m per g/m3)	0.01
KeTSS	Light extinction for total suspended solids (1/m per g/m3)	0.055
Cia	Weighting factor for solar radiation at current day	0.7
Cib	Weighting factor for solar radiation at (-1) days	0.2
Cic	Weighting factor for solar radiation at (-2) days	0.1
FD	Fraction of day that is daylight	from atmospheric input
I0	Initial solar radiation (Langley/day) at water surface	28
ISMIN	Minimum optimum solar radiation (Langley/day)	40
PARAdj	Solar radiation PAR adjustment factor	0.45
Rea	Global reaeration adjustment factor	1
TMc1	Lower optimal temperature for algal growth	20
TMc2	Upper optimal temperature for algal growth	30
KTG1c	Sub optimal temperature effect coefficient for growth	0.008
KTG2c	Super optimal temperature effect coefficient for growth	0.008
KTBc	Temperature effect coef. for algae metabolism	0.02
TRc	Reference temperature for algae metabolism	20
FCDc	Carbon distribution coef. for algae metabolism	1
FCDP	Carbon distribution coef. for algae predation: DOC	0.1
FCLP	Carbon distribution coef. for algae predation: labile POC	0.9
KHRc	Half-sat. constant (gO2/m3) for algae DOC excretion	0.5
KDC	Minimum dissolution rate (1/day) of DOC	0.045
KDCalg	Constant relating DOC dissolution rate to total chl-*a*	0
KLC	Minimum dissolution rate (1/day) of labile POC	0.01

Parameter Name	Parameter	Global Value
KLCalg	Constant relating labile POC dissolution rate to total chl-*a*	0
AANOX	Ratio of denitrification rate to oxic DOC respiration rate	0.25
KHDNN	Half-sat. constant for denitrification (gN/m^3) (for nitrate)	0.1
KHORDO	Oxic respiration half-sat. constant for D.O. (gO_2/m^3)	0.5
KTHDR	Temperature effect constant for hydrolysis	0.069
KTMNL	Temperature effect constant for mineralization	0.069
TRHDR	Reference temperature for hydrolysis (◦C)	20
TRMNL	Reference temperature for mineralization (◦C)	20
FPDP	Phos. distribution coef. for algae predation: DOP	0.2
FPIP	Phos. distribution coef. for algae predation: Inorganic P	0.2
FPLc	Phos. distribution coef. of LPOP for algae metabolism	0.5
FPLP	Phos. distribution coef. for algae predation: labile POP	0.6
FPDc	Phos. distribution coef. of DOP for algae metabolism	0.4
FPIc	Phos. distribution coef. of PO4T for algae metabolism	0.1
KPO4p	Partition coefficient for sorbed/dissolved PO_4	0.2
CPprm1	Constant used in determining algae Phos-to-Carbon ratio	20
CPprm2	Constant used in determining algae Phos-to-Carbon ratio	0
CPprm3	Constant used in determining algae Phos-to-Carbon ratio	0
KDP	Minimum mineralization rate (1/day) of DOP	0.04
KDPalg	Constant relating mineralization rate of DOP to algae	0
KLP	minimum hydrolysis rate (1/day) of LPOP	0.025
KLPalg	Constant relating hydrolysis rate of LPOP to algae	0
FNDP	Nitrogen distribution coef. for algae predation: DON	0.1
FNIP	Nitrogen distribution coef. for algae predation: Inorganic N	0.1
FNLc	Nitrogen distribution coef. of LPON for algae metabolism	0.4
FNLP	Nitrogen distribution coef. for algae predation: LPON	0.8
ANCc	Nitrogen-to-carbon ratio for algae	0.14
FNDc	Nitrogen distribution coef. of DON for algae metabolism	0.5
FNIc	Nitrogen distribution coef. of DIN for algae metabolism	0.1
ANDC	Mass NO_3 reduced per DOC oxidized (gN/gC)	0.933
KHNitDO	Nitrification half-sat. constant for DO (mg/L)	1
KHNitN	Nitrification half-sat. constant for NH_4 (mg/L)	0.25
KNit1	Temperature effect constant for nitrification	0.0045
rNitM	Maximum nitrification rate (gN/m_3/day)	spatially variable

Parameter Name	Parameter	Global Value
TNit	Reference temperature for nitrification (◦C)	20
KDN	Minimum mineralization rate (1/day) of DON	0.01
KDNalg	Constant relating mineralization rate of DON to algae	0
KLN	Minimum hydrolysis rate (1/day) of LPON	0.005
KLNalg	Constant relating hydrolysis rate of LPON to algae	0
AOCR	Stoichiometric algae oxygen-to-carbon ratio (gO_2/gC)	2.67
AONT	Stoichiometric algae oxygen-to-nitrate ratio (gO_2/gN)	4.33
KRO	Reaeration constant (3.933 for O'Connor-Dobbins)	3.933
KTR	Temperature rate constant for reaeration	1
BMRc	Basal metabolism rate for algae (1/day)	0.11
Keb	Background light extinction coefficient (1/m)	spatially variable
PMc	Maximum growth rate for algae (1/day)	3.4
PRRc	predation rate on algae (1/day)	0.02
REAC	reaeration adjustment factor	1
WSc	settling velocity for algae (m/day)	0.2
WSlp	settling velocity for labile POM (m/day)	0.1

Spatially variable nitrification rates and background light extinction are described in Section 3.6.4.

Benthos

SOD and benthic nutrient flux rates applied in the validated DO Model are described in section 3.6.4. The SOD rate in Frankford Creek was further increased through DO Model validation.

3.11.4 Carbon

DOC is generally underpredicted throughout the model domain by 1 to 2 mg/L in 2012 and 2013 (Figure 3-32). Predictions of DOC in the Philadelphia area and lower model extent are generally more underpredicted than in the upper model extent, with the latter having benefitted from time-variable loading at Trenton based on observed data.

Unlike other water quality models such as WASP which use BOD to represent oxygen demanding organic material, EFDC is carbon-based. However, most water quality data - particularly for point sources- is reported in terms of BOD, not TOC or DOC. DOC and POC loadings were derived in many cases based on available BOD data. It is possible that in performing this conversion, the true amount of DOC and POC loadings were underestimated. Boundary concentrations of DOC and POC were multiplied by 2.5 for all sources between River Miles 70.0 and 122.40, except the Schuylkill River, to improve model performance. The Schuylkill River was excluded from DOC and POC load scaling because the boundary concentrations for that tributary were based directly on DOC and TOC measurements. Investigations of higher scaling factors yielded unrealistically low DO concentrations.

The discrepancy in predicting carbon could also be due to underprediction of algal biomass, since algal predation and metabolism are sources of POC and DOC.

The along-channel plot of simulated TOC (as the sum of DOC and POC) (Figure 3-33) indicates a minimum is reached between River Miles 75 and 80 in the April to October periods of 2012 and 2013. The median prediction of 2 mg/L TOC in that extent indicates underprediction. The Chester USGS gage is located at RM 83.10, with similar TOC concentrations. The underprediction of DOC (Figure 3-34) in 2012 at RM 84.0 explains in part the overprediction of DO at the Chester gage, since there is insufficient DOC for heterotrophic bacteria to consume, and deplete DO through respiration. The TOC maxima near River Mile 110 in each year are due to the simulated influence of the Rancocas Creek on the New Jersey side of the channel, and are likely a localized modeling artifact of DOC and POC load scaling.

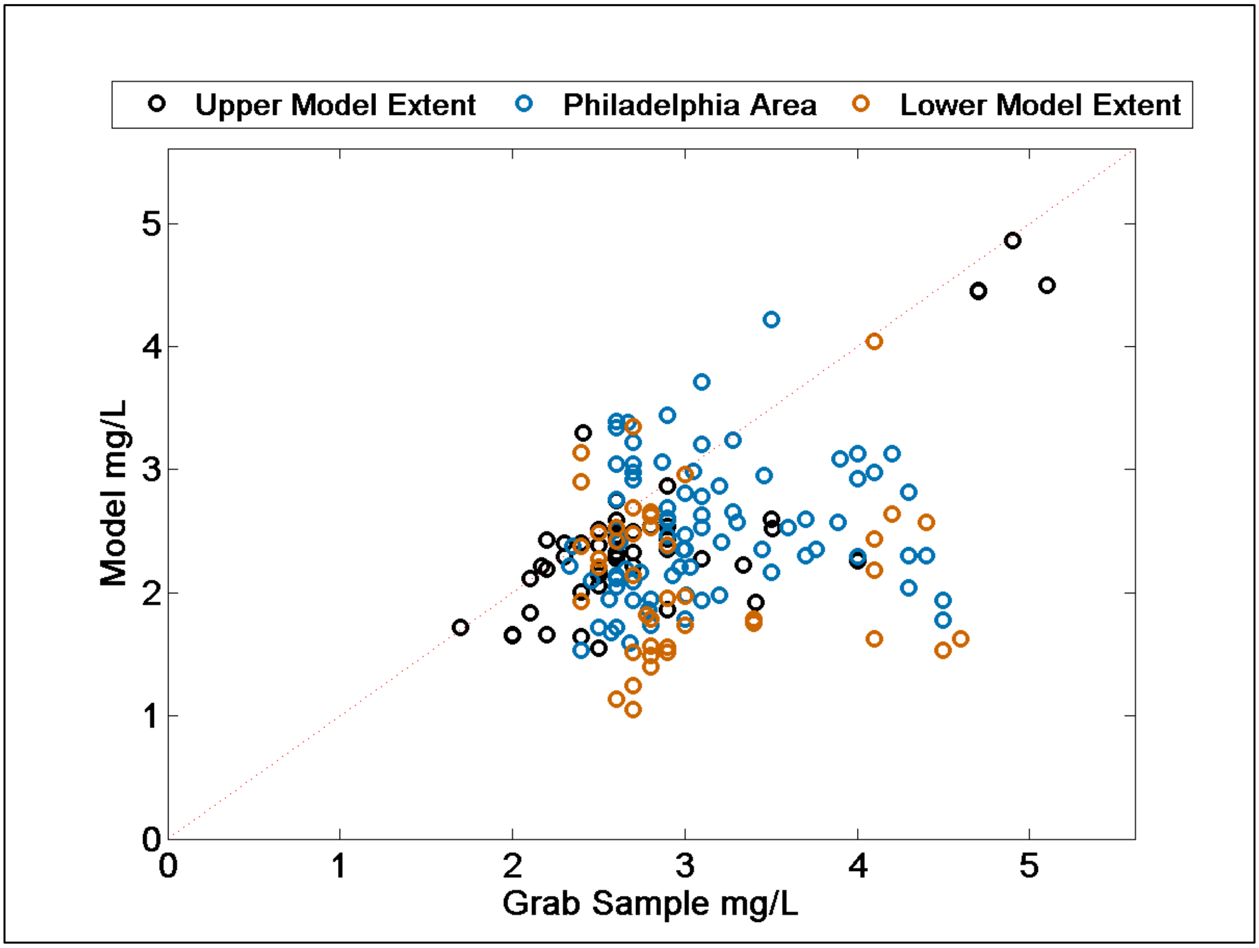


Figure 3-32: System-wide Scatter Plot of Modeled vs. Observed DOC in 2012-2013

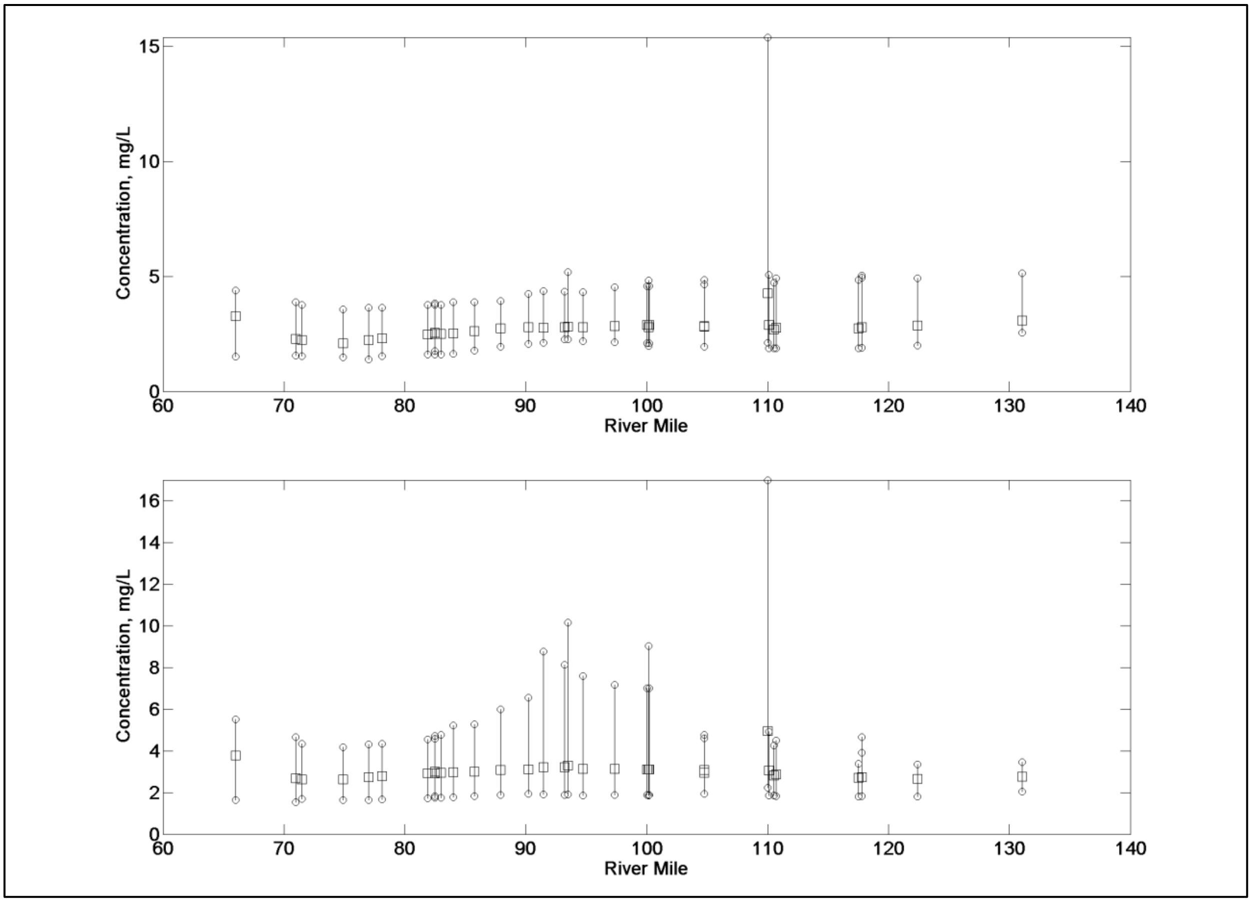


Figure 3-33: April to October 2012 and 2013 Modeled TOC Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

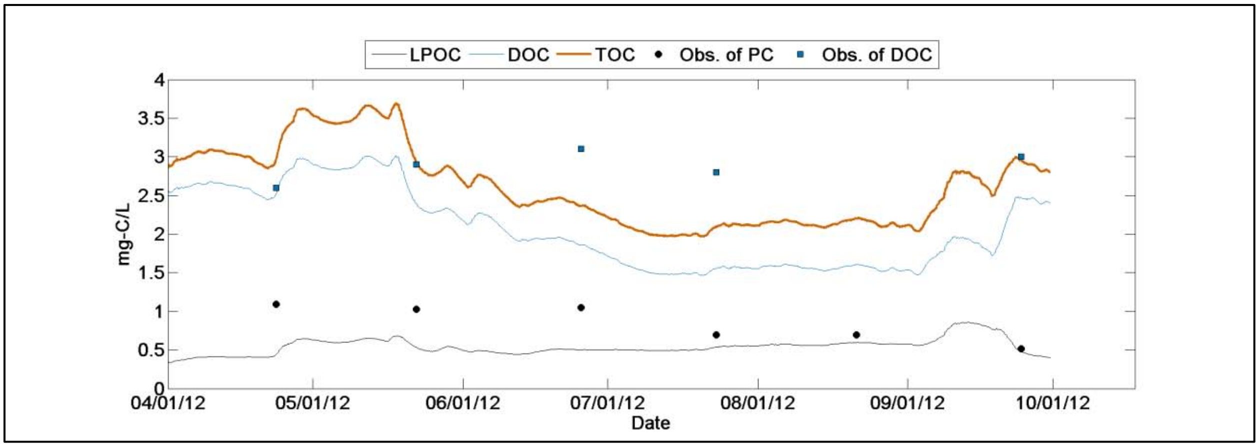


Figure 3-34: 2012 Time Series Plot of Modeled and Observed Carbon Species at River Mile 84.00

3.11.5 Nitrogen

In the Philadelphia area and lower model extent, ammonium is well predicted at observed concentrations less than 0.1 mg-N/L (Figure 3-35), a range that is observed seasonally in warm water temperatures when nitrification rates are elevated and DO is consequently most subject to depletion from ammonium loadings. Ammonium is generally underpredicted at observed concentrations greater than 0.1 mg-N/L, which occurs almost exclusively in the Philadelphia area and lower model extent, and seasonally outside the period of warm water temperatures when nitrification rates are suppressed and DO is less depleted by ammonium loadings. Time series output of ammonium at River Mile 93.20, located in the DO sag, demonstrate that ammonium concentrations are lower and best predicted around the summer season (Figure 3-36).

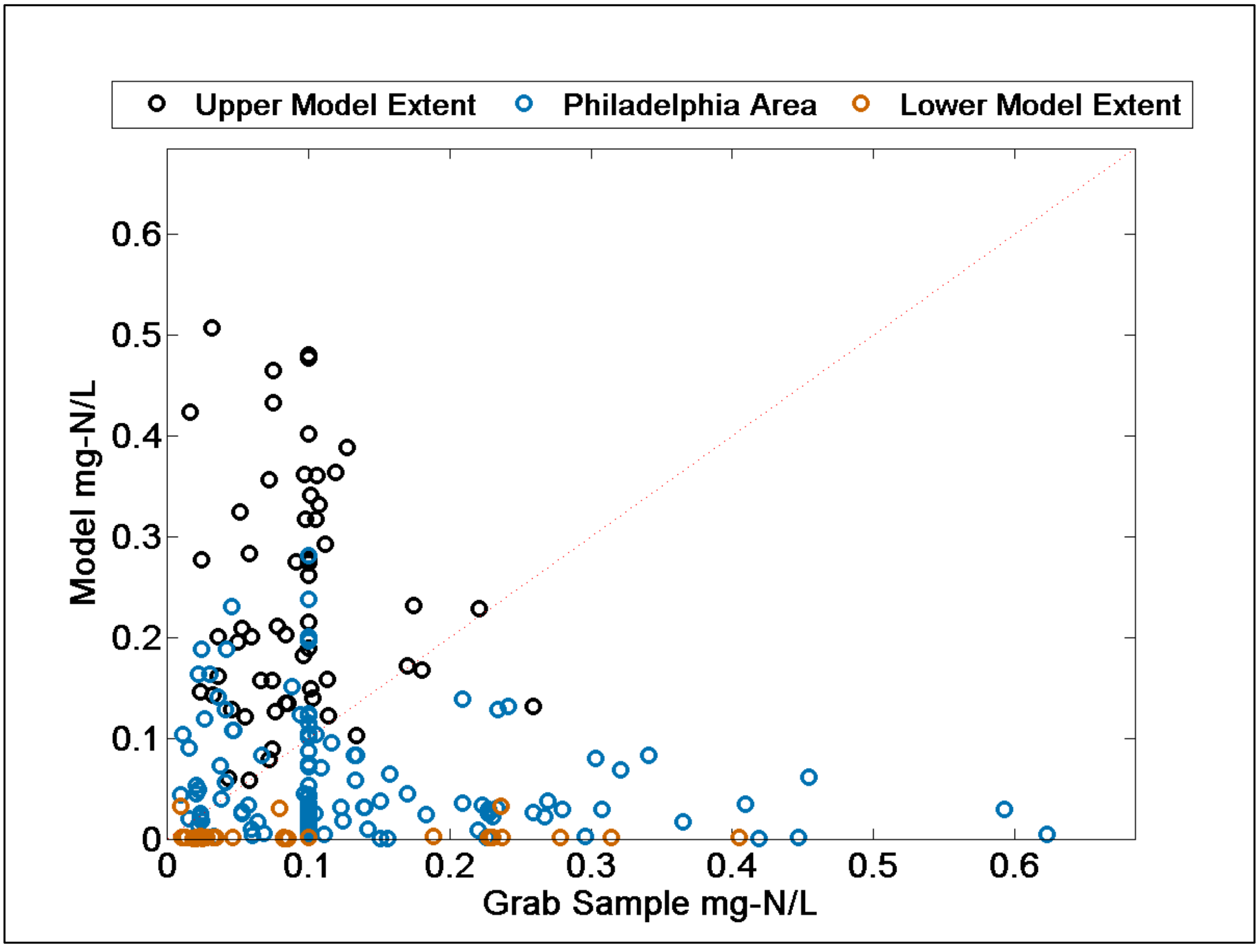


Figure 3-35: System-wide Scatter Plot of Modeled vs. Observed Ammonium in 2012-2013

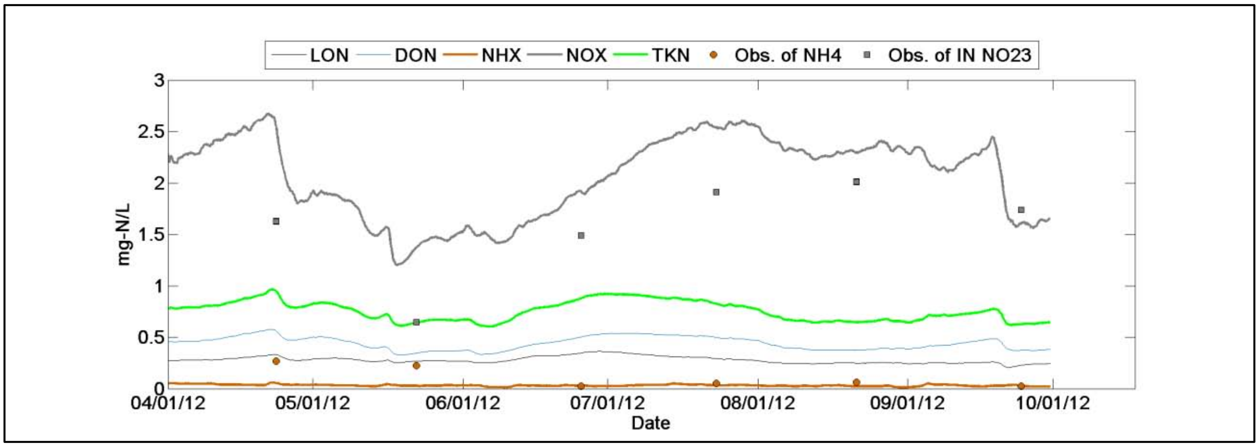


Figure 3-36: 2012 Time Series Plot of Modeled and Observed Nitrogen Species at River Mile 93.20

Ammonium is generally overpredicted in the upper model extent, probably because the assigned zonal nitrification rate of 0.01 per day is too low (Figure 3-37). In contrast, the comparatively better predicted ammonium in the Philadelphia area and lower model extent indicates the spatially-varying nitrification rates in this area are more robust (Figure 3-36); a more refined nitrification temperature adjustment coefficient setting may improve ammonium predictions in this zone outside the summer season. Nitrate concentrations increase in the extent between River Miles 110.70 and 93.20 due to permitted discharger inputs and higher rates of nitrification; considering that ammonium is well predicted in summer (Figure 3-36), the overprediction of nitrate at RM 93.20 is more likely due to overestimate of permitted discharger loadings.

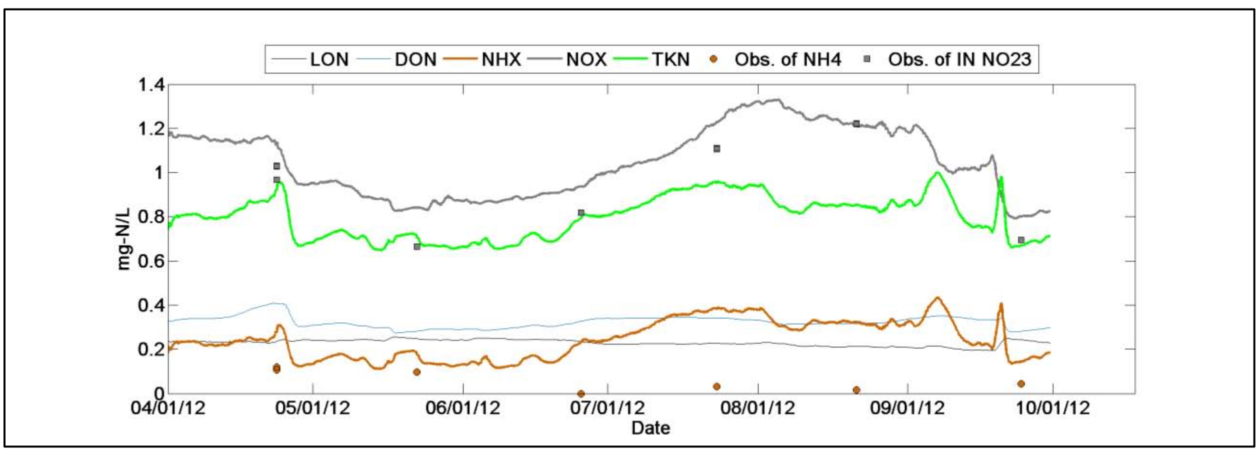


Figure 3-37: 2012 Time Series Plot of Modeled and Observed Nitrogen Species at River Mile 110.70

Along-channel plots of simulated ammonium (Figure 3-38) in July 1 – Sep 15, 2012 demonstrate the effects of spatially-varying nitrification rates which increase going downstream, causing ammonium to decrease downstream despite the high loadings in the Philadelphia area.

In the Philadelphia area and lower model extent, ammonium is subject to high rates of nitrification which yield the increased nitrate concentrations seen in the extent of River Miles 70 to 100 (Figure 3-38).

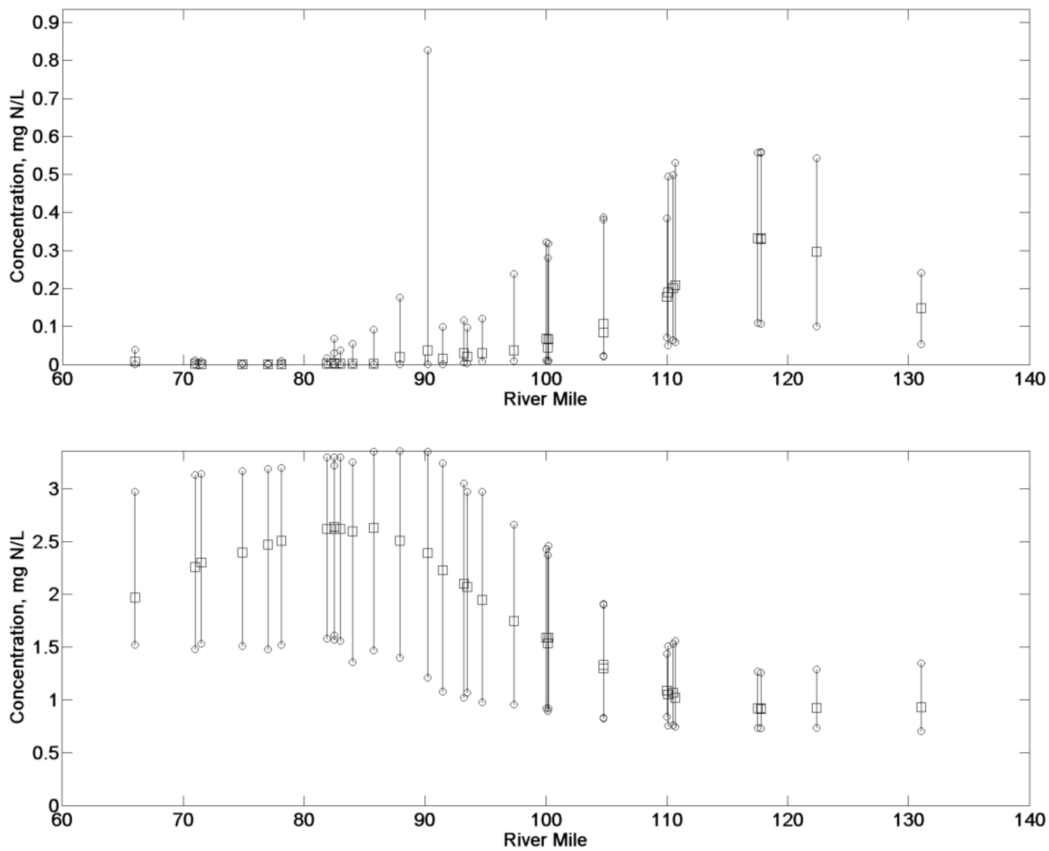


Figure 3-38: Summer 2012 Modeled NH_4 and NO_3 Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

Overall, the proportions of dissolved inorganic nitrogen (DIN) that are made up by nitrate and ammonium are consistent with Sharp (2010) and indicate that in terms of inorganic nitrogen, the DO Model is qualitatively characterizing the system quite well. In terms of organic nitrogen, the range of predicted TKN is less than observed (Figure 3-39). Consideration of both TKN and NH4 scatter plots infer that DON and PON are generally predicted as well as NH4 when the latter is evaluated over the entire range of observed concentrations.

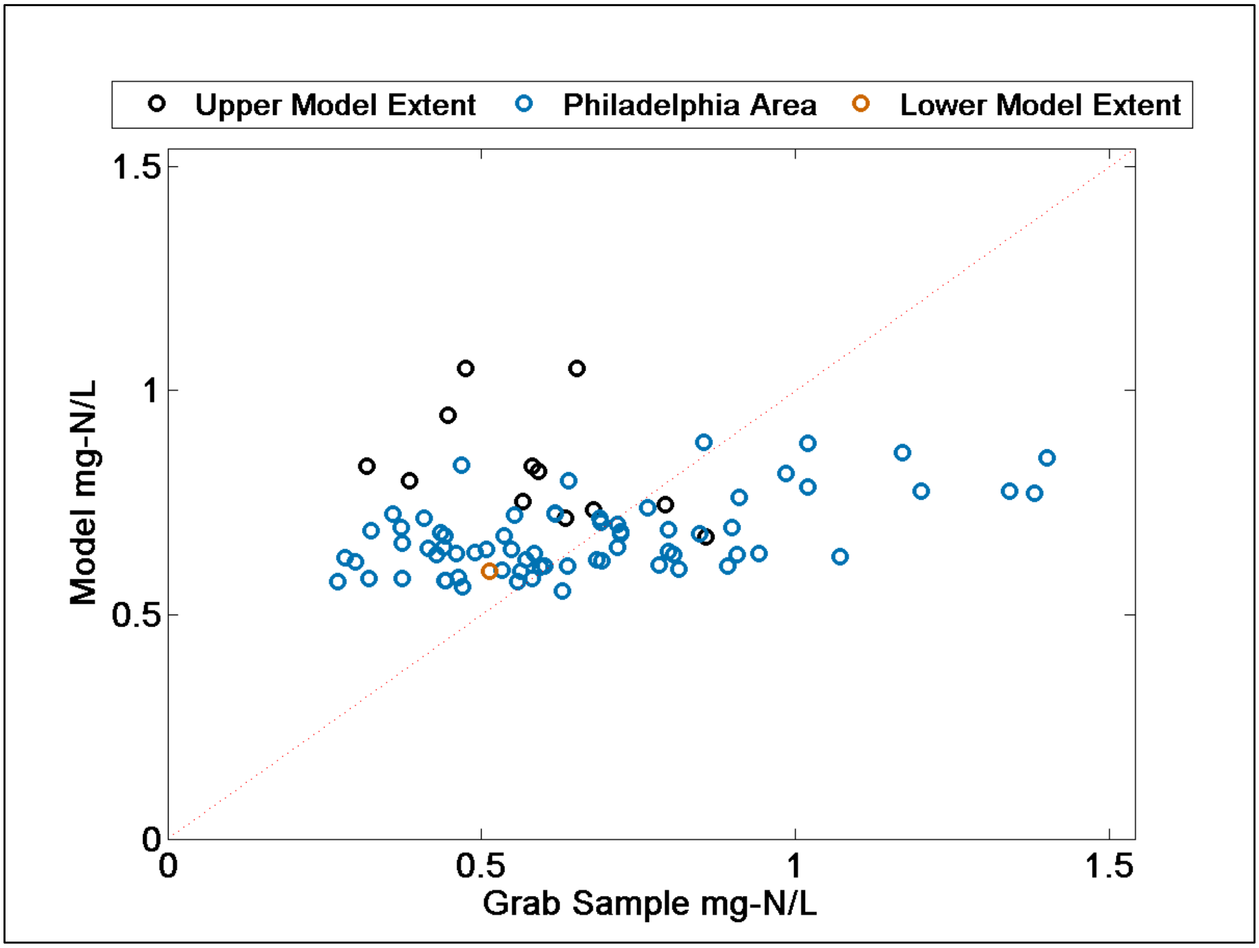


Figure 3-39: System-wide Scatter Plot of Modeled vs. Observed TKN in 2012-2013

Nitrate is overpredicted in the Philadelphia area and lower model extent (Figure 3-40), possibly due to overestimation of nitrate for permitted dischargers that did not report this parameter on DMRs. Underprediction of algal biomass is also a factor, resulting in less uptake of nitrate. Nitrification of ammonium is likely not overestimated considering the discussion of ammonium results above, and the basis of spatially-varying nitrification rates on observed data.

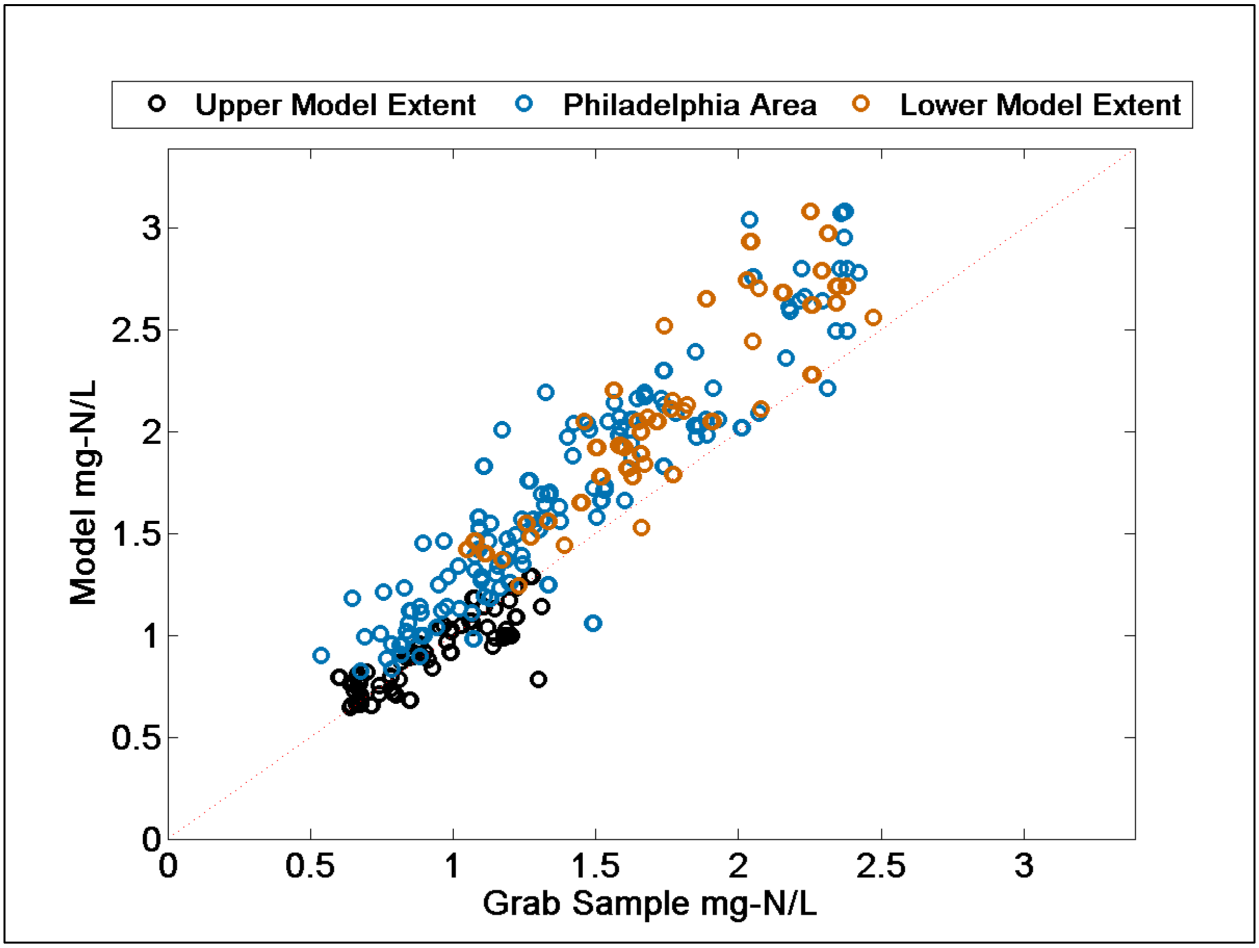


Figure 3-40: System-wide Scatter Plot of Modeled vs. Observed Nitrate in 2012-2013

3.11.6 Phosphorus

PO_4 is generally overpredicted throughout the model domain (Figure 3-41). Potential causes are overestimation of PO_4 for the numerous point sources that did not report PO_4 effluent concentrations, and underprediction of algal biomass resulting in less uptake of PO_4.

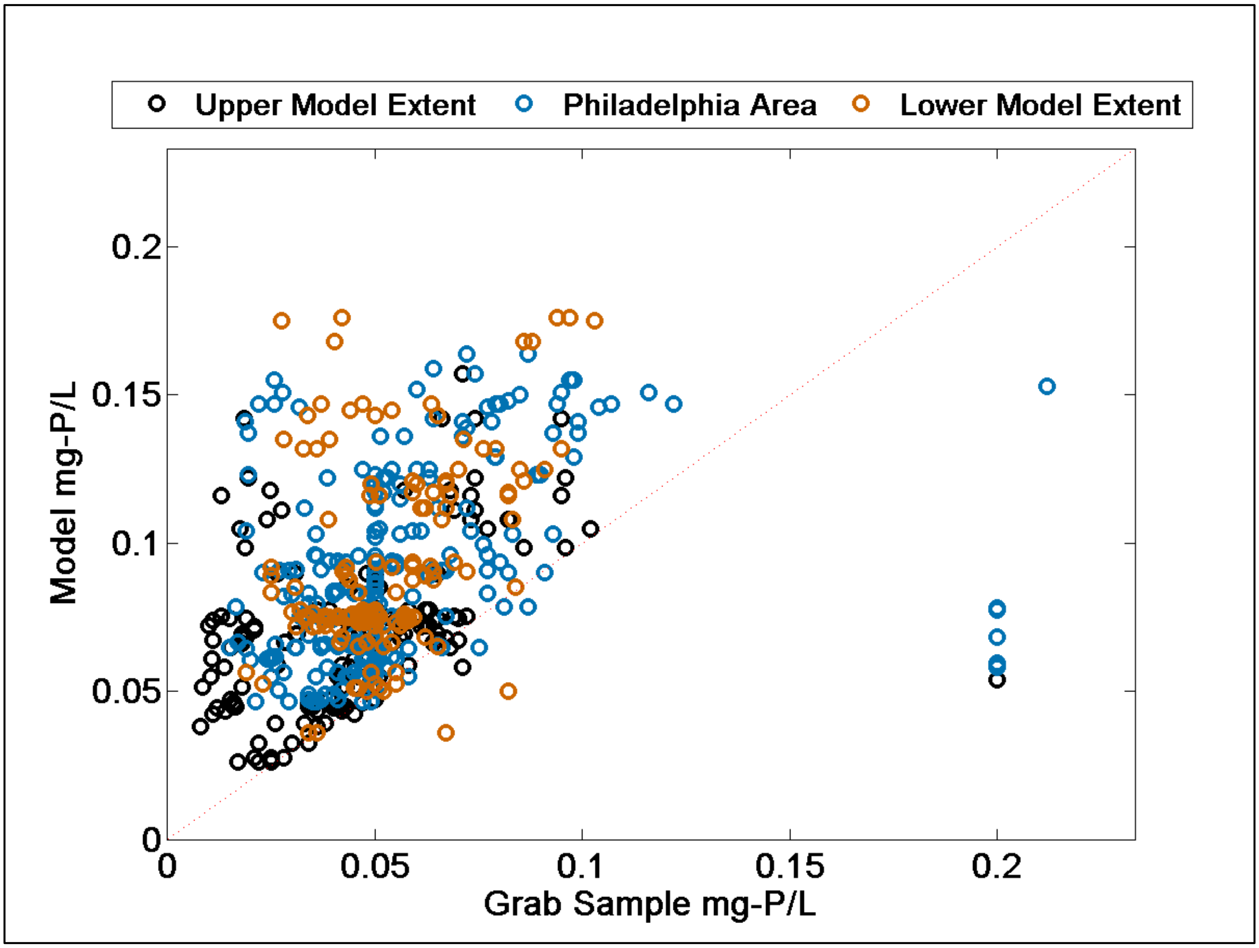


Figure 3-41: System-wide Scatter Plot of Modeled vs. Observed PO_4 in 2012-2013

System-wide scatter plots for 2012 and 2013 of modeled total phosphorus concentration resemble PO4 (Figure 3-42). The overprediction of TP is due primarily to overprediction of PO_4.

Along-channel plots of April to October, 2012 and 2013 show increased PO_4 concentrations starting at the Philadelphia area, with a gradual decrease near the lower model extent (Figure 3-43). This finding is in agreement with Sharp *et al.* (2009) and indicates the DO Model is qualitatively characterizing the system adequately for phosphorus.

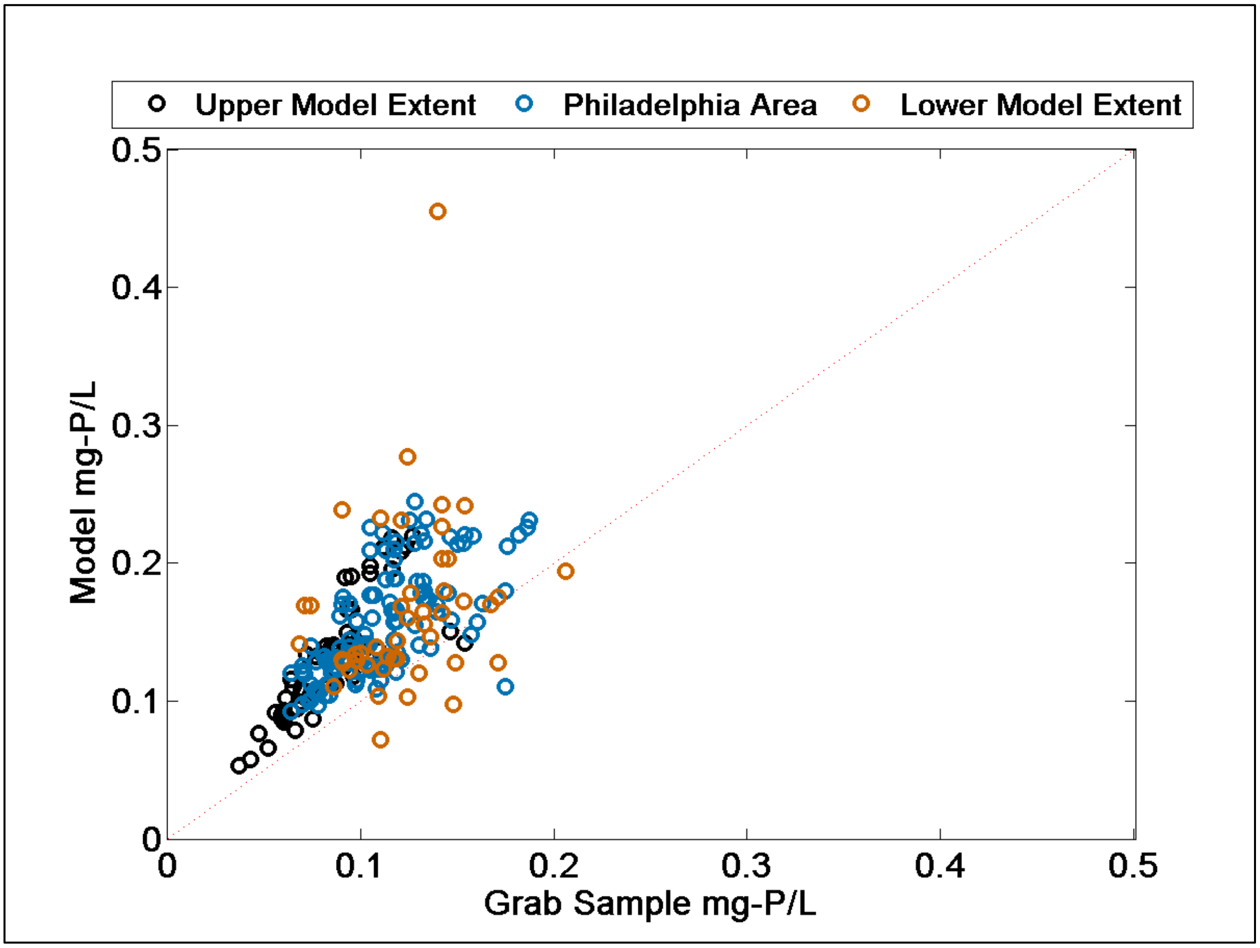


Figure 3-42: System-wide Scatter Plot of Modeled vs. Observed Total Phosphorus in 2012-2013

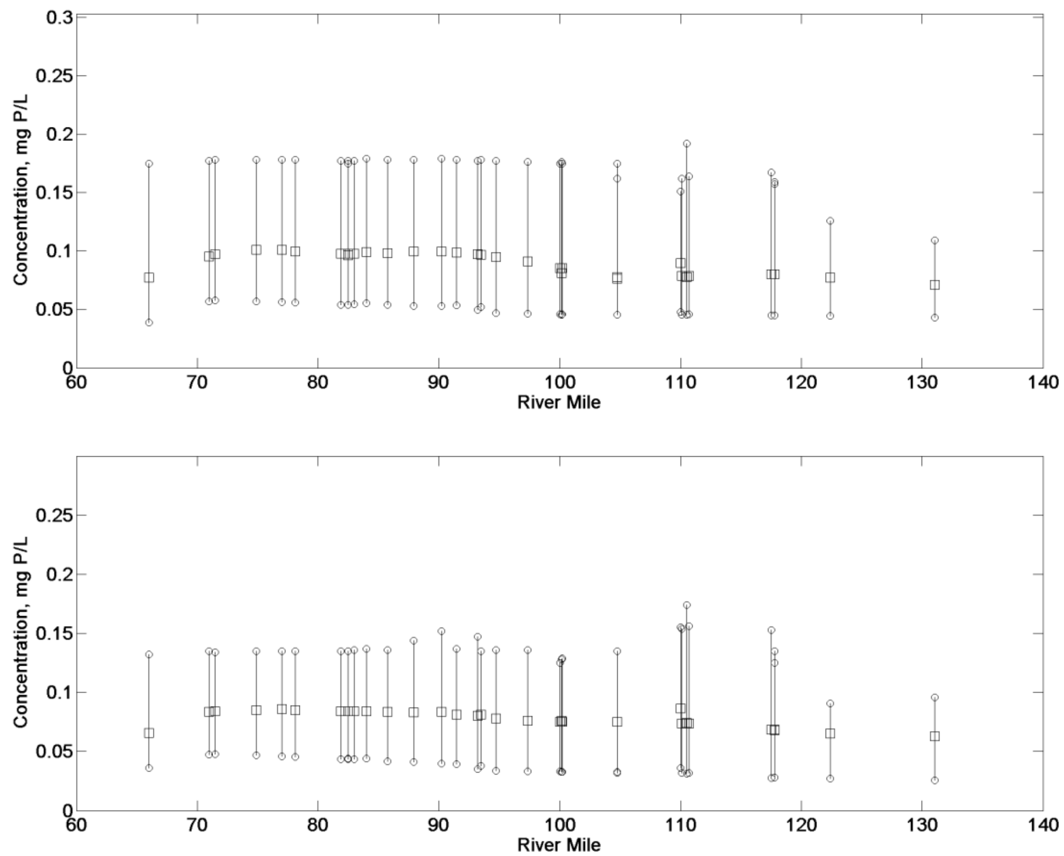


Figure 3-43: April to October 2012 and 2013 Modeled PO_4 Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

3.11.7 Chl-*a*

System-wide scatter plots of 2012 and 2013 (Figure 3-44) indicate that chl-a is underpredicted at all observations greater than 15 µg/L. Time-variable loading of chl-a was applied at the upper and lower boundaries, and predictions are generally favorable as far downstream as River Mile 117.80 (Figure 3-45). The reason algae is underpredicted at instances of higher observed biomass, particularly below RM 117.80, could be due to uncertainty in tributary loadings, and the application of a single algal class. The great temporal variability in observed chl-a indicates the inherent difficulty in simulating this state variable (Figure 3-45), and that one set of optimal temperatures for growth, metabolism and predation may be too constraining. Multiple algal classes and their discrete sets of optimal temperatures may be needed to better simulate chl-a across the system.

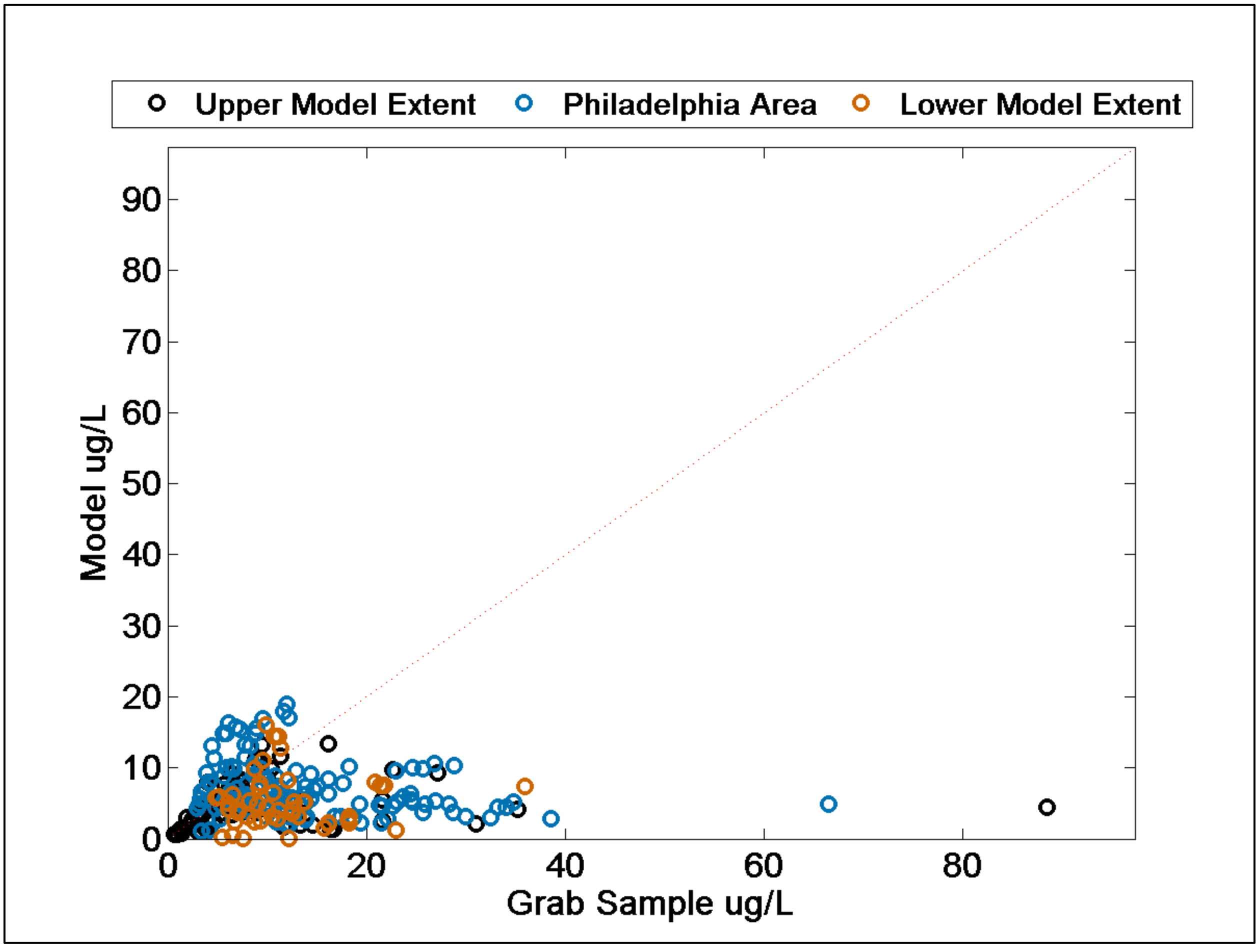


Figure 3-44: System-wide Scatter Plot of Modeled vs. Observed Chl-*a* in 2012-2013

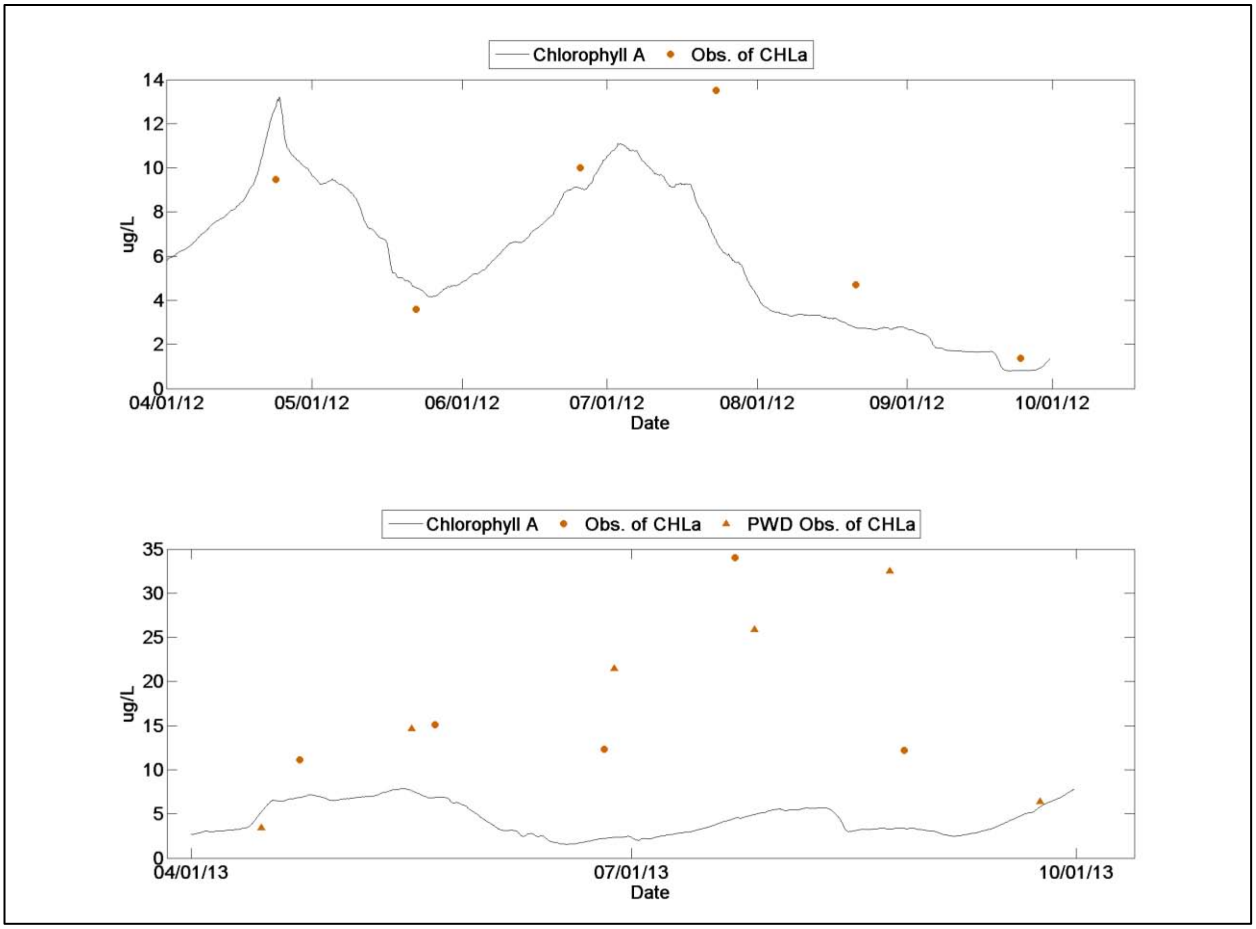


Figure 3-45: Time Series Plots of Modeled and Observed Chl-*a* at River Mile 117.80 in 2012, and at River Mile 100.20 in 2013

Overall, greater chl-a concentrations were simulated in 2012 than 2013 (Figure 3-46), due to the effect of warmer water temperatures on modeled algal growth. However, greater chl-a concentrations were actually observed in 2013 than 2012, which suggests that the effect of temperature on algal kinetics in the current single algal class model could be improved upon.

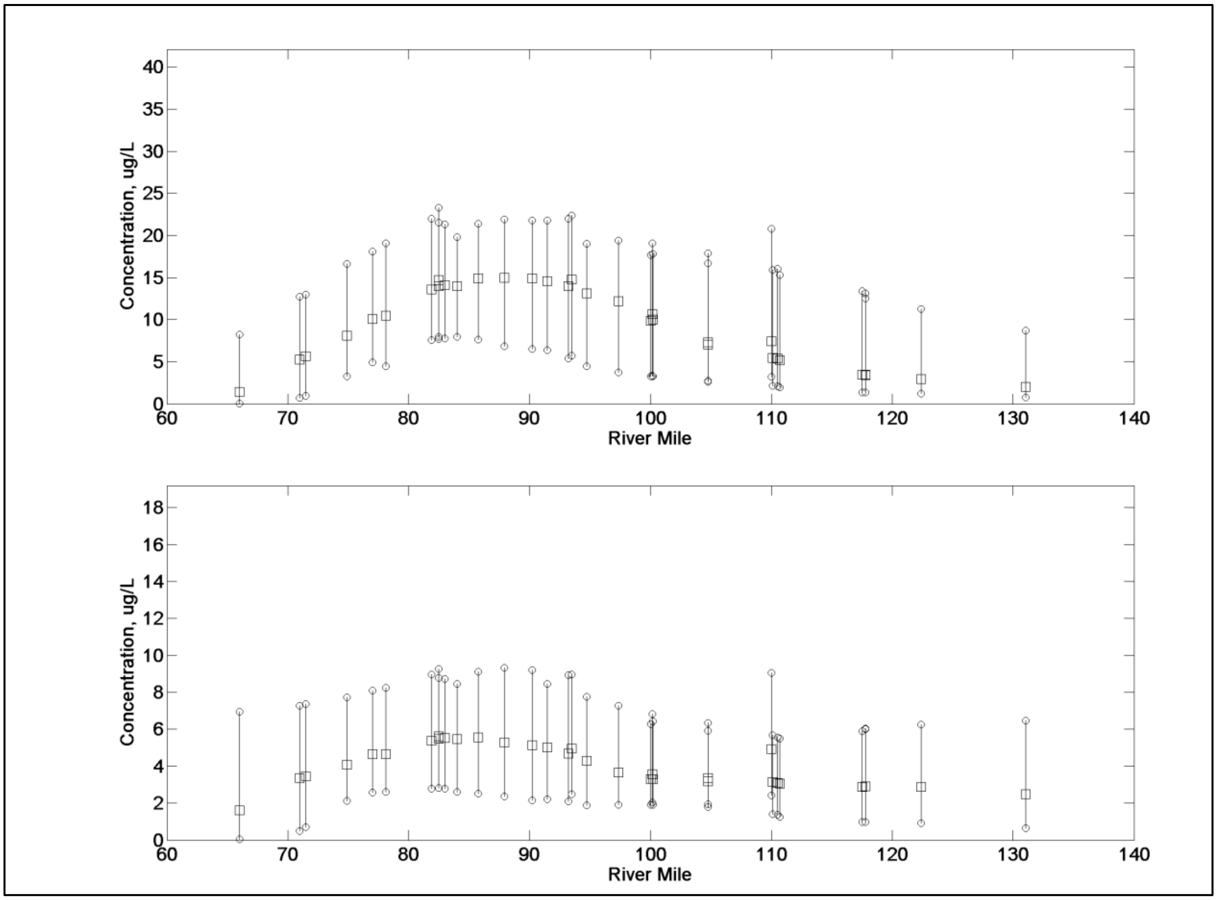


Figure 3-46: Summer 2012 and 2013 Modeled Chl-*a* Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

The consequences of underpredicting algae are not as great considering that the tidal Delaware River is not a eutrophic system (Sharp, 2010) and that NBOD –which is predicted more accurately than algae– is the primary stressor on DO (Hydroqual, 1998). Nevertheless, algae simulation should be a focus area of future model improvement.

3.11.8 Dissolved Oxygen

Delaware River

In the mainstem Delaware River, simulations of DO were compared at three locations with continuous observed DO data: the USGS gages at Baxter, Ben Franklin Bridge, and the Chester River confluence. For the purpose of model evaluation, these gages are well spaced at River Miles 110.11, 100.20, and 83.10. Minimum DO concentrations observed in the validation periods were 4.0, 3.1, and 3.2 mg/L in 2012 at River Miles 110.11, 100.05, and 83.10, respectively; and 5.4, 3.7 and 4.0 mg/L in 2013. Decreased DO concentrations were observed in July 1 to September 15 of each year, and these were designated as critical periods for further analysis.

Time series plots at each station and year that compare simulated and observed data are shown in Figure 3-47 and Figure 3-48.

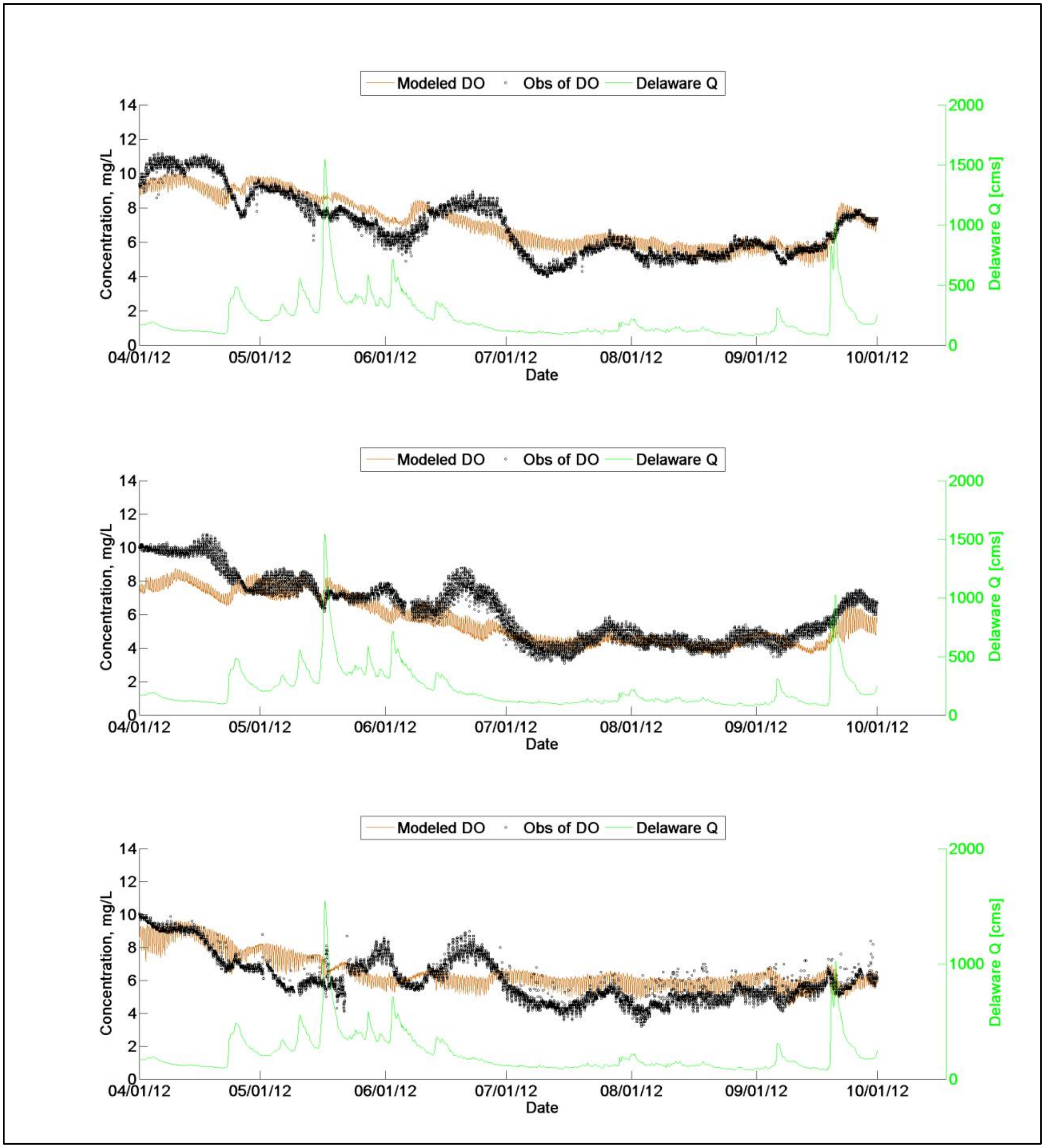


Figure 3-47: 2012 Time Series Plots of Modeled and Observed DO at River Miles 110.11, 100.20, and 83.10

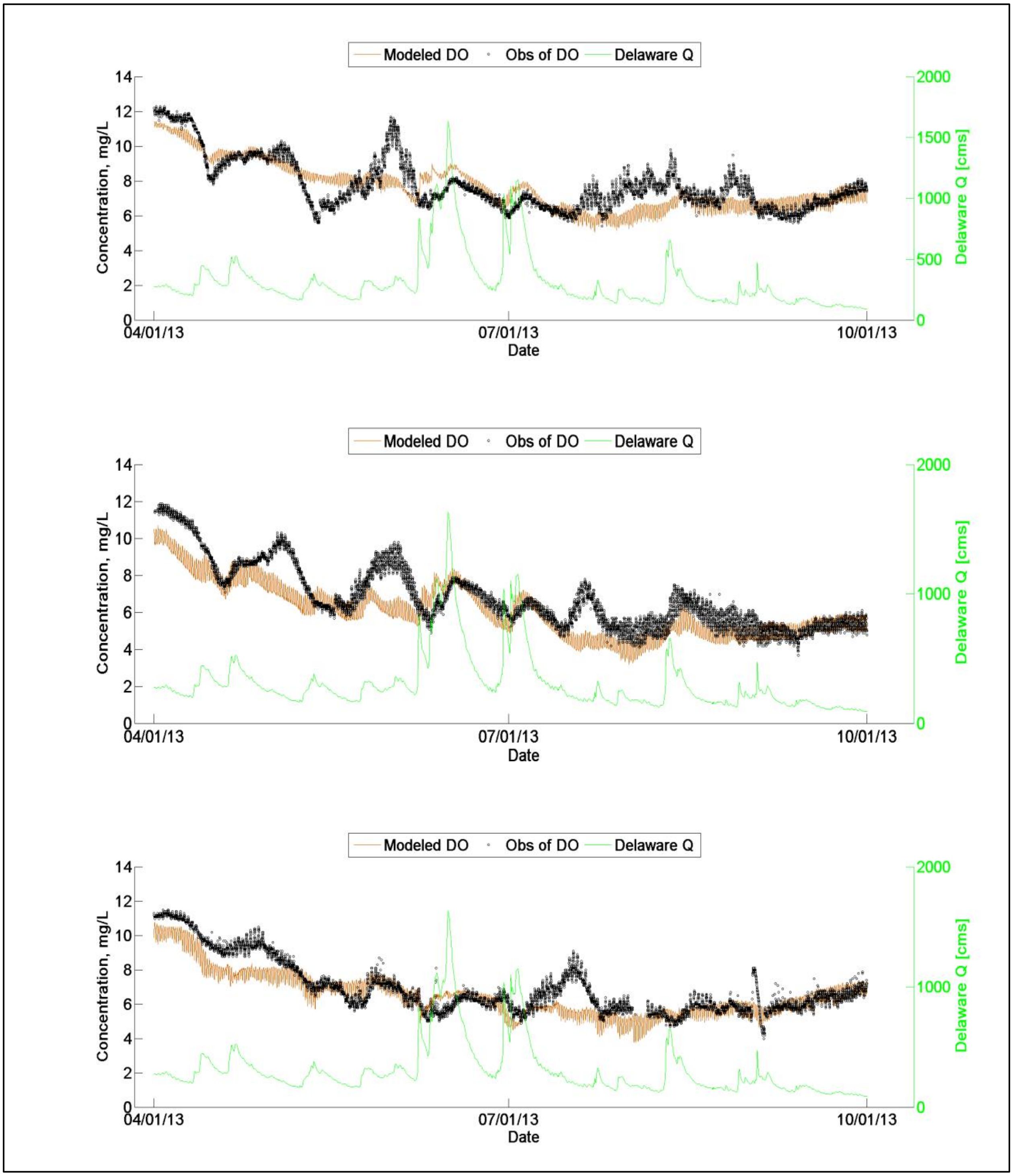


Figure 3-48: 2013 Time Series Plots of Modeled and Observed DO at River Miles 110.11, 100.20, and 83.10

Overall, model performance is better at the upstream two stations than at the downstream station. At River Mile 110.11 (Baxter), there are prolonged periods in each year when the simulation nearly matches the observed data (*e.g.,* August 2012, July 2013; September 2013), showing great precision and accuracy (top panels in Figure 3-47 and Figure 3-48). High discharges from the Delaware River do not appear to affect model performance at this location. The main periods of divergence are seen around mid-June to mid-July 2012, mid-May to mid-June 2013, and mid-July to August 2013. These are concurrent with periods of elevated chl-*a* concentrations observed nearby at River Mile 110.70. The low frequency variability of the observed DO data in these periods, on an approximate weekly scale (as opposed to daily or seasonal), is likely due to algal kinetics. Due to the DO Model's underprediction of algae in those periods, simulated DO displays less low frequency variability in those three distinct periods. A subset of these periods are concurrent with overprediction of daily average DO (Figure 3-49 and Figure 3-50). Periods when algae is better predicted at River Mile 110.70 overlap when DO is predicted more accurately and precisely at River Mile 110.11.

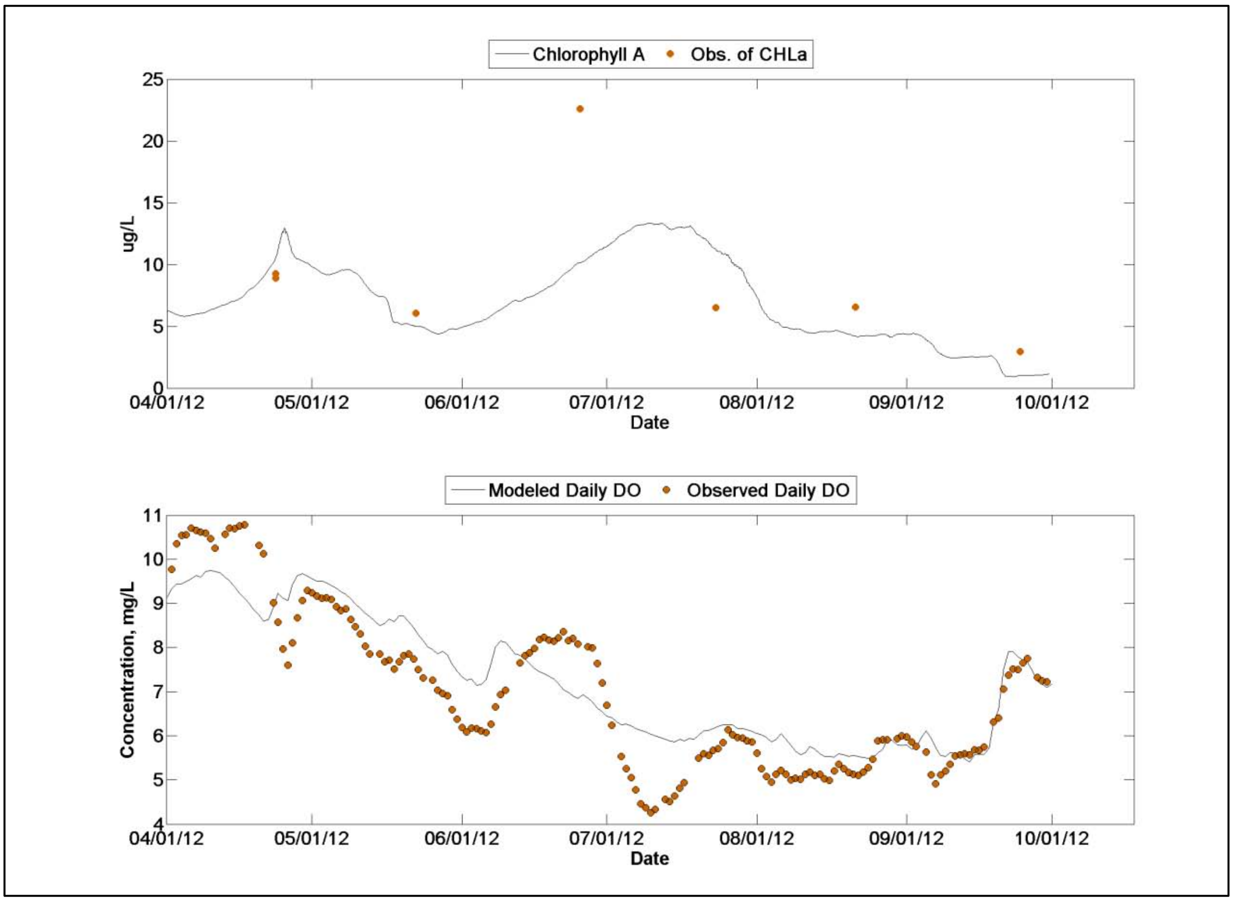


Figure 3-49: 2012 Time Series Plots of Modeled and Observed Chl-a at River Mile 110.70, and Daily Average DO at River Mile 110.11

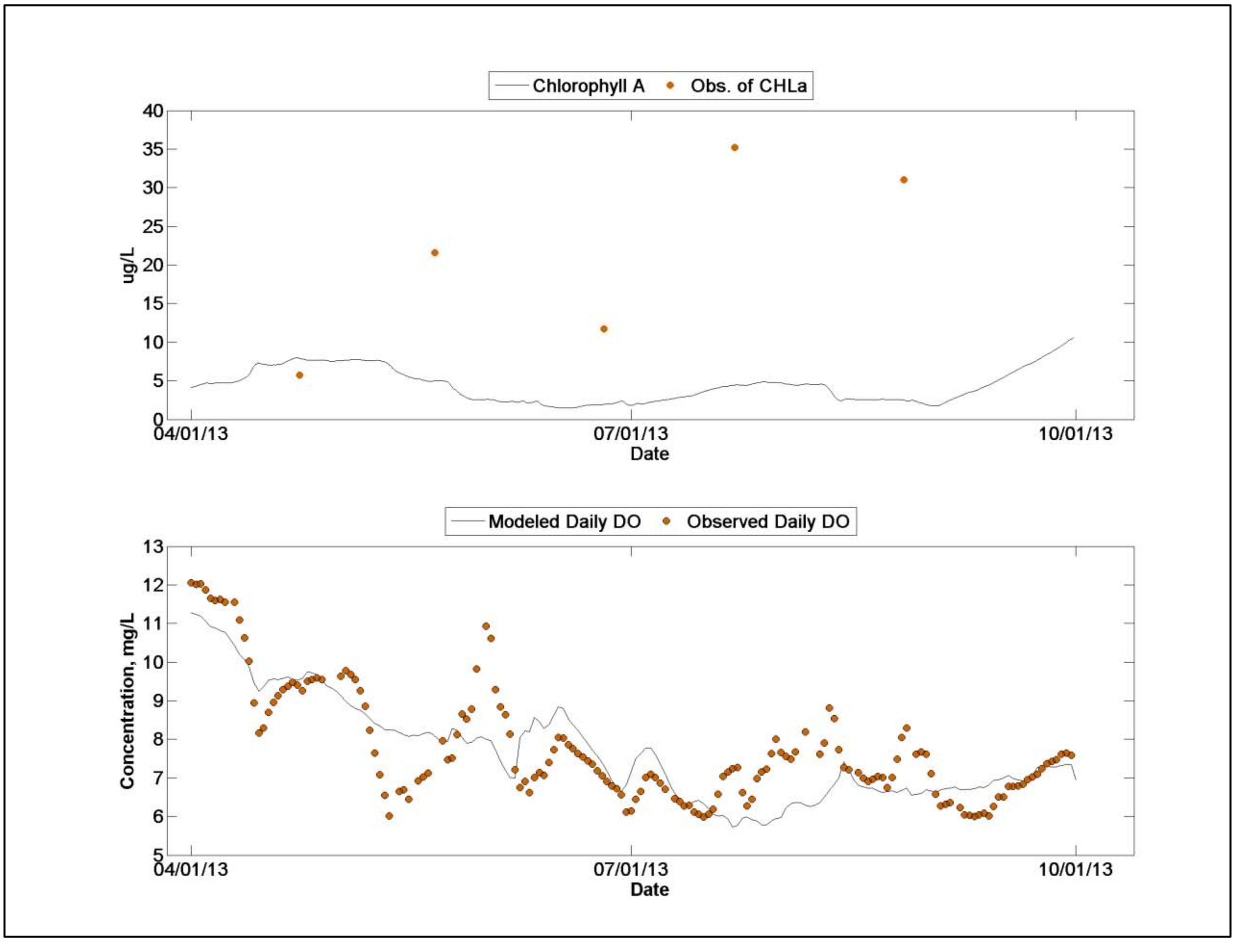


Figure 3-50: 2013 Time Series Plots of Modeled and Observed Chl-a at River Mile 110.70, and Daily Average DO at River Mile 110.11

CDF plots of DO at River Mile 110.11 indicate that across the time periods of April to October, and July 1 to September 15 in 2012 and 2013, the DO Model adequately characterizes the entire range of observed DO, with the greatest discrepancy being a 1 mg/L overprediction at the median and lower percentiles in summer 2012 (Figure 3-51 and Figure 3-52).

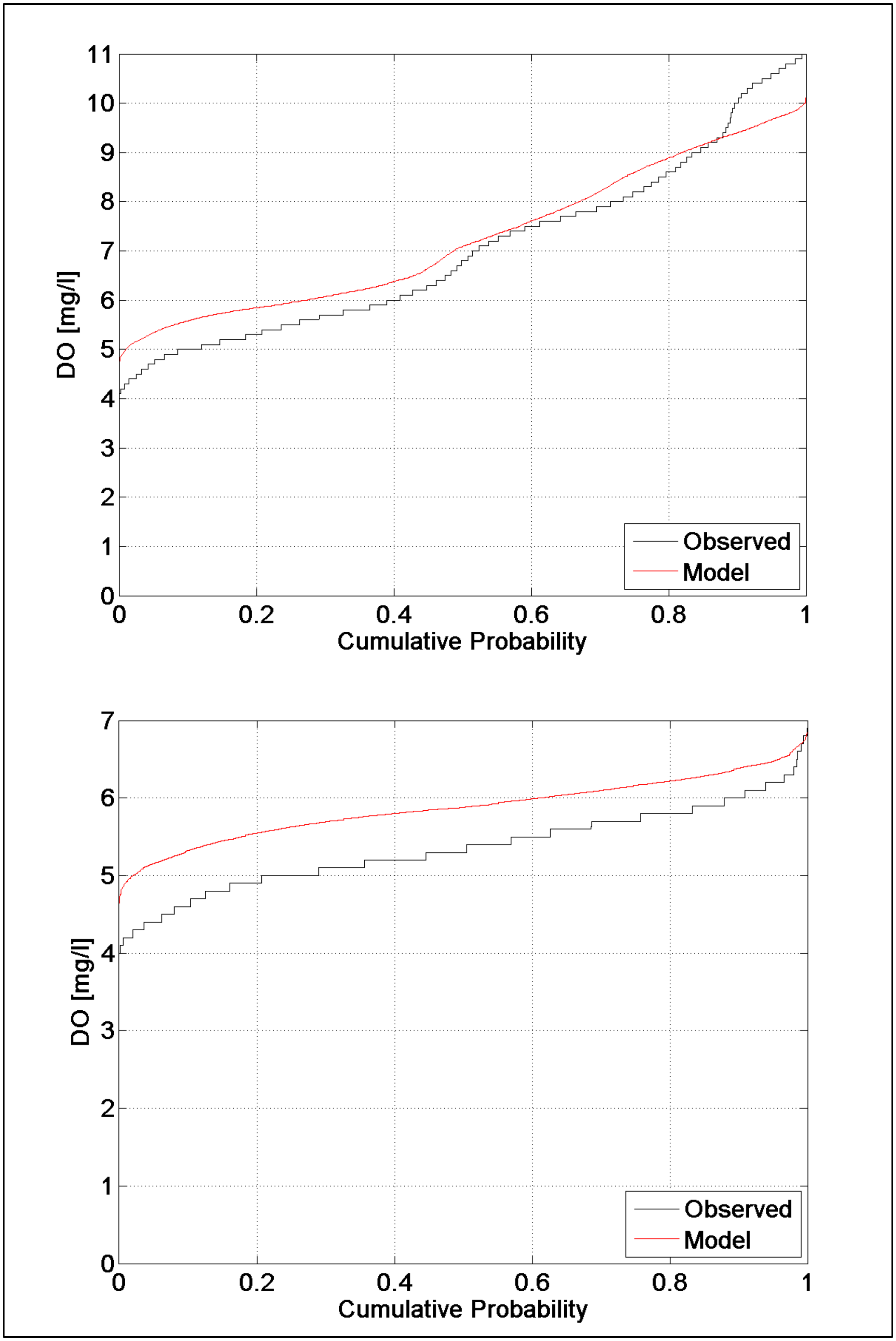


Figure 3-51: CDF Plots of Modeled and Observed DO at River Mile 110.11 for Apr-Oct and Jul-mid Sep, 2012

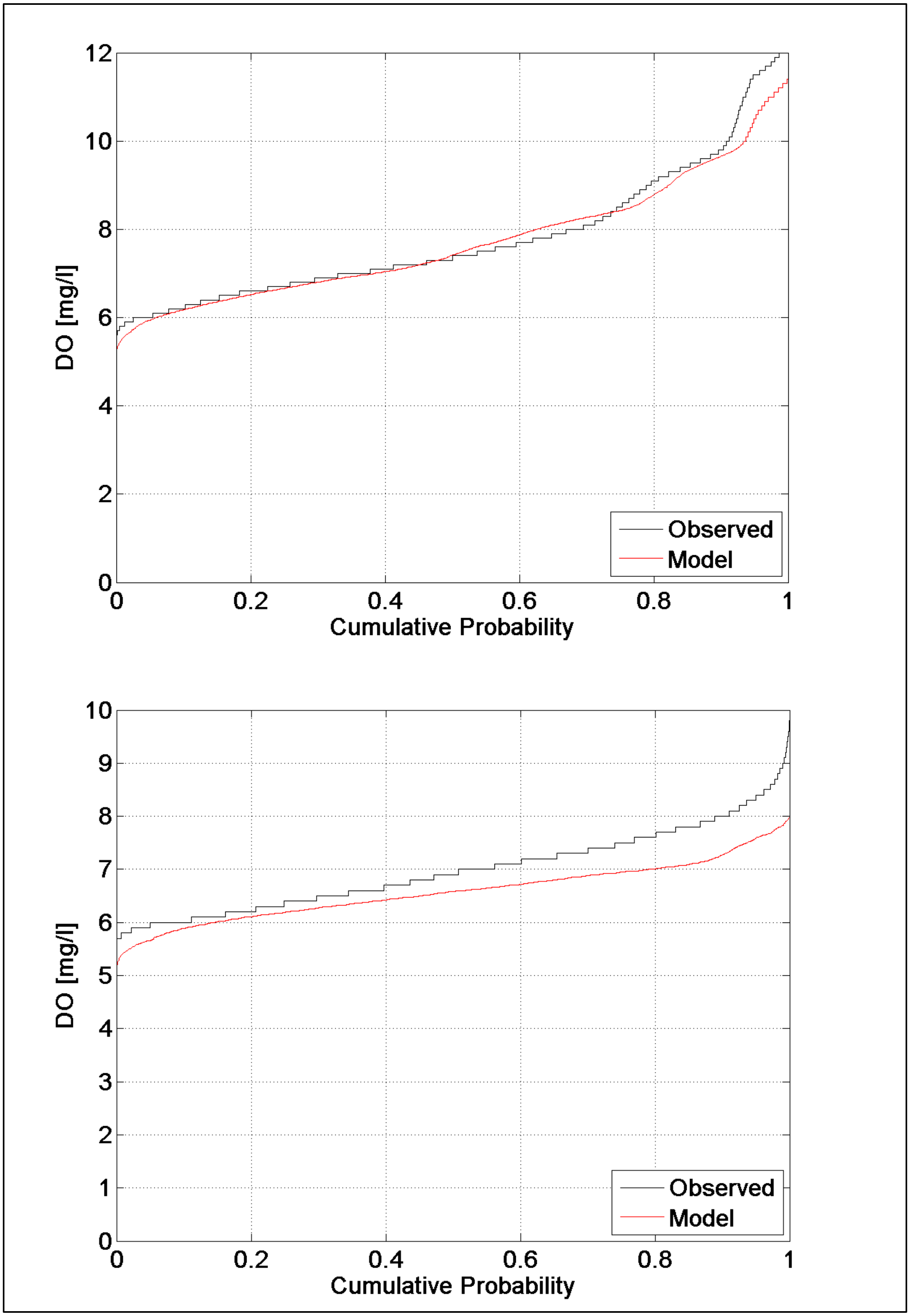


Figure 3-52:CDF Plots of Modeled and Observed DO at River Mile 110.11 for Apr-Oct and Jul-mid Sep, 2013

At River Mile 100.20, the DO Model reflects the increase in diel DO variability at this station compared to River Mile 110.11, which is consistent with the spatial pattern in algae between these two stations (Figure 3-46). Increased algal biomass results in greater photosynthesis and respiration which cause the increase in diel DO variability. High discharges from the Delaware River do not appear to affect model performance at this location. At River Mile 100.20, just as at RM 110.11, instances of underpredicted algae correspond with periods when low frequency DO variability is not well simulated. This generally results in overprediction of daily average DO (Figure 3-53 and Figure 3-54)

In 2012, when observed algae concentrations are lower and better predicted, there is better agreement between modeled and observed DO (Figure 3-53).

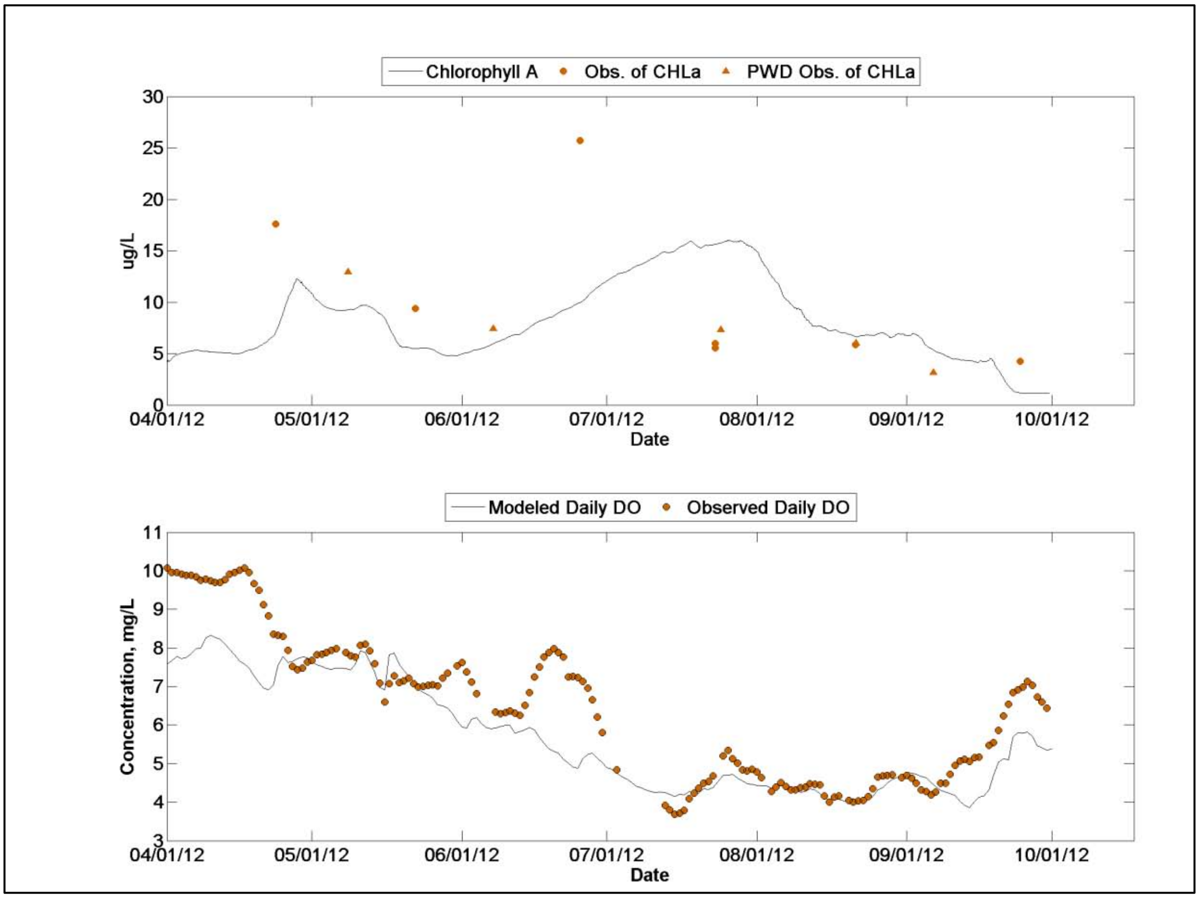


Figure 3-53: 2012 Time Series Plots of Modeled and Observed Chl-*a* and Daily Average DO at River Mile 100.20

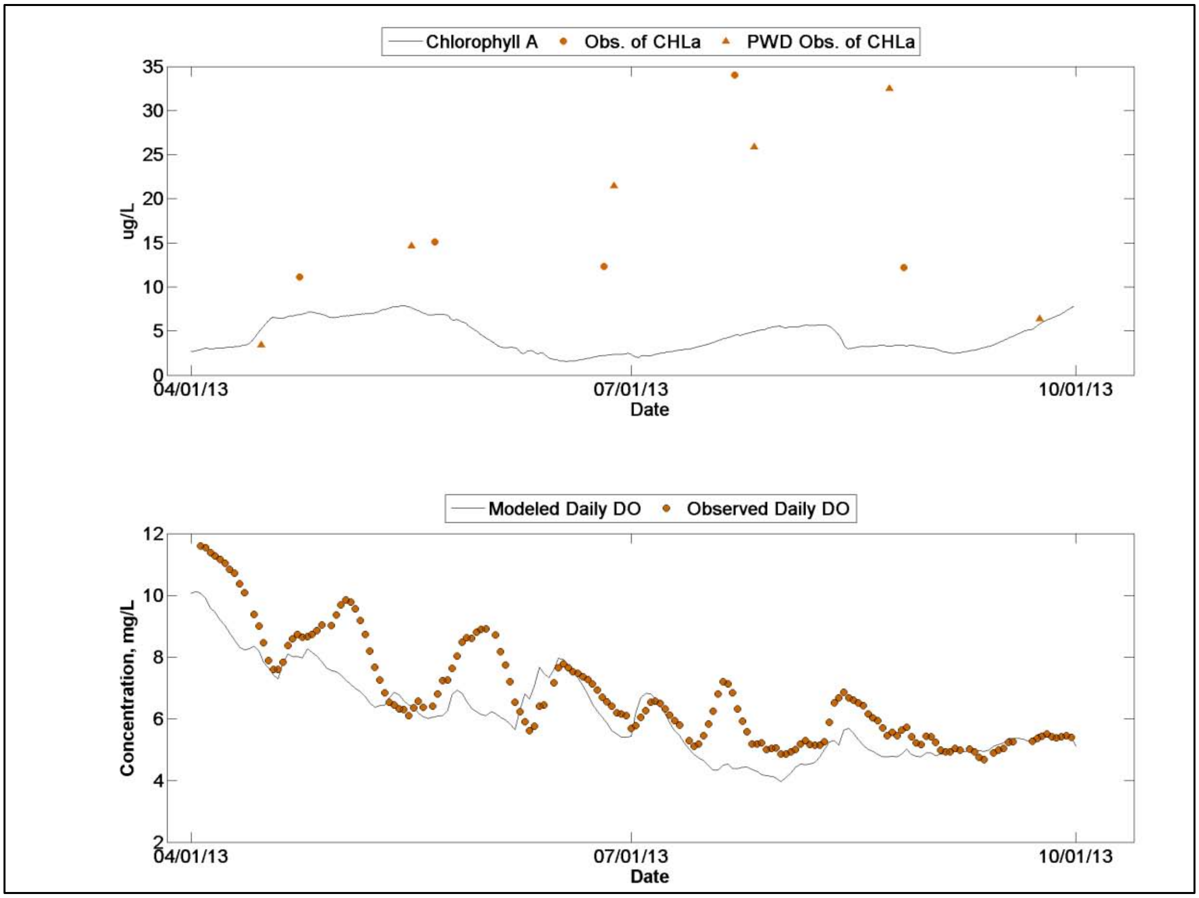


Figure 3-54: 2013 Time Series Plots of Modeled and Observed Chl-*a* and Daily Average DO at River Mile 100.20

It would appear that the combined effects of DO loading at the tributary boundaries, nitrification, heterotrophic respiration of DOC, SOD, and reaeration – along with daily loadings from the three Water Department WPCPs – are sufficiently well represented in the DO Model to produce DO concentrations that are broadly accurate at River Miles 110.11 and 100.20 in terms of achieving mean bias errors that range from -0.71 to 0.22 mg/L across the full validation periods (Table 3-18). Effects of algal kinetic processes are not always as well predicted, resulting in modest periods of divergent DO prediction.

CDF plots of DO at River Mile 100.20 indicate that across the time periods of April to October, and July 1 to Sep 15 in 2012 and 2013, the DO Model adequately characterizes the entire range of observed DO, with the greatest discrepancy being a 1 mg/L underprediction at the median and lower percentiles in summer 2013 (Figure 3-55 and Figure 3-56).

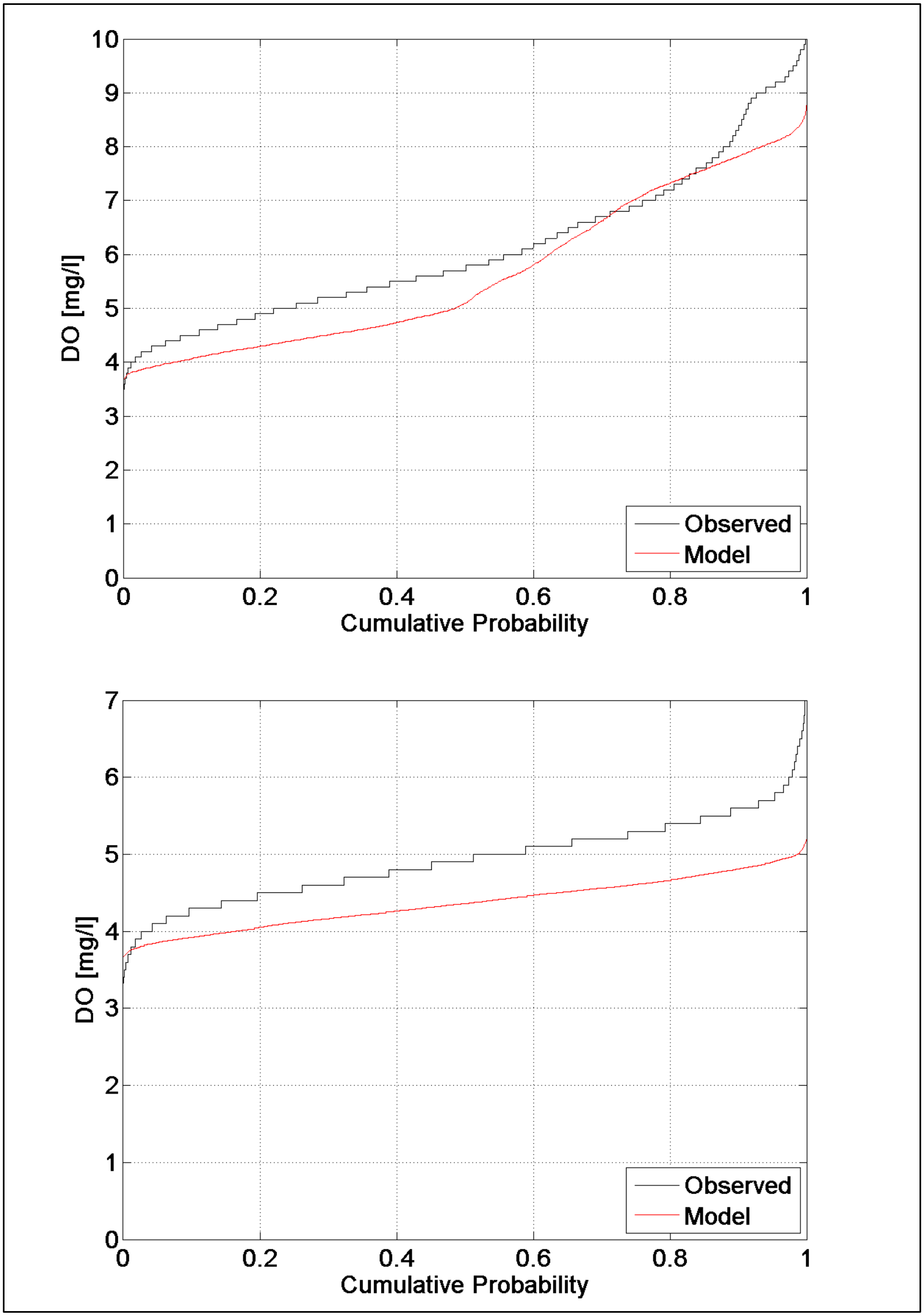


Figure 3-55: CDF Plots of Modeled and Observed DO at River Mile 100.20 for Apr-Oct and Jul-mid Sep, 2012

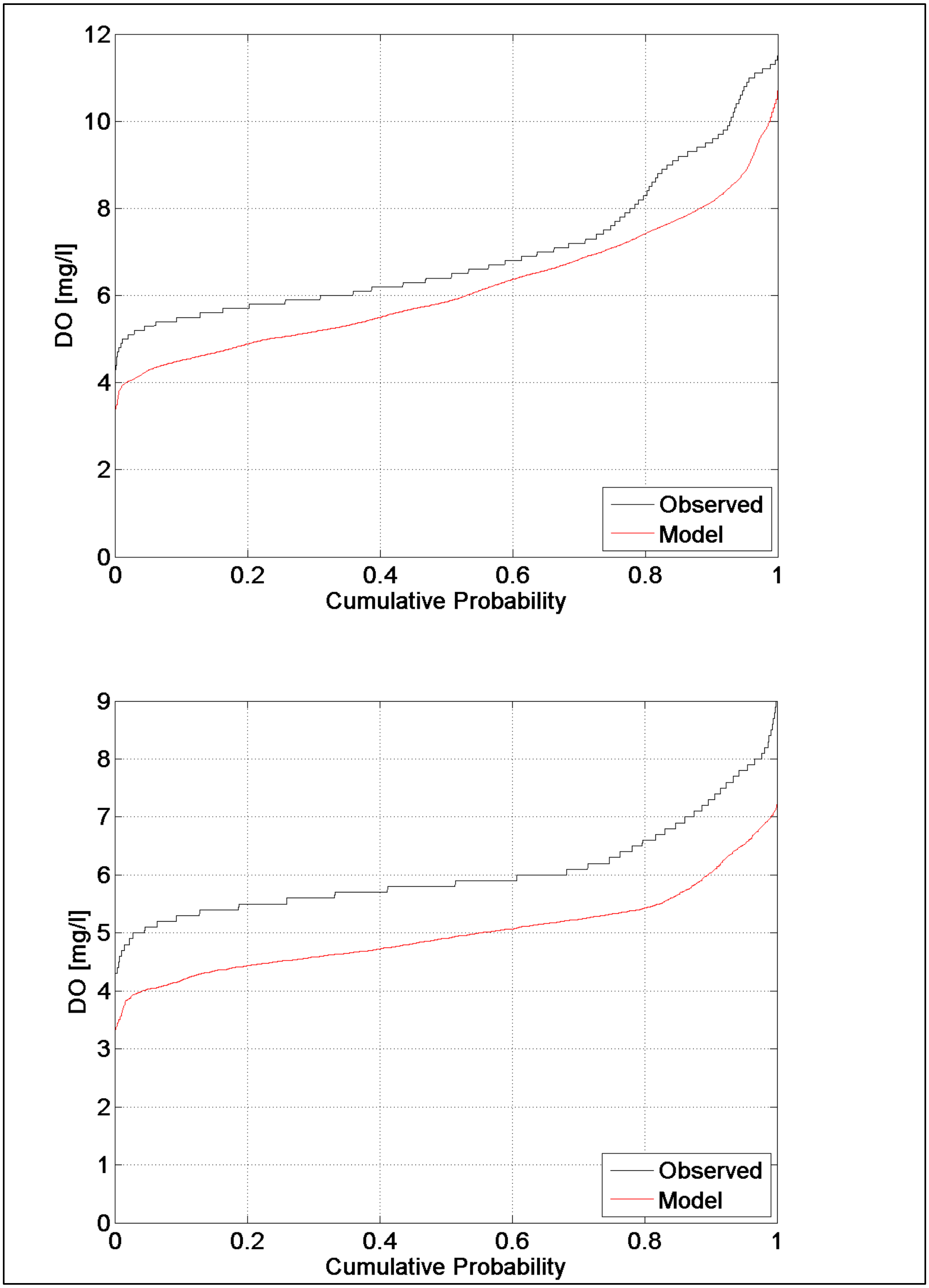


Figure 3-56: CDF Plots of Modeled and Observed DO at River Mile 100.20 for Apr-Oct and Jul-mid Sep, 2013

At River Mile 83.10, DO is generally overpredicted in 2012 with a mean bias error of 0.48 mg/L; performance is improved in 2013 with a mean bias error of -0.39 mg/L. Error statistics in the July to September 15 period are less favorable at this site compared to the two upstream sites (Table 3-18 through Table 3-20). Water temperature is well predicted throughout the model domain (Figure 3-21), so differences in DO saturation are not the cause. It is more likely that underpredicted DOC in this area, along with monthly-scale loadings from nearby point sources (in contrast with daily loadings from the Philadelphia WPCPs) contribute to the less accurate DO prediction at this station. Table 3-18: Error Statistics of Continuous Modeled DO in Mainstem Delaware River Estuary

CDF plots of DO at River Mile 83.10 indicate that across the time periods of April to October and July 1 to September 15 in 2012, the DO Model overpredicts DO by approximately 0.5-1.25 mg/L at median observed concentrations and below (Figure 3-57). However, DO prediction is improved across the entire range of observed concentrations in 2013 (Figure 3-58).

The box plots in Figure 3-59 – Figure 3-62 summarize model performance in predicting DO at the three mainstem locations. Overall, for both April to October 2012 and the July to September 15, 2012 subset at Baxter, the mean and median are overpredicted, and variability is similar between predicted and observed. At Ben Franklin Bridge, the mean, median, and variability are underpredicted for both April to October 2012 and the July to September 15, 2012 subset. The mean and median are overpredicted at Chester in 2012, while variability is underpredicted (Figure 3-59 and Figure 3-60). Predictions are improved at Chester for April to October 2013 and the July to September 15, 2013 subset (Figure 3-61 and Figure 3-62), during which medians and means are underpredicted at Baxter and Ben Franklin Bridge, except for a slight overprediction of median DO at Baxter in April to October 2013.

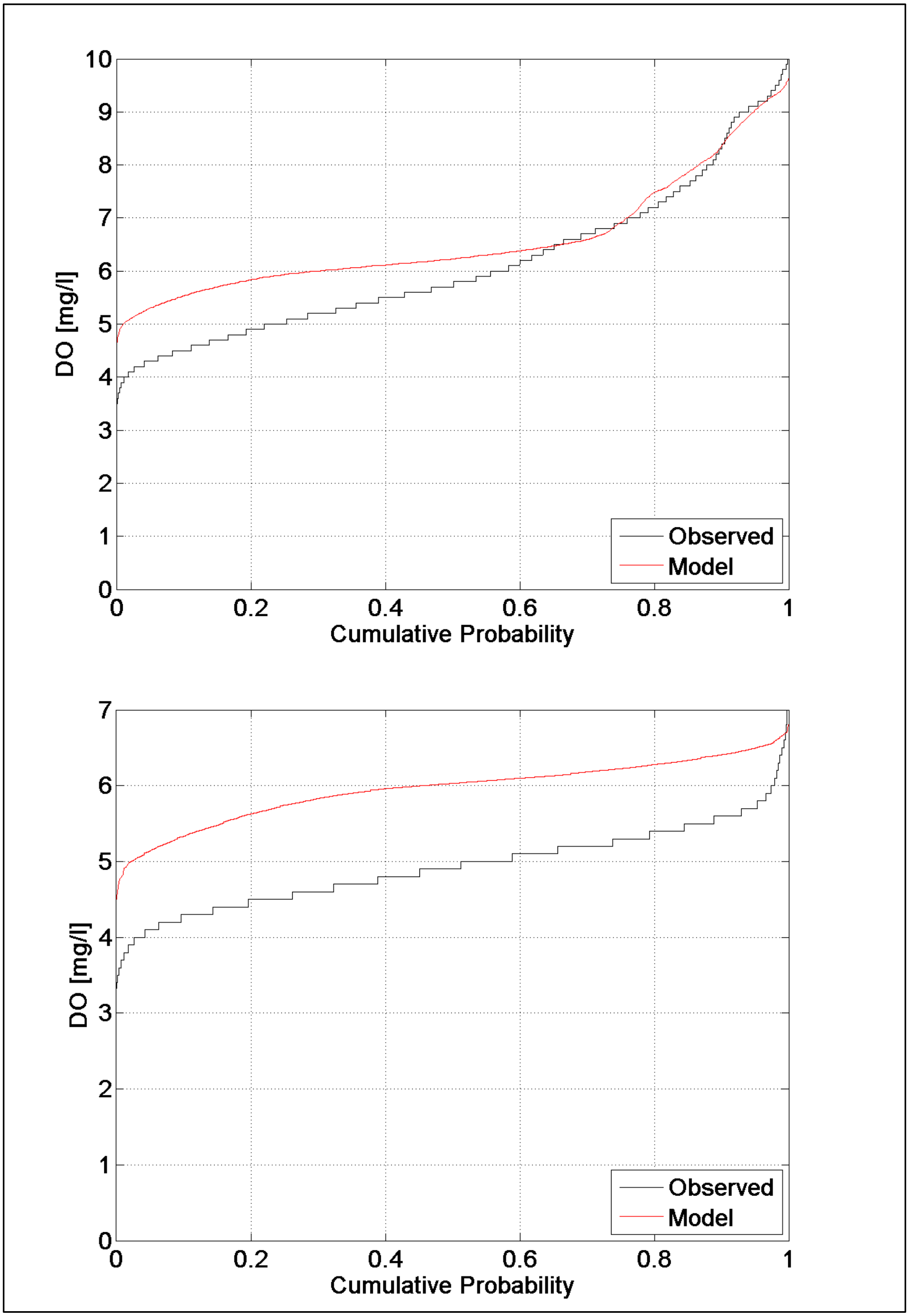


Figure 3-57: CDF Plots of Modeled and Observed DO at River Mile 83.10 for Apr-Oct and Jul-mid Sep, 2012

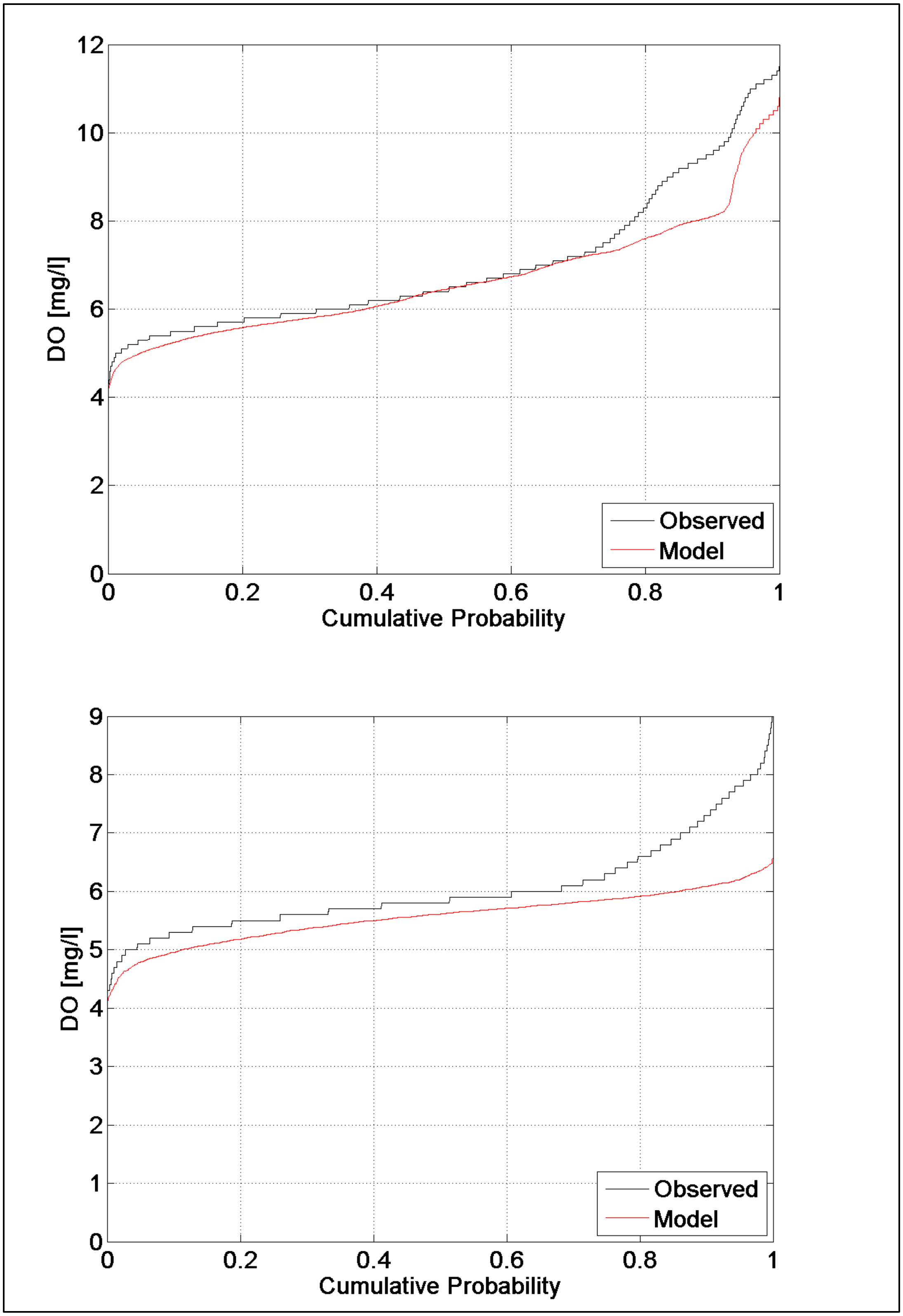


Figure 3-58: CDF Plots of Modeled and Observed DO at River Mile 83.10 for Apr-Oct and Jul-mid Sep, 2013

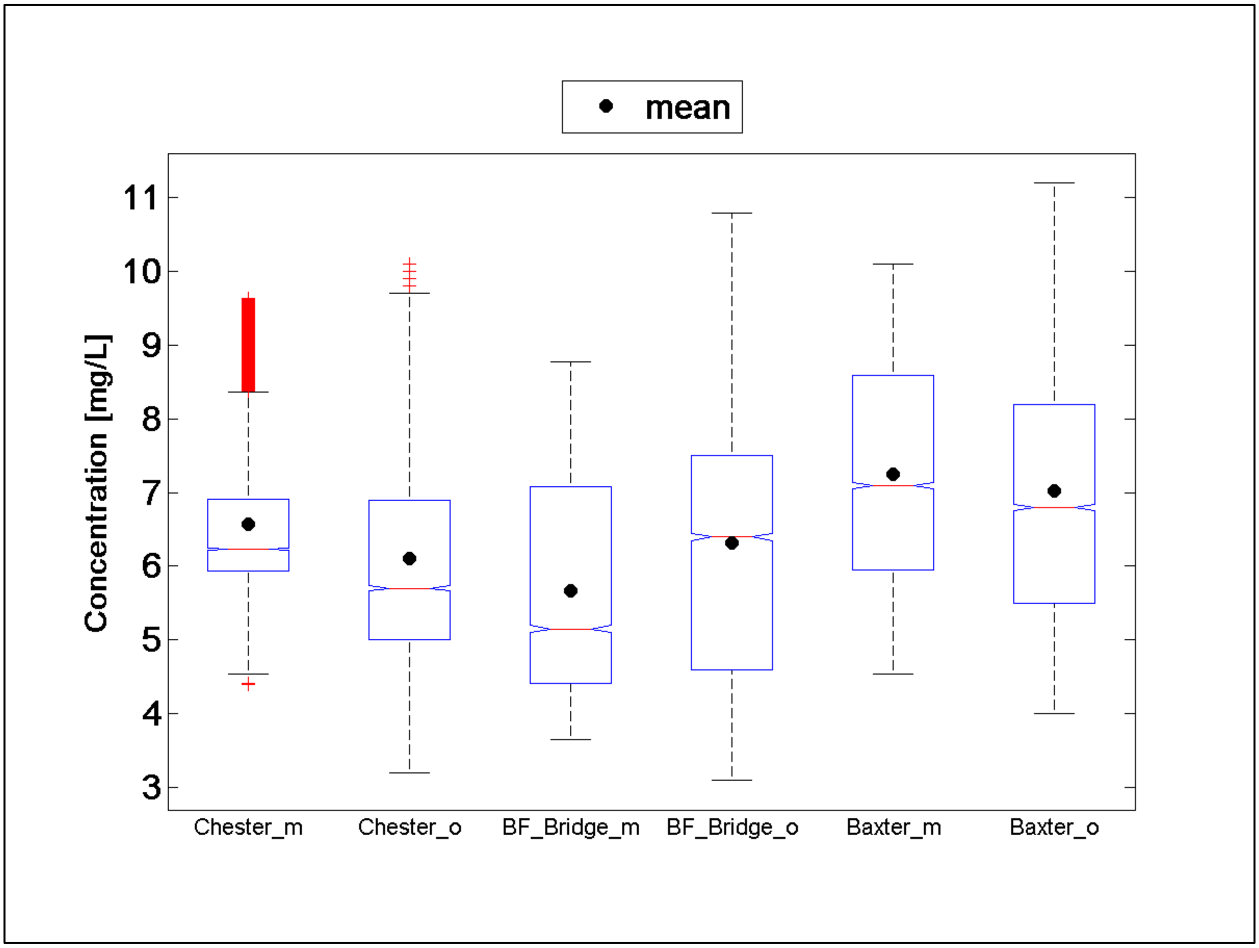


Figure 3-59: Box Plot of April to October 2012 Modeled (m) and Observed (o) DO at Chester (RM 83.10), Ben Franklin Bridge (RM 100.20), and Baxter (RM 110.11)

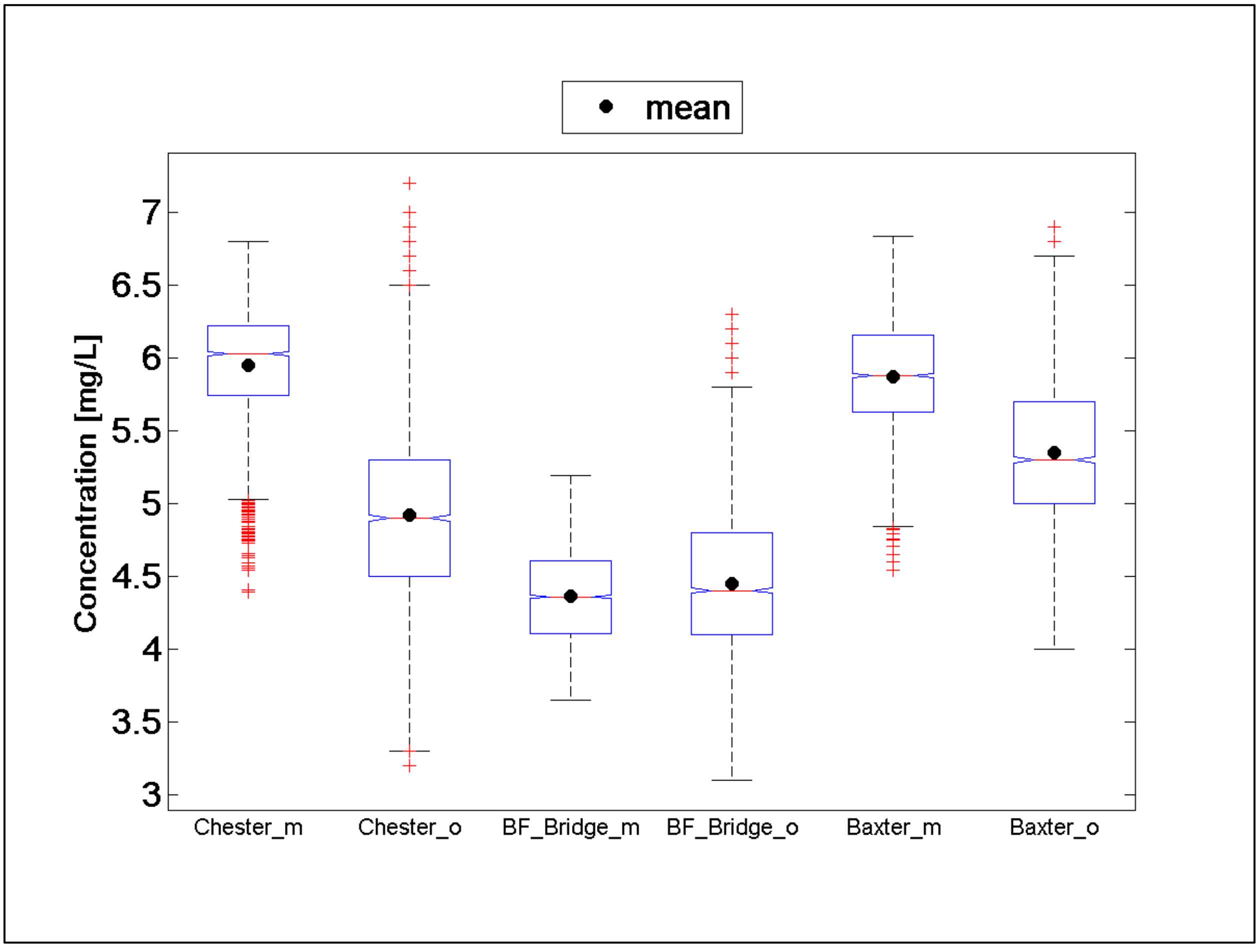


Figure 3-60: Box Plot of July to September 15, 2012 Modeled (m) and Observed (o) DO at Chester (RM 83.10), Ben Franklin Bridge (RM 100.20), and Baxter (RM 110.11)

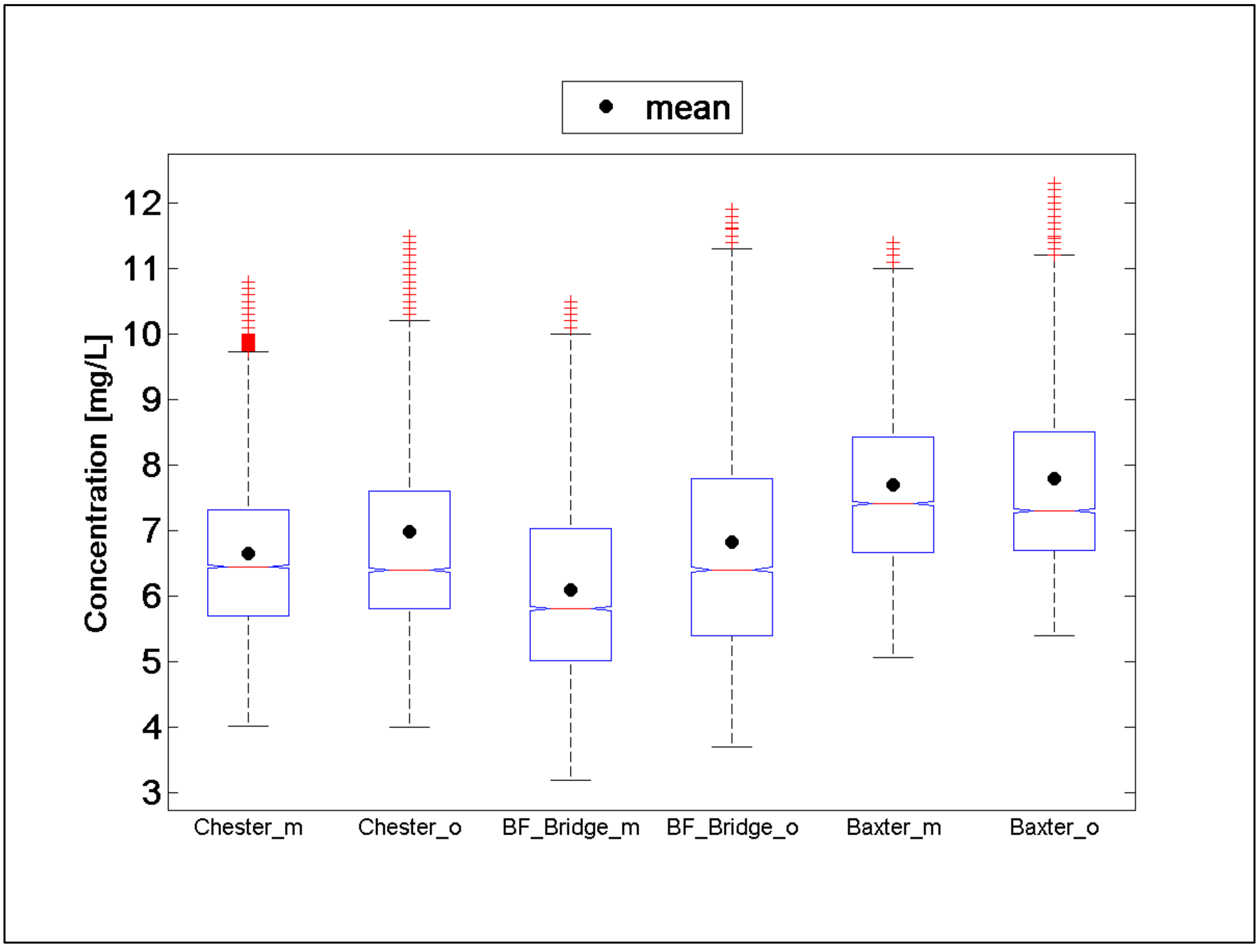


Figure 3-61: Box Plot of April to October 2013 Modeled (m) and Observed (o) DO at Chester (RM 83.10), Ben Franklin Bridge (RM 100.20), and Baxter (RM 110.11)

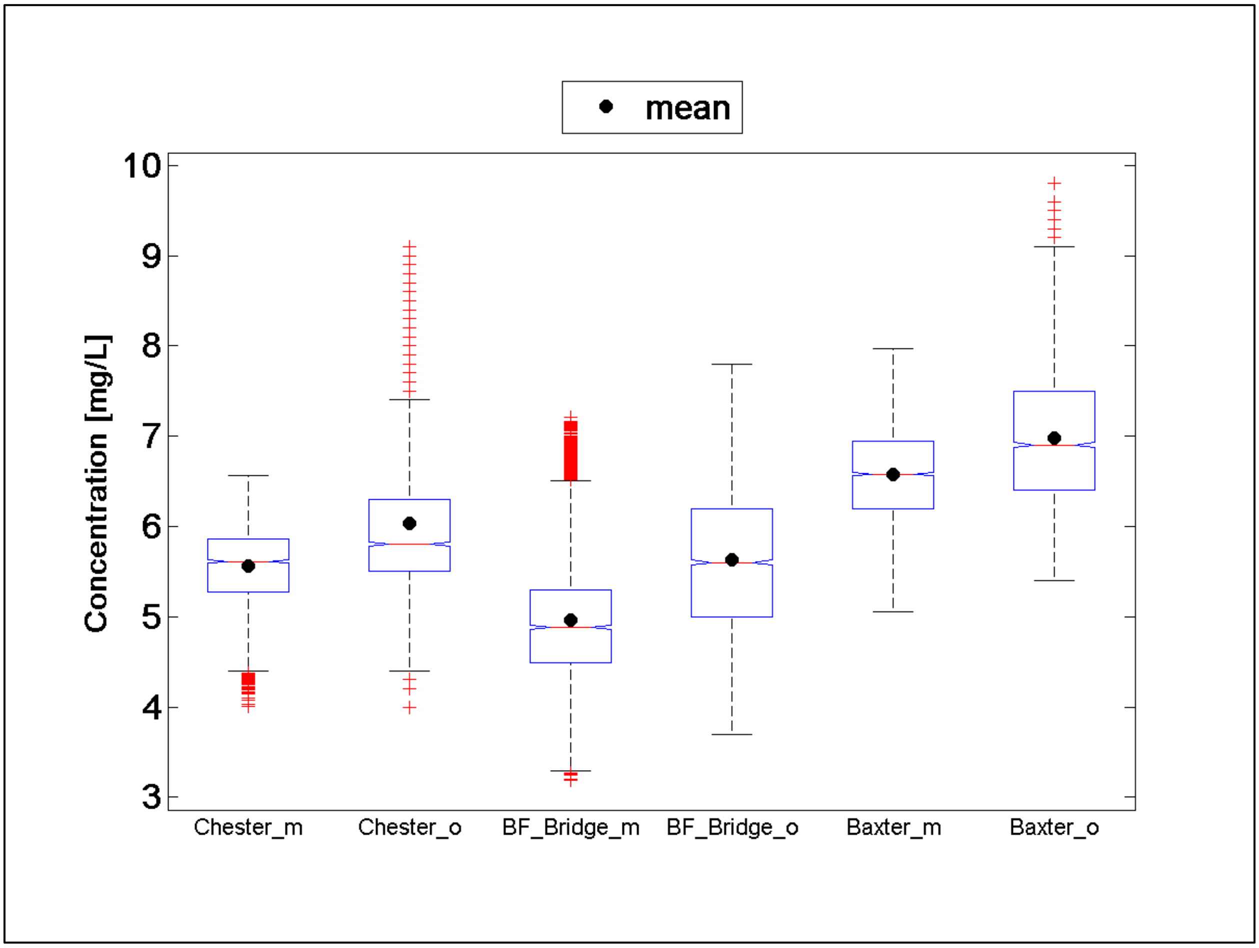


Figure 3-62: Box Plot of July to September 15, 2013 Modeled (m) and Observed (o) DO at Chester (RM 83.10), Ben Franklin Bridge (RM 100.20), and Baxter (RM 110.11)

Along-channel plots of summer simulation periods for 2012 and 2013 display the minimum DO concentration occurring around RM 85 to 90. The length of the DO sag extends from RM 105 to 80, broadly consistent with previous literature (Sharp, 2010) (Figure 3-63).

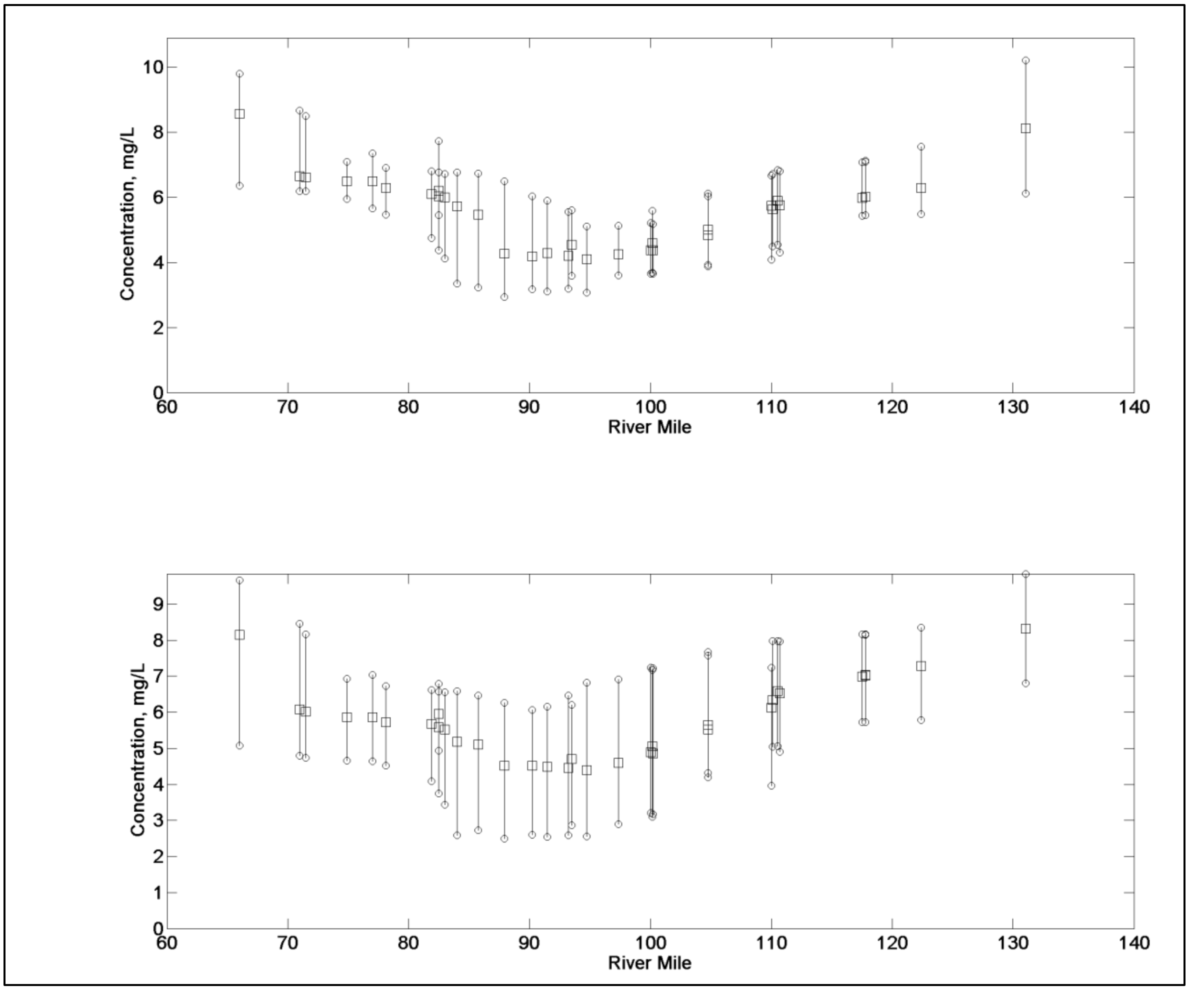


Figure 3-63: Summer 2012 and 2013 Modeled DO Concentration (Minimum, Maximum and Median) by Longitudinal River Mile

Error statistics for the full April to October period and July to September 15 "summer" period at the three mainstem sites are listed in Table 3-18 through Table 3-20. The equations and descriptions of the error statistics are as follows (Hamrick, 2007):

The mean bias error of the model predictions is given by

$$MBE = \bar{O} - \bar{P} \qquad \text{Eq. 3-14}$$

Where Ō and P are the means of observed and predicted values. MBE is a measure of systematic over or underprediction, with a positive result indicating overprediction.

Root mean square error (RMSE) and mean absolute error (MAE) measure the average differences between observations and predictions without regard to over or underprediction.

$$MAE = \frac{1}{N}\sum_{n=1}^{N}|O_n - P_n| \qquad \text{Eq. 3-15}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(O_n - P_n)^2} \qquad \text{Eq. 3-16}$$

Standard deviation of the differences compares if the model has the same level of variability as the observations.

$$SDD = \sqrt{\frac{1}{N-1}\sum_{n-1}^{N}(O'_n - P'_n)^2} \qquad \text{Eq. 3-17}$$

with $$O'_n = O_n - \bar{O} \qquad \text{Eq. 3-18}$$

$$P'_n = P_n - \bar{P} \qquad \text{Eq. 3-19}$$

With respect to continuous data, MBE may be the most appropriate measure since slight errors in phase can skew the comparisons for RMSE, MAE and SDD. Across the three stations and both years, MBE ranges from -0.71 to 0.48 mg/L for April to October, and -0.67 to 1.03 mg/L for July to September 15. RMSE, MAE, and SDD range from 0.88 to 1.18, 0.69 to 0.96, and 0.85 to 1.04 mg/L, respectively, for April to October; and from 0.42 to 1.16, 0.31 to 1.06, and 0.41 to 0.96 mg/L, respectively, for July to September 15 (Table 3-18). Maximum errors occur most often at the USGS Chester gage. This pattern is also seen in error statistics for daily average and daily minimum data (Table 3-19 and Table 3-20).

Table 3-18: Error Statistics of Continuous Modeled DO in Mainstem Delaware River Estuary

	April to October				July to Sep 15			
Station-year	**RMSE**	**MBE**	**MAE**	**SDD**	**RMSE**	**MBE**	**MAE**	**SDD**
Baxter 2012	0.88	0.22	0.73	0.85	0.78	0.52	0.62	0.58
Baxter 2013	1.02	-0.10	0.80	1.01	1.04	-0.40	0.84	0.96
BF Bridge 2012	1.10	-0.65	0.79	0.89	0.42	-0.08	0.31	0.41
BF Bridge 2013	1.18	-0.71	0.90	0.93	1.00	-0.67	0.76	0.74
Chester 2012	1.14	0.48	0.96	1.04	1.16	1.03	1.06	0.55
Chester 2013	0.93	-0.39	0.69	0.86	0.99	-0.51	0.69	0.86

Table 3-19: Error Statistics of Daily Average Modeled DO in Mainstem Delaware River Estuary

	April to October				July to Sep 15			
Station-year	RMSE	MBE	MAE	SDD	RMSE	MBE	MAE	SDD
Baxter 2012	0.81	0.26	0.68	0.77	0.72	0.51	0.57	0.52
Baxter 2013	0.93	-0.07	0.74	0.92	0.95	-0.35	0.77	0.88
BF Bridge 2012	1.12	-0.82	0.81	0.87	0.38	-0.11	0.27	0.36
BF Bridge 2013	1.15	-0.69	0.88	0.88	0.97	-0.68	0.76	0.69
Chester 2012	1.07	0.50	0.92	0.96	1.10	1.03	1.02	0.41
Chester 2013	0.93	-0.65	0.71	0.82	1.00	-0.65	0.69	0.84

Table 3-20: Error Statistics of Daily Minimum Modeled DO in Mainstem Delaware River Estuary

	April to October				July to Sep 15			
Station-year	RMSE	MBE	MAE	SDD	RMSE	MBE	MAE	SDD
Baxter 2012	0.86	0.13	0.69	0.85	0.59	0.21	0.46	0.55
Baxter 2013	0.90	-0.11	0.71	0.90	0.94	-0.41	0.76	0.85
BF Bridge 2012	1.00	-0.50	0.71	0.86	0.38	0.13	0.30	0.36
BF Bridge 2013	1.11	-0.69	0.84	0.87	0.84	-0.51	0.62	0.66
Chester 2012	1.03	0.24	0.87	1.00	0.95	0.83	0.85	0.47
Chester 2013	0.97	-0.56	0.73	0.81	0.93	-0.60	0.66	0.73

Philadelphia Tributaries

In Philadelphia tributaries to the Delaware River, simulations of DO were compared at three locations with continuous observed DO data: the Schuylkill River at Bartram's Garden and Navy Yard, and the Tacony-Frankford Creek mouth. These sites are termed SC482, SC048, and TF018, respectively. Minimum DO concentrations observed in the validation periods were 3.28, 5.35, and 0.02 mg/L in 2012 at SC482, SC048, and TF018, respectively; and 5.80, 3.97 and 0.05 mg/L in 2013.

Time series plots of simulated and observed data were produced for each station and year (Figure 3-64 and Figure 3-65). In each year, DO at SC482 (*i.e.*, Schuylkill River Mile 4.82) is well predicted until the occurrence of the first major discharge event (May 16, 2012 and June 6, 2013), after which the observed signal shifts modally upward from the predicted DO. The predicted DO appears to capture the same variability of the observed DO throughout the validation period, but with a negative bias that results in underpredicted DO following major discharge events. This may be due to an actual scouring process of Schuylkill River sediments that is not represented in the DO Model. Implementation of a sediment diagenesis model may improve this situation.

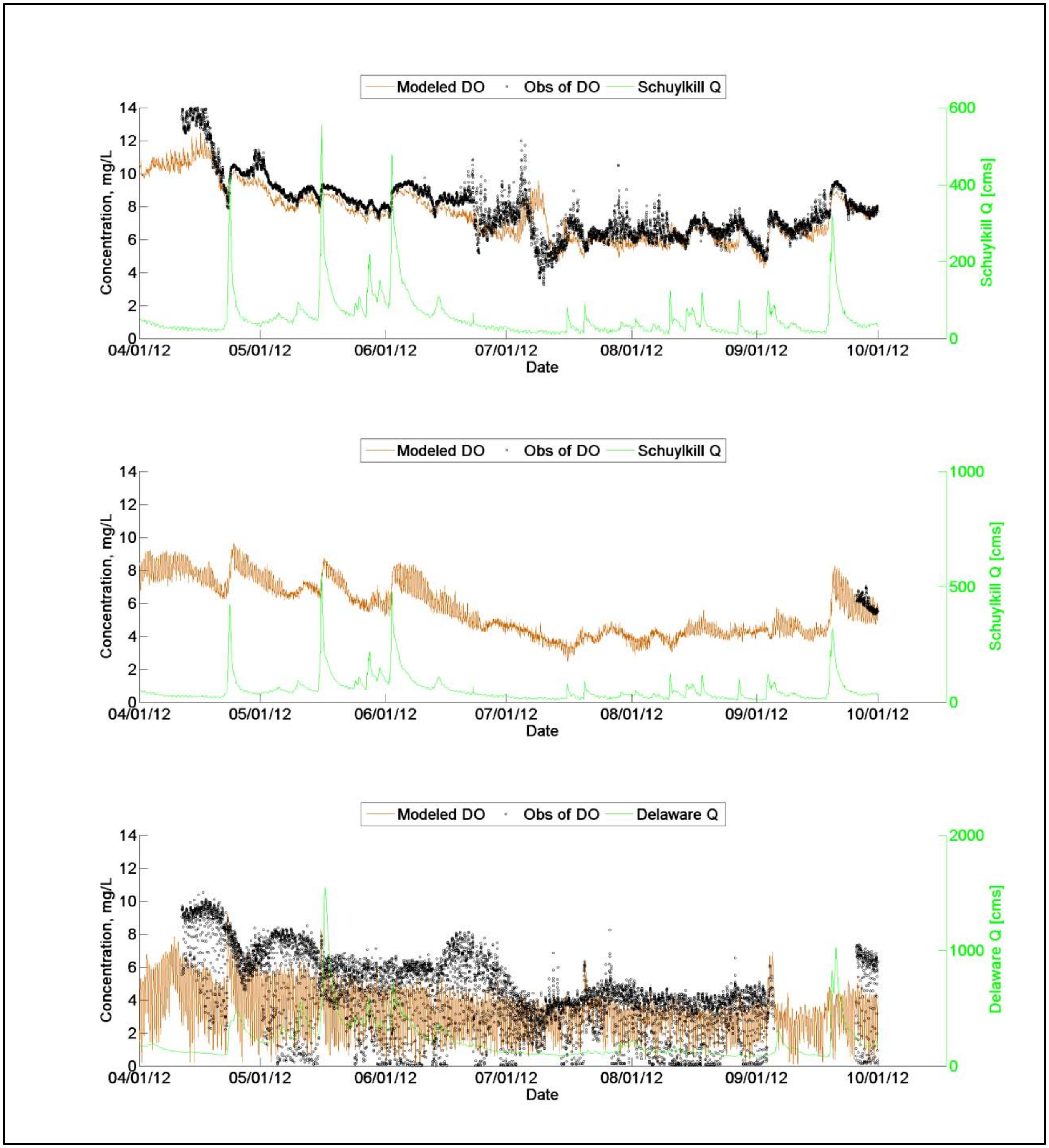


Figure 3-64: 2012 Time Series Plots of Modeled and Observed DO at Schuylkill River Miles 4.82 and 0.48, and Tacony-Frankford Creek River Mile 0.18

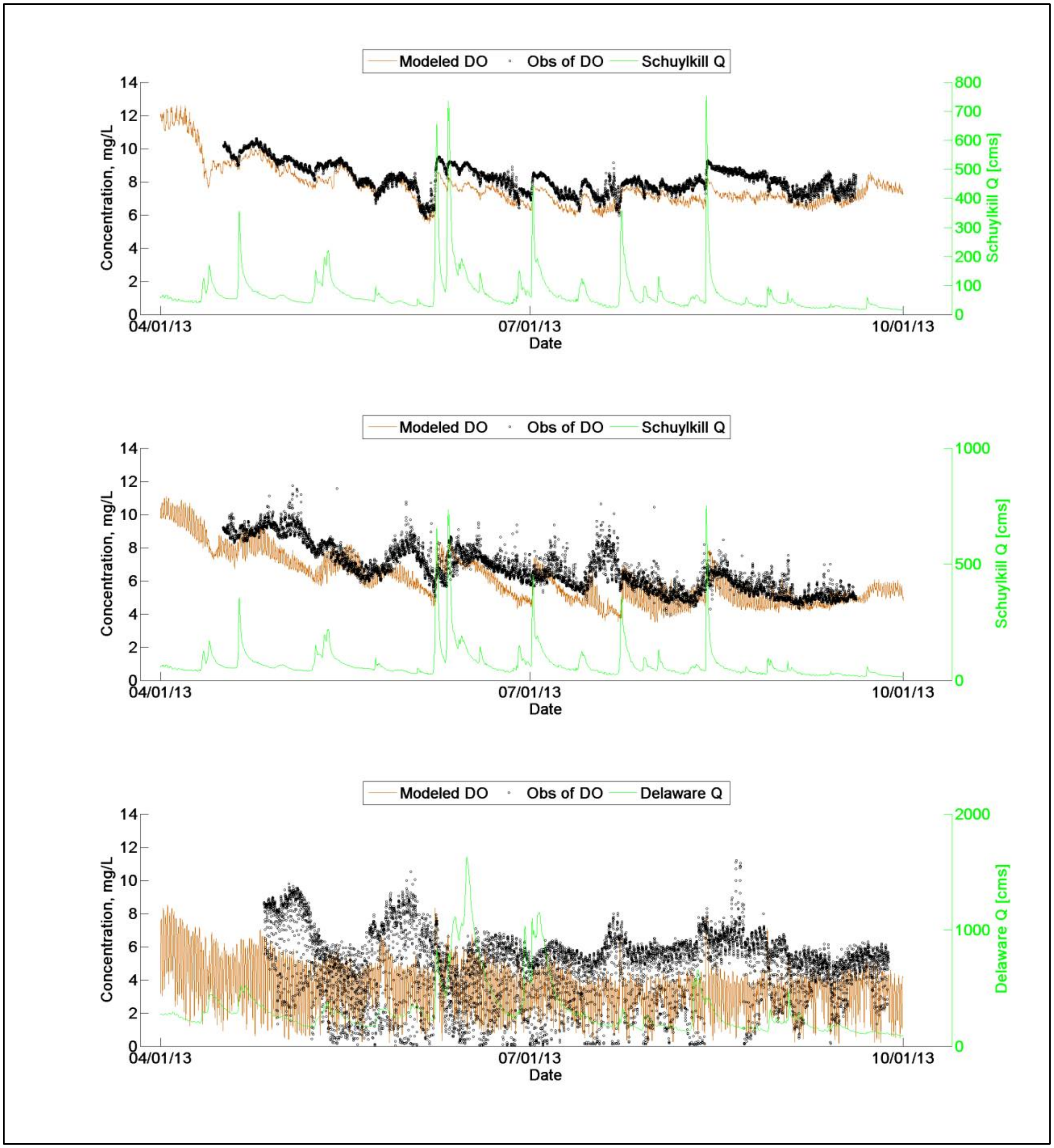


Figure 3-65: 2013 Time Series Plots of Modeled and Observed DO at Schuylkill River Miles 4.82 and 0.48, and Tacony-Frankford Creek River Mile 0.18

Low concentrations of DO in the Tacony-Frankford Creek mouth were observed throughout the 2012 and 2013 validation periods. DO Model simulations at this location are broadly representative of the range of observed DO, as indicated by the CDF plots (Figure 3-66). However, on a time step by time step basis, predictions of DO at this site are less accurate compared to other sites. This could be due in part to the much smaller volume of water being modeled at this location compared to the mainstem Delaware River or even the Schuylkill River, which increases the chance of hydrodynamic simulation error, coupled with DO concentrations that are more naturally variable at TF018 than at the other continuous DO data sites. Also, the data quality of DO at USGS Gage 01467087 (TTF Creek at Castor Ave.), which provides the DO boundary condition for the tidal Frankford Creek, is slightly less reliable than the other USGS gages used in the study.

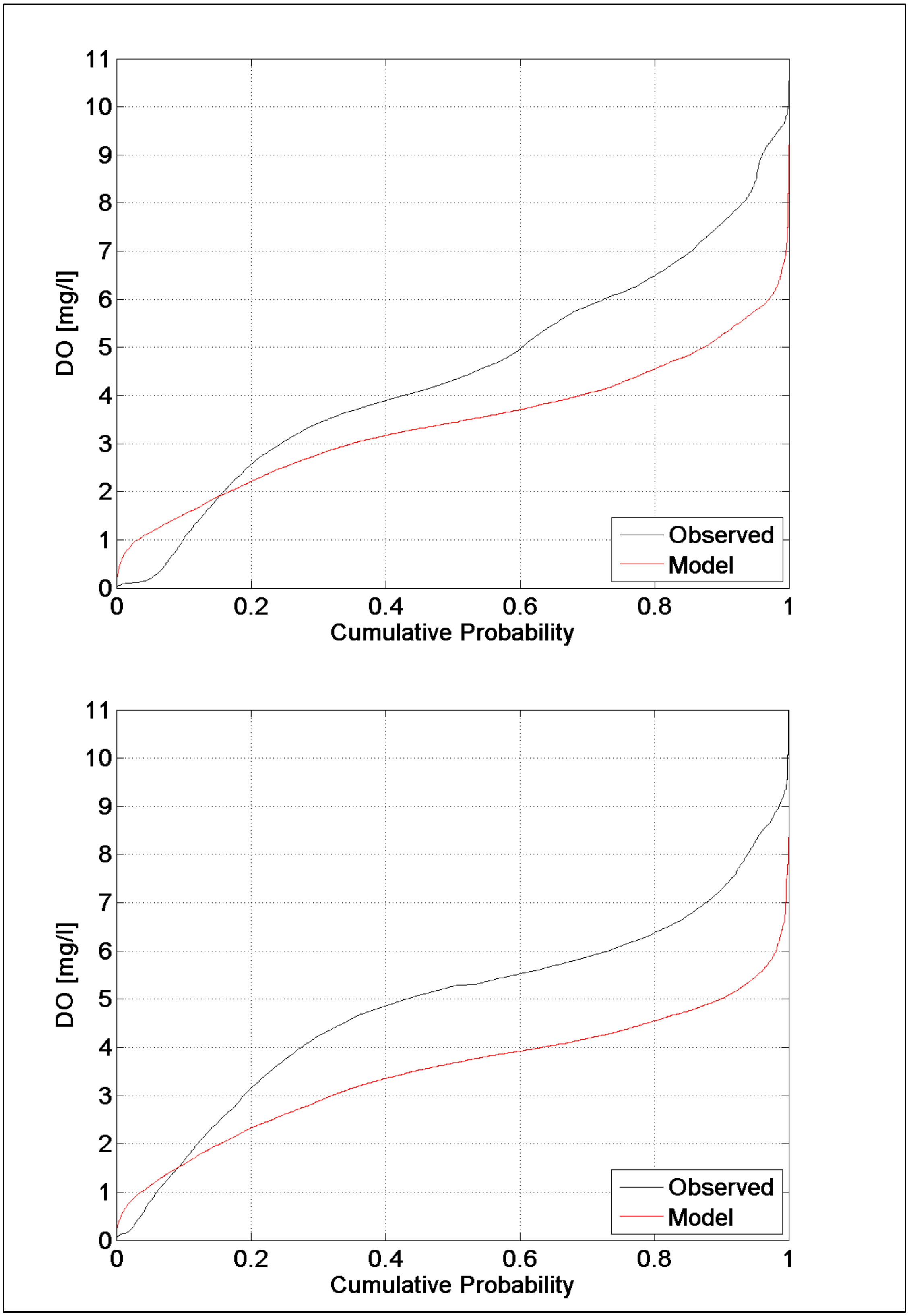


Figure 3-66: CDF Plots of Modeled and Observed DO at Tacony-Frankford Creek Mouth for April to October in 2012 and 2013

Error statistics for the Philadelphia tributary sites are presented in Table 3-21 - Table 3-23.

Table 3-21: Error Statistics of Continuous Modeled DO in Philadelphia Tributaries

	April to October				July to Sep 15			
Station-year	RMS	MBE	MAE	SDD	RMS	MBE	MAE	SDD
SC482-2012	1.01	-0.36	0.74	0.87	1.06	-0.32	0.73	1.01
SC482-2013	0.85	-0.47	0.76	0.49	0.95	-0.87	0.87	0.39
SC048-2012	0.71	-0.33	0.62	0.55	NA			
SC048-2013	1.32	-0.57	1.03	1.03	1.31	-0.81	0.97	1.03
TF018-2012	1.97	-1.02	1.54	1.66	1.15	-0.13	0.90	1.15
TF018-2013	2.17	-1.16	1.79	1.71	2.15	-1.54	1.80	1.50

Table 3-22: Error Statistics of Modeled Daily Average DO in Philadelphia Tributaries

	April to October				July to Sep 15			
Station-year	RMS	MBE	MAE	SDD	RMS	MBE	MAE	SDD
SC482-2012	0.89	-0.35	0.68	0.73	0.91	-0.36	0.66	0.83
SC482-2013	0.83	-0.47	0.75	0.45	0.93	-0.87	0.87	0.33
SC048-2012	0.51	-0.24	0.45	0.32	NA			
SC048-2013	1.22	-0.57	0.96	0.90	1.17	-0.80	0.87	0.86
TF018-2012	1.62	-1.03	1.20	1.21	0.58	-0.11	0.43	0.56
TF018-2013	1.80	-1.15	1.50	1.20	1.79	-1.54	1.56	0.92

Table 3-23: Error Statistics of Modeled Daily Minimum DO in Philadelphia Tributaries

	April to October				July to Sep 15			
Station-year	RMS	MBE	MAE	SDD	RMS	MBE	MAE	SDD
SC482-2012	0.87	-0.20	0.61	0.81	0.91	-0.11	0.56	0.91
SC482-2013	0.76	-0.37	0.65	0.50	0.84	-0.72	0.73	0.43
SC048-2012	0.90	-0.63	0.86	0.35	NA			
SC048-2013	1.15	-0.56	0.96	0.82	1.04	-0.76	0.85	0.71
TF018-2012	1.63	-0.13	1.21	1.62	1.07	0.48	0.89	0.94
TF018-2013	1.67	-0.19	1.27	1.65	1.74	-0.43	1.25	1.69

Target Diagrams

Visualizations with target diagrams (Jolliff *et al.* 2009) allow for a quick comparison of model performance at all station-years on a single plot (
Figure 3-67-
Figure 3-70). The biased and unbiased portions of total Root Mean Square Difference (RMSD) are presented in a target diagram. The unbiased RMSD (*i.e.*, error in predicting DO amplitude or variability) is plotted on the x-axis, with negative values for underestimated variability and positive values for overestimates. The difference in series mean between model results and reference data is plotted as Bias on the y-axis. A positive bias indicates the model overpredicts the series mean DO and negative values show an underprediction. The total RMSD is the distance from each plotted point to the origin; the ideal model would have a point on the origin.

April to October results are presented for continuous data (Figure 3-67). July to September 15 results are presented for continuous, daily average, and daily minimum cases (Figure 3-68 – Figure 3-70). The color of each plotted point is scaled to the magnitude of total RMSD.

Considering the relatively small magnitude of DO prediction error depicted in the target diagrams, particularly in the Delaware River and Schuylkill River sites (*i.e.,* biased and unbiased RMSD each within ±1 mg/L), and the overall level of system characterization achieved, the DO Model is considered a validated model for existing conditions.

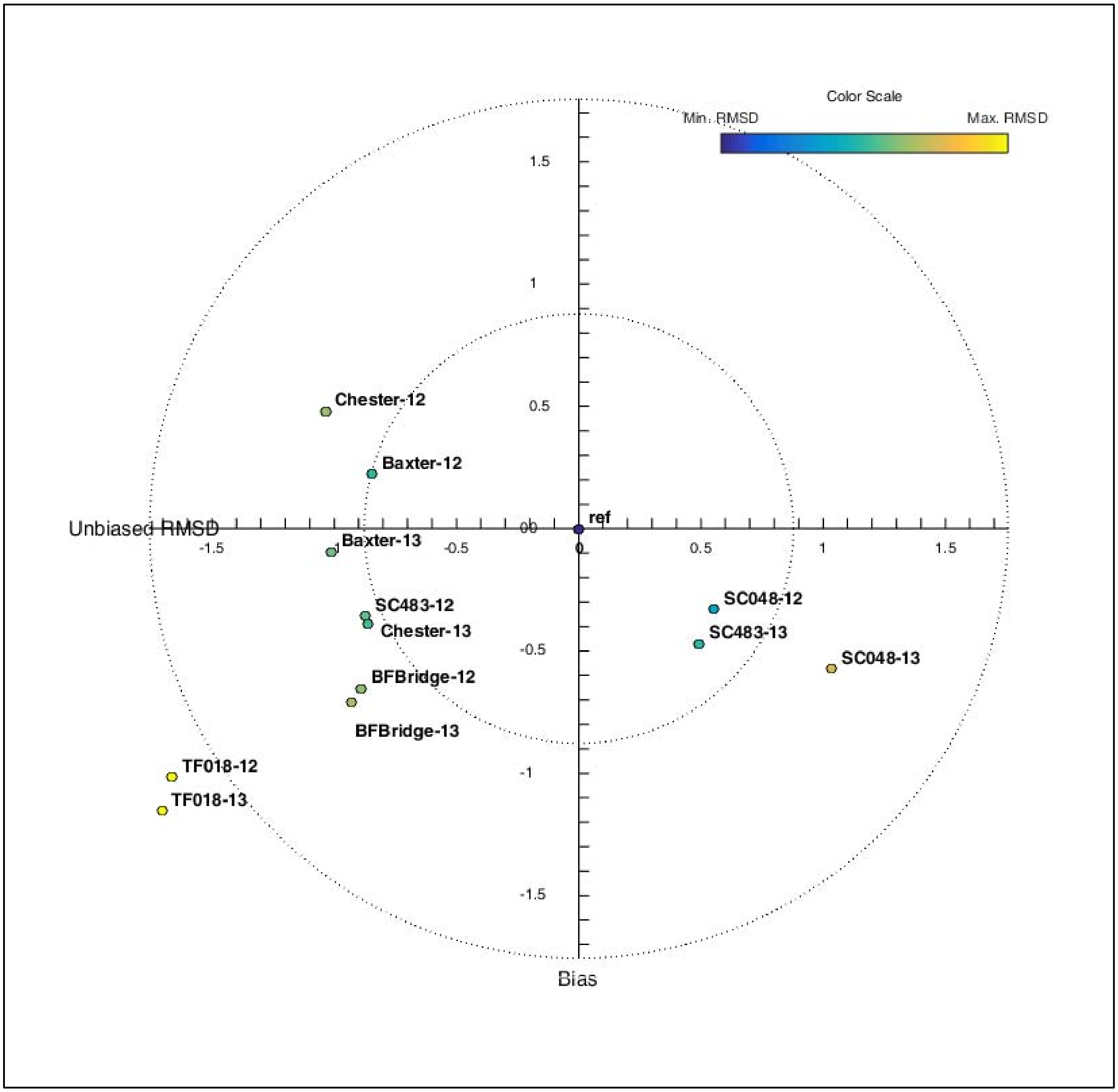


Figure 3-67: Target Diagram of Continuous DO Model Performance for April to October at all Station-Years. Axis units are mg/L.

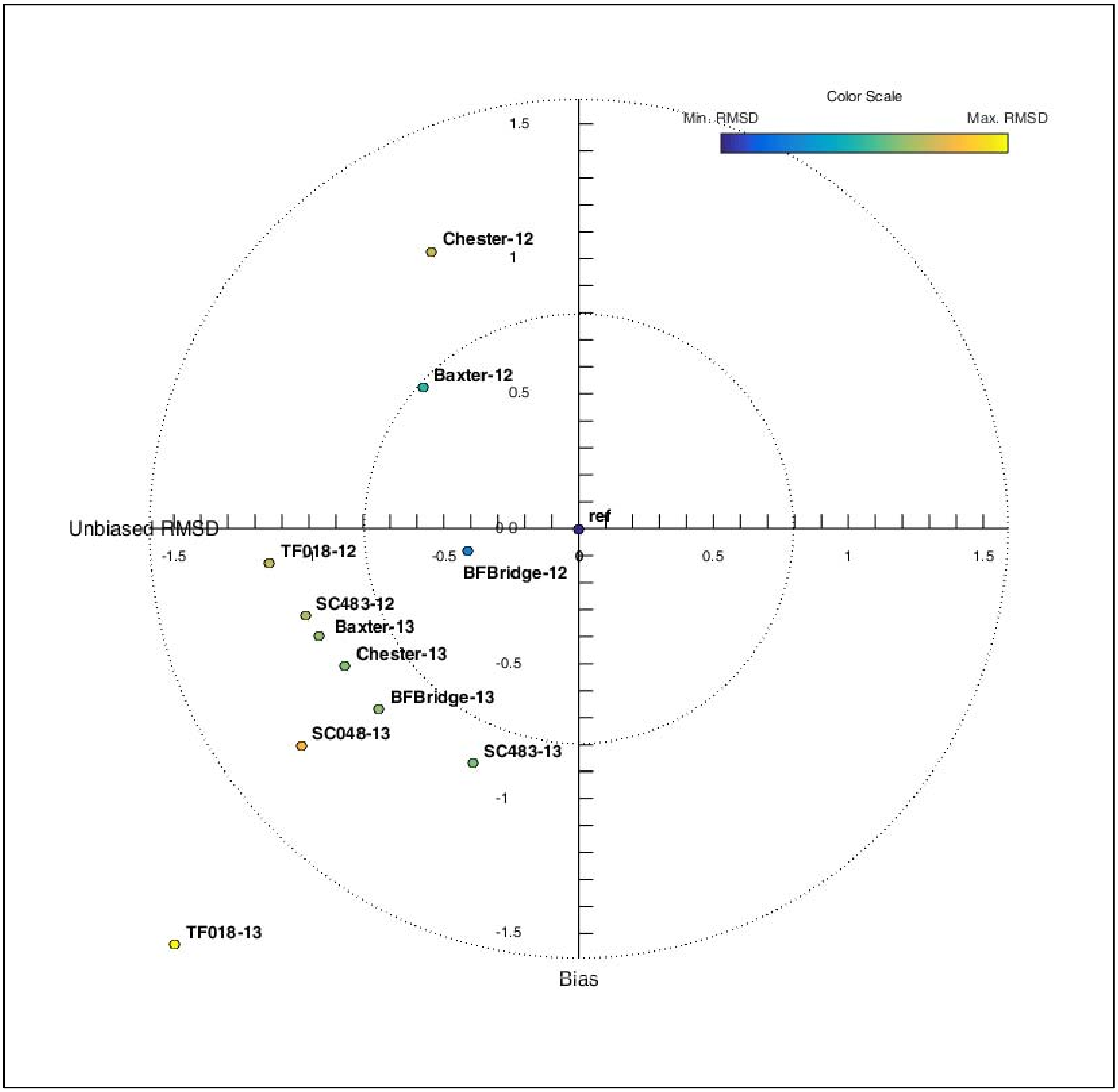


Figure 3-68: Target Diagram of Continuous DO Model Performance for July to September 15 at all Station-Years. Axis units are mg/L.

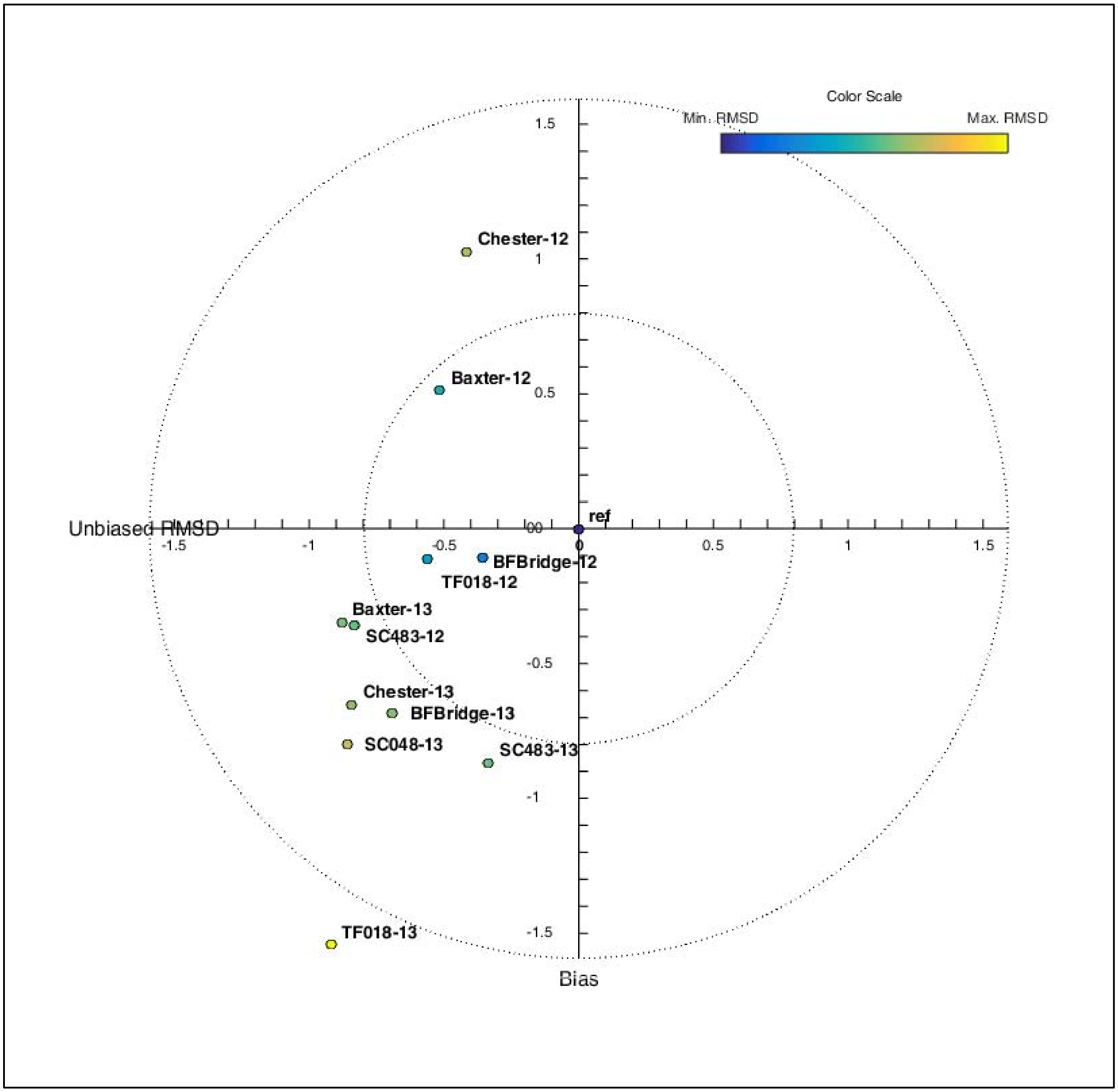


Figure 3-69: Target Diagram of Daily Average DO Model Performance for July to September 15 at all Station-Years. Axis units are mg/L.

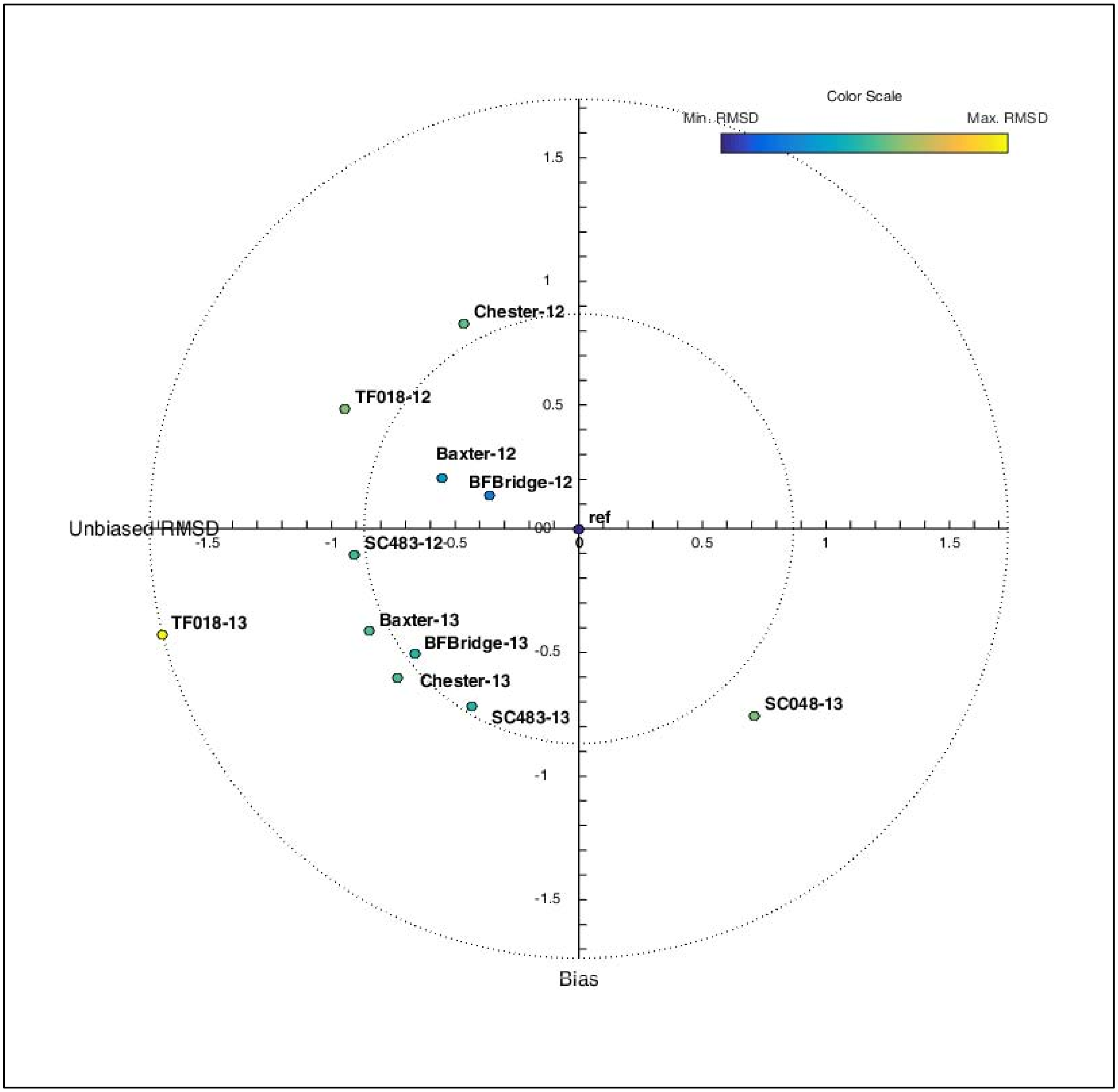


Figure 3-70: Target Diagram of Daily Minimum DO Model Performance for July to September 15 at all Station-Years. Axis units are mg/L.

3.12 Areas for future improvement

The development of the Bacteria and DO Models followed an approach of continuous improvement and validation. The selected versions of the models presented in this report represent a snapshot in time, and do not limit the development of future updates, which may include more detailed and accurate information, additional simplifications, changes to a different model platform version, or even the selection of a different model platform. Model development flexibility is paramount to achieving models that best fit a variety of applications and analysis goals.

As with all models, the Bacteria and DO Models are limited by the quality of the monitored validation data, both hydrodynamic and water quality, as well as the accuracy of the information used to construct the models. While an effort was made to use the best available data, future improvements to GIS data sets, additional bathymetry data, additional water level and current monitoring data, and additional water quality monitoring data could be used to improve the predictive ability of these models.

Specific areas for model improvement are listed below.

- **Improved estimates of loading from non-Philadelphia wastewater treatment plants**. DMR data from Pennsylvania, New Jersey and Delaware was leveraged to generate monthly loadings of carbon, nitrogen, phosphorus, DO, and bacteria effluents for 50 point sources outside the City of Philadelphia. In many cases, the parameter of interest was not reported and the effluent concentration was estimated based on methods detailed in Section 3.8.3. In 2011, all major point sources in the model domain were instructed to begin a two year nutrient monitoring program by DRBC, in accordance with DRBC Resolution No. 2010-5. The future provision of effluent data from this two year program could aid model development of point source loadings and reduce uncertainty. In parallel, efforts could be made to acquire daily-scale flow and effluent data from CCMUA, DELCORA, and City of Wilmington (*i.e.*, the three largest municipal WWTPs outside of Philadelphia) in hopes of improving water quality simulations, particularly downstream of the Philadelphia area.
- **Improved estimates of CSO inputs from outside Philadelphia.** In contrast with the sophisticated SWMM5 CSS Model that was used to generate CSO loadings from City of Philadelphia, less advanced rainfall-runoff approaches were needed to estimate CSO loadings from CCMUA, DELCORA and City of Wilmington. Less uncertain estimates of CSO loading from these entities would improve water quality simulations, particularly for bacteria downstream of the Philadelphia area.
- **Sediment diagenesis modeling.** The DO Model described in this report applies spatially variable zero-order rates to represent fluxes of oxygen, ammomium, nitrate, and orthophosphate into or out of the sediment. This simplification does not allow simulation of time-varying fluxes, limits spatial variability to defined zones rather than individual grid cells, and severs the link between deposition of organic matter, including algae and sediment processes. Although extensive sediment studies undertaken for this project did not find great variability in oxygen fluxes, highly variable fluxes were

observed across the model domain for nitrate, ammonium and orthophosphate. Future implementation of the sediment diagenesis capabilities in EFDC might improve the representation of biogeochemical cycling in the system, and establish the link between changes to loading and the response of sediment processes.

- **Simulation of multiple algal groups.** Future efforts could be made to simulate additional classes of phytoplankton, and better capture the seasonal variation observed in taxonomic analyses and chl-*a* concentrations. Including two or three algal groups might improve DO predictions that are currently divergent at times of peak chl-*a* concentrations.
- **Incorporate additional data on nitrification and CBOD decay rates.** A second round of studies was conducted in May 2014 on these processes, as a supplement to the August 2013 studies. Analysis of data from May 2014 studies has not been completed yet. However, when available, these data might help further refine spatially variable rates of nitrification and DOC decay, and their dependence on temperature.
- **Incorporate atmospheric deposition.** Although this is not thought to be a major source of carbon, nitrogen or phosphorus loading to the system, atmospheric deposition should nevertheless be included for completeness. Estimates were developed for the Wilmington area for the Christina River draft TMDL report and could be adapted to this Water Quality Model.
- **Uncertainty analysis.** Water quality models are imperfect representations of natural systems, and are subject to uncertainties. For the Bacteria and DO Models, a computationally-efficient method such as Latin Hypercube Sampling could be explored using kinetic rate constant probability distributions from literature and from local sampling data. This would provide a probabilistic range of model output, rather than a single-value fixed model output.
- **Simulation of system response to changing conditions.** As the Water Department moves ahead with the further refinement of these models over the next 3-4 years, capabilities to simulate the receiving waters response to changes in source loadings and other environmental conditions could be developed and included in the continuing process of re-validation.

3.13 Conclusions

A multidimensional hydrodynamic and water quality modeling system was developed and validated for the Delaware River Estuary from Trenton, NJ to Delaware City, DE. Hydrodynamic simulations were performed with EFDC, and water quality simulations of bacteria and DO were performed with EFDC-WQ. With respect to water level and current prediction, and based on calculations of RMSE and Skill, harmonics, progressive wave characterization, tidal asymmetry, and subtidal analysis, the Hydrodynamic Model is validated against a nine month period, and has achieved results that fall well within the criteria for acceptability according to NOAA (Zhang, 2006). Spatially variable bottom roughness was applied. Accurate representation of physical transport processes in the EFDC model applied to the Delaware River was demonstrated using both a fine-resolution grid designed for accurate hydrodynamic representation, and also using a coarser grid modified to increase computational efficiency without losing hydrodynamic accuracy.

The Bacteria and DO Models were validated over two 6 month periods in 2012 and 2013 that each encompassed the summer season when lowest DO conditions are typically observed. Loadings of carbon, nitrogen, phosphorus, DO, algae, and bacteria from varied sources such as wastewater treatment plants, CSOs, stormwater runoff, and tributaries, were each considered in model development. Meteorological data was utilized to achieve accurate representations of water temperature, wind, and solar radiation. An extensive database of instream water quality data was compiled from multiple agencies for comparison to model output. Continuous DO data at six sites along the mainstem Delaware River Estuary and Philadelphia tributaries were used for high frequency comparison of simulated and observed DO concentrations. A sensitivity analysis was conducted to identify the key global and spatially variable rate constants. Spatially variable constants were parameterized with the aid of extensive measurements of nitrification rate, SOD, and benthic nutrient fluxes.

Time series plots, CDF plots, box plots, along-channel plots, target diagrams, and error statistics were used to evaluate Water Quality Model performance. Analyses indicate adequate Water Quality Model performance, particularly for the Philadelphia area where higher resolution loading data was available. Although the Water Quality Model is validated for existing conditions, additional studies will need to be done to best represent the system as future conditions change. Future areas of improvement have been identified and can be pursued to enhance model performance.

3.14 Section 3 Appendix

Loading Summaries

Table A3-1: Tributary Concentrations for Carbon Species

Trib loading subsets	DOC [mg/L]	POC [mg/L]
Brandywine	seasons	
	2.7/2.9/2.7	0/0/0
Chester	see Crum	
	1.7	0/0/0
Christina	seasons	
	4.0/4.2/4.1	0/0/0
Cobbs	wet/dry	
	1.128/0.147	1.128/0.147
Cooper	wet/dry	all-year
	4.61/3.3	0.12
Crosswicks	all-year	
	4.32	0.16
Crum	all-year	see Brandywine
	1.7	0/0/0
Delaware	all-year	
	2.9	0.095
Frankford	wet/dry	
	2.04/0.29	2.04/0.29
Neshaminy	see Poquessing	
	0.29/0.29 - 1.11/0.29 - 1.27/0.29	0.29/0.29 - 1.11/0.29 - 1.27/0.29
Pennsauken	all-year	
	4.4	0.165
Pennypack	seasons-wet/dry	
	1.48/0.29 - 1.48/0.29 - 0.29/0.29	1.48/0.29 - 1.48/0.29 - 0.29/0.29
Poquessing	seasons-wet/dry	
	0.29/0.29 - 1.11/0.29 - 1.27/0.29	0.29/0.29 - 1.11/0.29 - 1.27/0.29
Raccoon	all-year	

Loading Options:

all-year: constant value

seasons: spring/summer/winter

wet/dry: wet/dry

seasons-wet/dry:
spring-wet/dry /
summer-wet/dry /
winter-wet/dry

Based on different tributary due to lack of data: *e.g.,* see Crum

Trib loading subsets	DOC [mg/L]	POC [mg/L]
	3.34	0.48
Rancocas	all-year	see Crosswicks
	7.15	0.16
Schuylkill	seasons-wet/dry	all-year
	2.21/2.4 - 2.7/3.05 - 3.9/3.2	0.26

Table A3-2: Tributary Concentrations for Nitrogen Species

Trib loading subsets	NH4 [mg-N/L]	NO3 [mg-N/L]	DON [mg-N/L]	PON [mg-N/L]
Brandywine	seasons	see Schuylkill		
	0.043/0.0425/0.041	2.62/2.55 - 3.08/2.83 - 3.18/2.95	0.26425/0.3325	0.26/0.26
Chester	see Crum			
	0.043/0.0425/0.041	2.62/2.55 - 3.08/2.83 - 3.18/2.95	0.26425/0.3325	0.26/0.26
Christina	seasons	see Brandywine		
	0.078/0.0615/0.086	2.62/2.55 - 3.08/2.83 - 3.18/2.95	0.26425/0.3325	0.26/0.26
Cobbs	wet/dry			
	0.145/0.05	0.87/2.152	0.375/0.23	0.375/0.23
Cooper	seasons			
	0.17/0.1085/0.175	0.83/0.395/0.975	0.2815/0.262/0.21	0/0/0
Crosswicks	all-year	see Rancocas	all-year	
	0.08	1.26/1.1/0.96	0.54	0
Crum	see Brandywine			
	0.043/0.0425/0.041	2.62/2.55 - 3.08/2.83 - 3.18/2.95	0.26425/0.3325	0.26/0.26
Delaware	seasons-wet/dry		see Schuylkill	
	0.166/0.045 - 0.098/0.12 - 0.256/0.263	1.29/1.64 - 1.62/1.1 - 1.19/1.26	0.26425/0.3325	0.26/0.26
Frankford	wet/dry			
	0.31/0.1	1.27/1.84	0.55/0.225	0.55/0.225

Trib loading subsets	NH4 [mg-N/L]	NO3 [mg-N/L]	DON [mg-N/L]	PON [mg-N/L]
Neshaminy	seasons		see Poquessing	
	0.045/0.04/0.015	1.965/1.8/2.435	0.259/0.175	0.259/0.175
Pennsauken	all-year			
	0.211	0.655	0.47	0
Pennypack	seasons-wet/dry		wet/dry	
	0.25/0.05 - 0.12/0.05 - 0.05/0.05	2.02/3.24 - 2.72/3.74 - 4.92/4.19	0.4475/0.215	0.4475/0.215
Poquessing	seasons-wet/dry		wet/dry	
	0.25/0.097 - 0.25/0.25 - 0.25/0.05	1.1/1.37 - 0.8/1.21 - 0.4/1.85	0.259/0.175	0.259/0.175
Raccoon	seasons		all-year	
	0.12/0.039/0.13	1.8/1.08/1.64	0.26	0
Rancocas	seasons			see Crosswicks
	0.079/0.04/0.079	1.26/1.1/0.96	0.47/0.54/0.32	0
Schuylkill	wet/dry	seasons-wet/dry	wet/dry	
	0.128/0.05	2.62/2.55 - 3.08/2.83 - 3.18/2.95	0.26425/0.3325	0.26/0.26

Table A3-3: Tributary concentrations for Phosphorus Species and DO

Trib loading subsets	PO4 [mg-P/L]	DOP [mg-P/L]	POP [mg-P/L]	DO [mg/L]
Brandywine	seasons	see Schuylkill		USGS 01481500
	0.08/0.11/0.08	0.0338/0.0355	0.0338/0.0355	time series
Chester	see Crum			
	0.08/0.11/0.08	0.0338/0.0355	0.0338/0.0355	11.05
Christina	seasons	see Brandywine		USGS 01480065
	0.085/0.105/0.08	0.0338/0.0355	0.0338/0.0355	time series
Cobbs	wet/dry			USGS 01475548
	0.025/0.0125	0.0875/0.0275	0.0875/0.0275	time series
Cooper	seasons	see Pennypack		seasons
	0.04/0.12/0.03	0.065/0.03	0.065/0.03	8.2/7.1/11.1
Crosswicks	all-year	see Poquessing		seasons
	0.04	0.0375/0.0045	0.0375/0.0045	8.6/6.95/11.61
Crum	see Brandywine			all-year
	0.08/0.11/0.08	0.0338/0.0355	0.0338/0.0355	11.05
Delaware	seasons-wet/dry	see Schuylkill		USGS 01463500
	0.12/0.13 - 0.12/0.09 - 0.12/0.12	0.0338/0.0355	0.0338/0.0355	time series
Frankford	wet/dry			USGS 01467087
	0.05/0.05	0.0725/0.03	0.0725/0.03	time series
Neshaminy	seasons	see Poquessing		seasons
	0.305/0.42/0.265	0.0375/0.0045	0.0375/0.0045	11.65/10.25/14.4
Pennsauken	all-year	see Pennypack		seasons
	0.14	0.065/0.03	0.065/0.03	7.9/6.4/10.7
Pennypack	seasons wet/dry	wet/dry		USGS 01467048
	0.13/0.23 - 0.46/0.45 - 0.85/0.285	0.065/0.03	0.065/0.03	time series
Poquessing	wet/dry			USGS 01465798
	0.025/0.025	0.0375/0.0045	0.0375/0.0045	time series
Raccoon	all-year	see Pennypack		seasons

Trib loading subsets	PO4 [mg-P/L]	DOP [mg-P/L]	POP [mg-P/L]	DO [mg/L]
	0.13	0.065/0.03	0.065/0.03	8.9/7/11
Rancocas	seasons	see Pennypack		seasons
	0.16/0.13/0.2	0.065/0.03	0.065/0.03	8.6/6.6/11.4
Schuylkill	seasons-wet/dry	wet/dry		USGS 01474500
	0.127/0.05 - 0.169/0.174 - 0.079/0.067	0.0338/0.0355	0.0338/0.0355	time series

Table A3-4: Tributary concentrations for Phytoplankton Algae and Fecal Coliforn

Trib loading subsets	Algae [µg/L]	Fecal coliform [CFU/100mL]
Brandywine	seasons	see Schuylkill
	4.5/1.36/2.4	36/10.5 - 91/51 - 85/45
Chester	see Crum	
	4.5/1.36/2.4	36/10.5 - 91/51 - 85/45
Christina	seasons	see Brandywine
	10.03/20.8/2.87	36/10.5 - 91/51 - 85/45
Cobbs	constant	wet/dry
	2	31000/380
Cooper	all-year	wet/dry
	12.7	1950/540
Crosswicks	all-year	wet/dry
	4.7	600/230
Crum	see Brandywine	
	4.5/1.36/2.4	36/10.5 - 91/51 - 85/45
Delaware	seasons	seasons
	5/5/1	42/48/31
Frankford	constant	wet/dry
	2	24000/380
Neshaminy	see Crosswicks	see Poquessing

Trib loading subsets	Algae [µg/L]	Fecal coliform [CFU/100mL]
	4.7	660/110 - 7000/290 - 11000/173
Pennsauken	all-year	wet/dry
	2.25	9000/800
Pennypack	constant	seasons-wet/dry
	2	12000/150 - 10550/77 - 2200/300
Poquessing	constant	seasons-wet/dry
	2	660/110 - 7000/290 - 11000/173
Raccoon	seasons	wet/dry
	13.06/19.05/5.08	500/110
Rancocas	see Crosswicks	all-year
	4.7	150
Schuylkill	wet/dry	seasons-wet/dry
	2.55/4.61	36/10.5 - 91/51 - 85/45

Table A3-5: Municipal WWTPS - Average flow and concentration 2012

		2012 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
Ewing Lawrence Sewerage Authority	0.406	0.38[b]	3.44[b]	0.58[d]	0.58[d]	1.15[d]	0.02[a]	0.06[a]	0.10	17.25	6.95	4.0
Morrisville Boro Mun. Auth-STP	0.192	0.48[b]	4.31[b]	0.20[d]	0.20[d]	0.41[d]	1.75[a]	5.24[a]	9.19	1.19[a]	6.37	55.4
Trenton DPW Sewerage Authority	0.472	1.18[b]	10.64[b]	0.12[a]	0.12[a]	0.24[a]	1.26[a]	3.78[a]	6.64	0.86[a]	6.95[a]	1.0
Hamilton Twp WPCF	0.372	1.18[b]	10.65[b]	1.05[d]	1.05[d]	2.11[d]	4.55[a]	13.64[a]	23.93	4.76	6.95[a]	3.2
Bordentown Sewerage Authority	0.073	0.18[b]	1.65[b]	0.02[a]	0.02[a]	0.04[a]	0.03[a]	0.09[a]	0.16	28.20	6.95[a]	12.9
Lower Bucks County Joint MA	0.261	0.34[b]	3.04[b]	0.03[a]	0.03[a]	0.07[a]	4.37[a]	13.11[a]	23.00	2.99[a]	3.73	145.3
Florence Twp STP	0.076	0.27[b]	2.4[b]	0.86[d]	0.86[d]	1.73[d]	0.41[a]	1.24[a]	0.70	5.80[a]	6.95[a]	6.9
Bristol Boro WSA	0.071	1.05[a]	9.42[a]	0.10[a]	0.10[a]	0.21[a]	0.66[a]	1.98[a]	1.20[a]	8.92[a]	8.22[a]	1.1[a]
Burlington Twp DPW	0.091	0.16[a]	1.41[a]	0.57[a]	0.57[a]	1.14[a]	0.94[a]	2.83[a]	4.97[a]	0.65[a]	6.95[a]	1.2[a]
Burlington City STP	0.075	0.53[b]	4.81[b]	0.80[a]	0.80[a]	1.60[a]	0.41[a]	1.22[a]	0.69	5.73[a]	6.95[a]	4.6
Bristol Twp WWTP	0.110	1.00[b]	8.97[b]	0.10[a]	0.10[a]	0.20[a]	0.56[a]	1.68[a]	2.95	0.38[a]	6.95[a]	52.8
Willingboro Twp MUA	0.001	0.34[b]	3.09[b]	0.11[a]	0.11[a]	0.23[a]	0.81[a]	2.42[a]	4.24	28.10	6.95[a]	20.8
Delran Sewerage Authority	0.087	0.22[b]	1.94[b]	0.76[d]	0.76[d]	1.51[d]	0.20[a]	0.61[a]	0.34	14.52[a]	6.95[a]	14.5
Cinnaminson Sewerage Authority	0.050	1.12[b]	10.10[b]	0.62[d]	0.62[d]	1.23[d]	2.38[a]	7.14[a]	12.53	1.63[a]	6.95[a]	20.4
Moorestown WWTP	0.089	0.43[b]	3.84[b]	0.75[d]	0.75[d]	1.51[d]	1.02[a]	3.05[a]	1.73	17.05	6.95[a]	16.3
Maple Shade POTW	0.095	0.14[b]	1.26[b]	0.05[d]	0.05[d]	0.09[d]	0.15[a]	0.45[a]	0.25	2.08[a]	6.95[a]	4.5
Philadelphia - Northeast	7.003	0.52[b]	4.69[b]	0.10[d]	0.10[d]	0.23	1.16[e]	1.16[e]	6.80	1.55	5.64	16.1

		2012 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
WPCP												
Camden County MUA	1.937	0.49[b]	4.40[b]	0.54[a]	0.54[a]	1.08[a]	4.22[a]	12.65[a]	22.19	2.88[a]	6.95[a]	1.5
Philadelphia - Southeast WPCP	2.953	0.70[b]	6.32[b]	0.16[d]	0.16[d]	0.45	0.62[e]	0.98[e]	9.24	0.15	5.12	14.2
Philadelphia - Southwest WPCP	7.256	0.36[b]	3.24[b]	0.09[d]	0.09[d]	0.08	1.86[e]	1.98[e]	20.92	1.12	5.13	30.5
Gloucester County Utility Authority	0.732	0.79[b]	7.12[b]	0.77[d]	0.77[d]	1.54[d]	3.14[a]	9.42[a]	16.52	6.99	6.95[a]	2.4
Tinicum Twp WWTP	0.038	1.00[b]	9.03[b]	0.10[d]	0.10[d]	0.20[d]	0.21[a]	1.90[a]	2.11[a]	6.24[a]	8.19	54.1
Little Washington STP	0.065	0.55[b]	4.98[b]	0.06[a]	0.06[a]	0.11[a]	0.36[a]	1.09[a]	0.62	5.11[a]	6.96	9.3
DELCORA	1.270	0.66[b]	5.93[b]	0.07[a]	0.07[a]	0.13[a]	0.88[e]	2.63[e]	4.61	4.05	6.95[a]	70.9
Southwest Delaware County MUA	0.185	0.57[b]	5.16[b]	0.06[a]	0.06[a]	0.11[a]	1.27[a]	3.81[a]	2.15	17.80[a]	8.37	44.1
Logan Twp MUA	0.045	0.28[b]	2.50[b]	0.79[d]	0.79[d]	1.57[d]	1.56[a]	4.68[a]	2.65	21.91[a]	6.95[a]	3.5
Carneys Point WWTP	0.038	0.71[b]	6.38[b]	1.08[a]	1.08[a]	2.15[a]	1.37[a]	4.11[a]	7.21[a]	0.94[a]	6.95[a]	20.7[a]
Pennsville Twp Sewerage Authority	0.055	0.62[b]	5.59[b]	0.39[d]	0.39[d]	0.78[d]	0.50[a]	1.51[a]	0.85	7.05[a]	6.95	6.3
Wilmington WWTP	2.865	0.50[b]	4.48[b]	0.05[a]	0.05[a]	0.10[a]	0.10[a]	0.94[a]	1.05[a]	6.24[a]	6.95[a]	0.6

a) estimated b) based on reported BOD or CBOD c) based on reported TOC or DOC

d) based on reported TP e) based on reported TKN f) based on reported TON

Table A3-6: Industrial Permitted Dischargers - Average flow and concentration 2012

	2012 average flow, concentration (geo. Mean for FCB)											
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
US Steel Fairless Hills Works (Outfall 103)	0.082	0.55[b]	0.55[b]	0.01[a]	0.01[a]	0.02[a]	0.12[a]	0.12[a]	0.23[a]	1.00[a]	6.95[a]	4.5[a]
Coastal Eagle Point Oil Co.	0.044	0.66[b]	0.66[b]	0.01[a]	0.01[a]	0.03[a]	0.17[a]	0.17[a]	0.33	1.00[a]	6.95[a]	0.8
Valero Refining Co. (Outfall 1)	0.345	0.96[b]	0.96[b]	0.26[d]	0.26[d]	0.51[d]	0.09[a]	0.09[a]	0.18	1.00[a]	6.95[a]	4.1
E I Dupont De Nemours & Co. Repauno Plant	0.044	0.80[b]	0.80[b]	0.02[a]	0.02[a]	0.03[a]	0.49[a]	0.49[a]	0.98	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 2)	0.438	0.49[a]	0.49[a]	0.01[a]	0.01[a]	0.02[a]	0.10[a]	0.10[a]	0.21[a]	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 101)	0.492	0.96[a]	0.96[a]	0.02[a]	0.02[a]	0.04[a]	0.20[a]	0.20[a]	0.40[a]	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 201)	0.059	0.33[b]	0.33[b]	0.01[a]	0.01[a]	0.01[a]	0.48[a]	0.48[a]	0.97	1.00[a]	6.95[a]	4.5[a]
Sunoco, Inc. Marcus Hook Refinery	0.326	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.49[a]	6.95[a]	4.5[a]
Dupont Edgemoor (Outfall 1)	0.110	1.51[a]	1.51[a]	0.03[a]	0.03[a]	0.06[a]	0.32[a]	0.32[a]	0.63[a]	1.00[a]	6.95[a]	4.5[a]
Dupont Edgemoor (Outfall 3)	0.175	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Ferro Corp.	0.037	6.75[b]	6.75[b]	0.14[a]	0.14[a]	0.27[a]	1.46[f]	1.46[f]	1.71	14.15[a]	6.95[a]	8.8
E I Dupont De Nemours & Co. (Outfall 1)	0.093	1.33[c]	1.33[c]	0.03[d]	0.03[d]	0.05[d]	0.28[a]	0.28[a]	0.56[a]	1.00[a]	6.95[a]	4.5[a]
E I Dupont De Nemours & Co. (Outfall 2)	1.022	0.96[a]	0.96[a]	0.08[d]	0.08[d]	0.16[d]	2.64[f]	2.64[f]	0.18	9.50	6.95[a]	42.7
E I Dupont De Nemours & Co. (Outfall 13)	0.149	3.07[c]	3.07	0.06[a]	0.06[a]	0.12[a]	0.64[a]	0.64[a]	1.29[a]	1.00[a]	6.95[a]	4.5[a]

		2012 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
E I Dupont De Nemours & Co. (Outfall 662)	0.369	5.67[c]	5.67	0.11[d]	0.11[d]	0.23[d]	1.74[f]	1.74[f]	0.33	2.76[a]	6.95[a]	4.1
Deepwater Energy Center (Outfall 3)	1.135	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Deepwater Energy Center (Outfall 10)	1.188	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 1)	15.674	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 201)	11.806	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 601)	0.026	7.51[c]	7.51[c]	0.09[a]	0.09[a]	0.18[a]	0.30[a]	0.30[a]	0.60[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 701)	0.609	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Conectiv Delaware City Power Plant	1.818	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Exelon Corp. Schuylkill Generating Station (Outfall 1)	2.167	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Exelon Corp. Schuylkill Generating Station (Outfall 301)	1.710	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]

a) estimated b) based on reported BOD or CBOD c) based on reported TOC or DOC

d) based on reported TP e) based on reported TKN f) based on reported TON

Table A3-7: Municipal WWTPs - Average flow and concentration 2013

	2013 average flow, concentration (geo. Mean for FCB)											
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
Ewing Lawrence Sewerage Authority	0.458	0.45[b]	4.06[b]	0.60[d]	0.60[d]	1.20[d]	0.04[a]	0.11[a]	0.20	12.92	6.95[a]	2.5
Morrisville Boro Mun. Auth-STP	0.221	0.71[b]	6.42[b]	0.20[d]	0.20[d]	0.41[d]	2.68[a]	8.04[a]	14.10	1.83[a]	6.15	53.7
Trenton DPW Sewerage Authority	0.503	1.10[b]	9.89[b]	0.11[a]	0.11[a]	0.22[a]	1.49[a]	4.48[a]	7.87	1.02[a]	6.95[a]	1.3
Hamilton Twp WPCF	0.355	1.13[b]	10.16[b]	0.98[d]	0.98[d]	1.96[d]	4.71[a]	14.12[a]	24.77	5.77	6.95[a]	3.2
Bordentown Sewerage Authority	0.078	0.19[b]	1.75[b]	0.02[a]	0.02[a]	0.04[a]	0.13[a]	0.38[a]	0.21	26.68	6.95[a]	5.7
Lower Bucks County Joint MA	0.295	0.38[b]	3.44[b]	0.04[a]	0.04[a]	0.08[a]	3.13[a]	9.38[a]	16.46	2.14[a]	3.53[a]	137.8
Florence Twp STP	0.061	0.30[b]	2.67[b]	0.72[d]	0.72[d]	1.45[d]	0.14[a]	0.41[a]	0.72	0.09[a]	6.95[a]	8.6
Bristol Boro WSA	0.055	0.22	1.98	0.02[a]	0.02[a]	0.04[a]	0.22[a]	0.66[a]	1.15	0.15[a]	6.95[a]	1.8[a]
Burlington Twp DPW	0.076	0.58[a]	5.20[a]	0.72[a]	0.72[a]	1.44[a]	0.48[a]	1.43[a]	0.81[a]	6.69[a]	6.95[a]	1.3[a]
Burlington City STP	0.888	0.58[b]	5.20[b]	0.72[d]	0.72[d]	1.44[d]	0.48[a]	1.43[a]	0.81	6.69[a]	6.95[a]	1.3
Bristol Twp WWTP	0.114	1.01[b]	9.06[b]	0.10[a]	0.10[a]	0.20[a]	0.68[a]	2.05[a]	3.59	0.47[a]	8.02	37.3
Willingboro Twp MUA	0.002	0.32[b]	2.89[b]	0.19[a]	0.19[a]	0.37[a]	0.72[a]	2.15[a]	1.22	22.60	6.95[a]	17.2
Delran Sewerage Authority	0.087	0.23[b]	2.11[b]	0.58[d]	0.58[d]	1.17[d]	0.56[a]	1.69[a]	0.95	7.89[a]	6.95[a]	10.2
Cinnaminson Sewerage Authority	0.054	0.82[b]	7.40[b]	0.47[d]	0.47[d]	0.94[d]	4.03[a]	12.08[a]	21.19	2.75[a]	6.95[a]	21.4
Moorestown WWTP	0.104	0.39[b]	3.49[b]	0.70[d]	0.70[d]	1.40[d]	0.70[a]	2.11[a]	1.19	19.52	6.95[a]	12.8
Maple Shade POTW	0.110	0.20[b]	1.77[b]	0.05[d]	0.05[d]	0.10[d]	1.39[a]	4.17[a]	2.36	19.51[a]	6.95[a]	5.0
Philadelphia - Northeast WPCP	7.077	0.70[b]	6.26[b]	0.10[d]	0.10[d]	0.10	0.89[e]	0.89[e]	7.23	1.52	5.67	35.7
Camden County MUA	2.342	0.25[b]	2.23[b]	0.34[a]	0.34[a]	0.69[a]	3.78[a]	11.35[a]	19.92	2.59[a]	6.95[a]	1.1

		2013 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
Philadelphia - Southeast WPCP	3.447	0.67[b]	6.04[b]	0.05[d]	0.05[d]	0.06	0.56[e]	0.89[e]	8.65	0.18	5.20	22.5
Philadelphia - Southwest WPCP	7.089	0.58[b]	5.22[b]	0.11[d]	0.11[d]	0.13	1.65[e]	1.76[e]	18.75	1.20	5.43	22.3
Gloucester County Utility Authority	0.797	1.17[b]	10.55[b]	0.73[d]	0.73[d]	1.46[d]	3.28[a]	9.83[a]	17.25	6.64	6.95[a]	2.2
Tinicum Twp WWTP	0.044	0.94[b]	8.50[b]	0.09[a]	0.09[a]	0.19[a]	0.20[a]	1.79[a]	1.98[a]	6.24[a]	8.63	70.0
Little Washington STP	0.058	0.59[b]	5.32[b]	0.06[a]	0.06[a]	0.12[a]	0.28[a]	0.83[a]	0.47	3.86[a]	7.13	5.8
DELCORA	1.329	0.65[b]	5.87[b]	0.07[a]	0.07[a]	0.13[a]	1.36[e]	4.07[e]	2.30	5.18	6.95[a]	17.4
Southwest Delaware County MUA	0.188	0.51[b]	4.56[b]	0.05[a]	0.05[a]	0.10[a]	1.21[a]	3.63[a]	2.05[a]	16.97[a]	8.91	46.2
Logan Twp MUA	0.052	0.60[b]	5.38[b]	0.62[d]	0.62[d]	1.25[d]	2.06[a]	6.18[a]	10.85	1.41[a]	6.95[a]	5.7
Carneys Point WWTP	0.044	0.67[b]	6.01[b]	0.80[a]	0.80[a]	1.60[a]	1.48[a]	4.43[a]	7.77[a]	1.01[a]	6.95[a]	11.2[a]
Pennsville Twp Sewerage Authority	0.063	0.64[b]	5.73[b]	0.40[d]	0.40[d]	0.79[d]	0.23[a]	0.68[a]	0.39	3.19[a]	6.95[a]	7.5
Wilmington WWTP	3.165	0.68[b]	6.12[b]	0.07[a]	0.07[a]	0.14[a]	0.14[a]	1.29[a]	1.43[a]	6.24[a]	6.95[a]	0.7

a) estimated
b) based on reported BOD or CBOD
c) based on reported TOC or DOC
d) based on reported TP
e) based on reported TKN
f) based on reported TON

Table A3-8:Industrial Permitted Dischargers - Average flow and concentration 2013

		2013 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
US Steel Fairless Hills Works (Outfall 103)	0.071	0.56[b]	0.56[b]	0.01[a]	0.01[a]	0.02[a]	0.12[a]	0.12[a]	0.23[a]	1.00[a]	6.95[a]	4.5[a]
Coastal Eagle Point Oil Co.	0.039	0.76[b]	0.76[b]	0.02[a]	0.02[a]	0.03[a]	0.11[a]	0.11[a]	0.23	1.00[a]	6.95[a]	1.2
Valero Refining Co. (Outfall 1)	0.384	1.63[b]	1.63[b]	0.05[d]	0.05[d]	0.11[d]	0.15[a]	0.15[a]	0.30	1.00[a]	6.95[a]	1.3
E I Dupont De Nemours & Co. Repauno Plant	0.049	1.66[b]	1.66[b]	0.03[a]	0.03[a]	0.07[a]	0.66[a]	0.66[a]	1.32	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 2)	2.024	0.49[a]	0.49[a]	0.01[a]	0.01[a]	0.02[a]	0.10[a]	0.10[a]	0.21[a]	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 101)	1.952	0.96[a]	0.96[a]	0.02[a]	0.02[a]	0.04[a]	0.20[a]	0.20[a]	0.40[a]	1.00[a]	6.95[a]	4.5[a]
Conoco Phillips Refinery (Outfall 201)	0.112	1.96[b]	1.96[b]	0.04[a]	0.04[a]	0.08[a]	4.24[a]	4.24[a]	8.48	1.00[a]	6.95[a]	4.5[a]
Sunoco, Inc. Marcus Hook Refinery	0.326	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.49[a]	6.95[a]	4.5[a]
Dupont Edgemoor (Outfall 1)	0.110	3.67[a]	3.67[a]	0.07[a]	0.07[a]	0.15[a]	0.77[a]	0.77[a]	1.54[a]	1.00[a]	6.95[a]	4.5[a]
Dupont Edgemoor (Outfall 3)	0.171	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Ferro Corp.	0.037	4.75[b]	4.75[b]	0.09[a]	0.09[a]	0.19[a]	1.42[f]	1.42[f]	0.50	4.14[a]	6.95[a]	5.0
E I Dupont De Nemours & Co. (Outfall 1)	0.100	1.54[c]	1.54[c]	0.03[d]	0.03[d]	0.06[d]	0.32[f]	0.32[f]	0.65	1.00[a]	6.95[a]	4.5[a]
E I Dupont De Nemours & Co. (Outfall 2)	0.964	1.13[c]	1.13[c]	0.02[d]	0.02[d]	0.05[d]	0.33[f]	0.33[f]	0.17	9.25	6.95[a]	4.5[a]

		2013 average flow, concentration (geo. Mean for FCB)										
	Q	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	cms	mg/L		mg-P/L			mg-N/L				mg/L	CFU/100mL
E I Dupont De Nemours & Co. (Outfall 13)	0.120	4.33[c]	4.33	0.09[a]	0.09[a]	0.17[a]	0.91[a]	0.91[a]	1.82[a]	1.00[a]	6.95[a]	4.5[a]
E I Dupont De Nemours & Co. (Outfall 662)	0.349	6.17[c]	6.17	0.12[a]	0.12[a]	0.25[a]	0.52[f]	0.52[f]	0.31	2.55[a]	6.95[a]	4.5[a]
Deepwater Energy Center (Outfall 3)	0.550	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Deepwater Energy Center (Outfall 10)	0.330	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 1)	15.107	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 201)	13.002	0.66[a]	0.66[a]	0.01[a]	0.01[a]	0.02[a]	0.12[a]	0.12[a]	0.23[a]	1.00[a]	6.95[a]	4.5[a]
Delaware City Refinery (Outfall 601)	0.470	7.25[c]	7.25[c]	0.09[a]	0.09[a]	0.18[a]	0.31[a]	0.31[a]	0.62[a]	1.00[a]	6.95[a]	4.5[a]
Conectiv Delaware City Power Plant	1.735	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Exelon Corp. Schuylkill Generating Station (Outfall 1)	0.758	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]
Exelon Corp. Schuylkill Generating Station (Outfall 301)	0.758	3.50[a]	3.50[a]	0.07[a]	0.07[a]	0.14[a]	1.08[a]	1.08[a]	2.27[a]	1.00[a]	6.95[a]	4.5[a]

a) estimated b) based on reported BOD or CBOD c) based on reported TOC or DOC

d) based on reported TP e) based on reported TKN f) based on reported TON

Table A3-9: Municipal WWTPs - Total Loads 2012

	2012 total loads									
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	FCB
Municipal	kg		kg P			kg N				CFU
Ewing Lawrence Sewerage Authority	4,767	42,905	7,000	7,000	14,000	242	725	1,271	210,090	3.11E+09
Morrisville Boro Mun. Auth-STP	2,961	26,648	1,246	1,246	2,492	10,550	31,649	55,524	7,218	3.66E+10
Trenton DPW Sewerage Authority	17,543	157,885	1,754	1,754	3,509	18,481	55,443	97,269	12,645	1.36E+09
Hamilton Twp WPCF	13,517	121,648	12,011	12,011	24,022	52,638	157,913	277,041	52,219	3.51E+09
Bordentown Sewerage Authority	413	3,716	41	41	83	64	191	335	62,666	1.75E+09
Lower Bucks County Joint MA	2,765	24,881	276	276	553	35,737	107,211	188,090	24,452	1.01E+11
Florence Twp STP	615	5,531	2,040	2,040	4,080	944	2,831	1,599	13,242	2.08E+09
Bristol Boro WSA	2,301	20,707	230	230	460	1,659	4,976	2,984	22,634	1.94E+08
Burlington Twp DPW	465	4,182	1,699	1,699	3,398	2,821	8,464	14,848	1,930	3.45E+08
Burlington City STP	1,349	12,145	1,855	1,855	3,710	967	2,901	1,639	13,571	1.47E+09
Bristol Twp WWTP	3,501	31,508	350	350	700	1,883	5,648	9,910	1,288	5.52E+10
Willingboro Twp MUA	16	142	5	5	10	34	103	181	1,279	1.88E+07
Delran Sewerage Authority	606	5,457	1,881	1,881	3,763	566	1,699	960	40,052	4.19E+09
Cinnaminson Sewerage Authority	1,649	14,844	813	813	1,626	4,089	12,266	21,519	2,797	2.81E+09
Moorestown WWTP	1,403	12,626	2,048	2,048	4,095	3,652	10,956	6,190	47,554	5.72E+09
Maple Shade POTW	408	3,671	137	137	274	432	1,295	732	6,057	1.97E+09

	2012 total loads									
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	FCB
Municipal	kg		kg P			kg N				CFU
Philadelphia - Northeast WPCP	121,051	1,089,492	21,537	21,537	50,710	257,680	257,680	1,504,955	346,376	2.83E+13
Camden County MUA	27,633	248,706	32,808	32,808	65,616	256,270	768,810	1,348,790	175,343	1.05E+10
Philadelphia - Southeast WPCP	69,778	628,005	14,468	14,468	37,783	55,900	88,509	840,499	14,518	7.37E+12
Philadelphia - Southwest WPCP	85,706	771,359	19,349	19,349	17,148	426,928	456,036	4,789,758	251,810	5.31E+13
Gloucester County Utility Authority	18,045	162,401	17,963	17,963	35,925	70,984	212,952	373,600	165,016	4.95E+09
Tinicum Twp WWTP	1,161	10,451	116	116	232	244	2,196	2,440	8,128	6.31E+09
Little Washington STP	1,220	10,983	122	122	244	877	2,632	1,487	12,313	2.52E+09
DELCORA	25,649	230,847	2,565	2,565	5,129	31,477	94,431	165,668	173,337	1.53E+11
Southwest Delaware County MUA	3,357	30,215	336	336	671	9,011	27,032	15,272	126,454	2.34E+10
Logan Twp MUA	392	3,525	1,117	1,117	2,234	2,321	6,964	3,935	32,578	5.50E+08
Carneys Point WWTP	880	7,920	1,220	1,220	2,439	1,554	4,662	8,179	1,063	6.12E+08
Pennsville Twp Sewerage Authority	1,081	9,733	649	649	1,299	818	2,454	1,386	11,479	4.93E+08
Wilmington WWTP	43,929	395,350	4,394	4,394	8,785	9,230	83,058	92,283	591,390	4.66E+09

Table A3-10: Industrial Permitted Dischargers - Total loads 2012

	2012 total loads									
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	FCB
Industrial	kg		kg P			kg N				CFU
US Steel Fairless Hills Works (Outfall 103)	1,489	1,489	30	30	60	313	313	626	2,573	1.13E+09
Coastal Eagle Point Oil Co.	882	882	18	18	35	227	227	454	1,380	7.87E+07
Valero Refining Co. (Outfall 1)	9,632	9,632	2,583	2,583	5,165	806	806	1,612	10,708	2.86E+09
E I Dupont De Nemours & Co. Repauno Plant	1,092	1,092	22	22	44	600	600	1,200	1,324	5.88E+08
Conoco Phillips Refinery (Outfall 2)	6,757	6,757	136	136	270	1,420	1,420	2,839	13,850	7.64E+07
Conoco Phillips Refinery (Outfall 101)	14,974	14,974	299	299	599	3,146	3,146	6,292	15,598	1.23E+09
Conoco Phillips Refinery (Outfall 201)	678	678	14	14	27	1,272	1,272	2,543	1,828	2.91E+08
Sunoco, Inc. Marcus Hook Refinery	35,776	35,776	724	724	1,447	11,339	11,339	23,558	15,322	4.66E+09
Dupont Edgemoor (Outfall 1)	4,770	4,770	95	95	191	1,002	1,002	2,004	3,427	1.64E+09
Dupont Edgemoor (Outfall 3)	18,819	18,819	381	381	762	5,989	5,989	12,369	5,456	2.17E+09
Ferro Corp.	7,457	7,457	149	149	298	1,788	1,788	1,933	16,007	6.04E+08
E I Dupont De Nemours & Co. (Outfall 1)	3,979	3,979	80	80	159	836	836	1,672	3,036	2.34E+08
E I Dupont De Nemours & Co. (Outfall 2)	35,948	35,948	2,367	2,367	4,735	93,505	93,505	6,080	300,203	2.25E+10

	2012 total loads									
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	FCB
Industrial	kg		kg P			kg N				CFU
E I Dupont De Nemours & Co. (Outfall 13)	11,994	11,994	240	240	480	2,520	2,520	5,039	4,205	5.89E+07
E I Dupont De Nemours & Co. (Outfall 662)	67,051	67,051	1,341	1,341	2,682	21,674	21,674	4,976	41,203	5.87E+08
Deepwater Energy Center (Outfall 3)	129,686	129,686	2,638	2,638	5,275	41,629	41,629	86,084	37,536	1.52E+10
Deepwater Energy Center (Outfall 10)	129,366	129,366	2,622	2,622	5,243	40,553	40,553	85,432	37,178	1.59E+10
Delaware City Refinery (Outfall 1)	1,673,405	1,673,405	33,952	33,952	67,881	534,975	534,975	1,098,729	488,163	1.76E+11
Delaware City Refinery (Outfall 201)	1,259,563	1,259,563	25,591	25,591	51,164	404,535	404,535	826,728	369,589	1.16E+11
Delaware City Refinery (Outfall 601)	6,421	6,421	78	78	157	317	317	634	855	2.93E+08
Delaware City Refinery (Outfall 701)	66,095	66,095	1,338	1,338	2,674	20,889	20,889	43,410	19,048	8.16E+09
Conectiv Delaware City Power Plant	189,995	189,995	3,886	3,886	7,771	62,453	62,453	123,396	57,145	1.44E+10
Exelon Corp. Schuylkill Generating Station (Outfall 1)	235,077	235,077	4,758	4,758	9,512	74,926	74,926	158,528	67,621	3.41E+10
Exelon Corp. Schuylkill Generating Station (Outfall 301)	185,759	185,759	3,759	3,759	7,516	59,302	59,302	126,168	53,372	2.80E+10

Table A3-11: Municipal WWTPs - Total loads 2013

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	kg		kg P			kg N				kg	CFU
Ewing Lawrence Sewerage Authority	6,459	58,124	8,351	8,351	16,702	553	1,659	2,911	180,076	98,711	2.45E+09
Morrisville Boro Mun. Auth-STP	4,899	44,094	1,423	1,423	2,846	17,722	53,166	93,274	12,126	41,783	2.25E+10
Trenton DPW Sewerage Authority	17,372	156,353	1,737	1,737	3,474	22,617	67,852	119,038	15,475	108,551	1.32E+09
Hamilton Twp WPCF	12,690	114,206	10,832	10,832	21,663	52,288	156,865	275,201	63,484	76,764	2.71E+09
Bordentown Sewerage Authority	493	4,441	49	49	99	277	831	469	64,919	16,854	1.44E+09
Lower Bucks County Joint MA	3,661	32,944	366	366	732	28,948	86,843	152,356	19,806	32,034	1.04E+11
Florence Twp STP	591	5,316	1,402	1,402	2,804	263	789	1,384	180	13,272	9.62E+08
Bristol Boro WSA	378	3,398	38	38	75	373	1,118	1,961	255	11,909	2.94E+08
Burlington Twp DPW	1,395	12,553	1,700	1,700	3,401	1,071	3,213	1,815	15,030	16,565	1.07E+08
Burlington City STP	1,395	12,553	1,700	1,700	3,401	1,071	3,213	1,815	15,030	16,565	1.07E+08
Bristol Twp WWTP	3,453	31,075	345	345	691	2,541	7,623	13,374	1,739	28,389	3.56E+09
Willingboro Twp MUA	17	151	10	10	21	35	106	60	1,112	337	1.74E+07
Delran Sewerage Authority	545	4,905	1,598	1,598	3,196	1,456	4,369	2,468	20,438	18,867	3.00E+09
Cinnaminson Sewerage Authority	1,460	13,142	856	856	1,712	6,749	20,246	35,519	4,617	11,748	1.47E+09
Moorestown WWTP	1,266	11,397	2,266	2,266	4,532	2,272	6,815	3,850	64,557	22,614	2.77E+09
Maple Shade POTW	700	6,302	188	188	377	5,412	16,235	9,172	75,947	23,926	2.07E+09

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Municipal	kg		kg P			kg N				kg	CFU
Philadelphia - Northeast WPCP	163,893	1,475,058	21,600	21,600	22,479	202,134	202,134	1,593,093	341,170	1,257,531	3.24E+13
Camden County MUA	18,717	168,458	25,292	25,292	50,579	271,618	814,853	1,429,566	185,844	505,763	6.91E+09
Philadelphia - Southeast WPCP	77,365	696,305	5,533	5,533	6,121	61,438	96,421	926,329	21,082	564,710	1.30E+13
Philadelphia - Southwest WPCP	134,866	1,213,798	25,463	25,463	29,392	364,382	389,226	4,135,654	261,549	1,219,120	2.41E+13
Gloucester County Utility Authority	26,100	234,902	18,083	18,083	36,167	80,264	240,791	422,441	167,668	172,648	4.67E+09
Tinicum Twp WWTP	1,269	11,423	127	127	254	267	2,400	2,666	9,024	11,918	4.70E+09
Little Washington STP	1,015	9,133	101	101	203	411	1,232	696	5,763	12,354	9.10E+08
DELCORA	27,548	247,935	2,755	2,755	5,509	52,586	157,758	89,129	222,288	288,547	1.57E+11
Southwest Delaware County MUA	3,023	27,204	302	302	604	7,579	22,736	12,845	106,357	52,497	3.51E+10
Logan Twp MUA	871	7,835	1,030	1,030	2,060	3,215	9,644	16,919	2,199	11,439	9.04E+08
Carneys Point WWTP	920	8,282	1,059	1,059	2,119	2,026	6,077	10,661	1,386	9,492	5.74E+09
Pennsville Twp Sewerage Authority	1,290	11,610	789	789	1,579	406	1,218	688	5,696	13,686	1.85E+09
Wilmington WWTP	64,917	584,262	6,491	6,491	12,984	13,638	122,746	136,381	639,607	685,770	8.43E+09

Table A3-12: Industrial Permitted Dischargers - Total loads 2013

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	kg		kg P			kg N				kg	CFU
US Steel Fairless Hills Works (Outfall 103)	1,237	1,237	25	25	50	260	260	520	2,194	15,281	9.11E+08
Coastal Eagle Point Oil Co.	950	950	19	19	38	120	120	239	1,252	8,662	56382403
Valero Refining Co. (Outfall 1)	20,860	20,860	597	597	1,194	1,814	1,814	3,627	11,997	83,000	5.45E+09
E I Dupont De Nemours & Co. Repauno Plant	2,438	2,438	49	49	98	825	825	1,650	1,540	10,404	5.33E+08
Conoco Phillips Refinery (Outfall 2)	30,776	30,776	618	618	1,230	6,466	6,466	12,931	63,079	434,699	2.28E+10
Conoco Phillips Refinery (Outfall 101)	56,683	56,683	1,134	1,134	2,267	11,909	11,909	23,819	59,044	405,240	2.22E+10
Conoco Phillips Refinery (Outfall 201)	6,707	6,707	134	134	268	15,107	15,107	30,215	3,513	24,392	1.35E+09
Sunoco, Inc. Marcus Hook Refinery	35,776	35,776	724	724	1,447	11,339	11,339	23,558	15,322	71,685	4.66E+09
Dupont Edgemoor (Outfall 1)	12,064	12,064	241	241	483	2,534	2,534	5,069	3,448	23,934	1.41E+09
Dupont Edgemoor (Outfall 3)	18,234	18,234	370	370	739	5,826	5,826	11,990	5,310	36,566	2.29E+09
Ferro Corp.	6,850	6,850	137	137	274	1,876	1,876	877	7,265	8,114	5.17E+08
E I Dupont De Nemours & Co. (Outfall 1)	5,643	5,643	113	113	226	1,186	1,186	2,371	3,124	20,900	1.75E+08

	2013 total loads										
	POC	DOC	POP	DOP	PO4	PON	DON	NH4	NOx	DO	FCB
Industrial	kg		kg P			kg N				kg	CFU
E I Dupont De Nemours & Co. (Outfall 2)	32,831	32,831	467	467	933	10,953	10,953	4,770	262,703	209,140	1.17E+10
E I Dupont De Nemours & Co. (Outfall 13)	15,375	15,375	307	307	615	3,230	3,230	6,460	3,732	26,285	1.23E+09
E I Dupont De Nemours & Co. (Outfall 662)	63,051	63,051	1,261	1,261	2,522	5,540	5,540	3,077	25,478	75,998	4.81E+09
Deepwater Energy Center (Outfall 3)	60,563	60,563	1,227	1,227	2,453	18,973	18,973	40,855	17,269	120,107	7.37E+09
Deepwater Energy Center (Outfall 10)	35,450	35,450	722	722	1,444	11,213	11,213	23,017	10,317	71,395	4.42E+09
Delaware City Refinery (Outfall 1)	1,619,991	1,619,991	32,875	32,875	65,728	519,915	519,915	1,065,338	473,287	3,245,741	1.67E+11
Delaware City Refinery (Outfall 201)	1,388,659	1,388,659	28,187	28,187	56,355	446,000	446,000	907,481	407,456	2,779,667	1.27E+11
Delaware City Refinery (Outfall 601)	110,525	110,525	1,348	1,348	2,696	4,604	4,604	9,208	14,821	102,978	6.4E+09
Conectiv Delaware City Power Plant	184,614	184,614	3,767	3,767	7,532	60,290	60,290	122,264	54,573	370,355	1.64E+10
Exelon Corp. Schuylkill Generating Station (Outfall 1)	81,910	81,910	1,655	1,655	3,309	26,026	26,026	55,137	23,563	163,507	1.33E+10
Exelon Corp. Schuylkill Generating Station (Outfall 301)	79,246	79,246	1,603	1,603	3,206	25,289	25,289	53,424	22,904	158,411	1.00E+10

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Appendix A

2012v5 Run146

2012v5 Run146

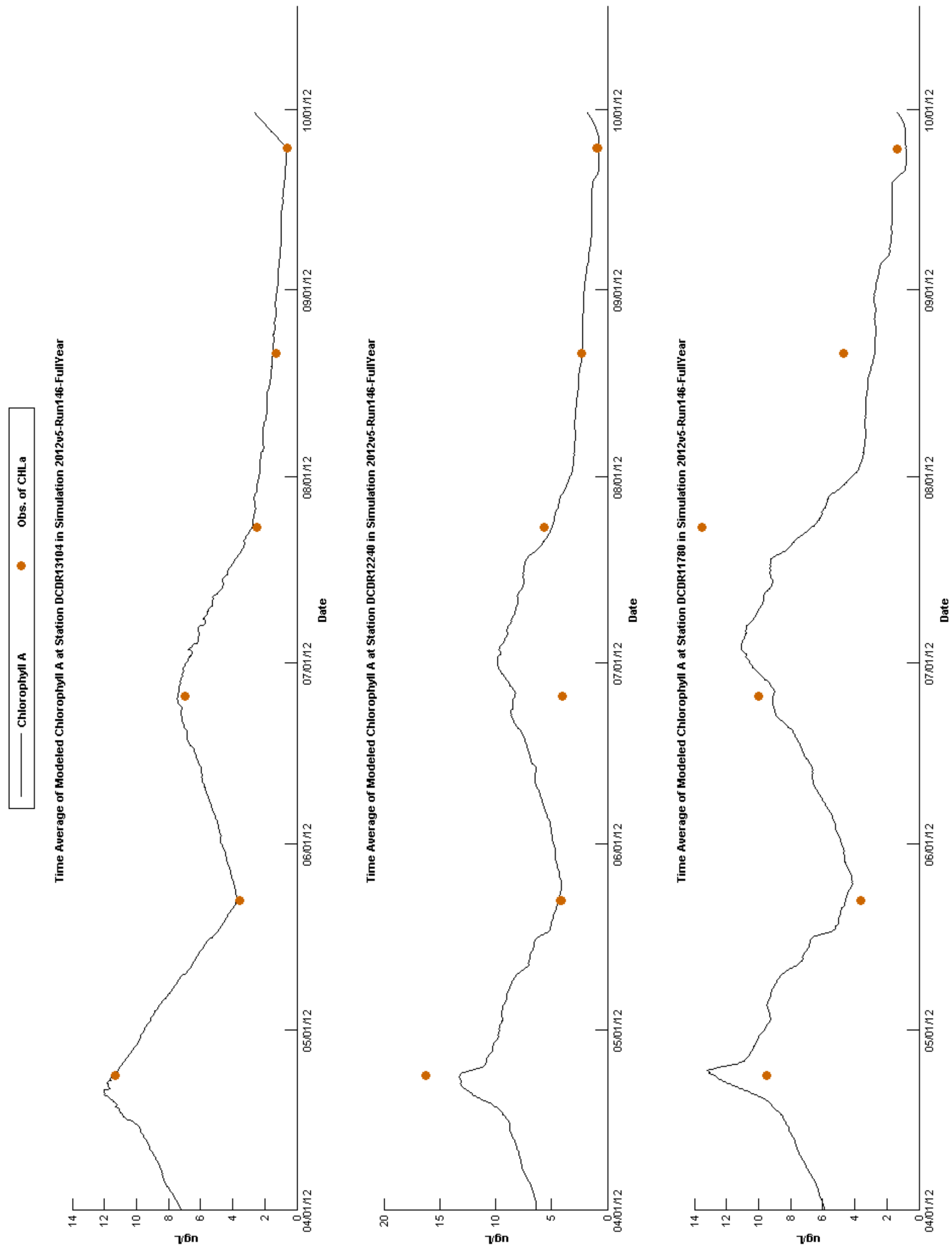
2012v5 Run146:

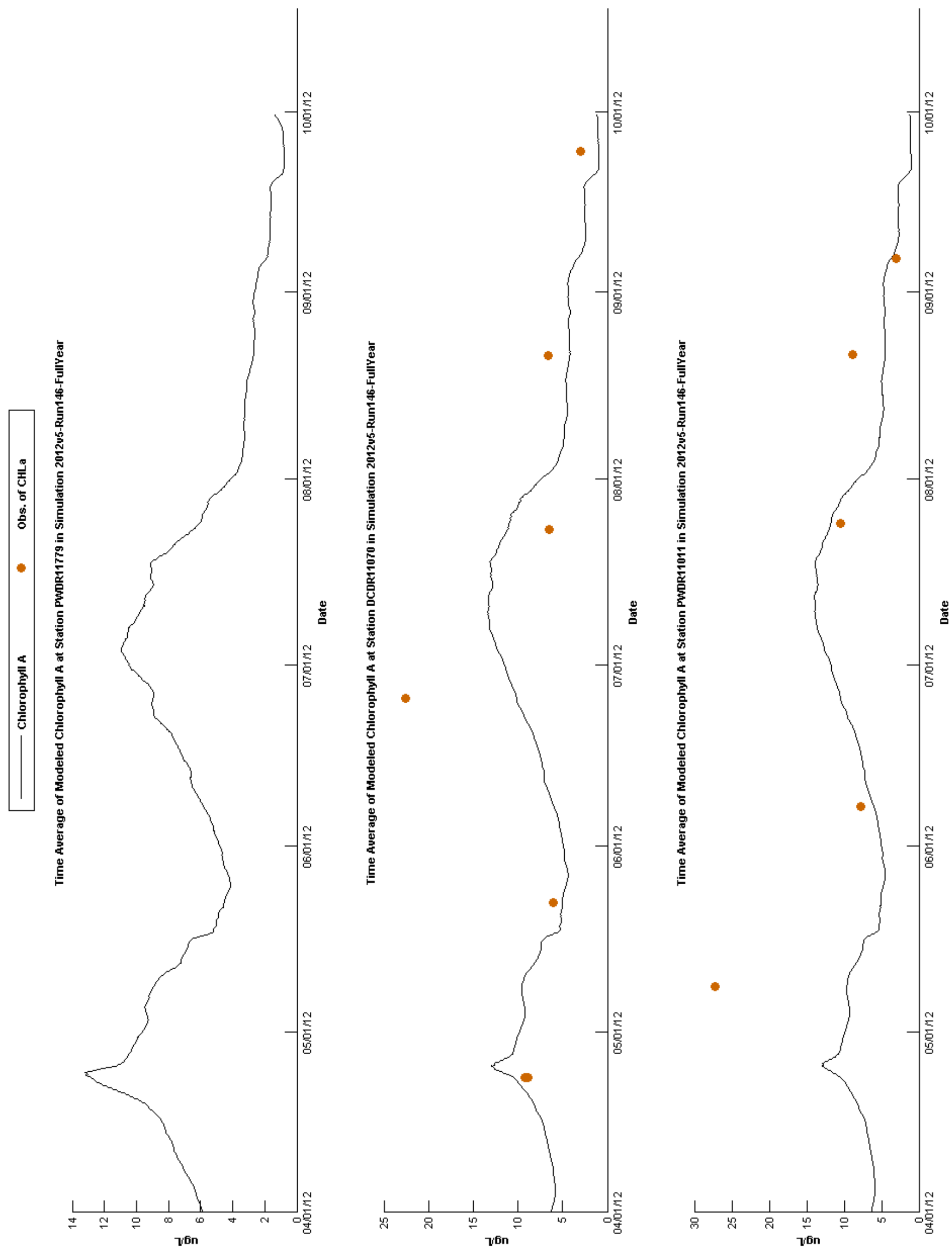
Table of Contents

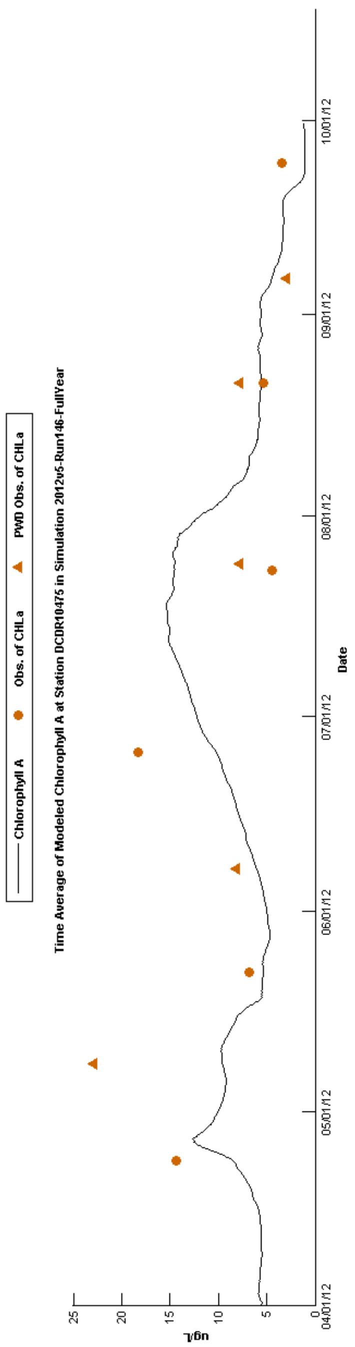
Chapter 1. Time series plots

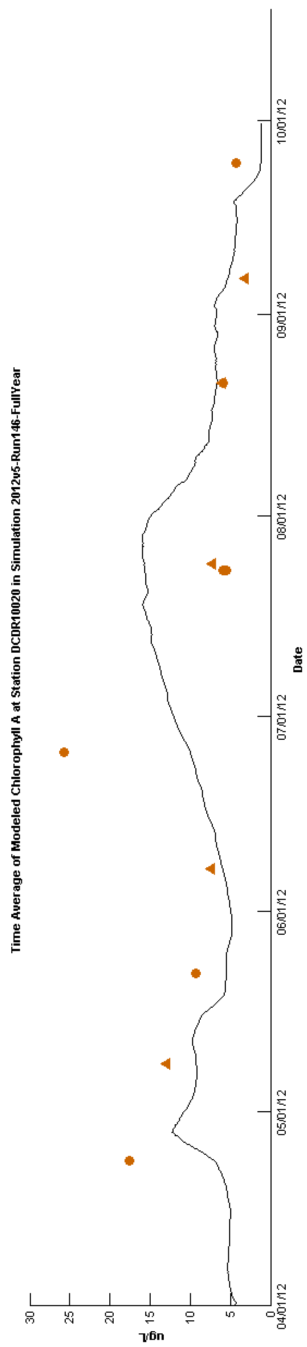
1.1. Biomass - Algae

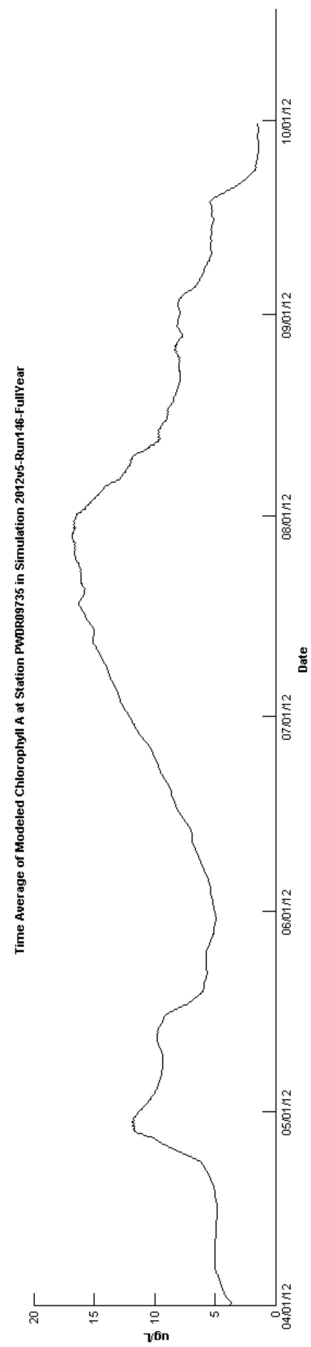
1.1.1. April to October

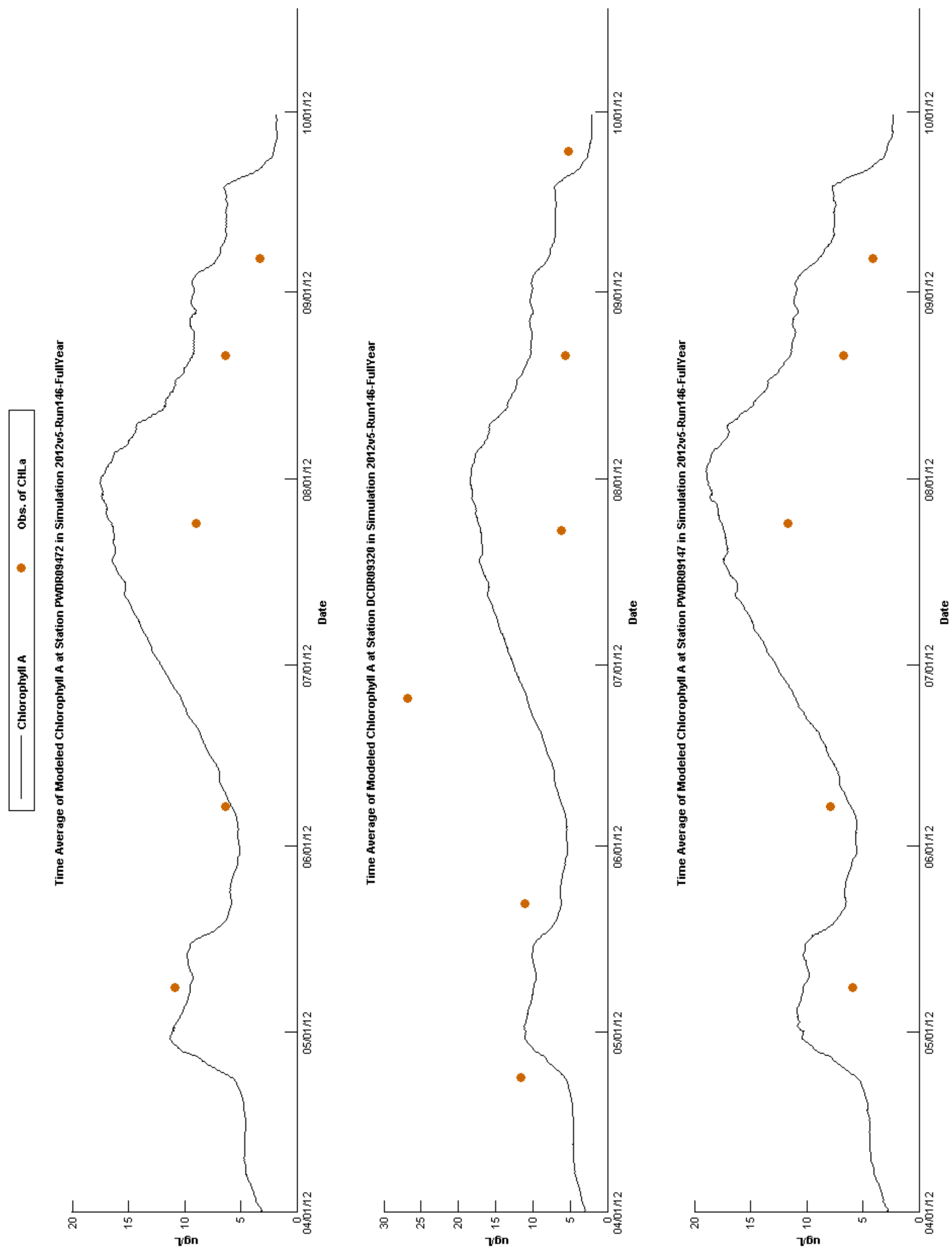


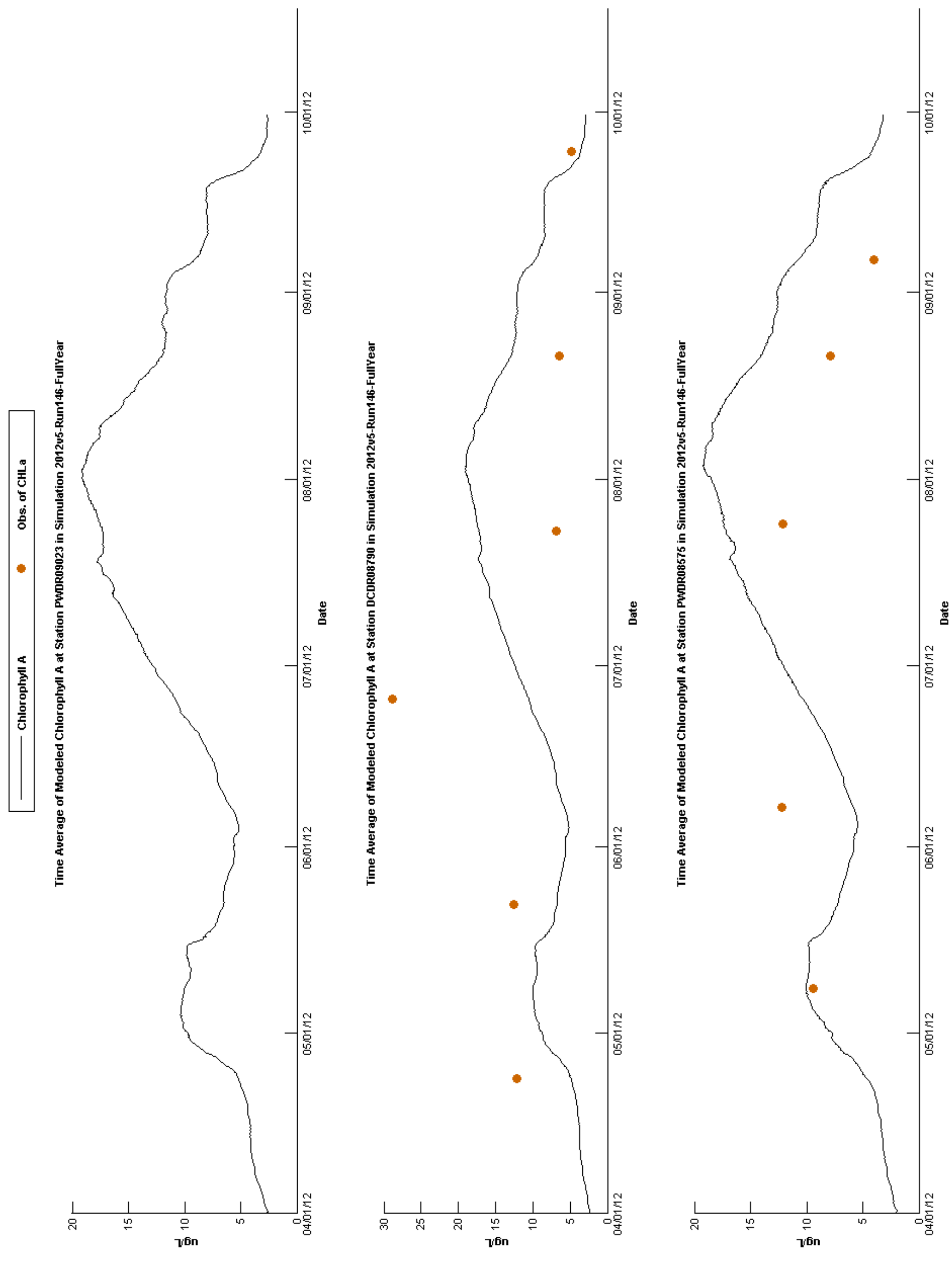

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR11779 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR11070 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station PWDR11011 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

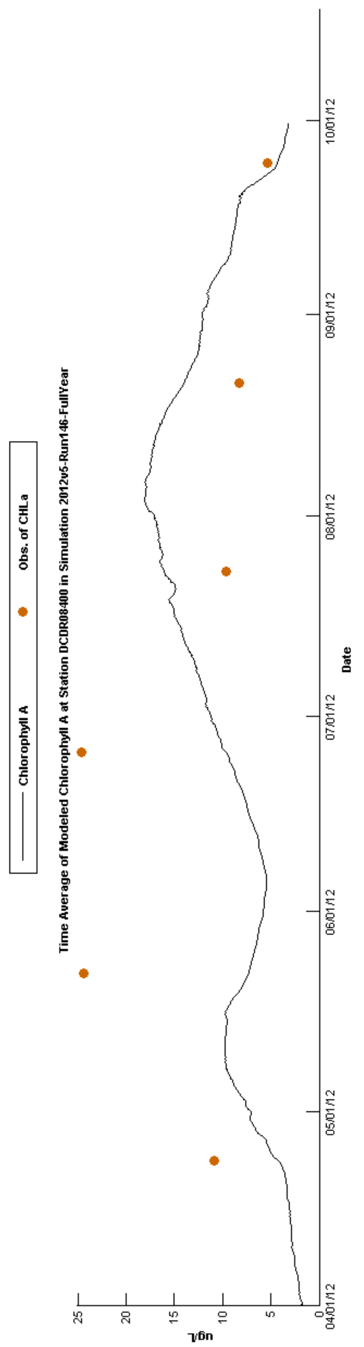

Chlorophyll A
Obs. of CHLa
PWD Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR10475 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

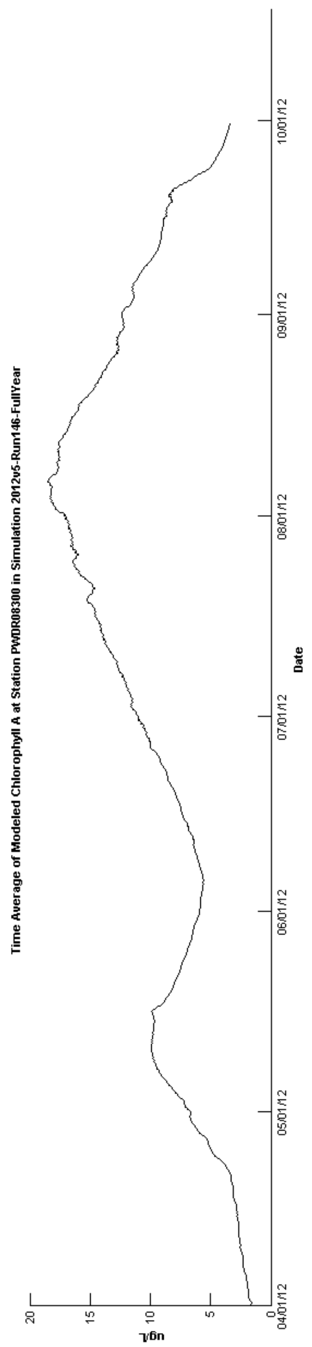

Time Average of Modeled Chlorophyll A at Station DCDR10020 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

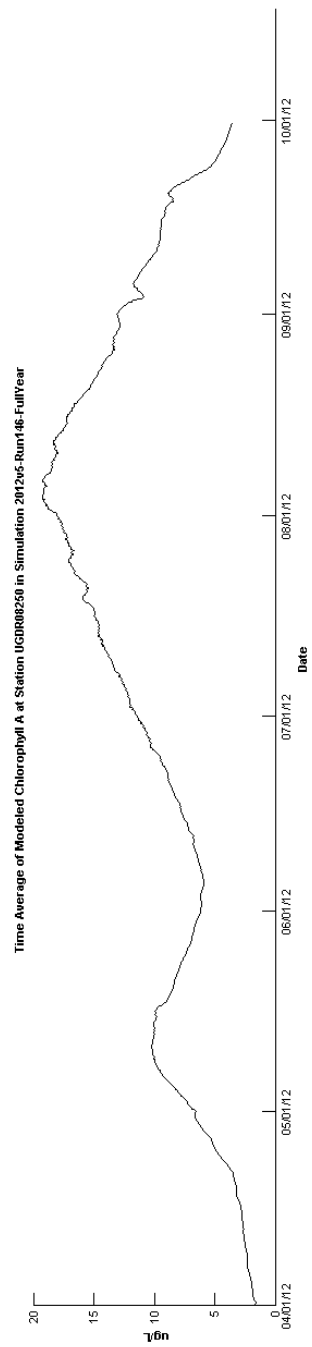

Time Average of Modeled Chlorophyll A at Station PWDR09735 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

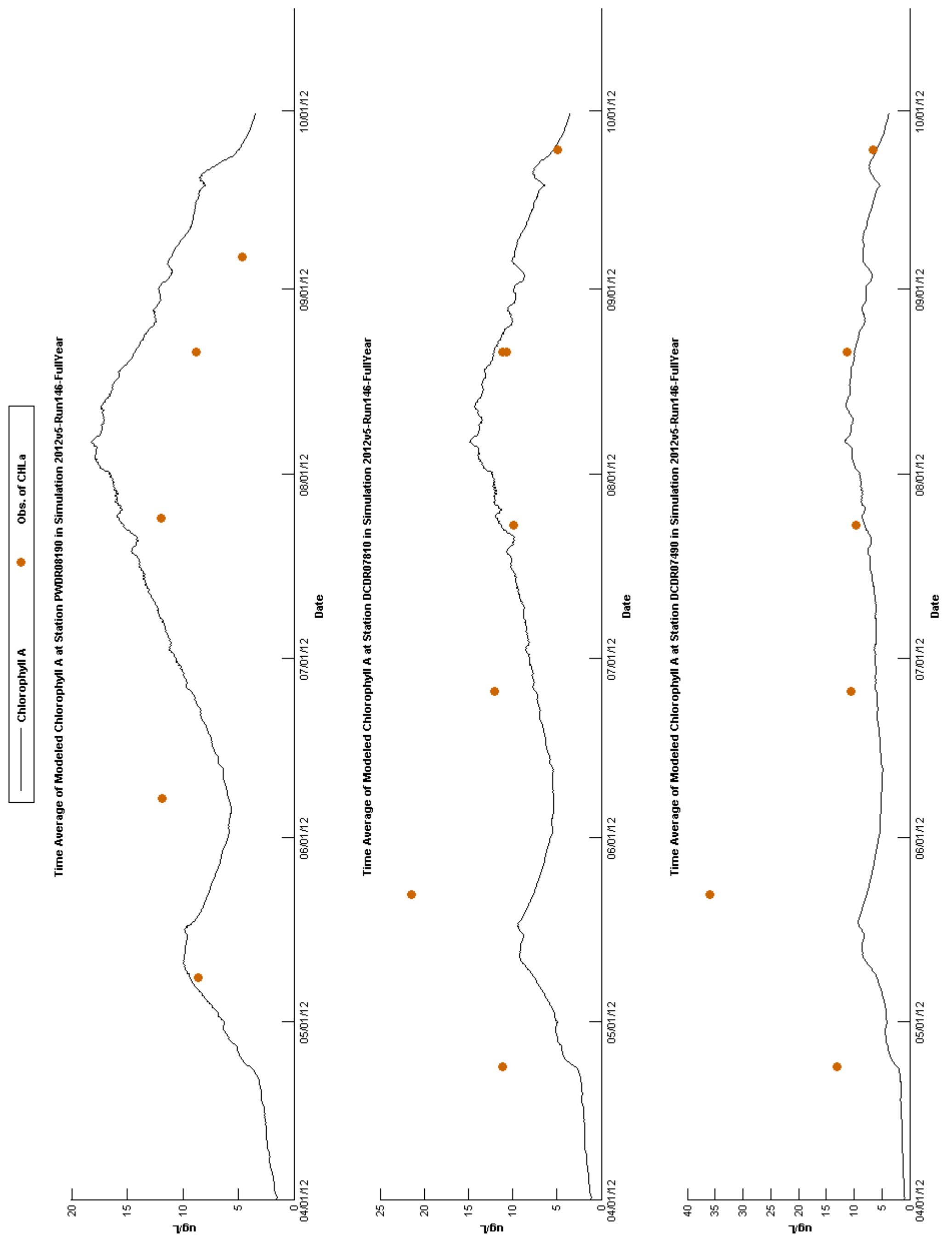

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR09472 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR09320 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station PWDR09147 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

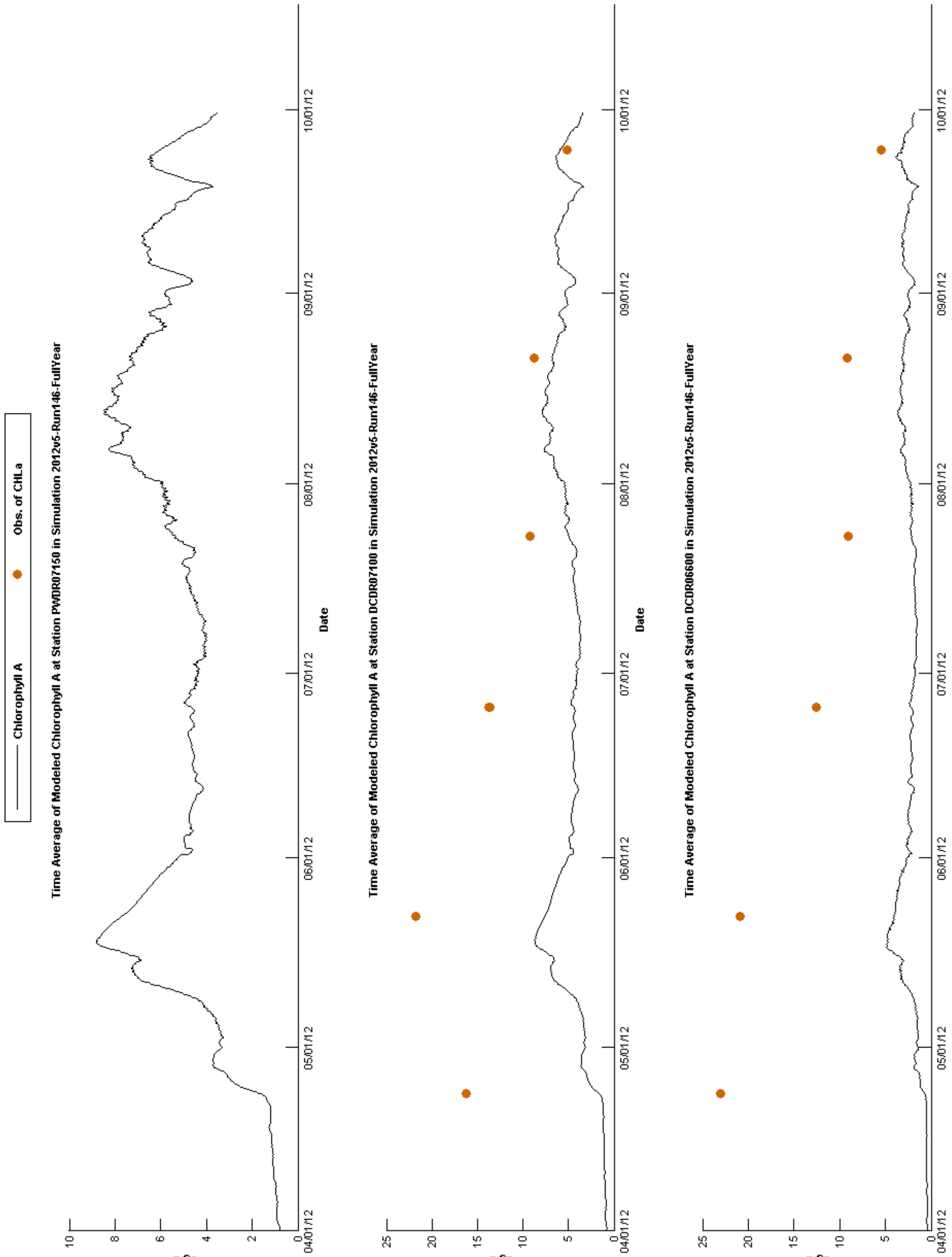

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR09023 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR08790 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station PWDR08575 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


Time Average of Modeled Chlorophyll A at Station DCDR08400 in Simulation 2012v5-Run146-FullYear
Chlorophyll A
Obs. of CHLa
ug/L
Date

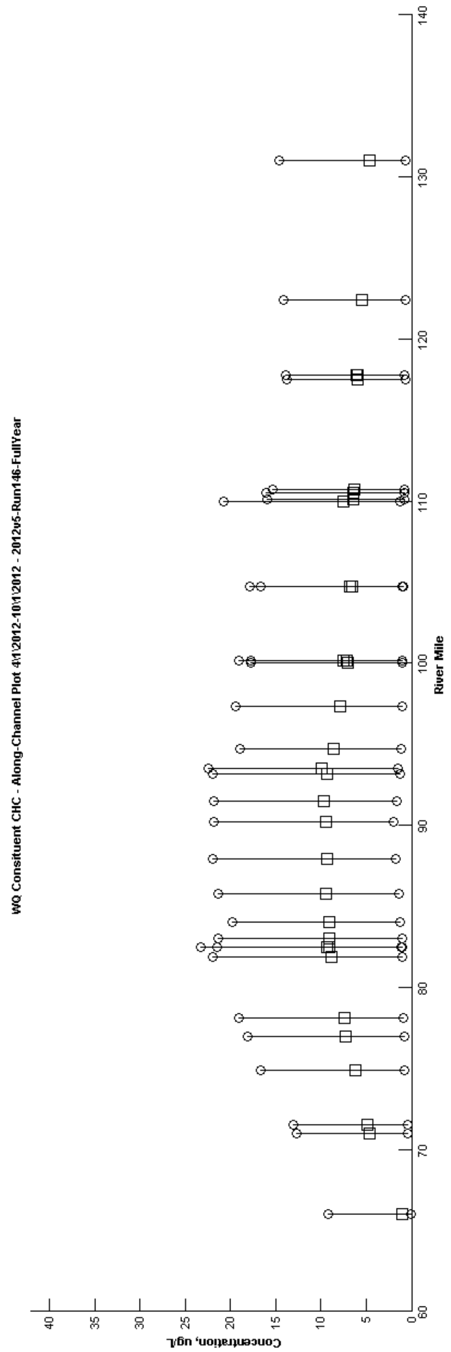

Time Average of Modeled Chlorophyll A at Station PWDR08300 in Simulation 2012v5-Run146-FullYear
ug/L
Date


Time Average of Modeled Chlorophyll A at Station UGDR08250 in Simulation 2012v5-Run146-FullYear
ug/L
Date

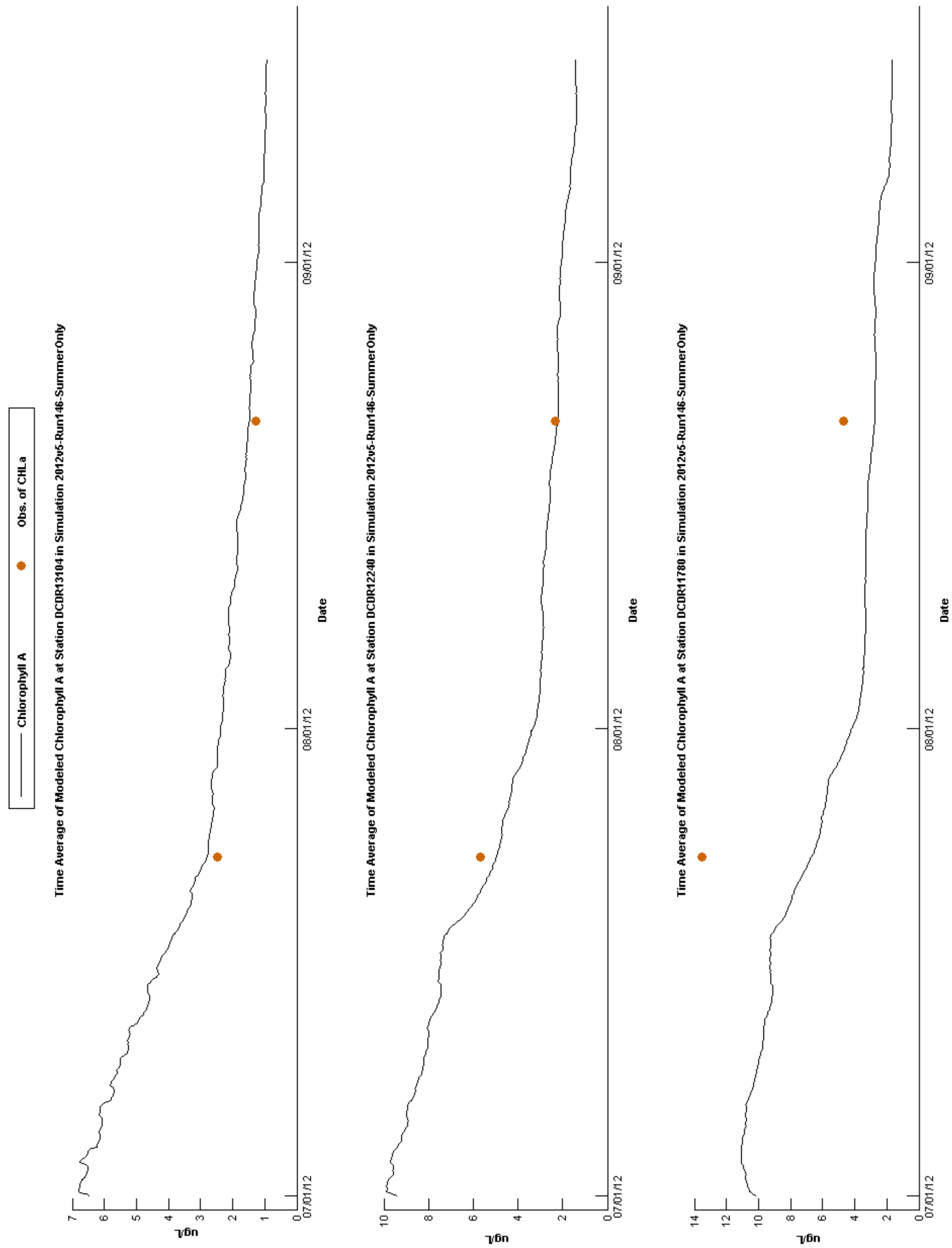

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR08190 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR07810 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR07490 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

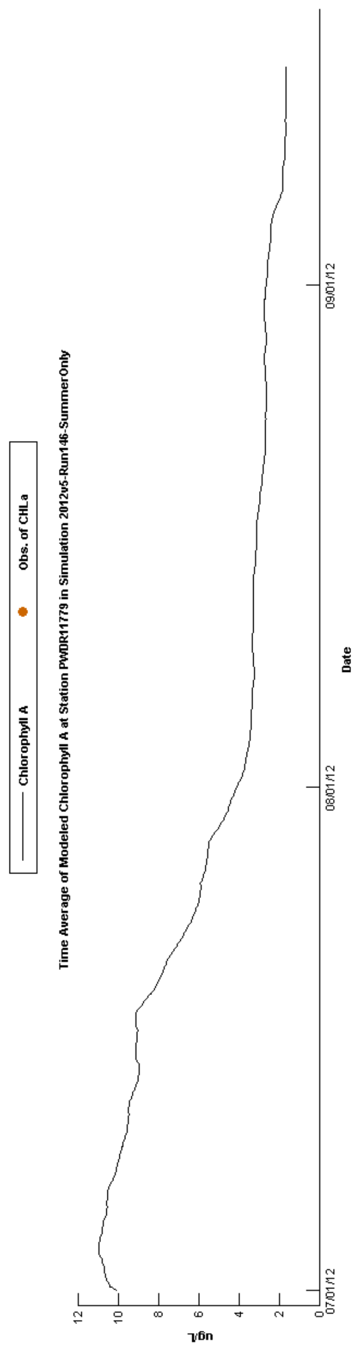


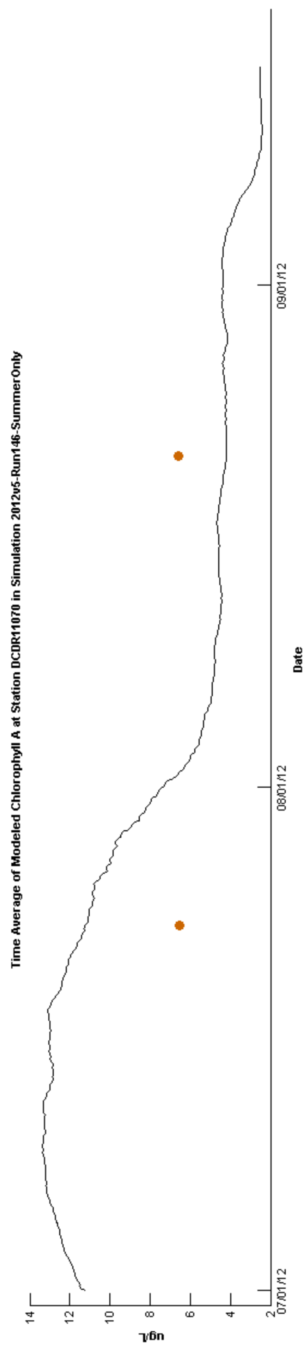
Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR07150 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR07100 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR06600 in Simulation 2012v5-Run146-FullYear
ug/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

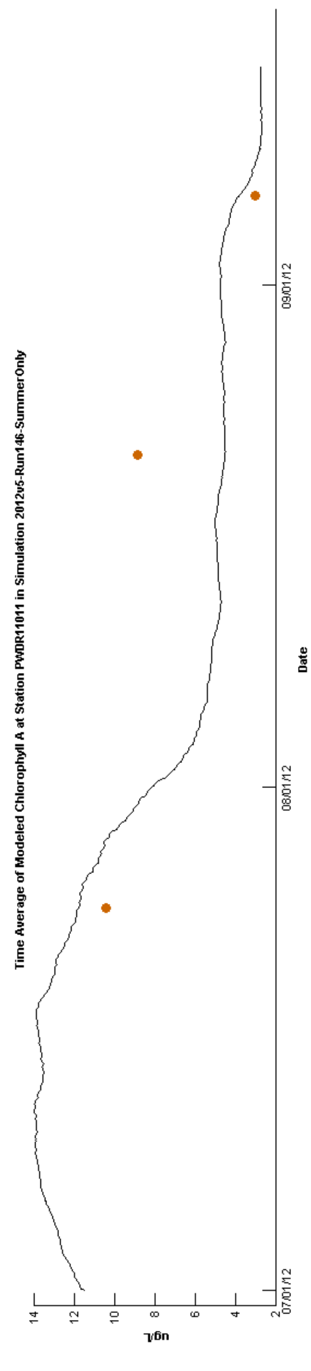

WQ Consituent CHC - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
River Mile
Concentration, ug/L
60
70
80
90
100
110
120
130
140
0
5
10
15
20
25
30
35
40

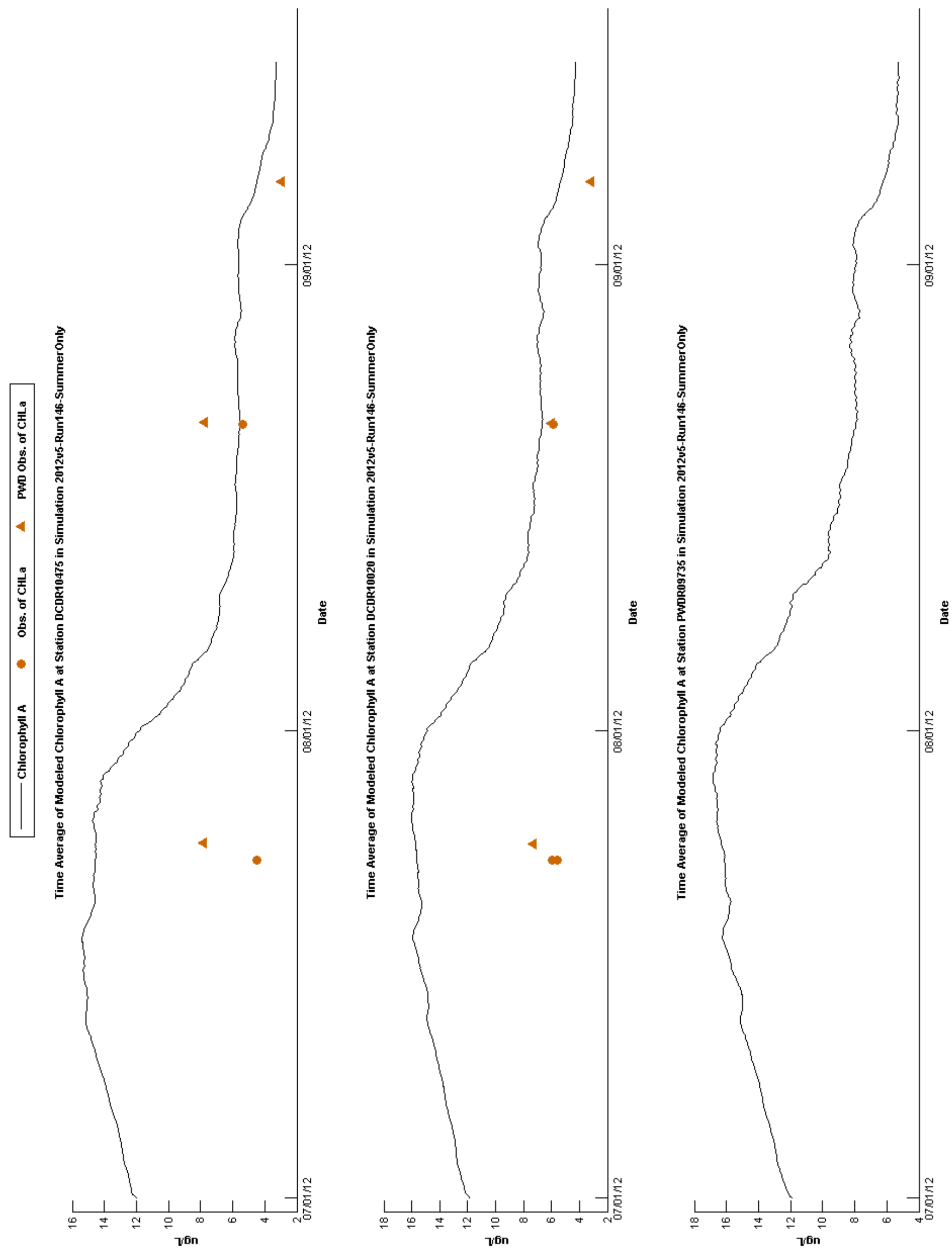
1.1.2. Summer


Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR13104 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR12240 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR11780 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

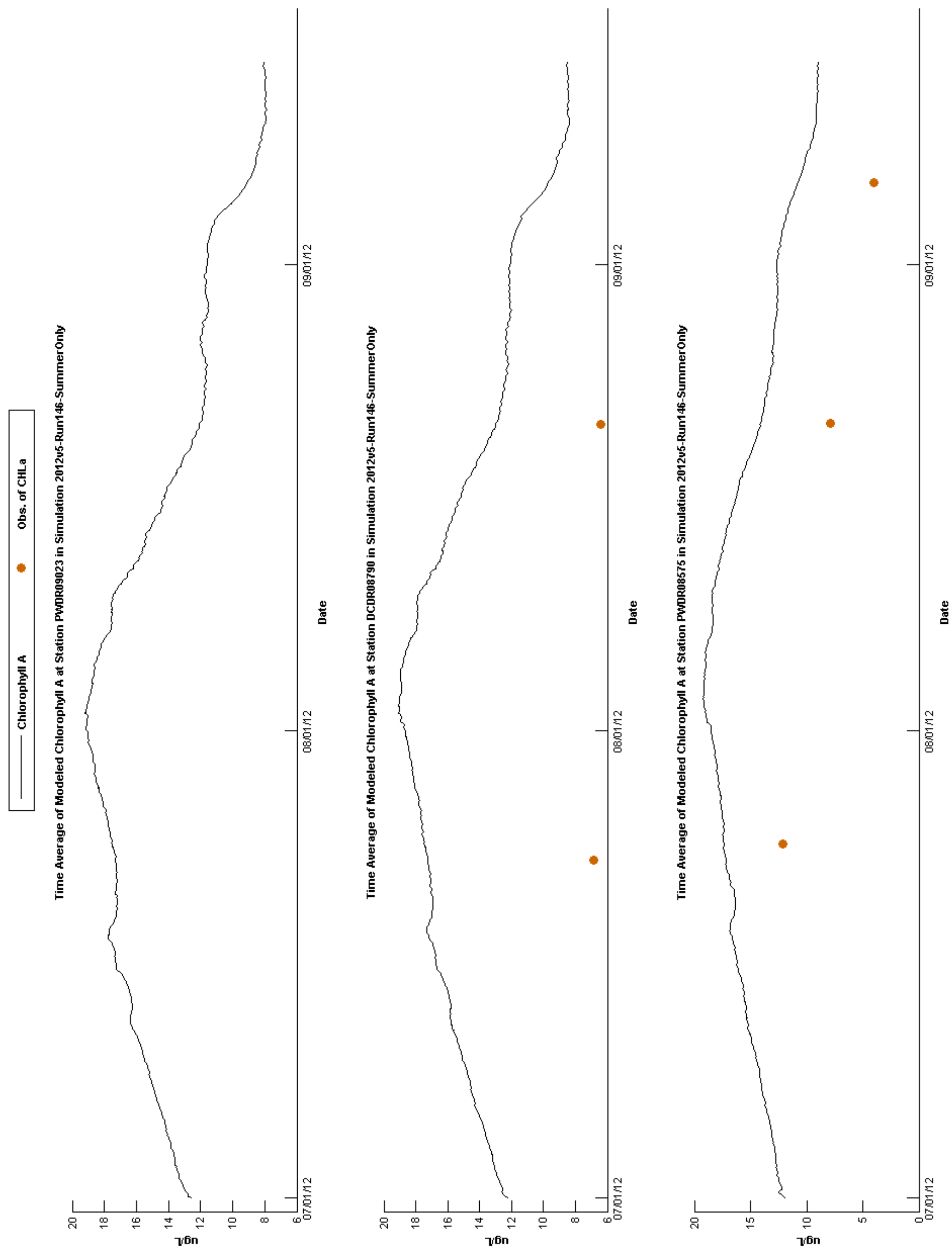

Time Average of Modeled Chlorophyll A at Station PWDR11779 in Simulation 2012v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
Date
07/01/12
08/01/12
09/01/12


Time Average of Modeled Chlorophyll A at Station DCDR11070 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

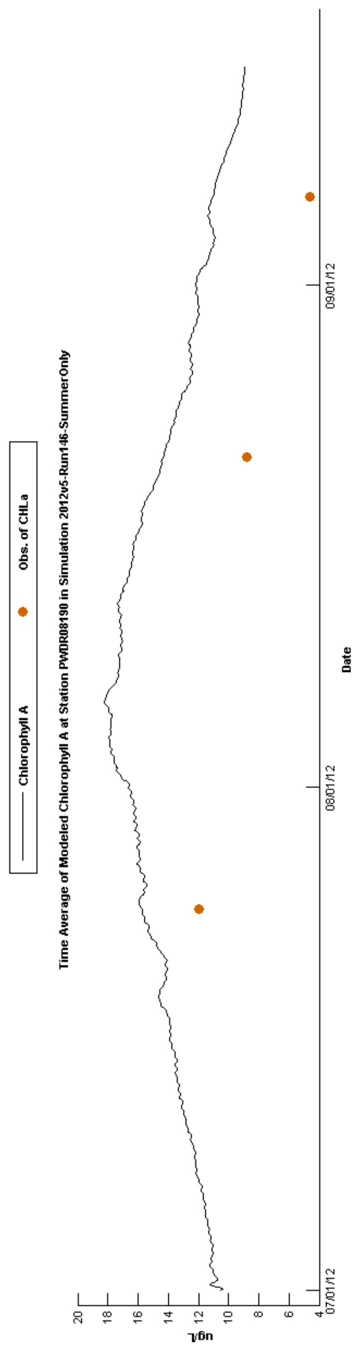

Time Average of Modeled Chlorophyll A at Station PWDR11011 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

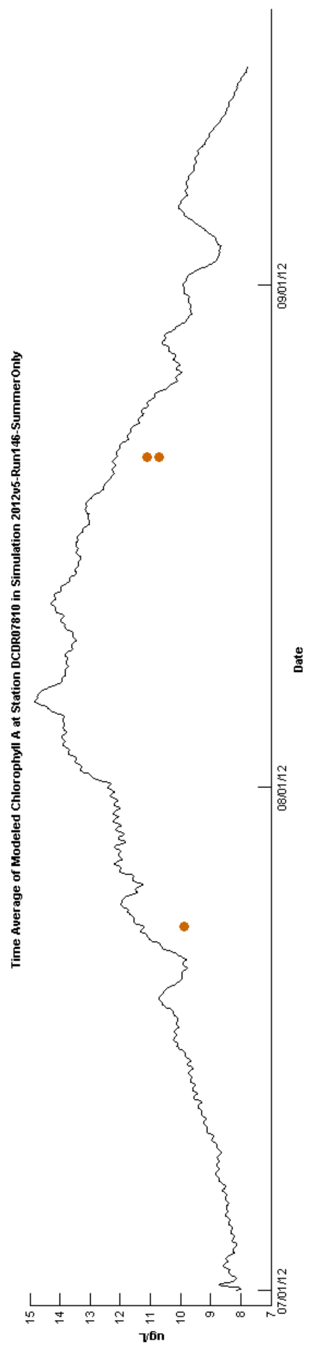

Time Average of Modeled Chlorophyll A at Station DCDR10475 in Simulation 2012v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
PWD Obs. of CHLa
ug/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Chlorophyll A at Station DCDR10020 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Chlorophyll A at Station PWDR09735 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

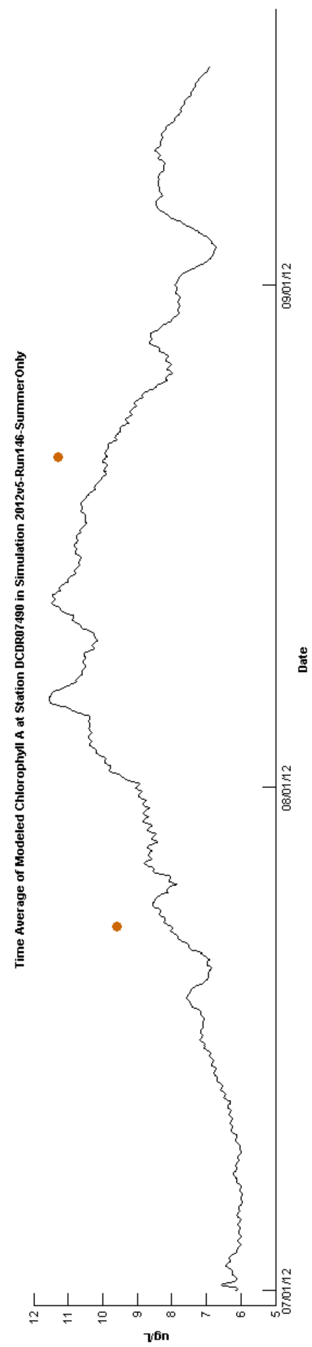

Time Average of Modeled Chlorophyll A at Station PWDR09472 in Simulation 2012v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Chlorophyll A at Station DCDR09320 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station PWDR09147 in Simulation 2012v5-Run146-SummerOnly

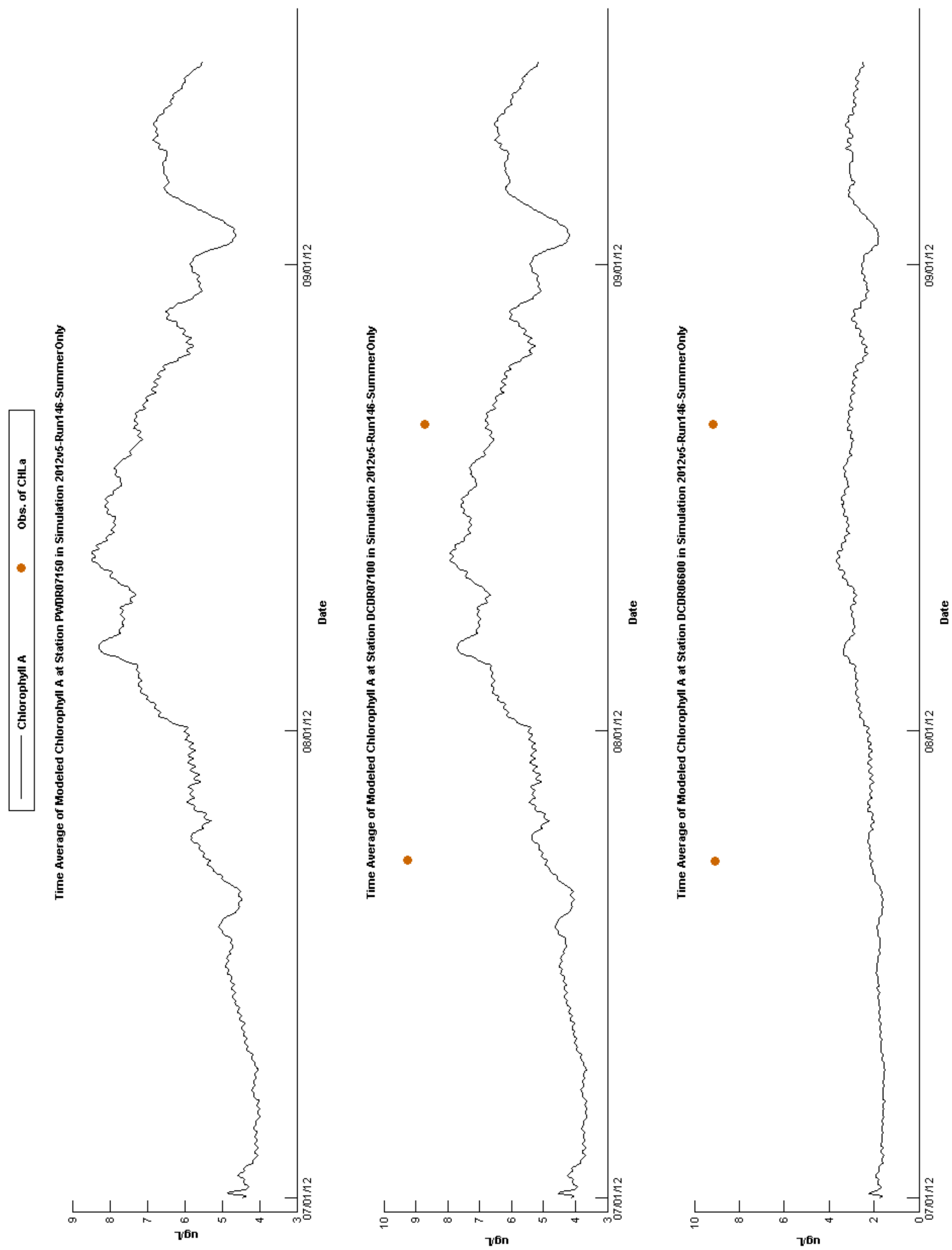

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR09023 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR08790 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station PWDR08575 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

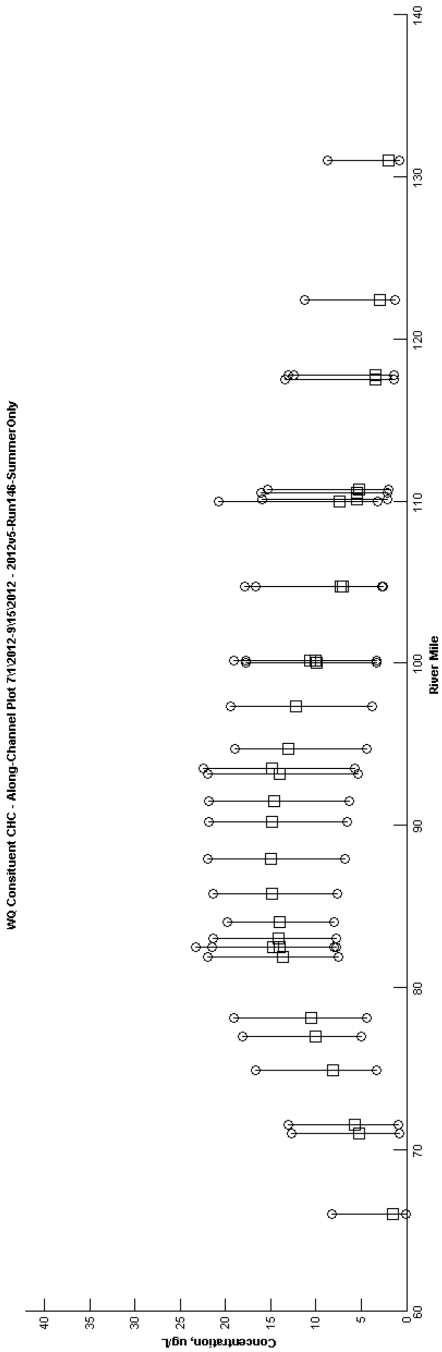

Time Average of Modeled Chlorophyll A at Station DCDR08400 in Simulation 2012v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
20
18
16
14
12
10
8
07/01/12
08/01/12
09/01/12
Date
Time Average of Modeled Chlorophyll A at Station PWDR08300 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
Time Average of Modeled Chlorophyll A at Station UGDR08250 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date


Time Average of Modeled Chlorophyll A at Station PWDR08190 in Simulation 2012v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
Date
07/01/12
08/01/12
09/01/12


Time Average of Modeled Chlorophyll A at Station DCDR07810 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

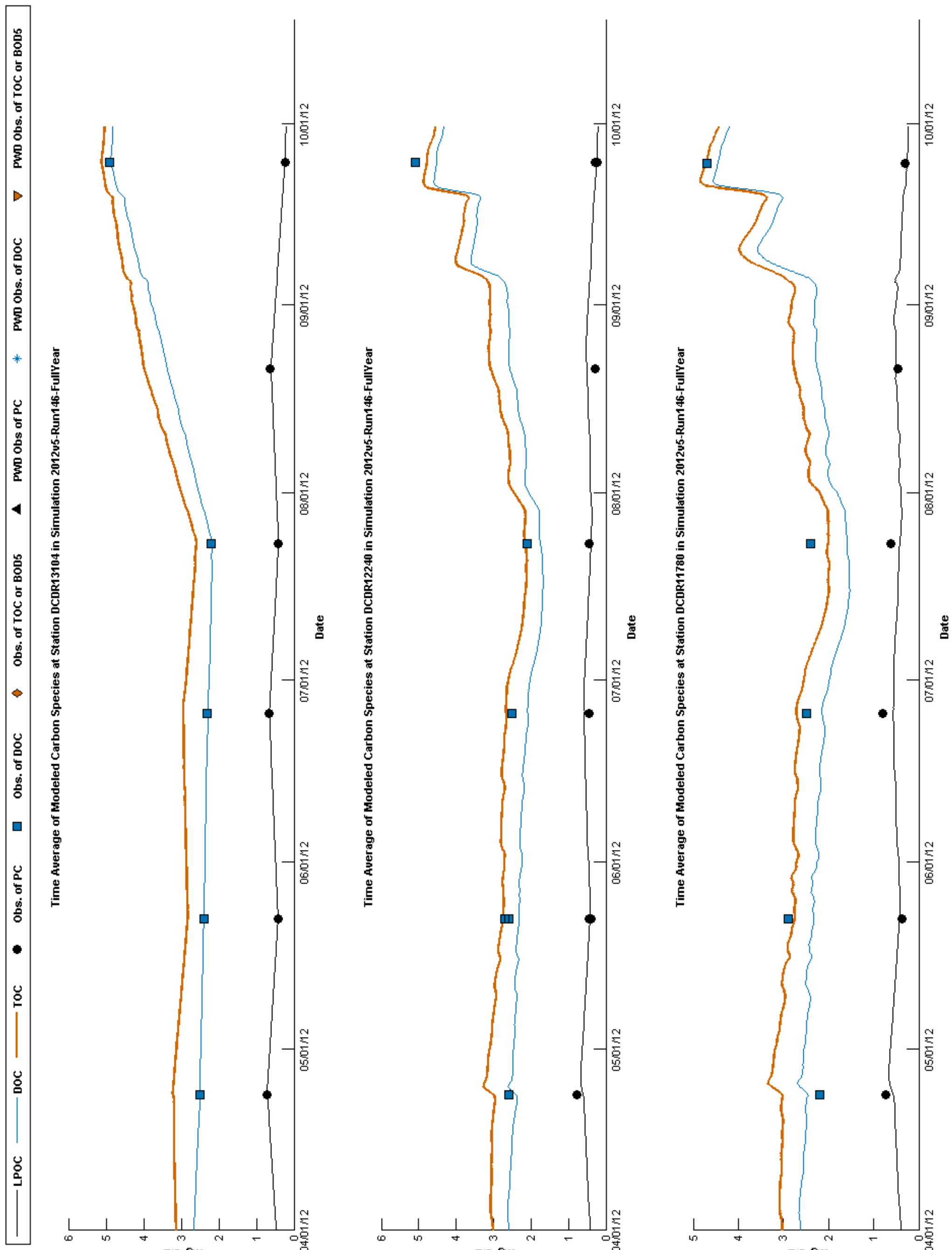

Time Average of Modeled Chlorophyll A at Station DCDR07490 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

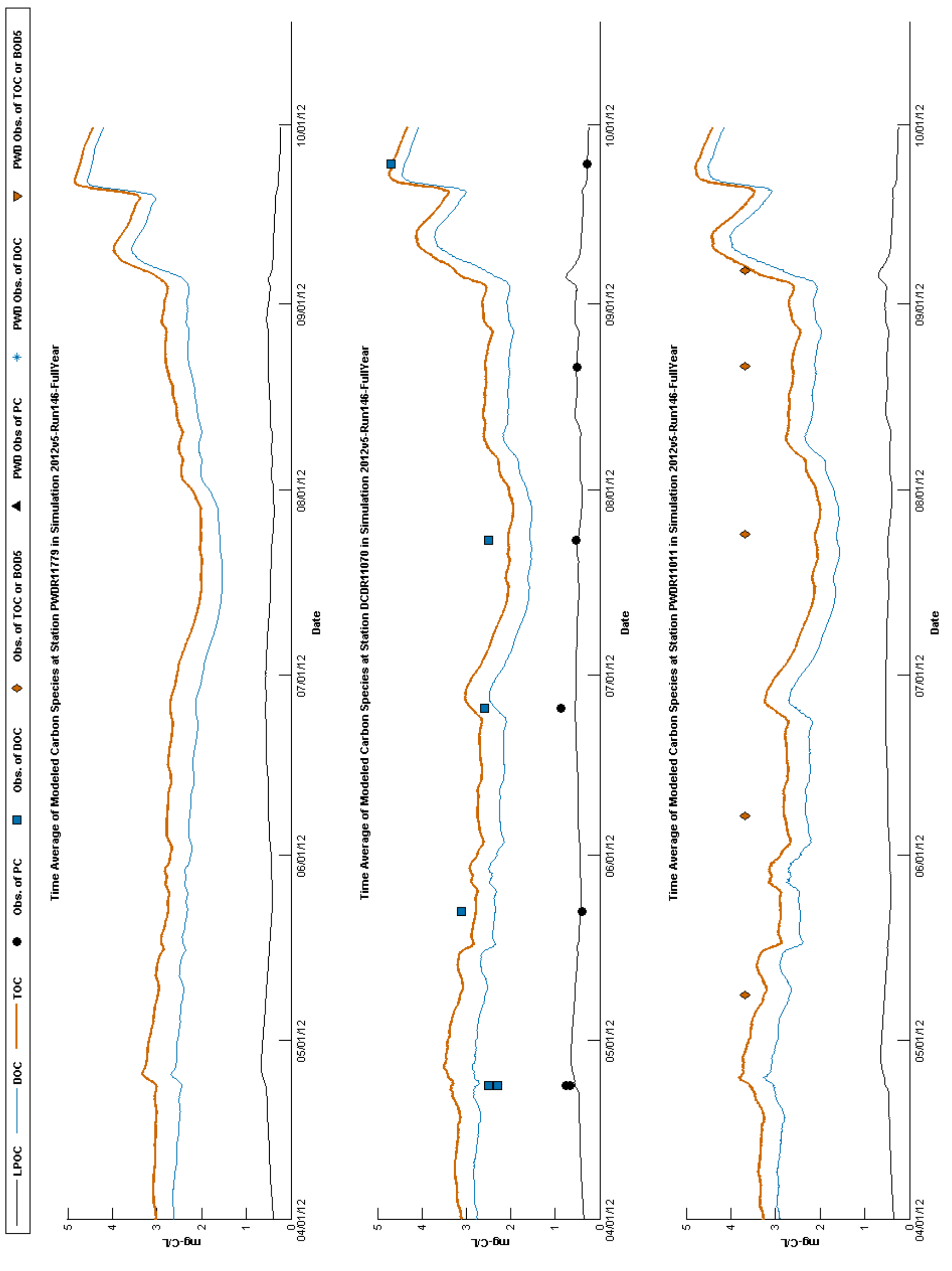

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR07150 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR07100 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR06600 in Simulation 2012v5-Run146-SummerOnly
ug/L
Date
07/01/12
08/01/12
09/01/12

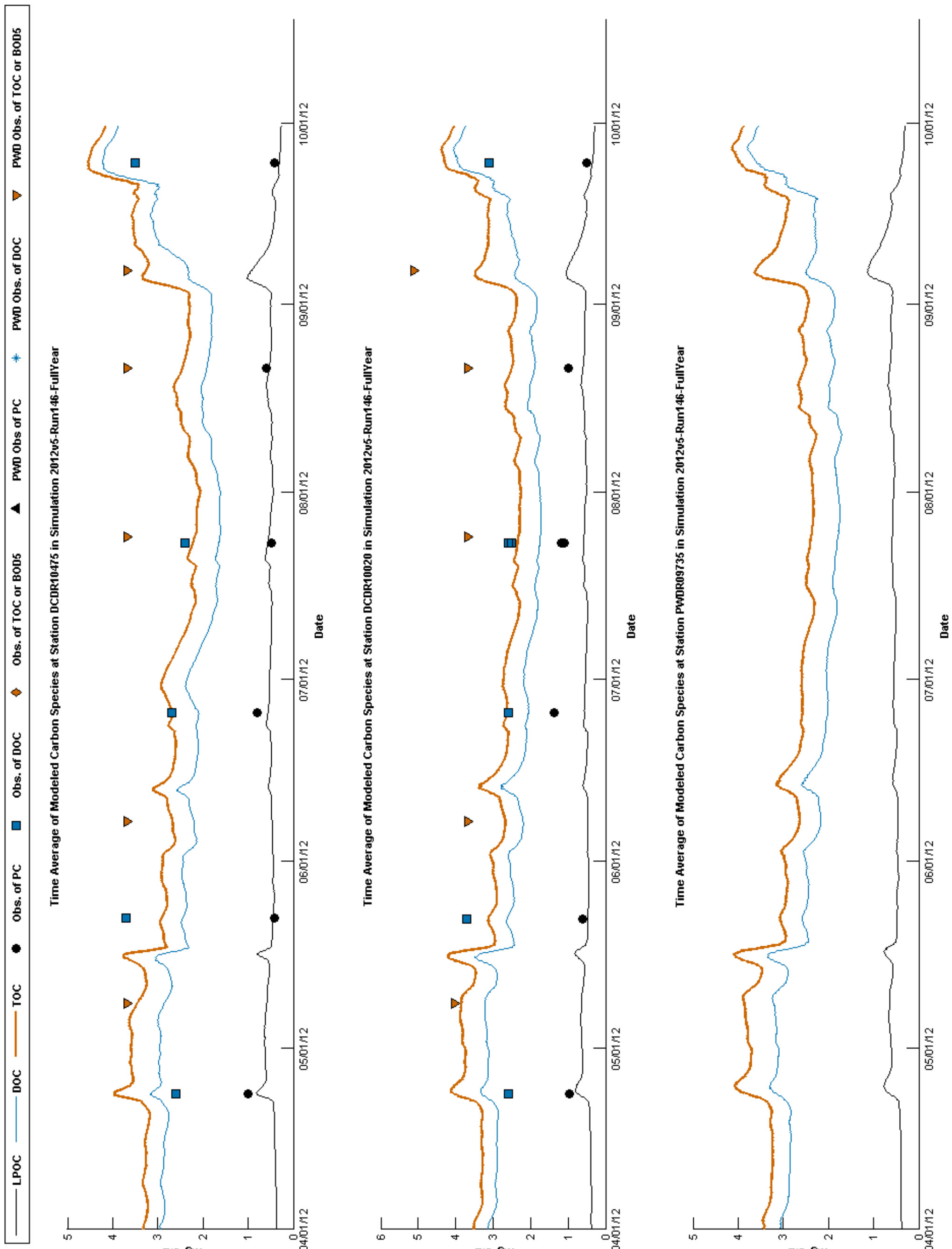

WQ Consituent CHC - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
Concentration, ug/L
River Mile
0
5
10
15
20
25
30
35
40
60
70
80
90
100
110
120
130
140

1.2. Carbon Species

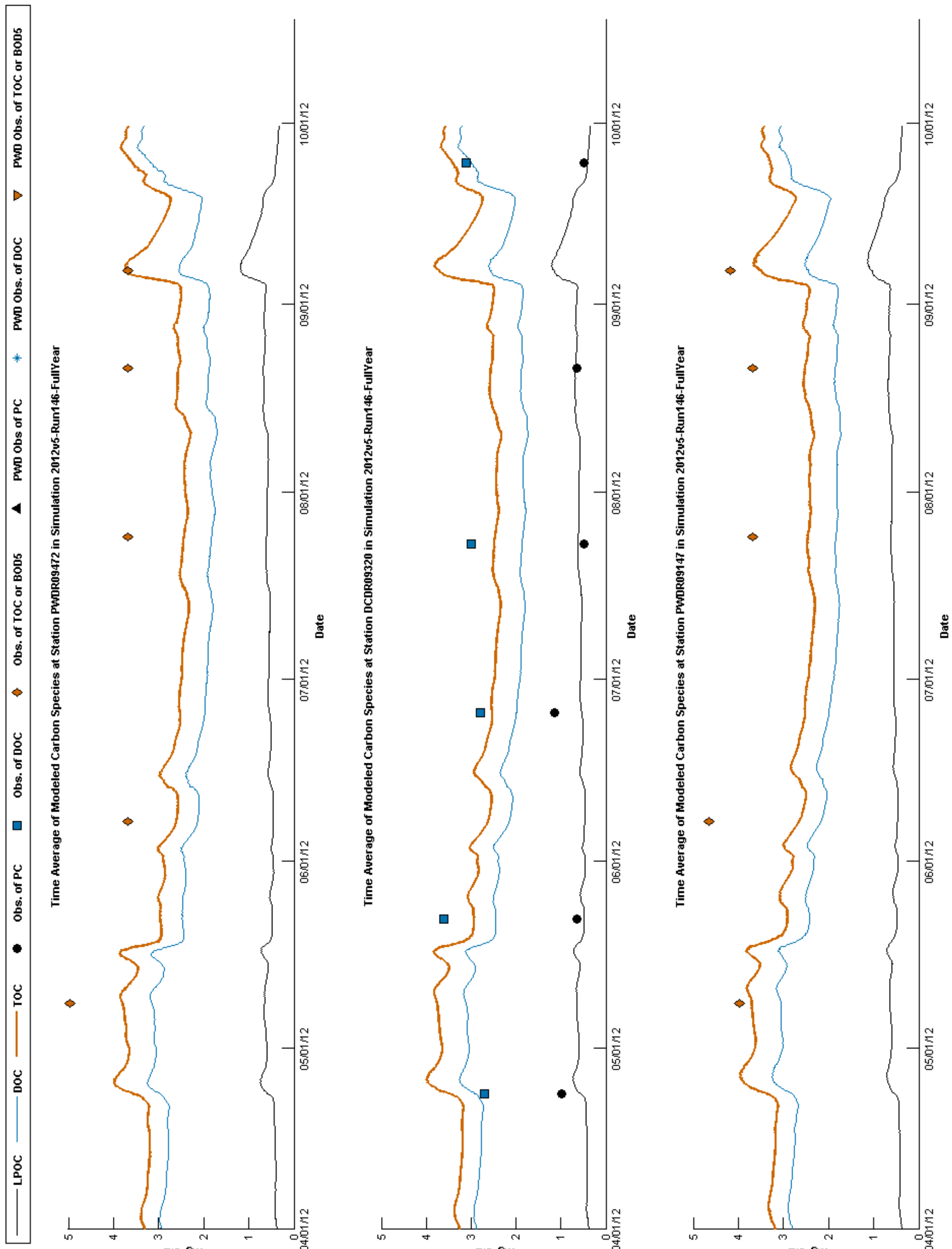
1.2.1. April to October

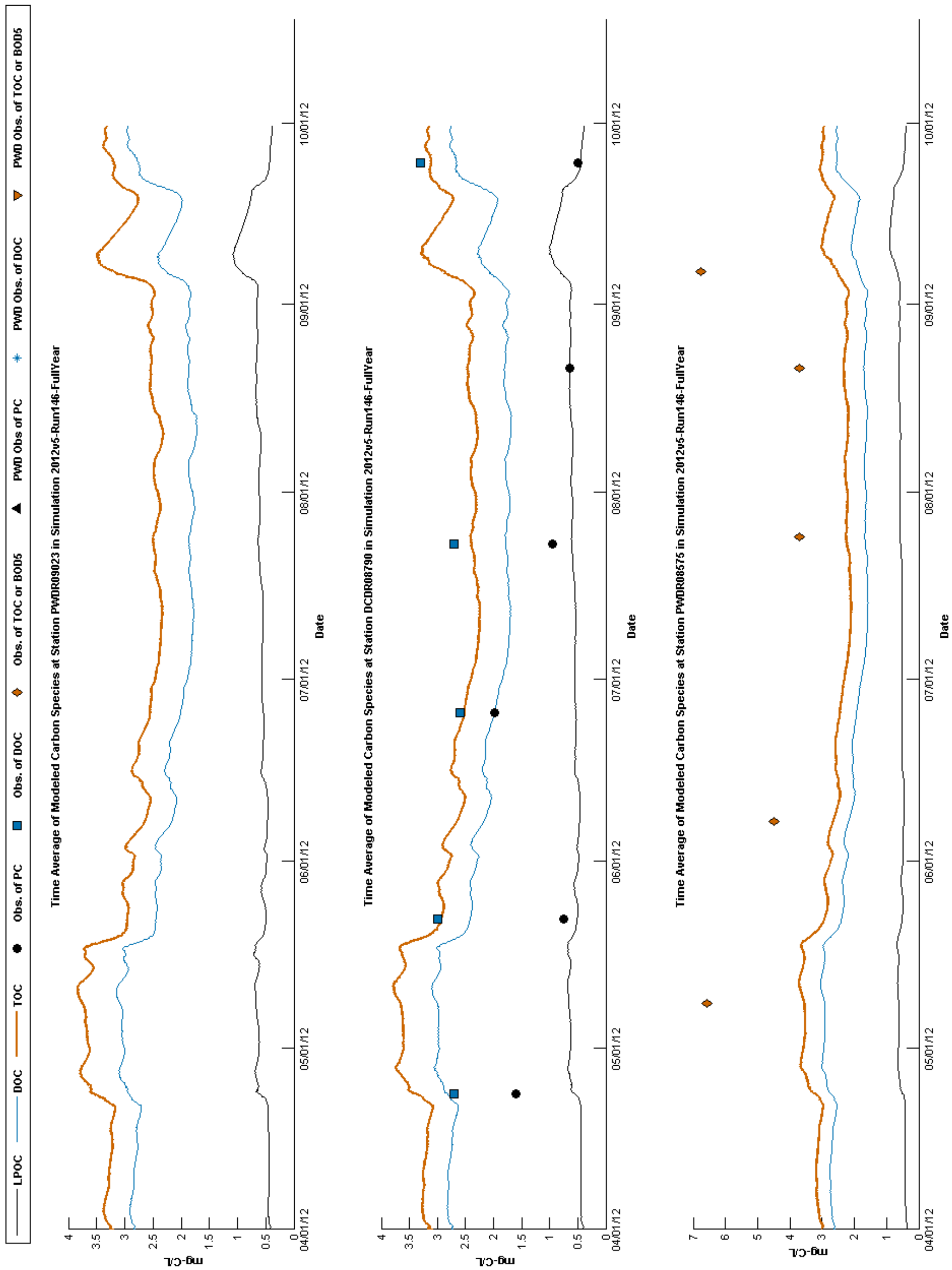


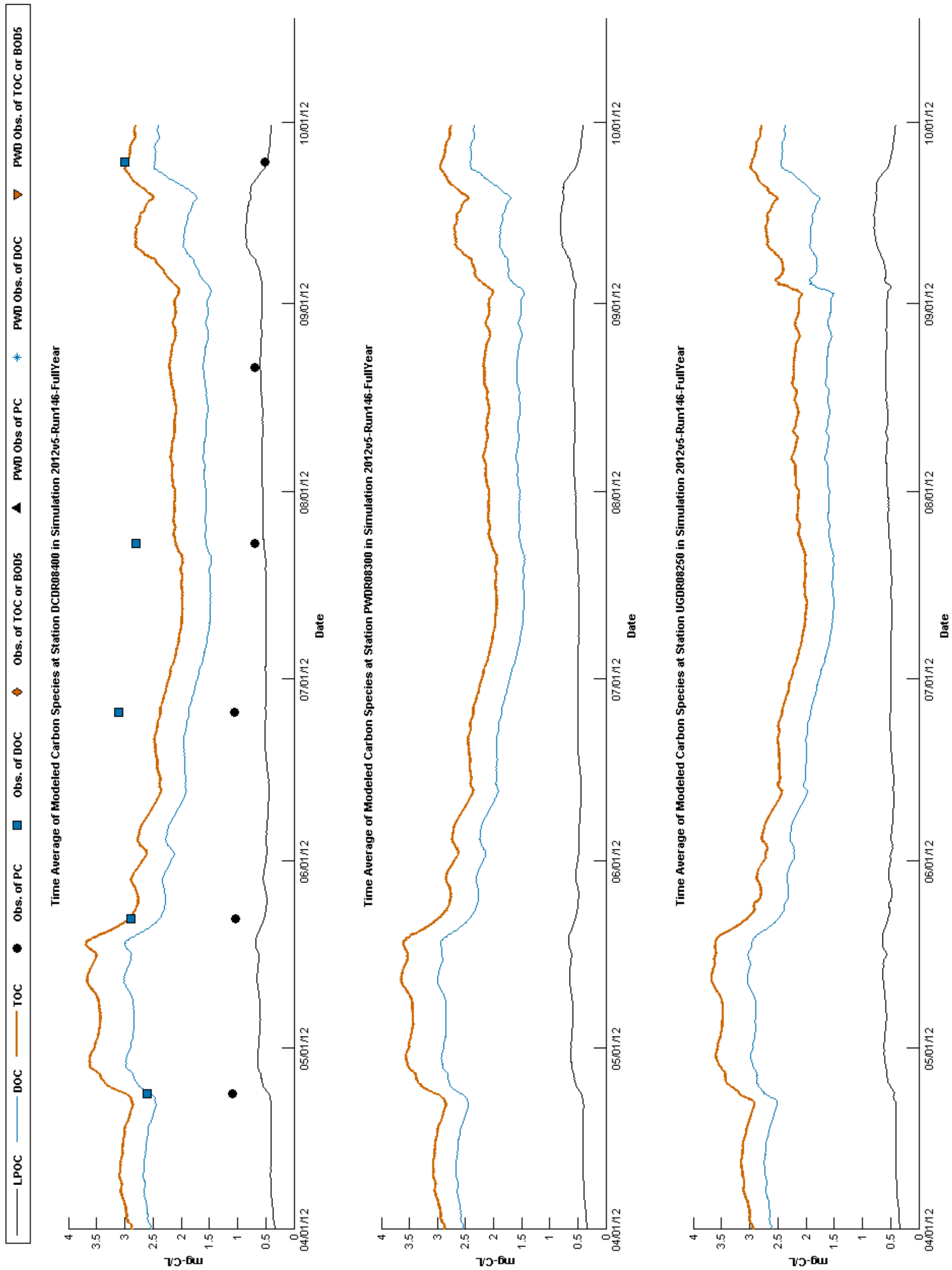

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR11779 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR11070 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR11011 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

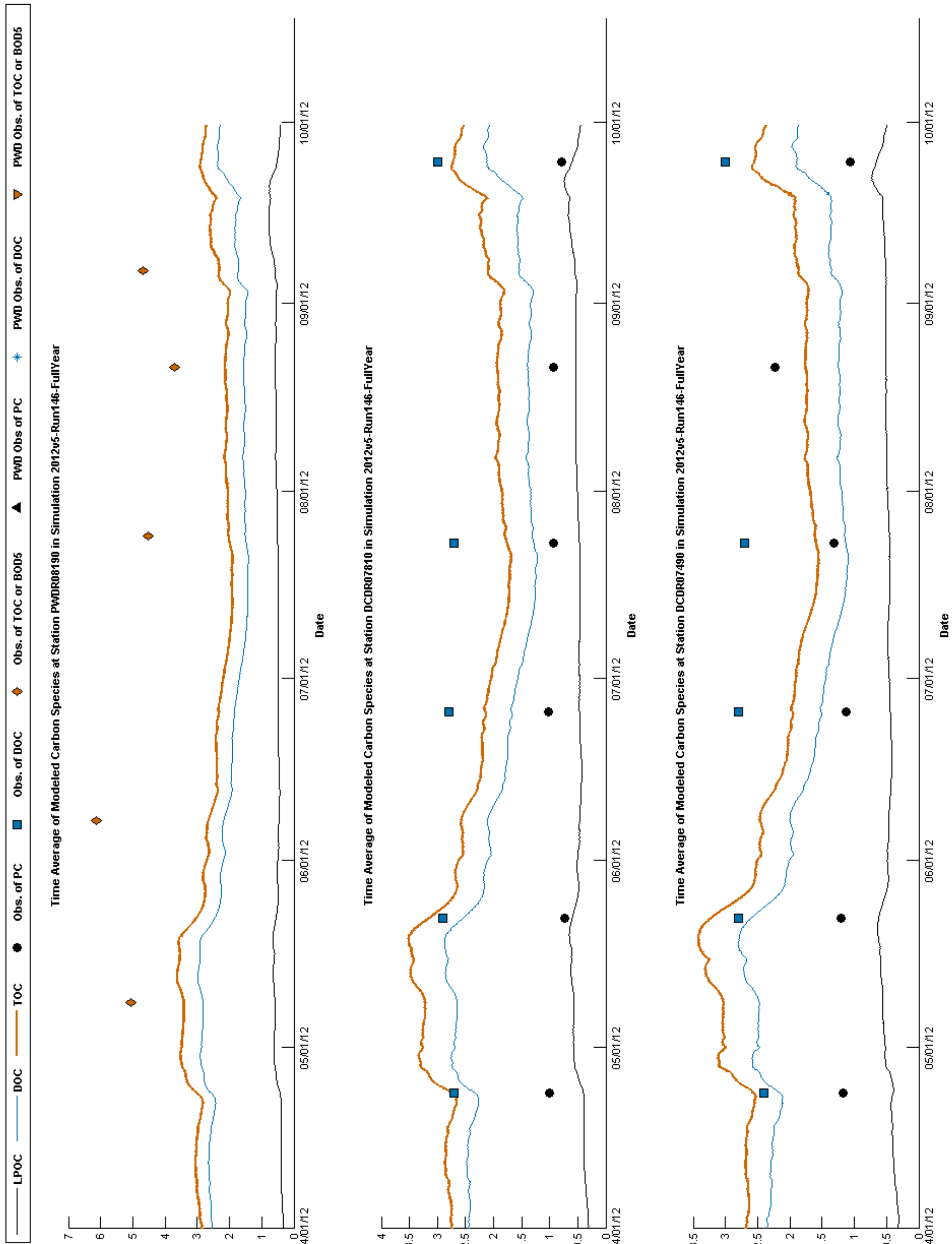


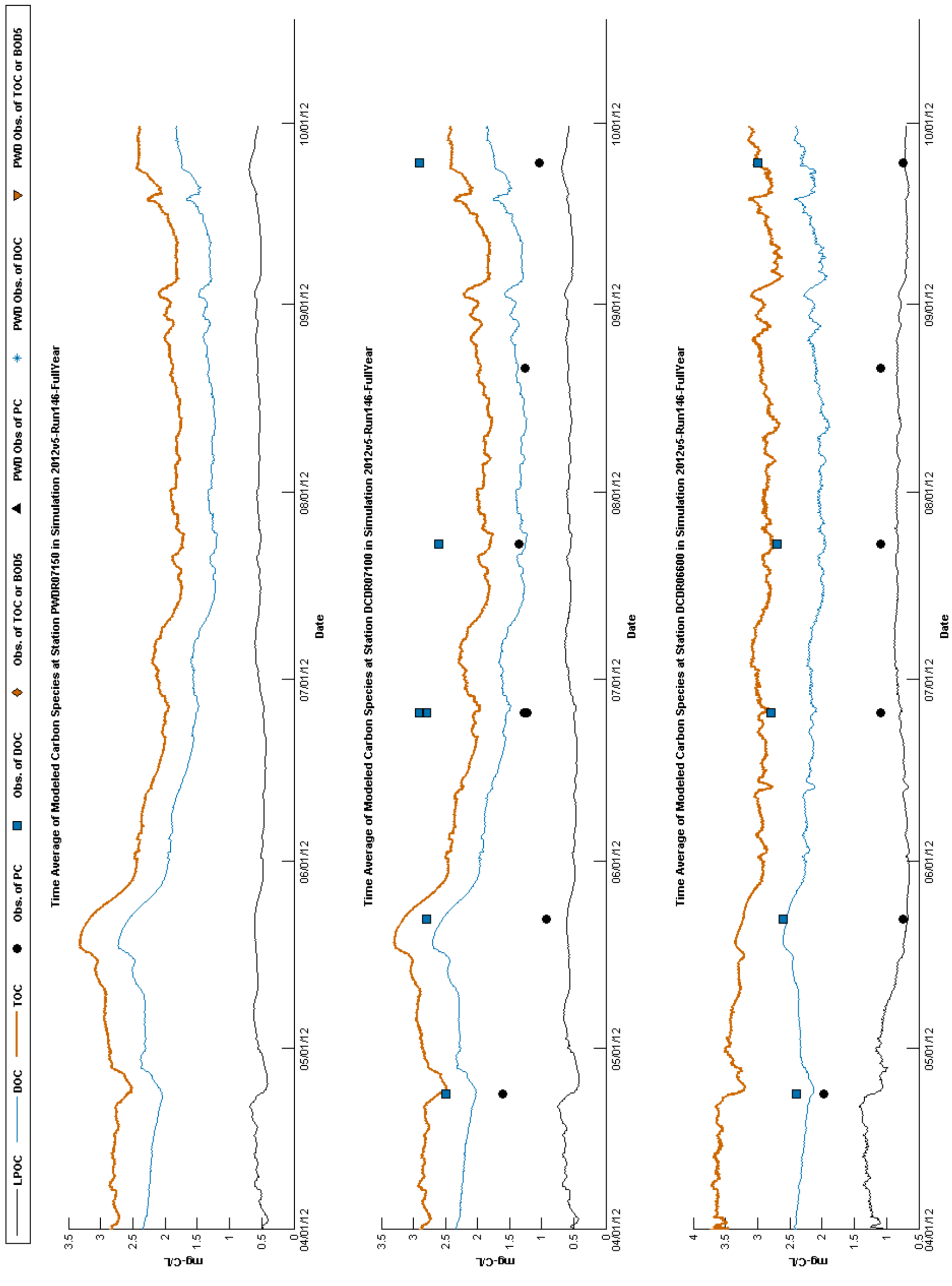
LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR10475 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR10020 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR09735 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09472 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR09320 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR09147 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

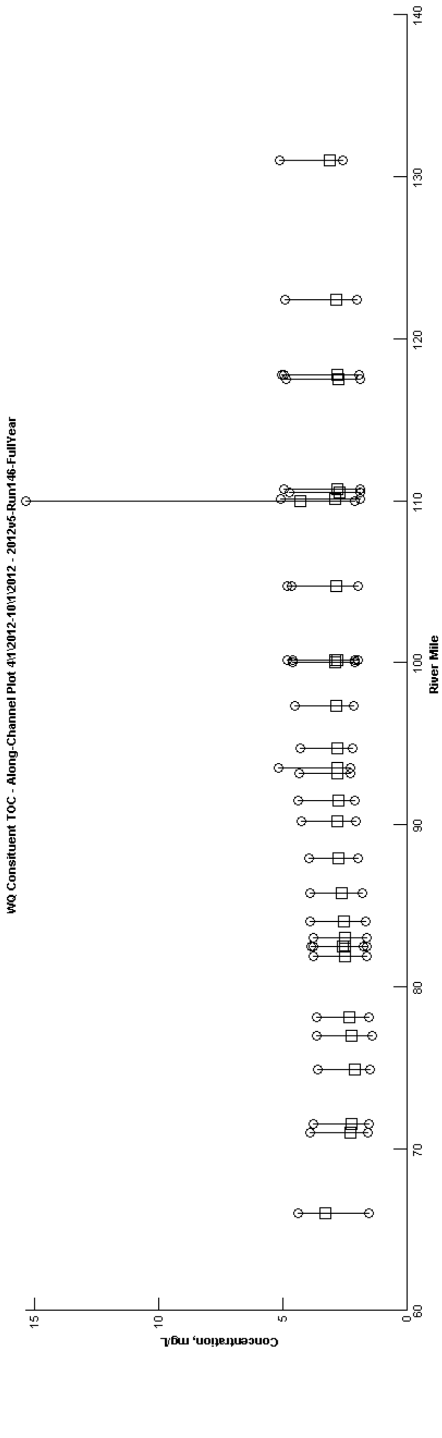

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09023 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR08790 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR08575 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR08400 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR08300 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station UGDR08250 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR08190 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07810 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07490 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

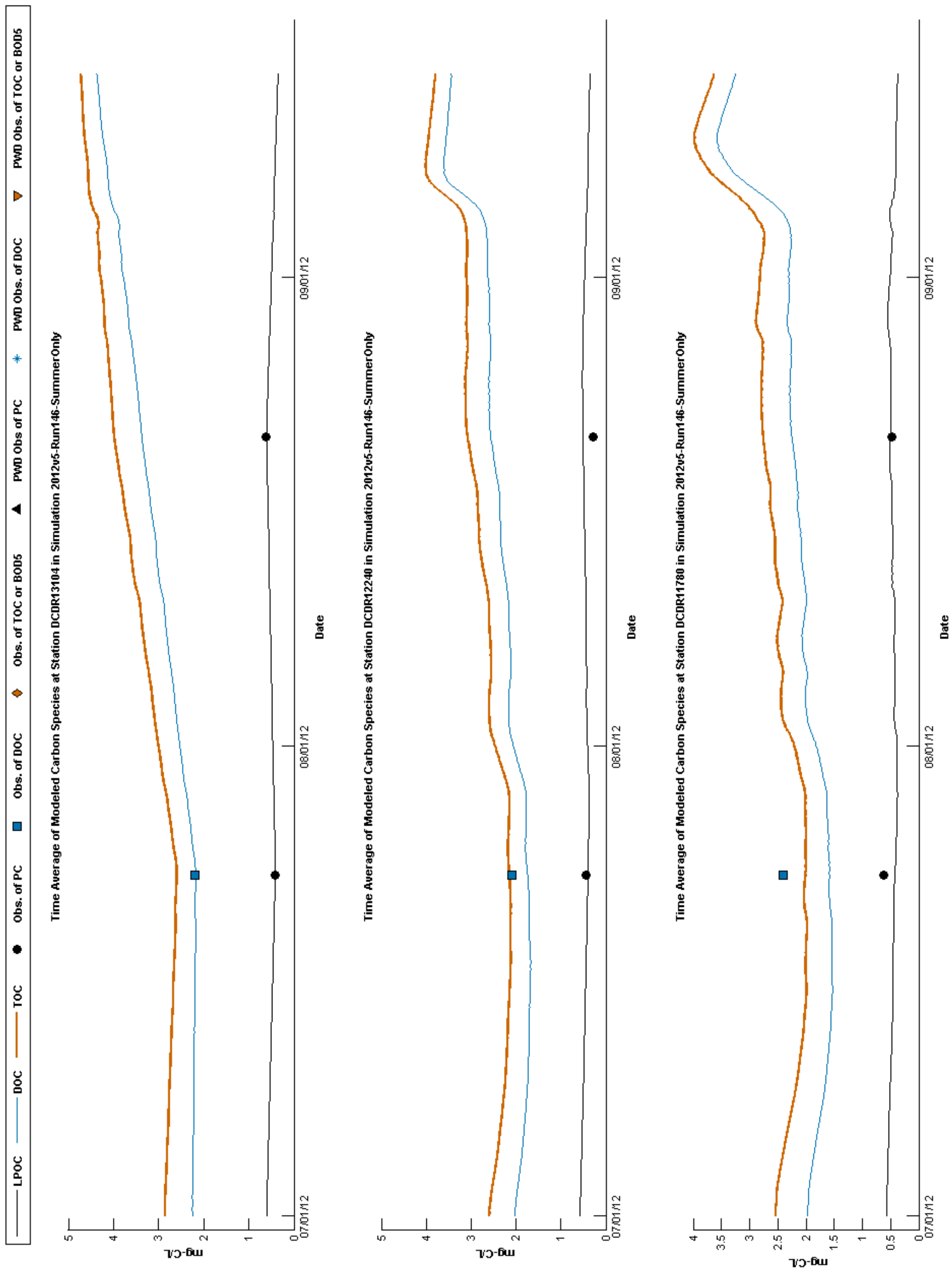


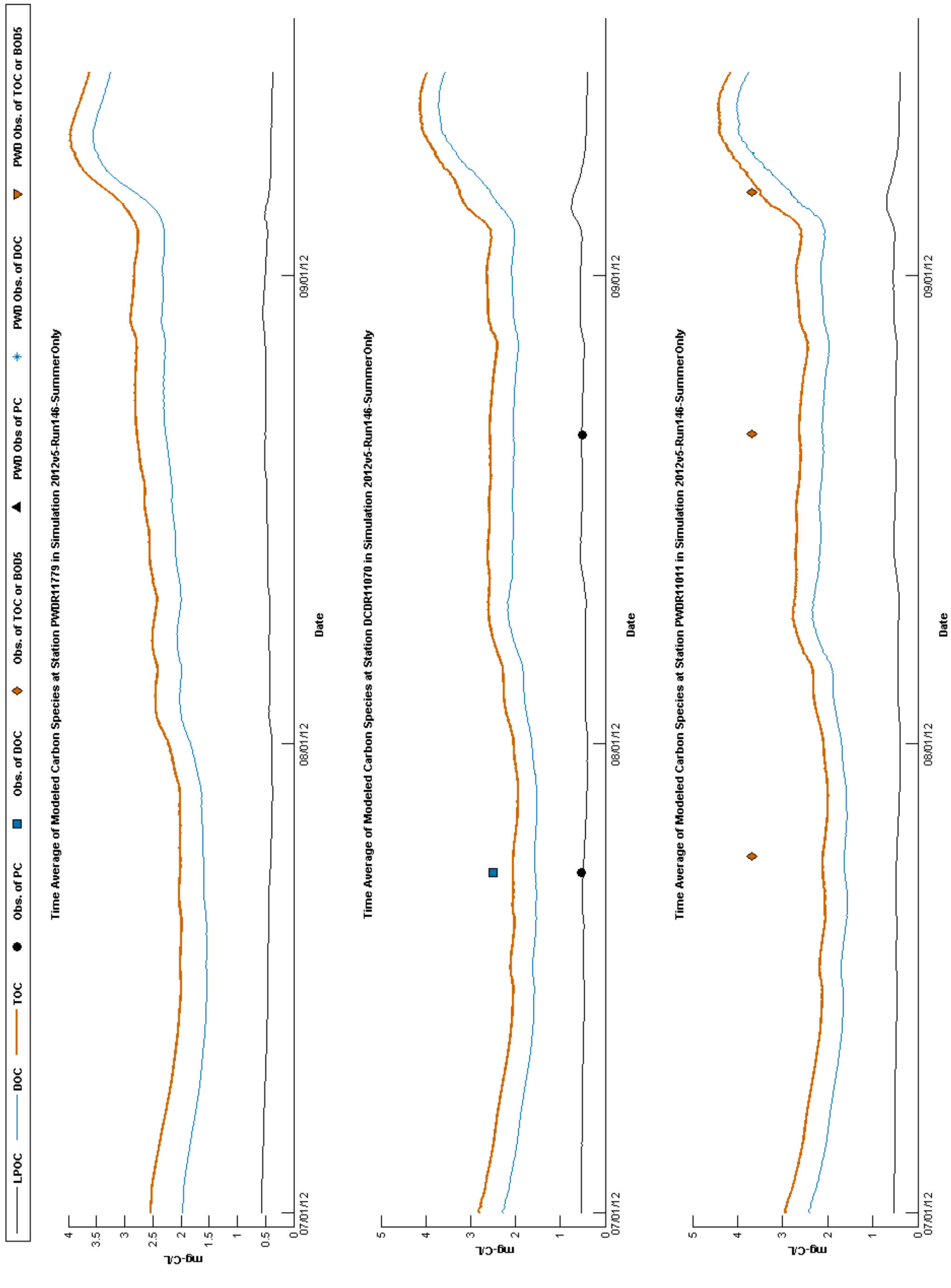
LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR07150 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07100 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR06600 in Simulation 2012v5-Run146-FullYear
mg-C/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

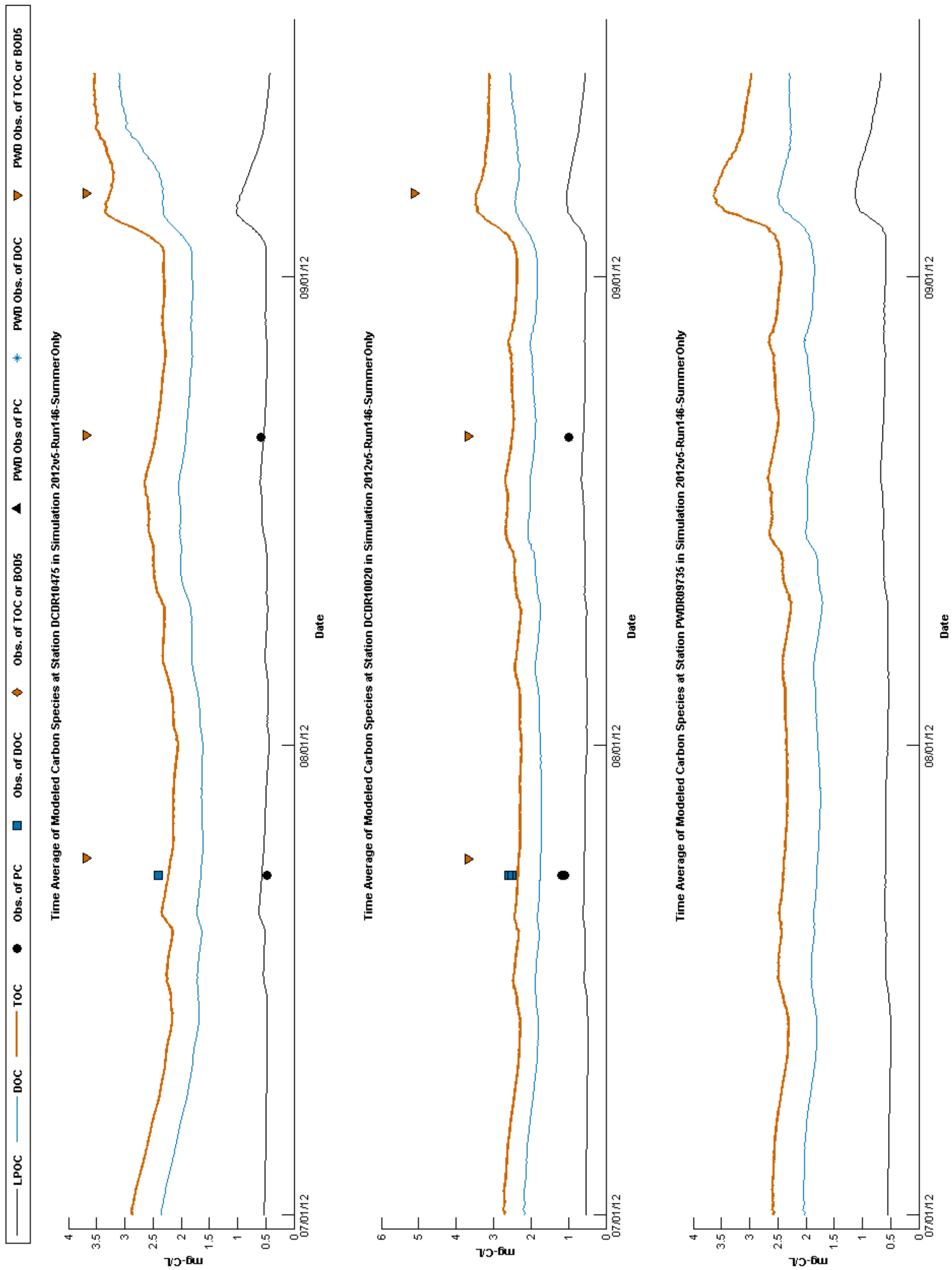


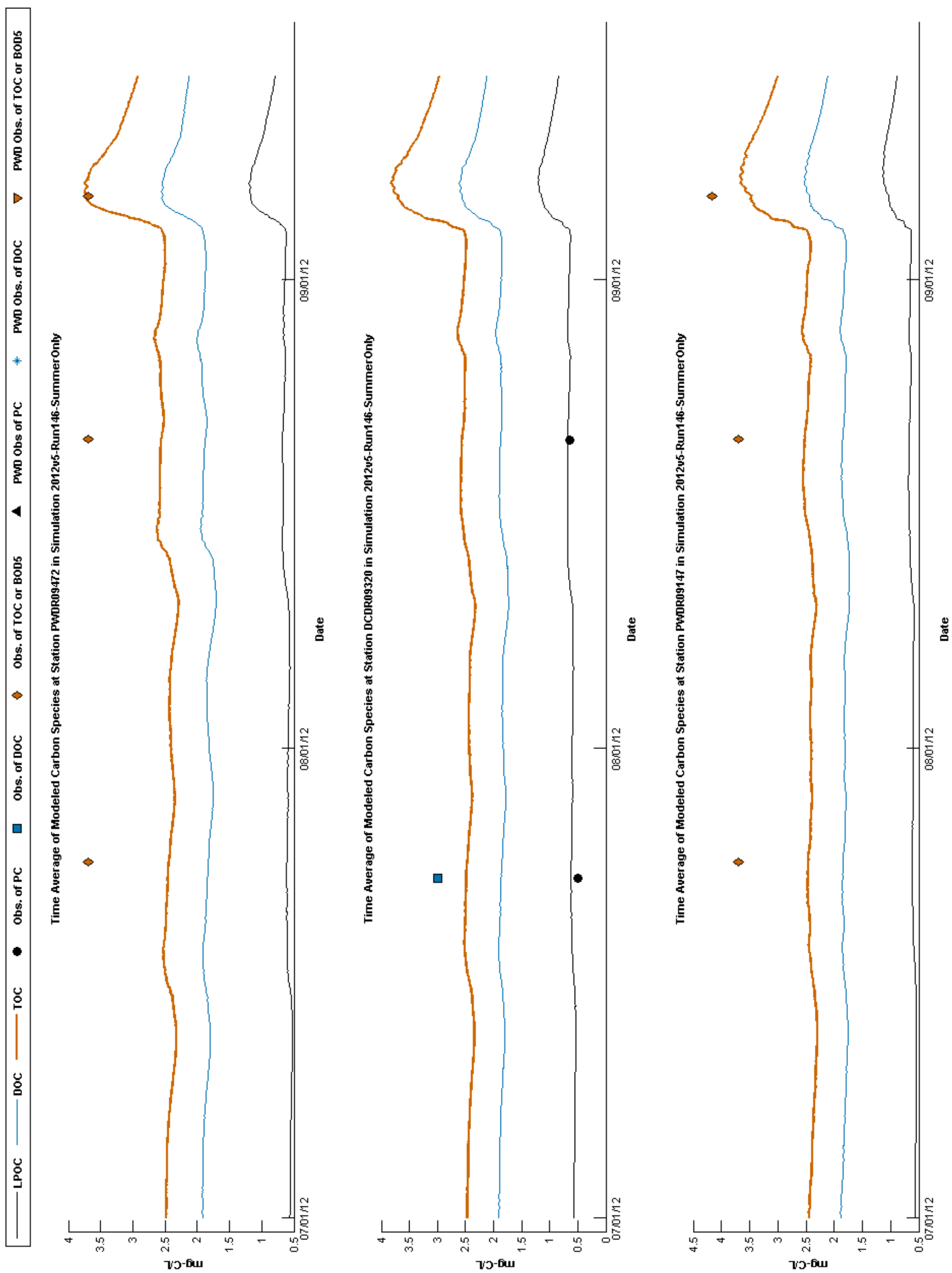
WQ Consituent TOC - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
River Mile
Concentration, mg/L
60
70
80
90
100
110
120
130
140
0
5
10
15

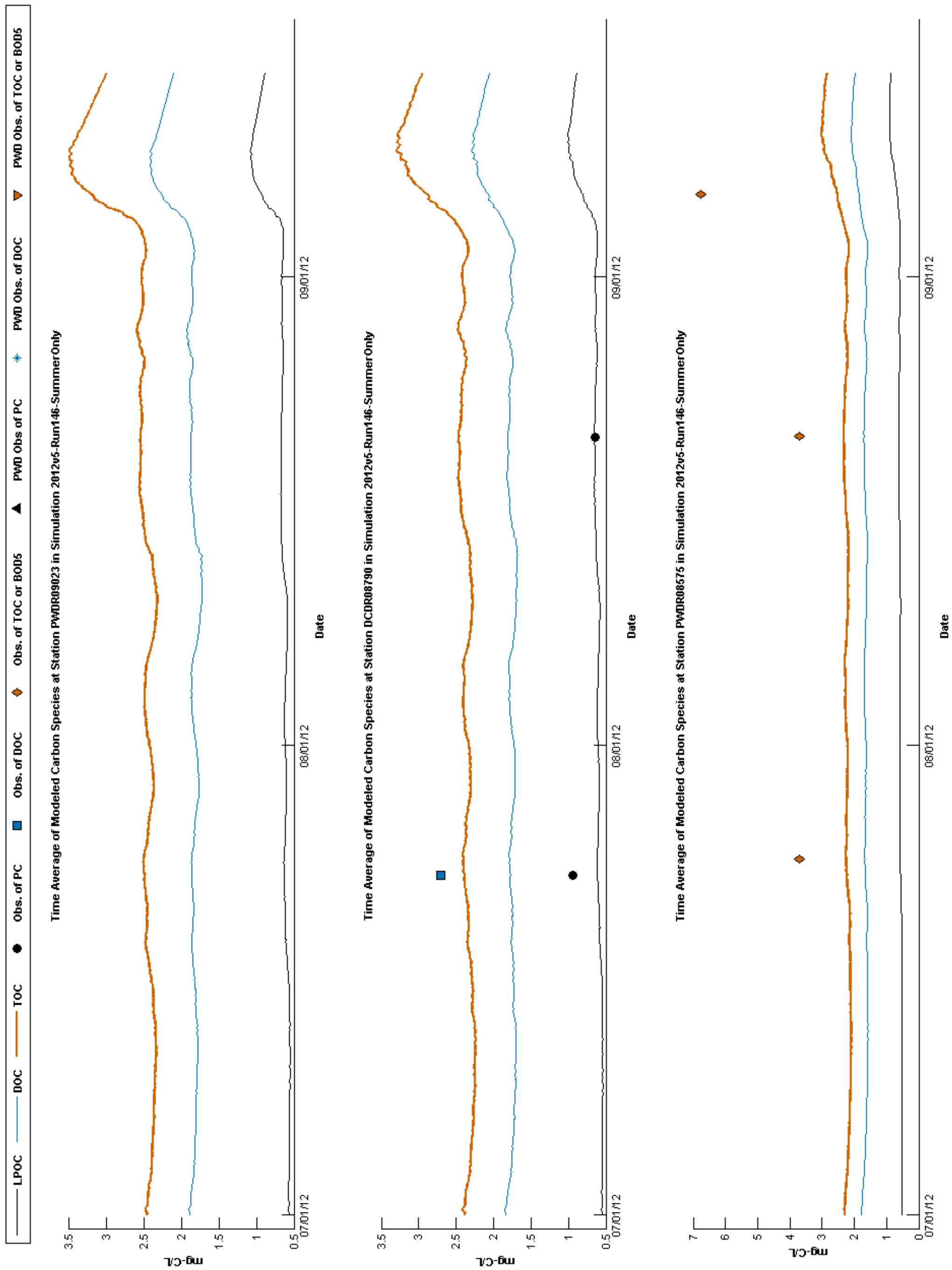
1.2.2. Summer

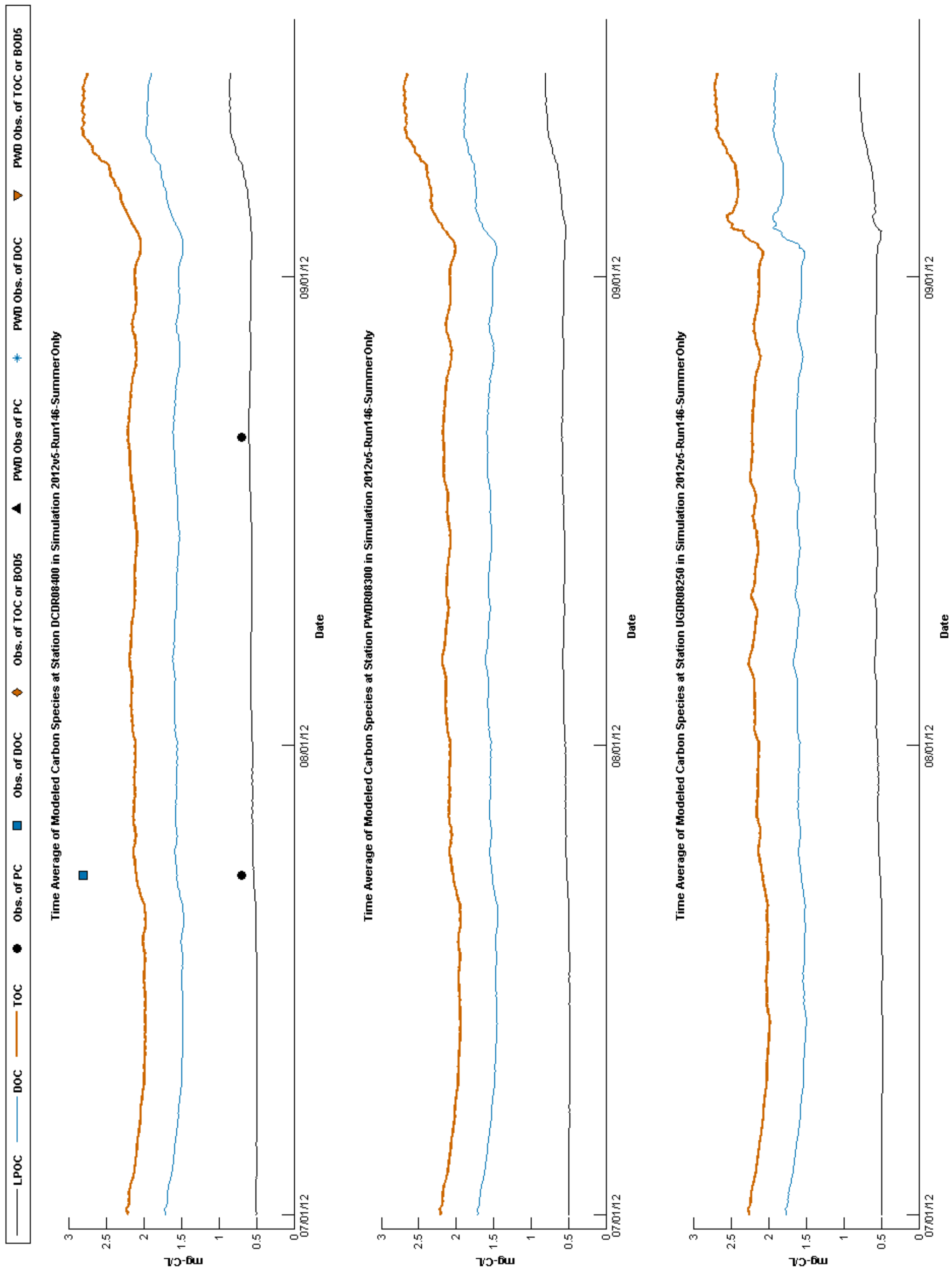

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR13104 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Carbon Species at Station DCDR12240 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Carbon Species at Station DCDR11780 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

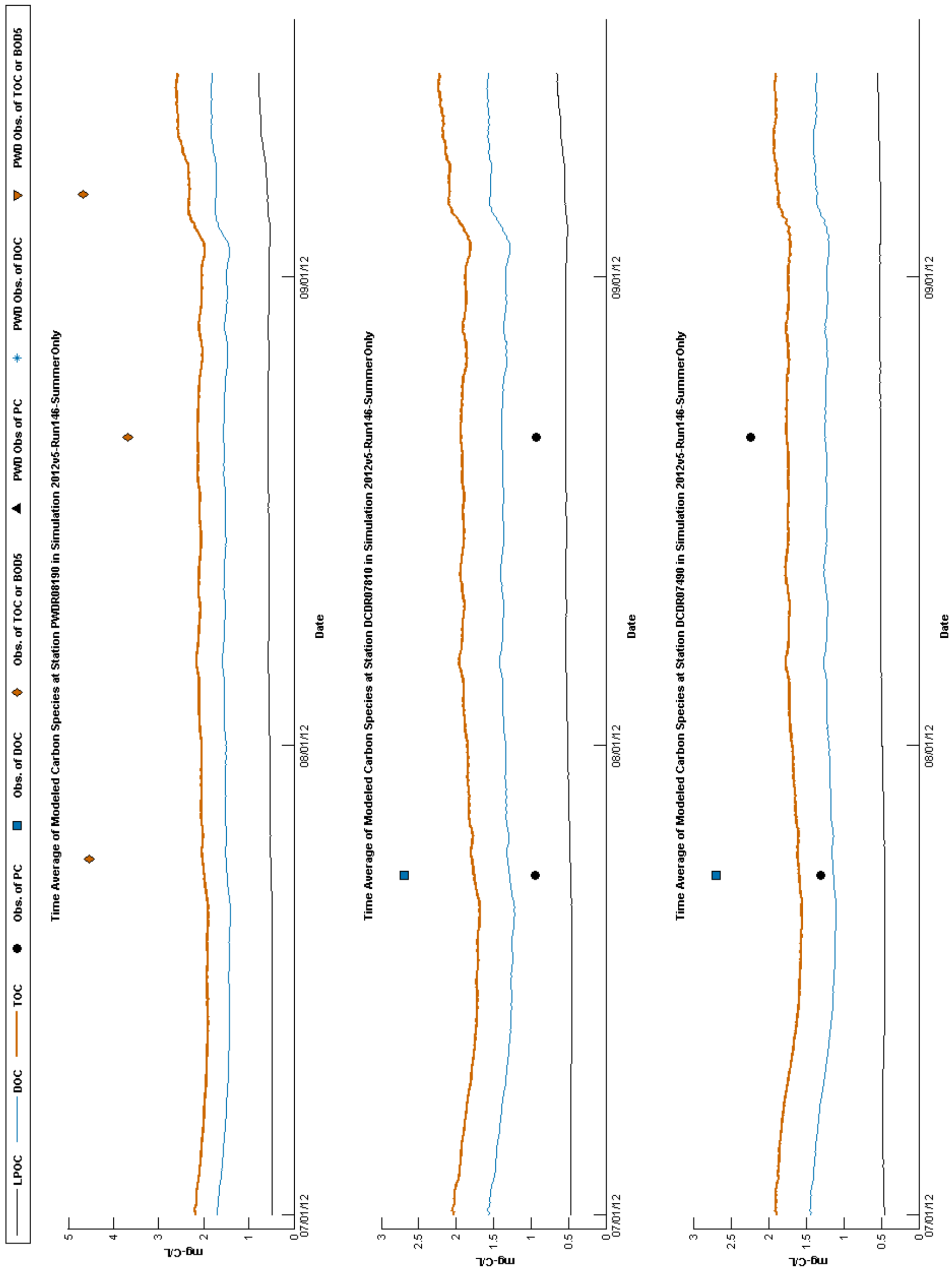

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR11779 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR11070 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR11011 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

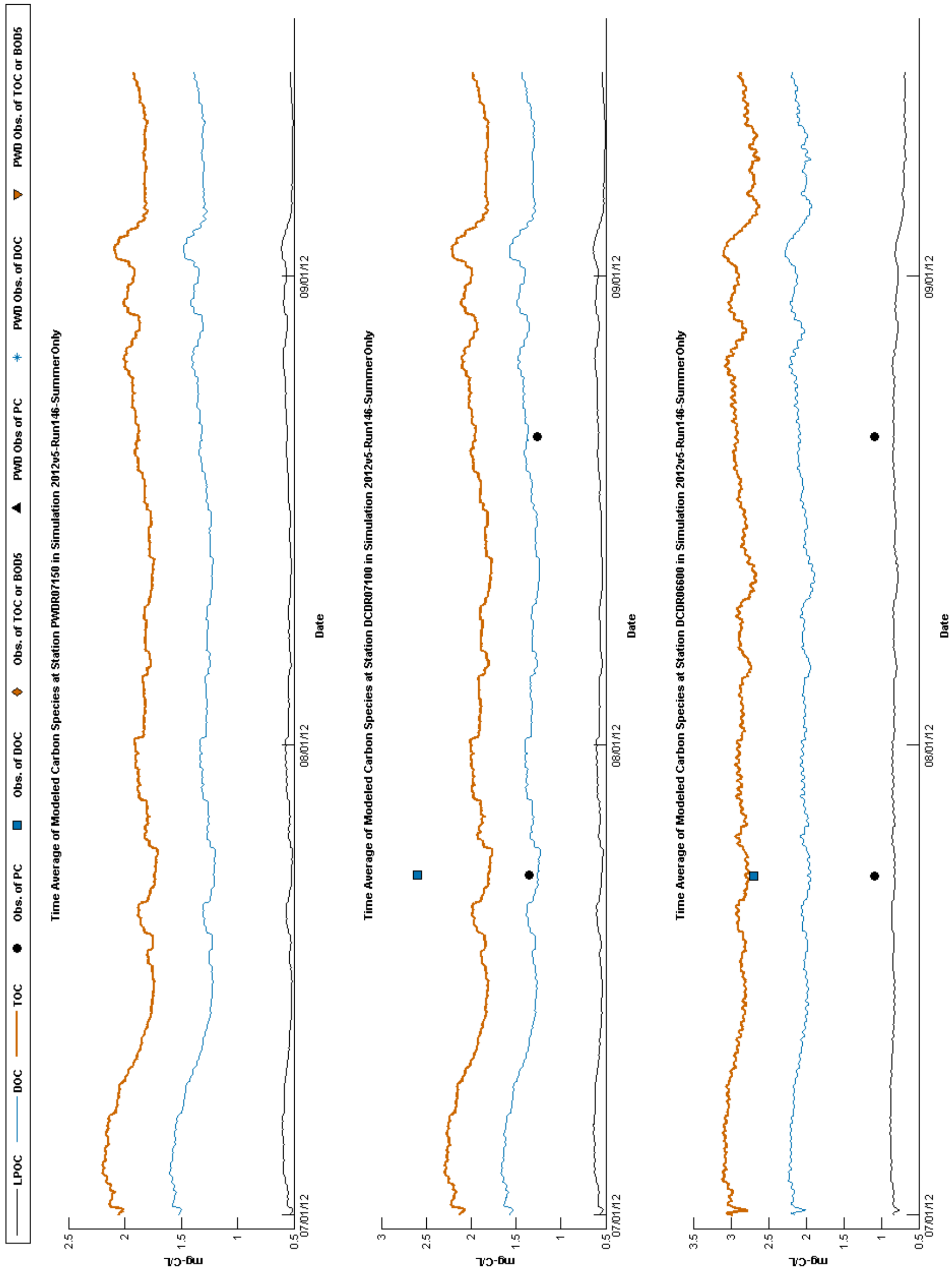

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR10475 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR10020 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR09735 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

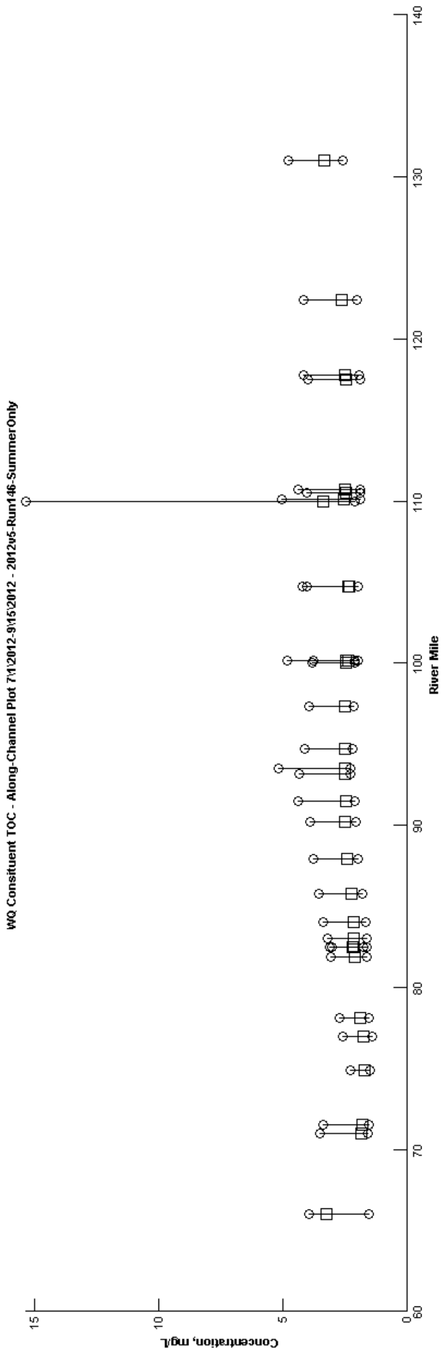

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09472 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR09320 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR09147 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09023 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR08790 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR08575 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR08400 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR08300 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station UGDR08250 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

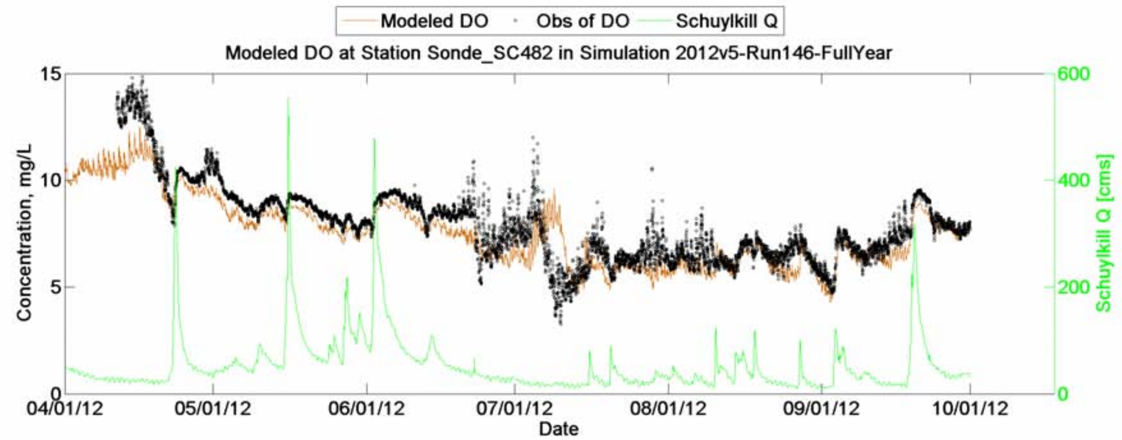

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR08190 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07810 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07490 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

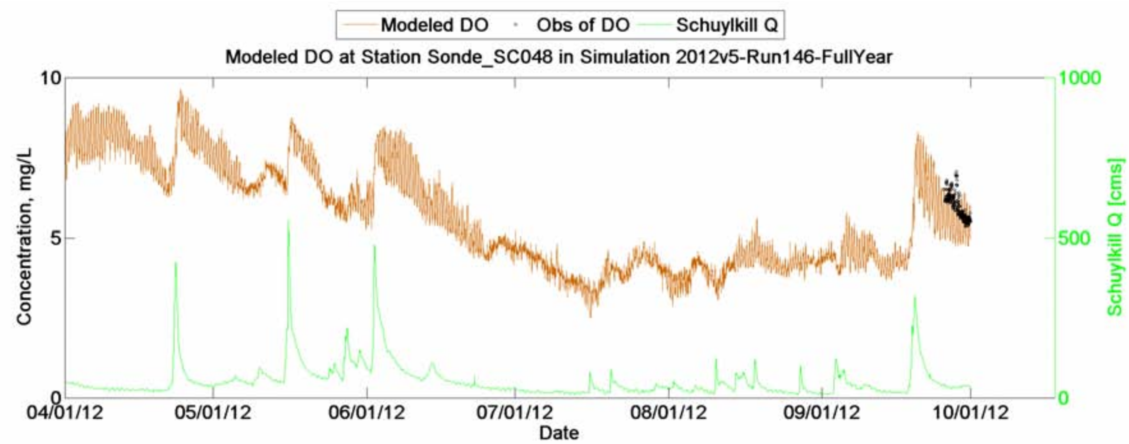

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR07150 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07100 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR06600 in Simulation 2012v5-Run146-SummerOnly
mg-C/L
Date
07/01/12
08/01/12
09/01/12

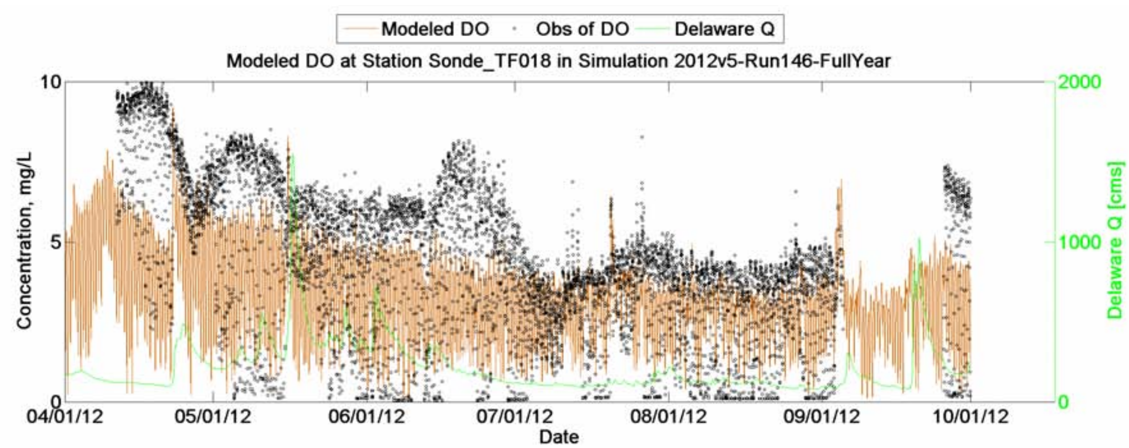

WQ Consituent TOC - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
Concentration, mg/L
River Mile

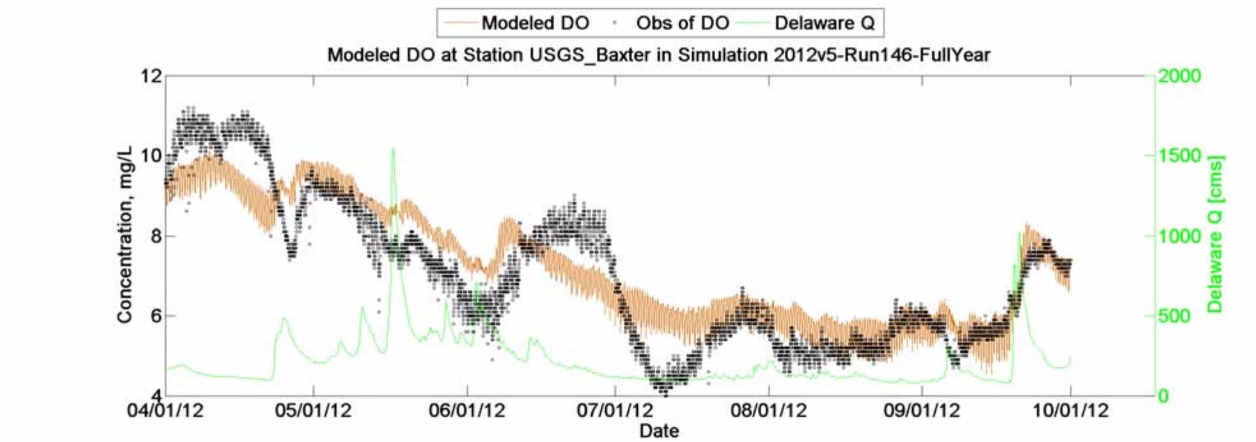
1.3. Dissolved Oxygen

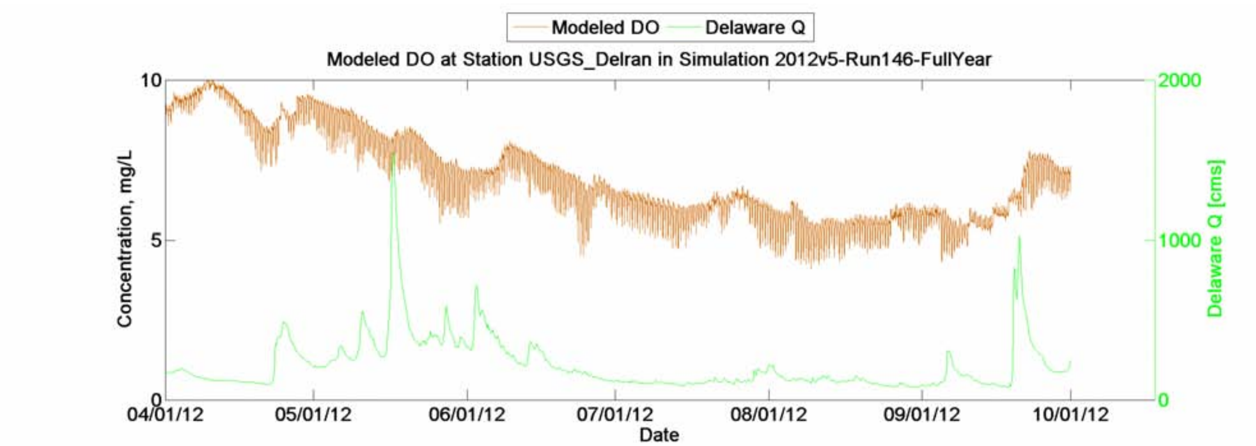
1.3.1. April to October

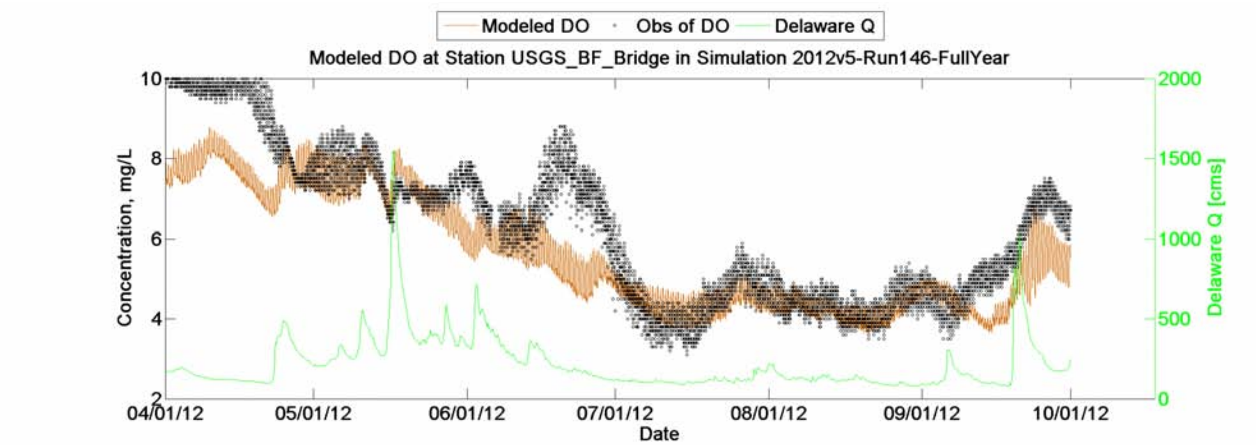


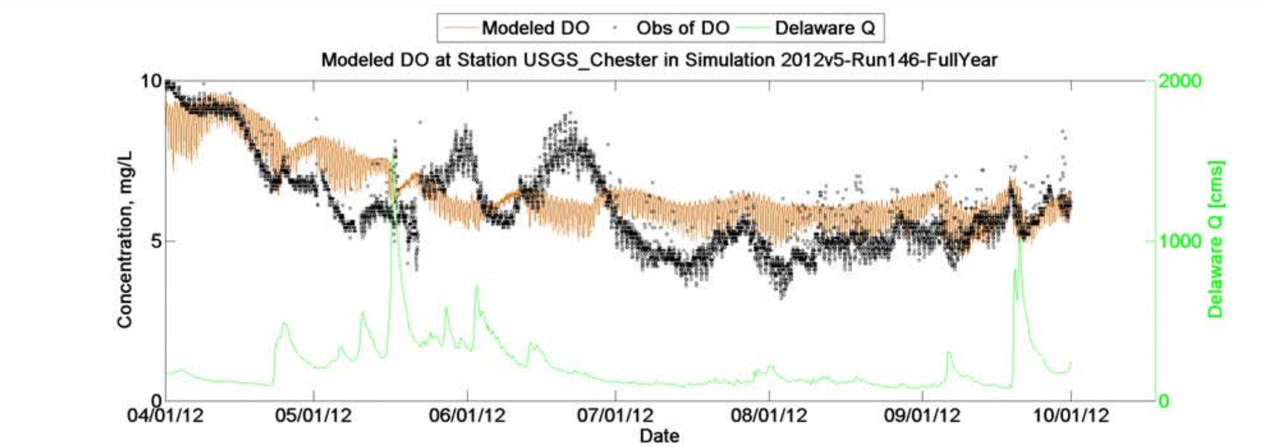


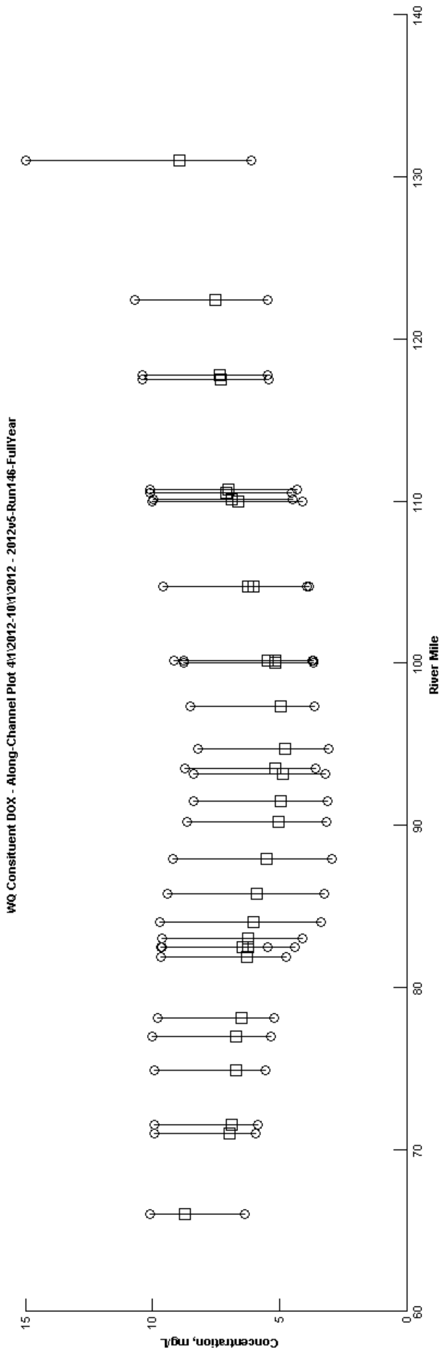



Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Baxter in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

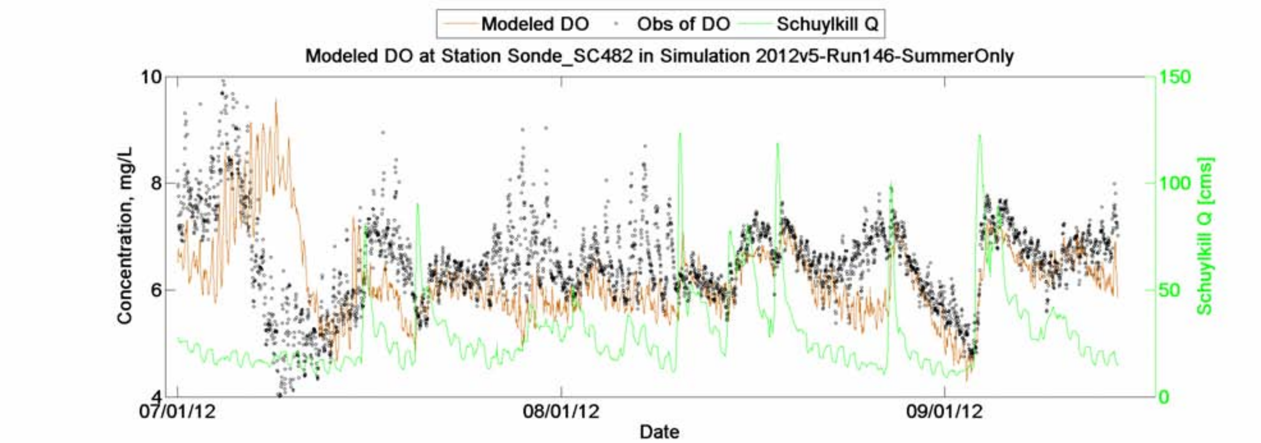

Modeled DO
Delaware Q
Modeled DO at Station USGS_Delran in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

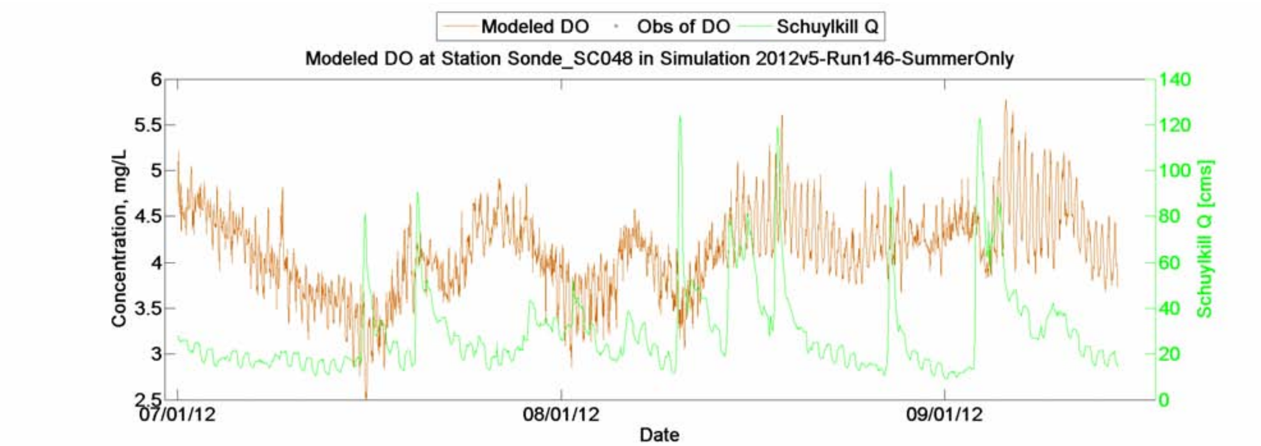

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_BF_Bridge in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

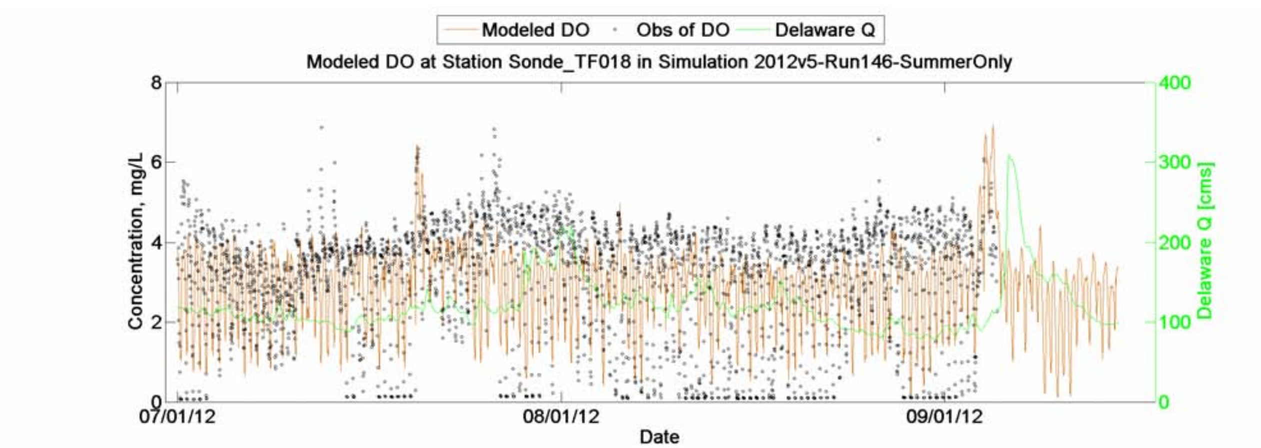

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Chester in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

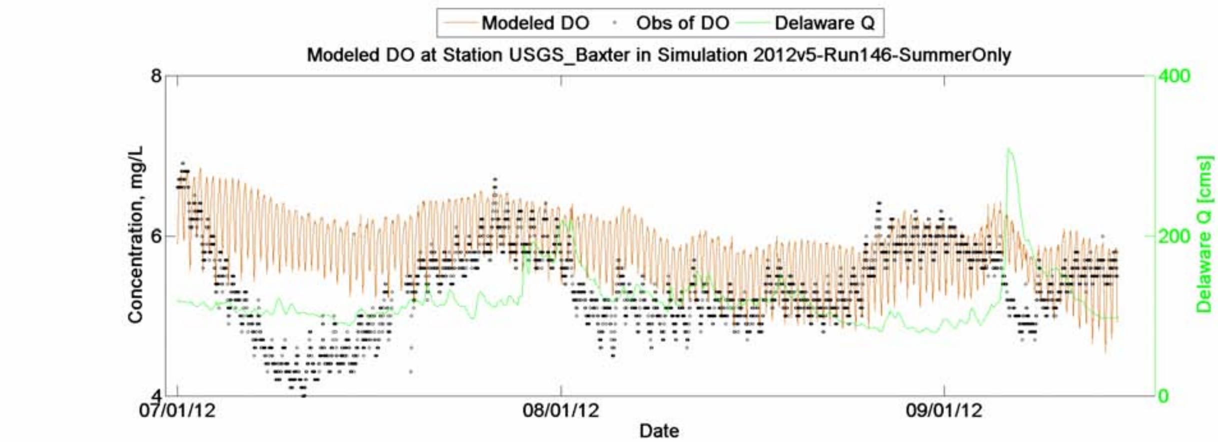

WQ Consituent DOX - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
River Mile
Concentration, mg/L
60
70
80
90
100
110
120
130
140
0
5
10
15

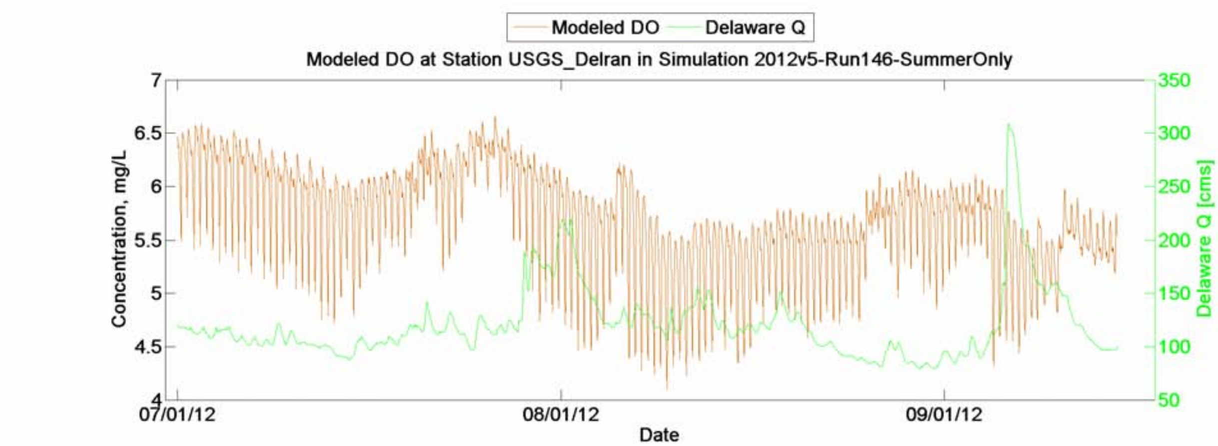
1.3.2. Summer

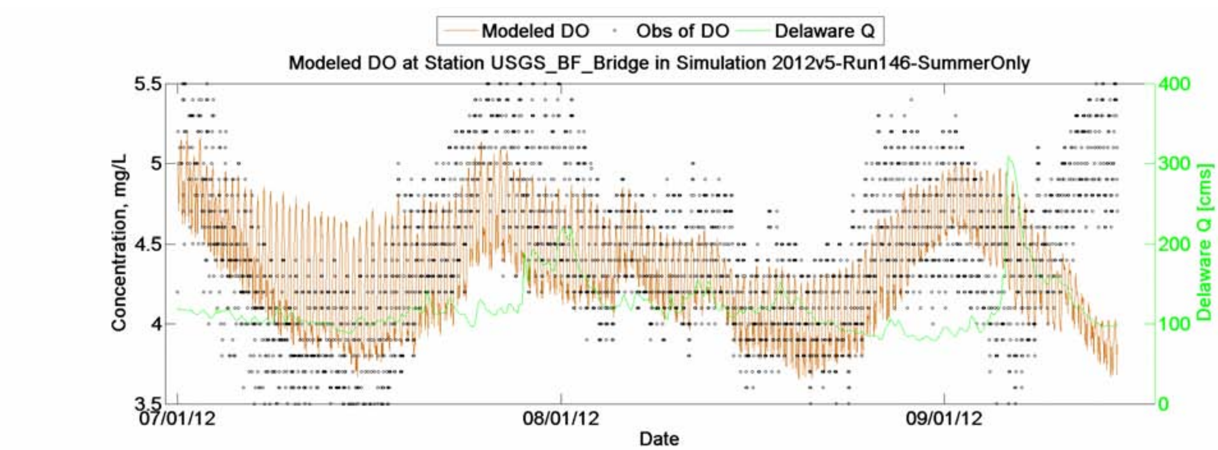

Modeled DO
Obs of DO
Schuylkill Q
Modeled DO at Station Sonde_SC482 in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Schuylkill Q [cms]
Date
07/01/12
08/01/12
09/01/12

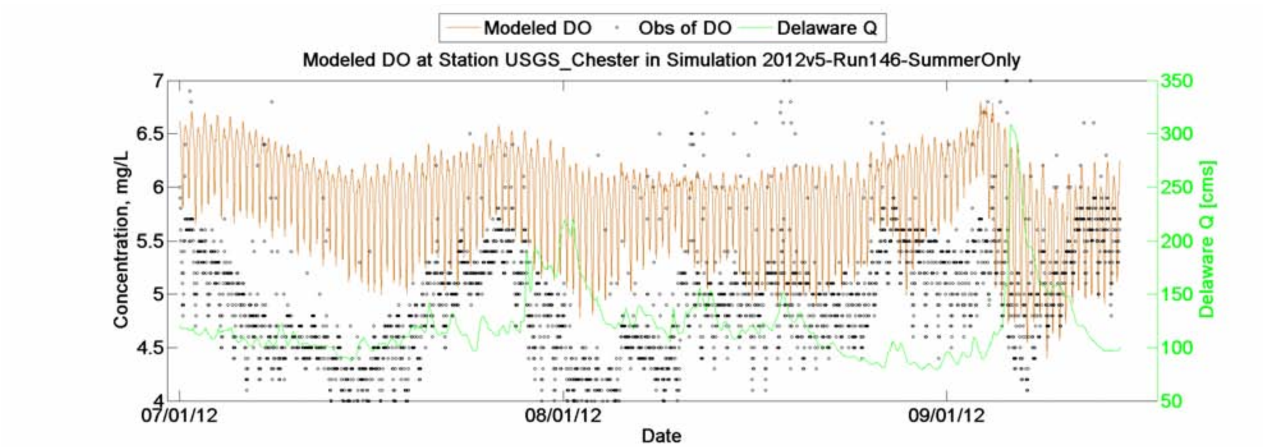

Modeled DO
Obs of DO
Schuylkill Q
Modeled DO at Station Sonde_SC048 in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Schuylkill Q [cms]
Date
07/01/12
08/01/12
09/01/12


Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station Sonde_TF018 in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/12
08/01/12
09/01/12

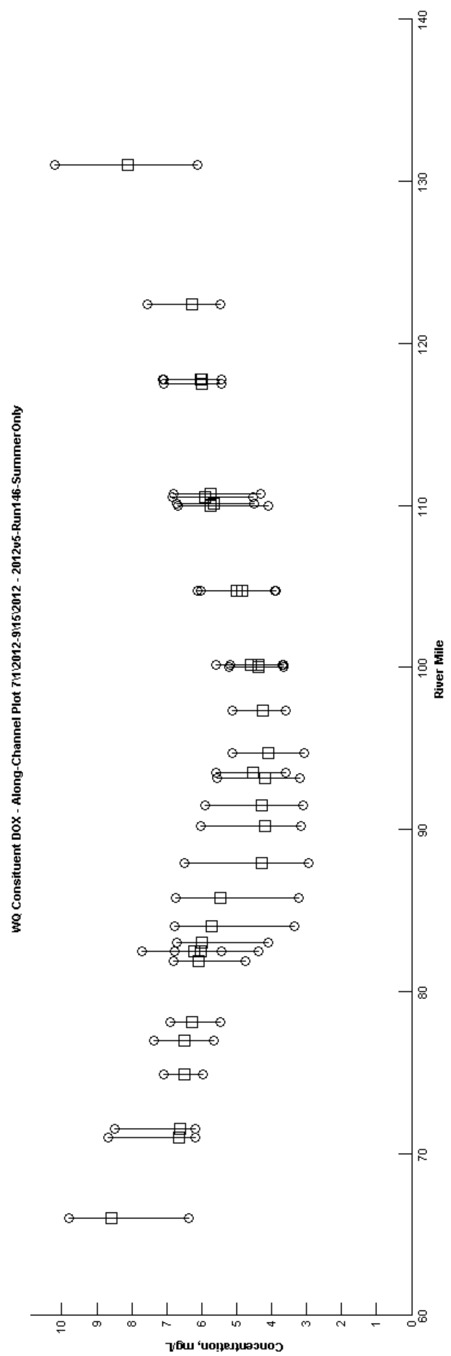

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Baxter in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/12
08/01/12
09/01/12
8
6
4
400
200
0


Modeled DO
Delaware Q
Modeled DO at Station USGS_Delran in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/12
08/01/12
09/01/12
7
6.5
6
5.5
5
4.5
4
350
300
250
200
150
100
50


Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_BF_Bridge in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/12
08/01/12
09/01/12
5.5
5
4.5
4
3.5
400
300
200
100
0

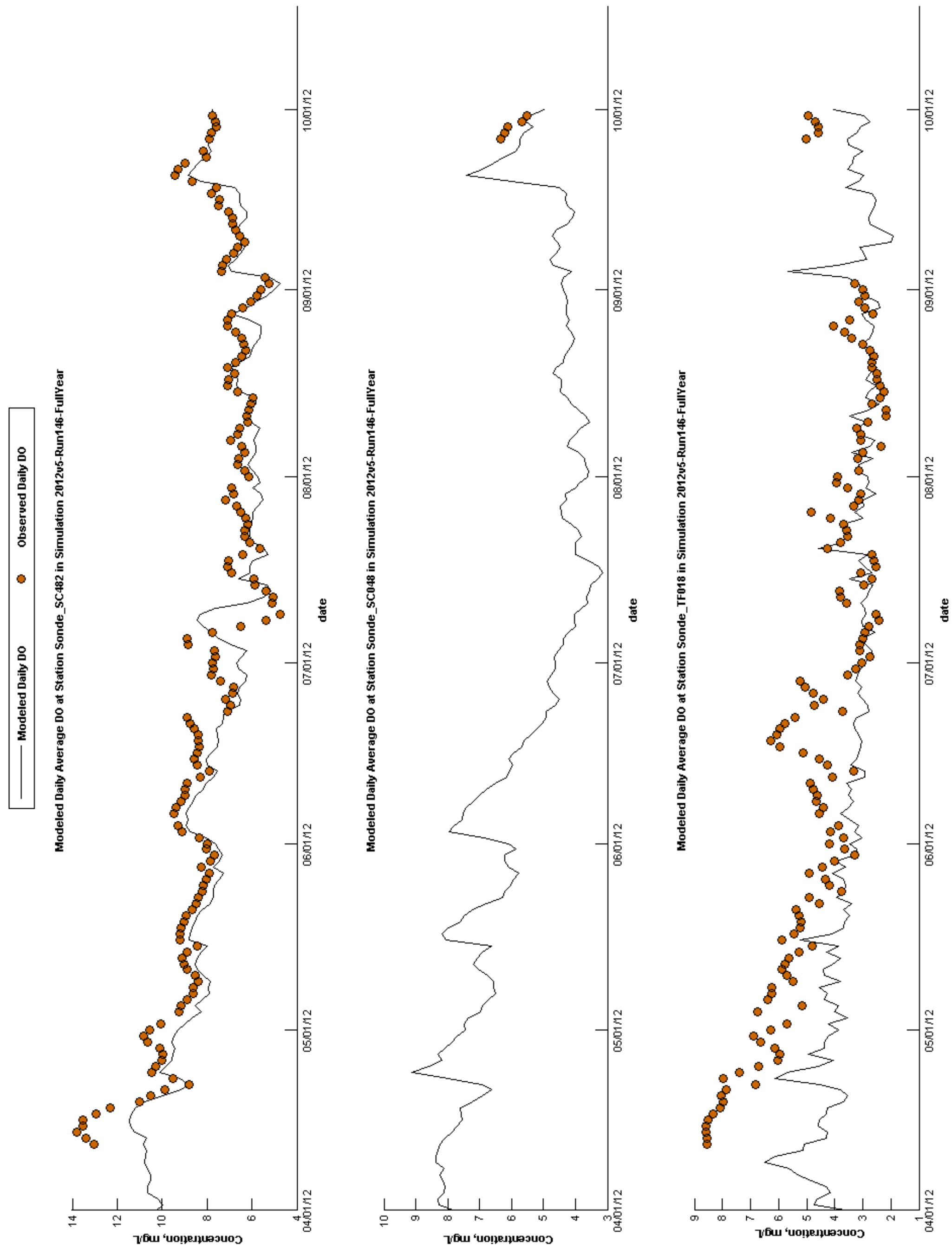


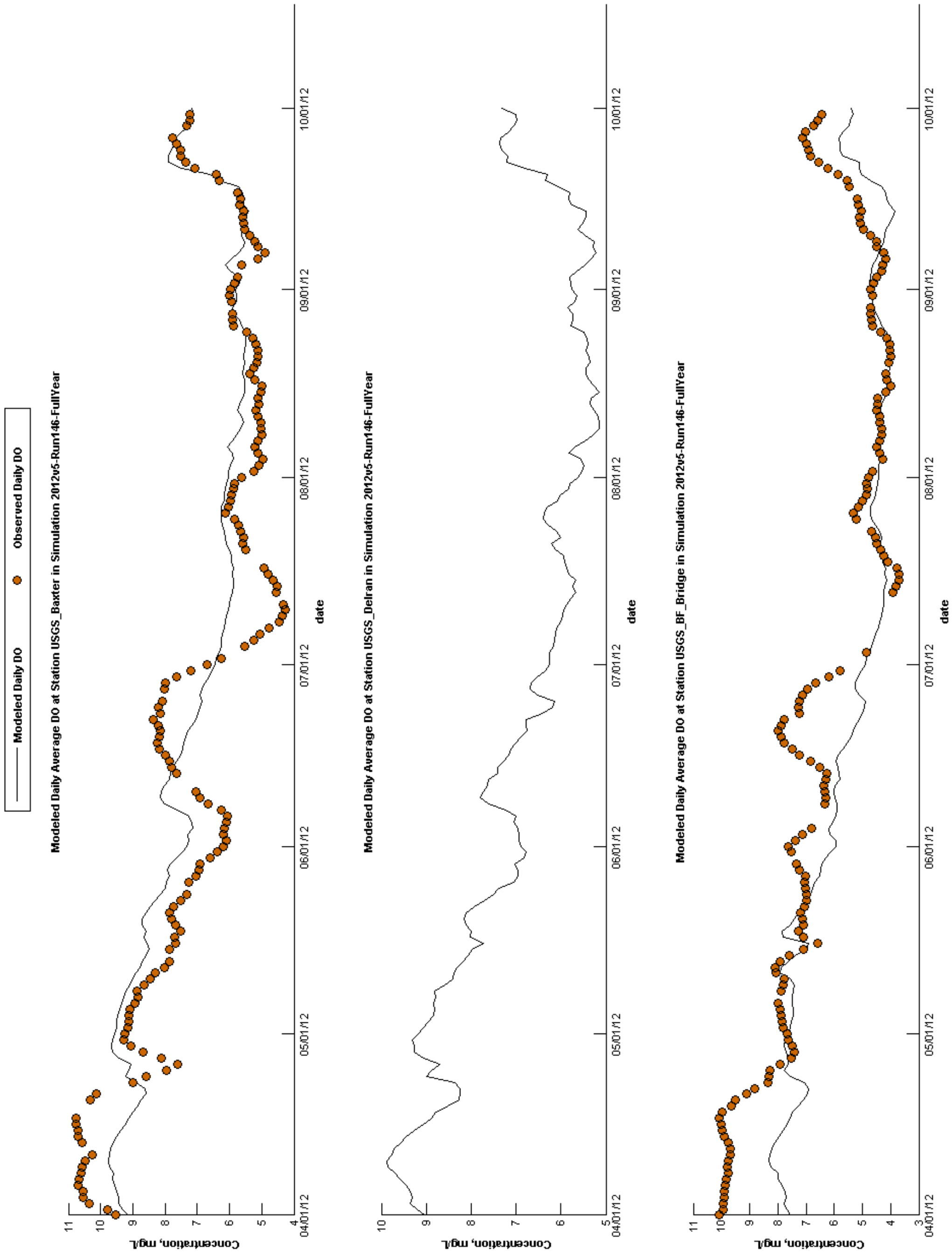
Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Chester in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/12
08/01/12
09/01/12


WQ Consituent DOX - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg/L
60
70
80
90
100
110
120
130
140
0
1
2
3
4
5
6
7
8
9
10

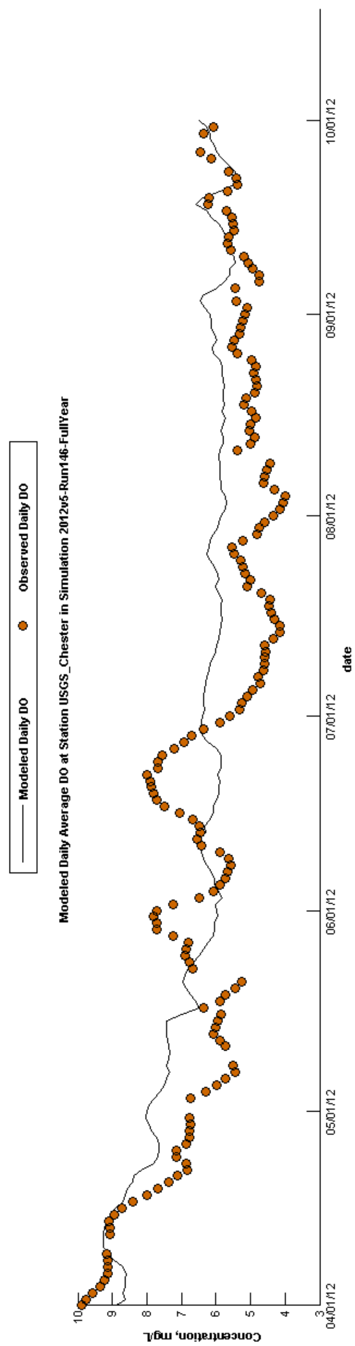
1.4. Daily Average Dissolved Oxygen

1.4.1. April to October

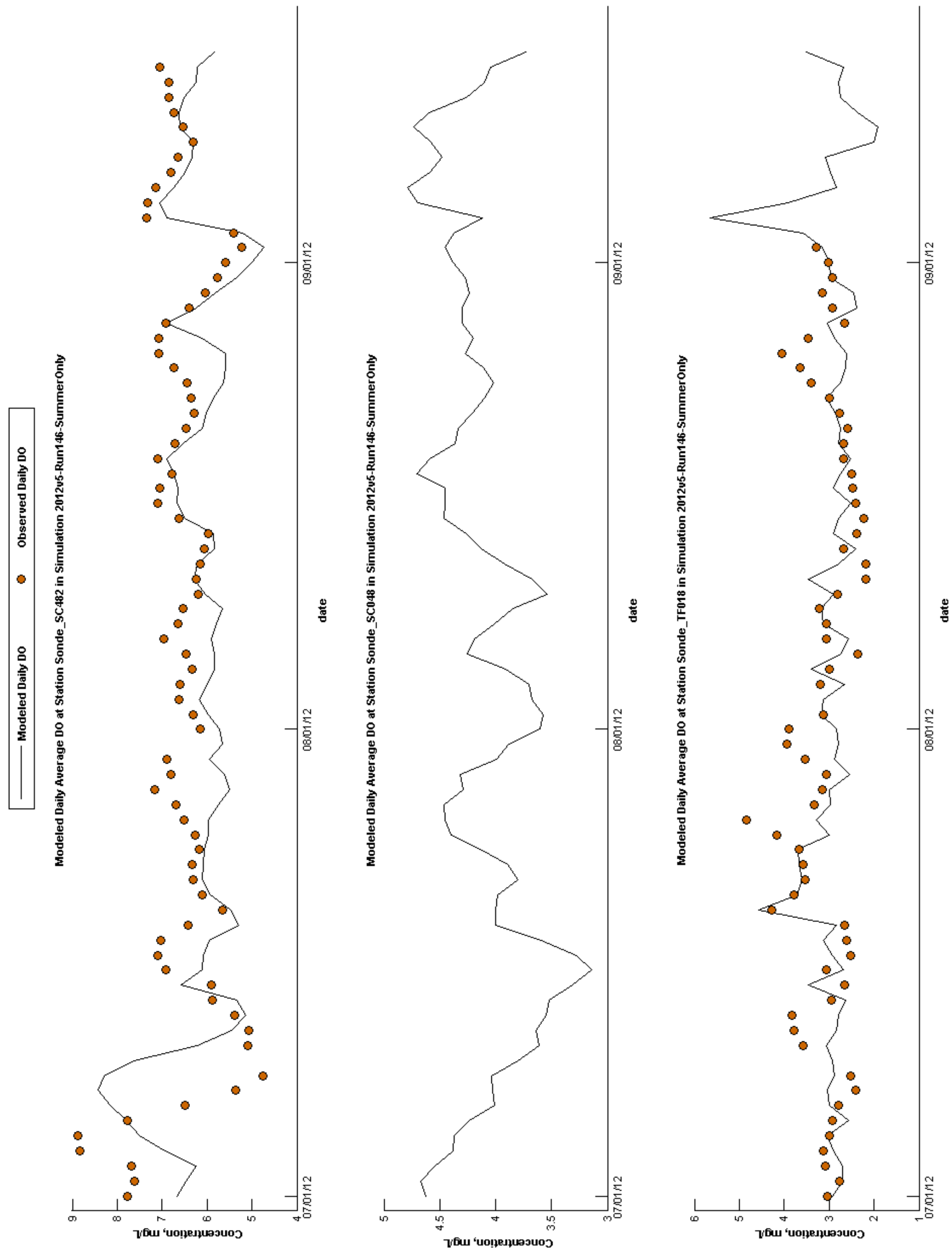


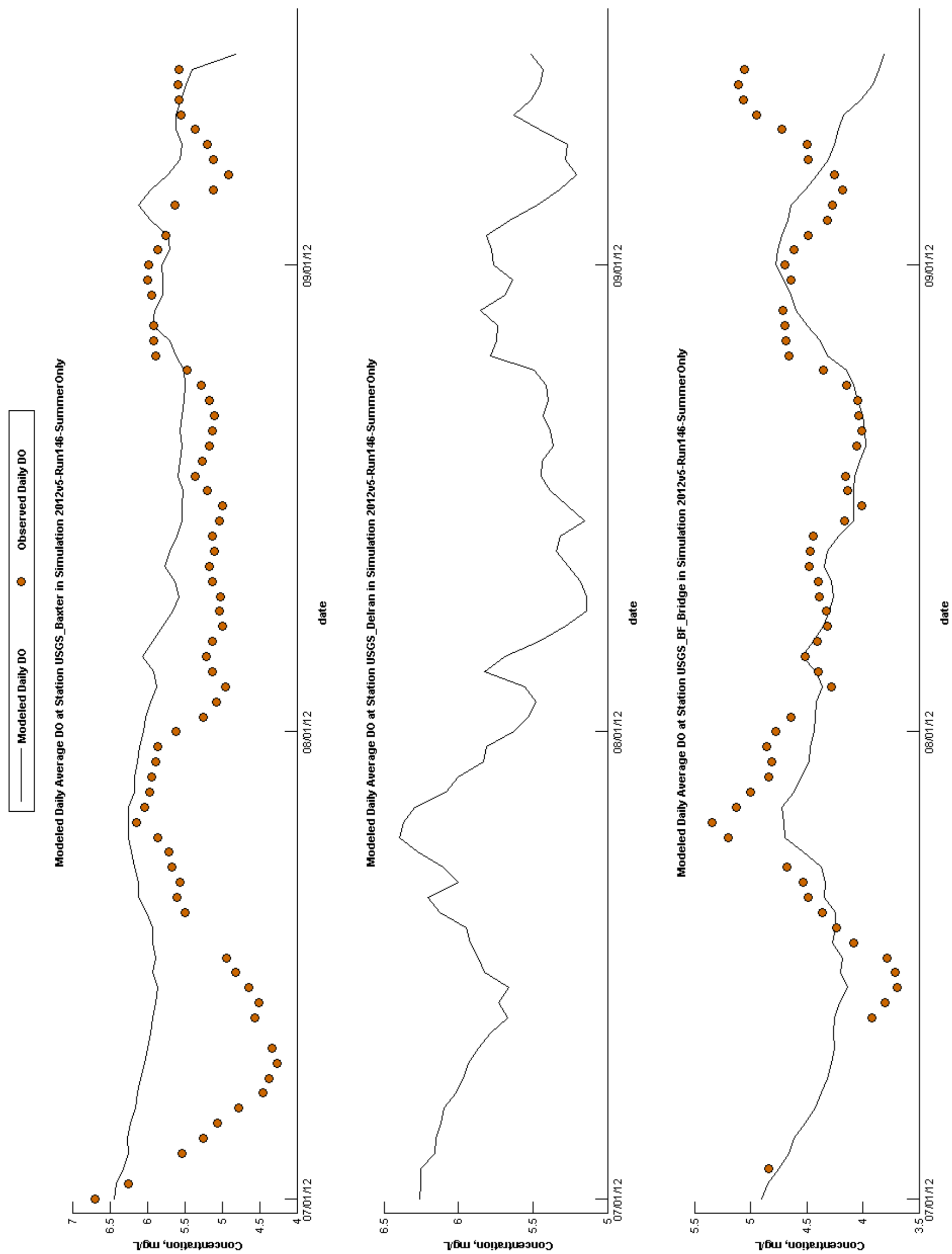


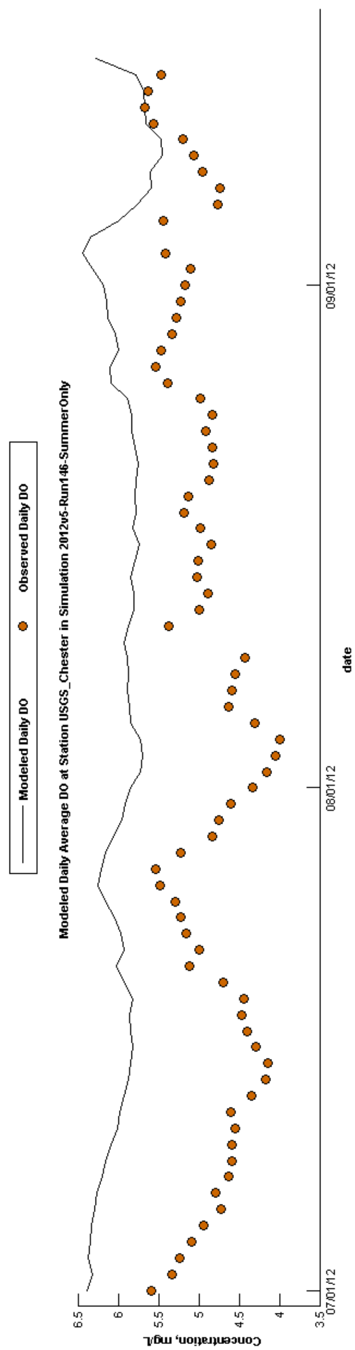
Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station USGS_Baxter in Simulation 2012v5-Run146-FullYear
Modeled Daily Average DO at Station USGS_Delran in Simulation 2012v5-Run146-FullYear
Modeled Daily Average DO at Station USGS_BF_Bridge in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station USGS_Chester in Simulation 2012v5-Run146-FullYear
Concentration, mg/L
10
9
8
7
6
5
4
3
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12
date

1.4.2. Summer

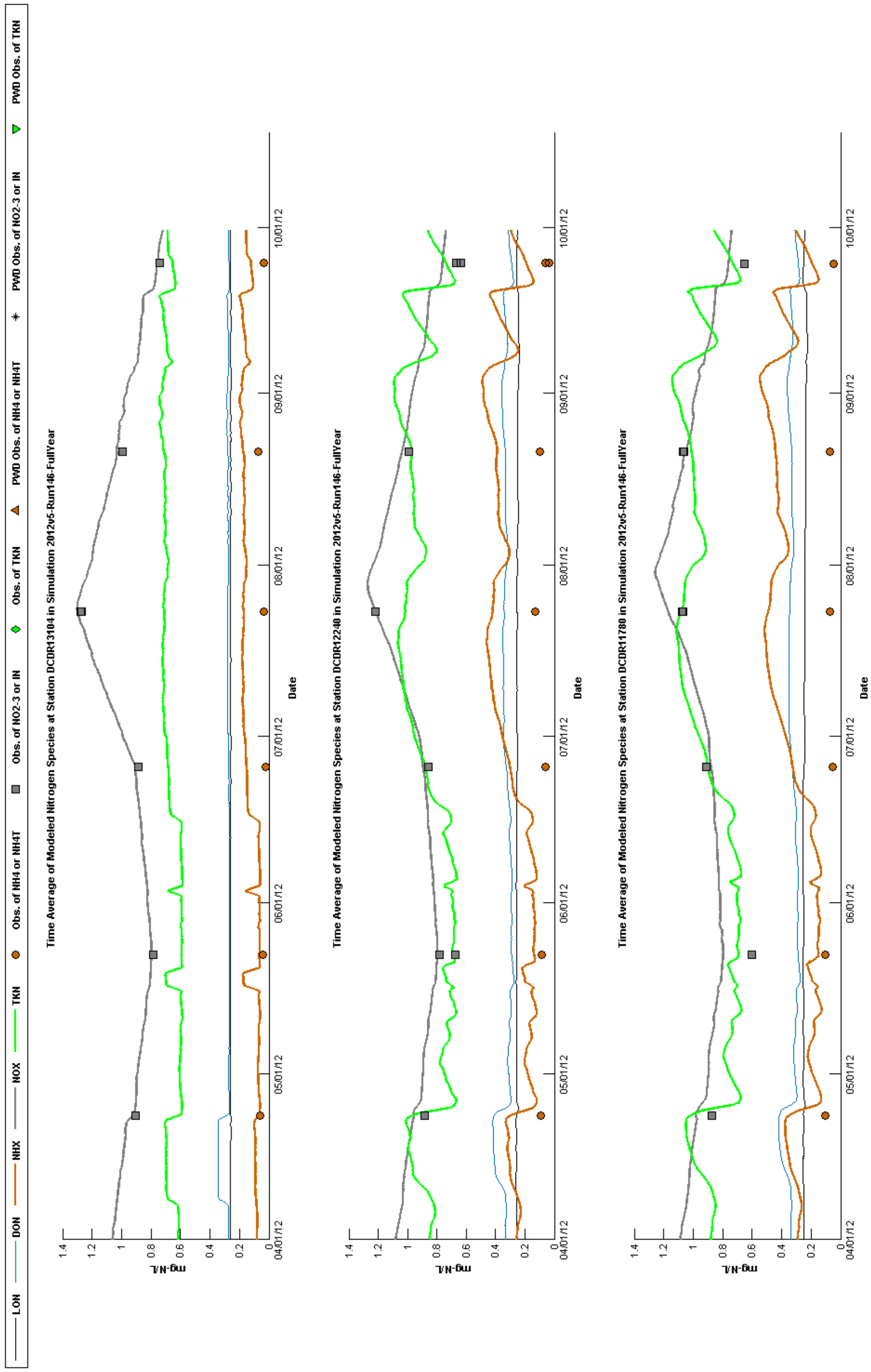

Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station Sonde_SC482 in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/12
08/01/12
09/01/12
Modeled Daily Average DO at Station Sonde_SC048 in Simulation 2012v5-Run146-SummerOnly
Modeled Daily Average DO at Station Sonde_TF018 in Simulation 2012v5-Run146-SummerOnly

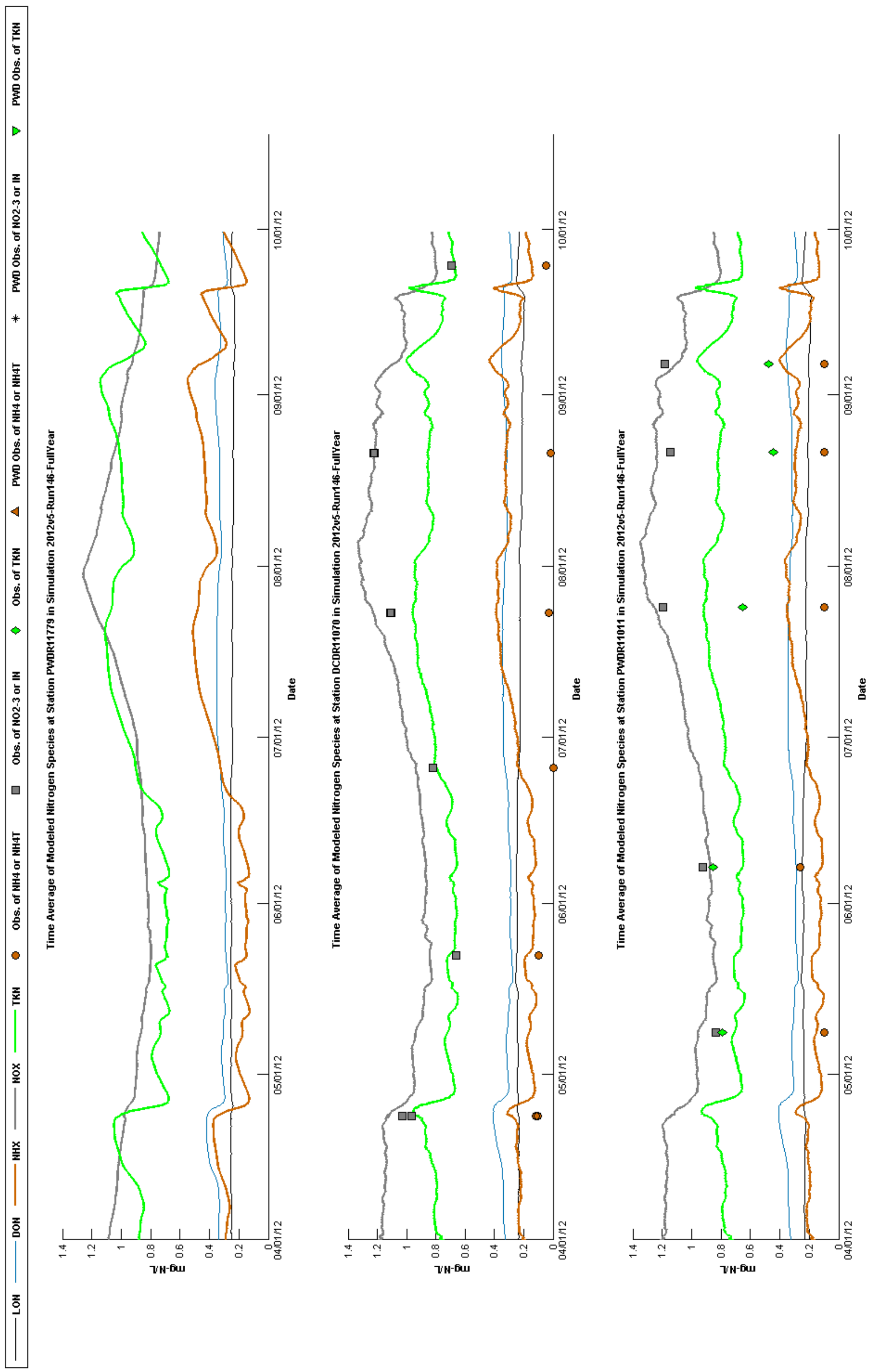

Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station USGS_Baxter in Simulation 2012v5-Run146-SummerOnly
Modeled Daily Average DO at Station USGS_Delran in Simulation 2012v5-Run146-SummerOnly
Modeled Daily Average DO at Station USGS_BF_Bridge in Simulation 2012v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/12
08/01/12
09/01/12

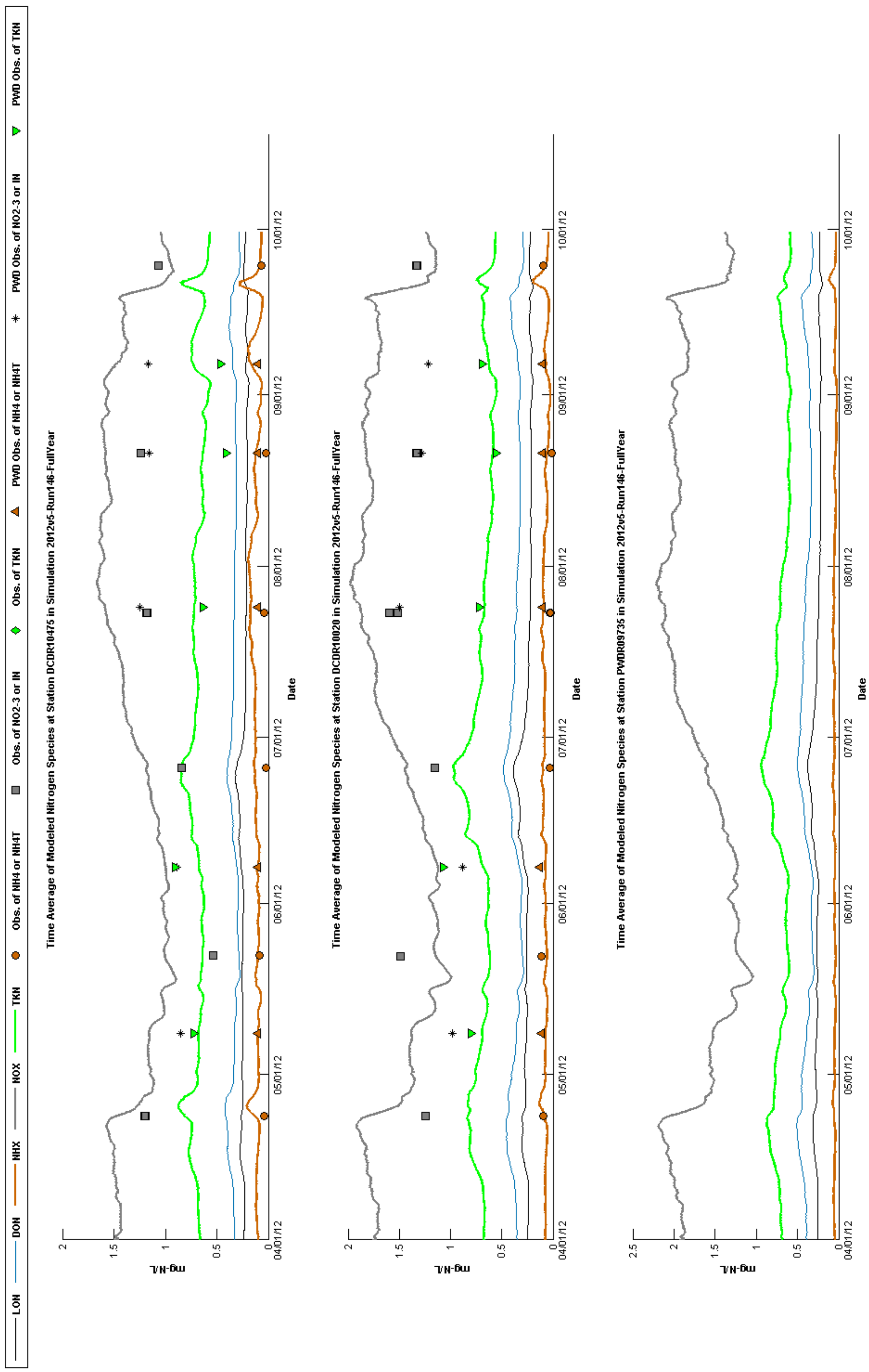

Modeled Daily Average DO at Station USGS_Chester in Simulation 2012v5-Run146-SummerOnly
Modeled Daily DO
Observed Daily DO
Concentration, mg/L
6.5
6
5.5
5
4.5
4
3.5
07/01/12
08/01/12
09/01/12
date

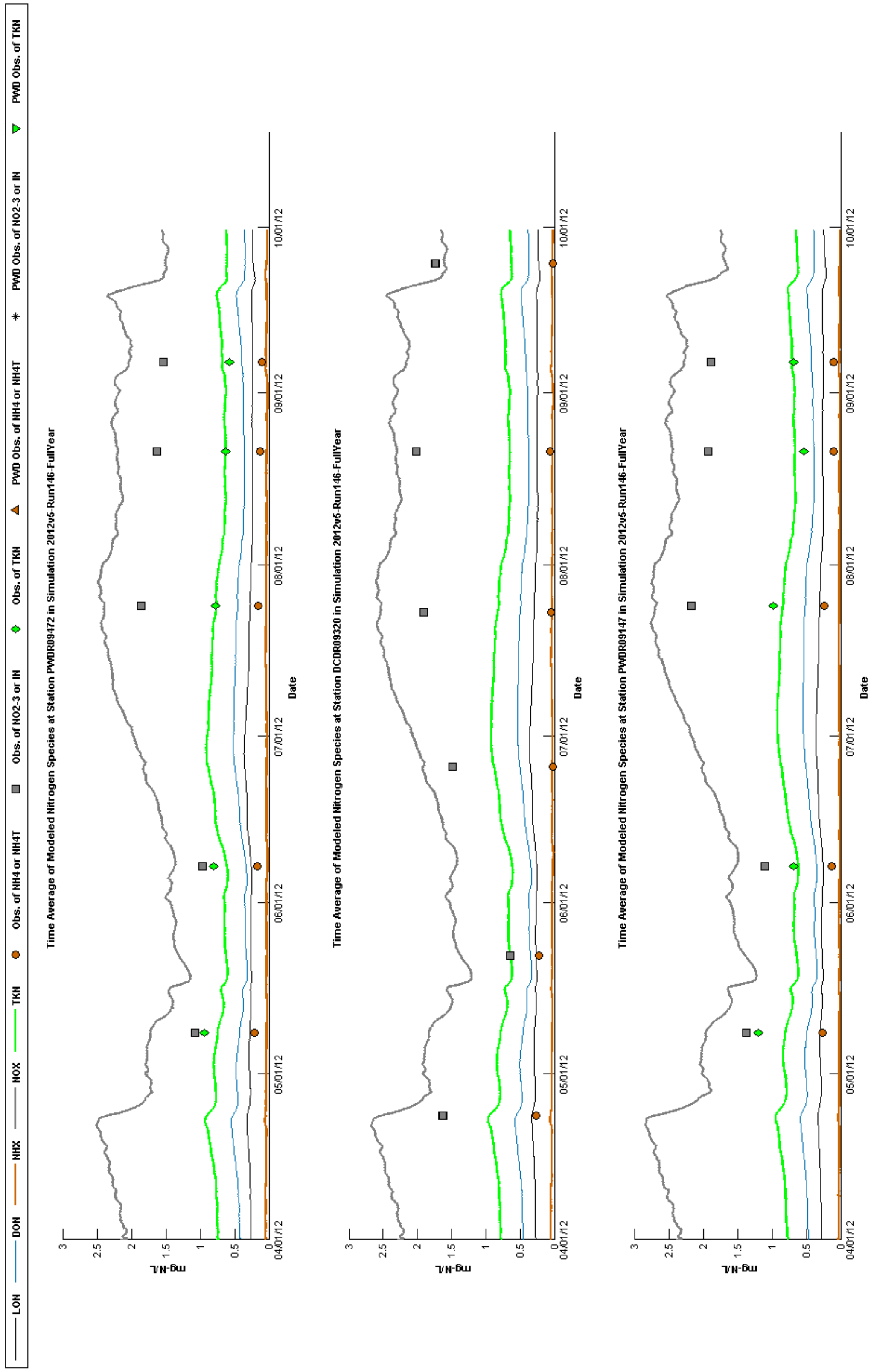
1.5. Nitrogen Species

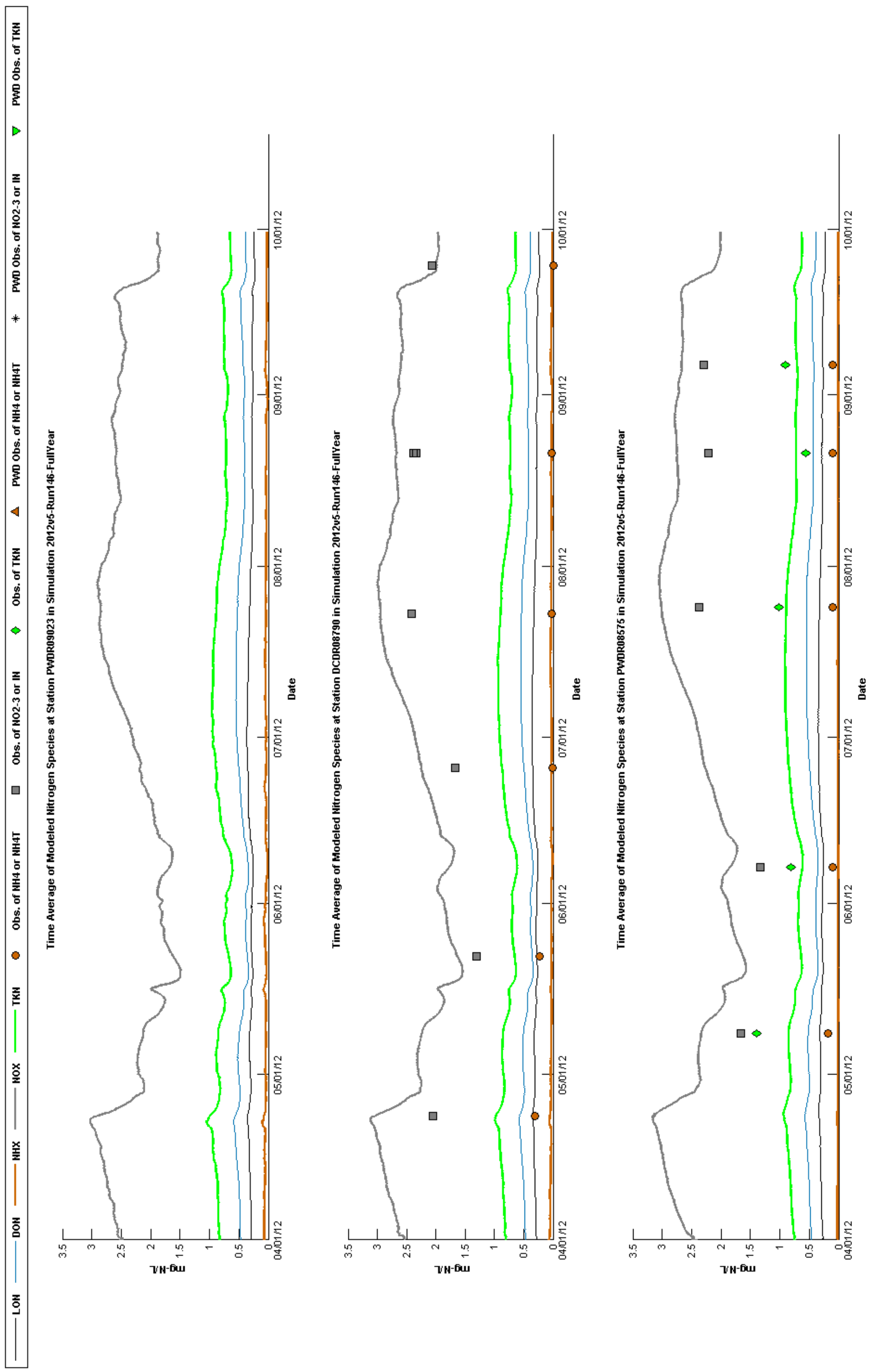
1.5.1. April to October

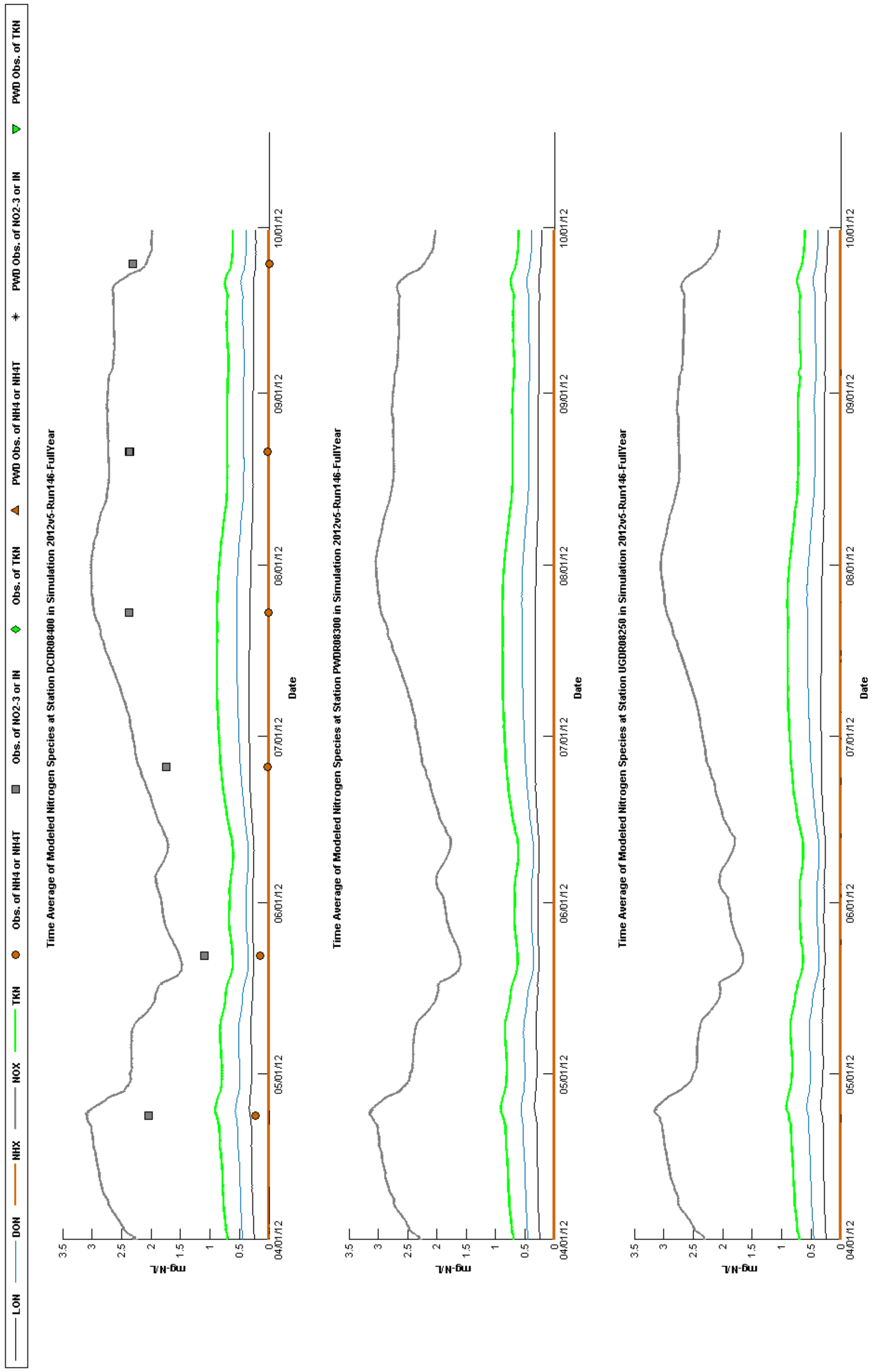


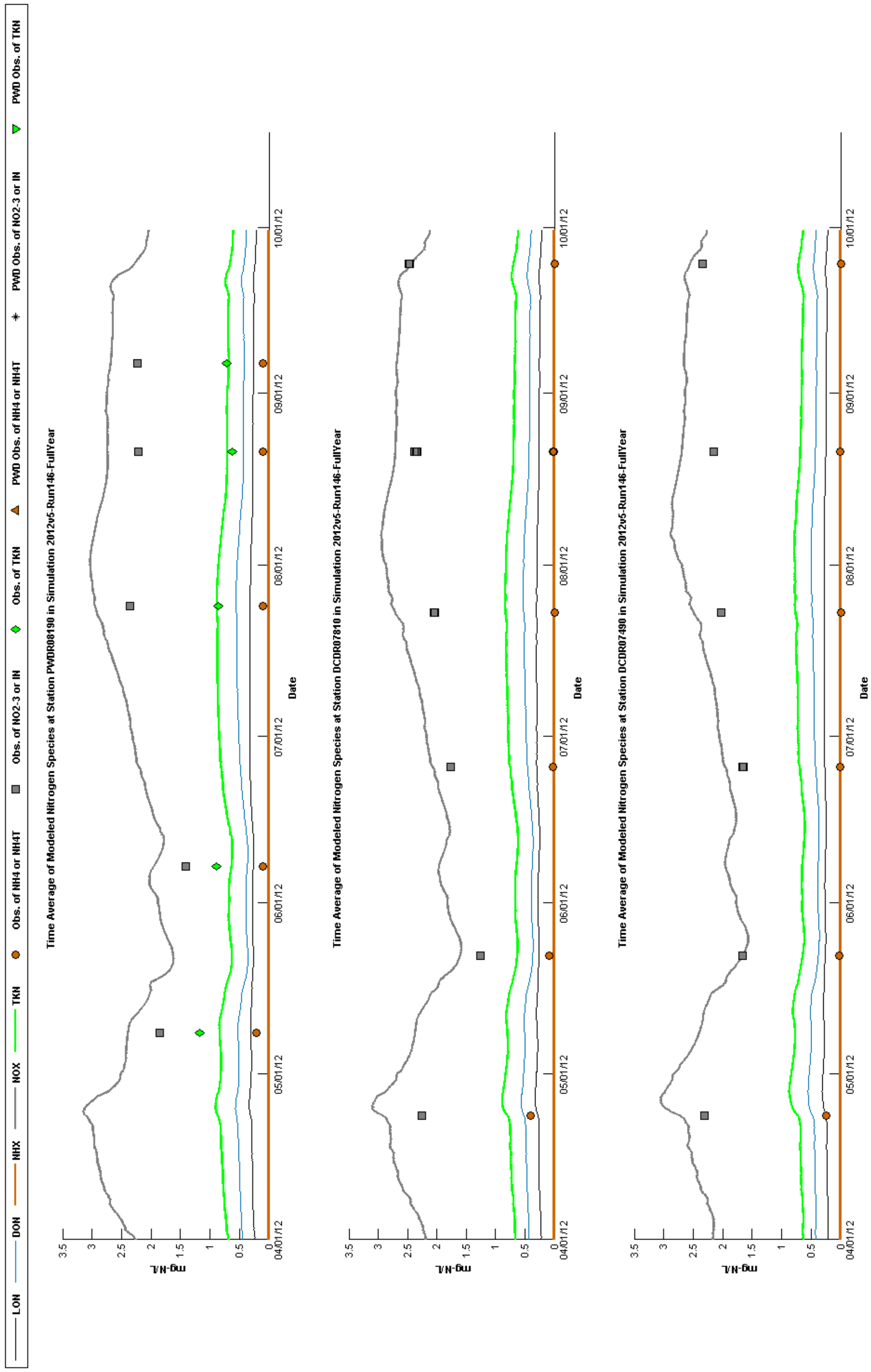

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR11779 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR11070 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR11011 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

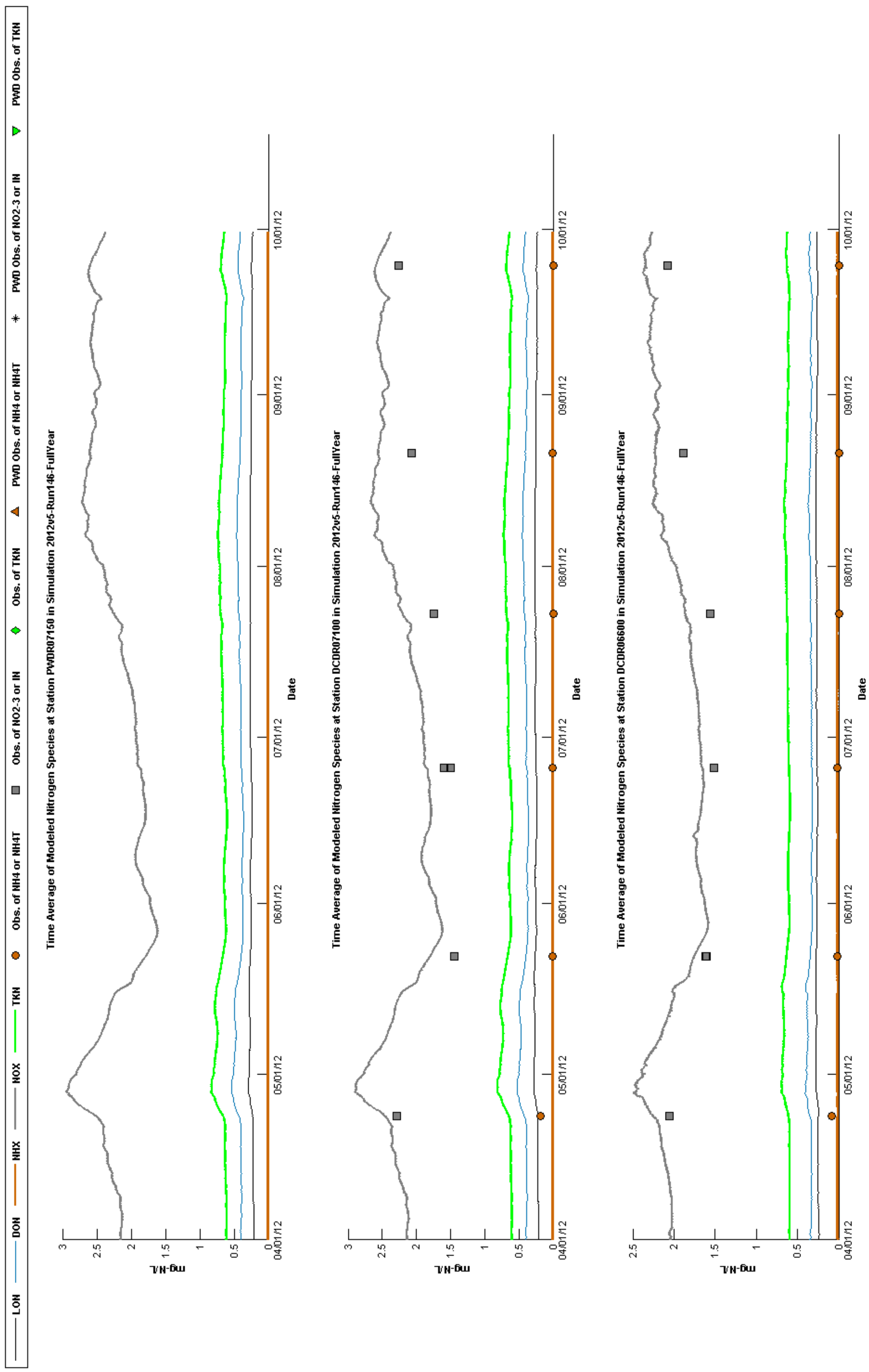

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR10475 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR10020 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR09735 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09472 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR09320 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR09147 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

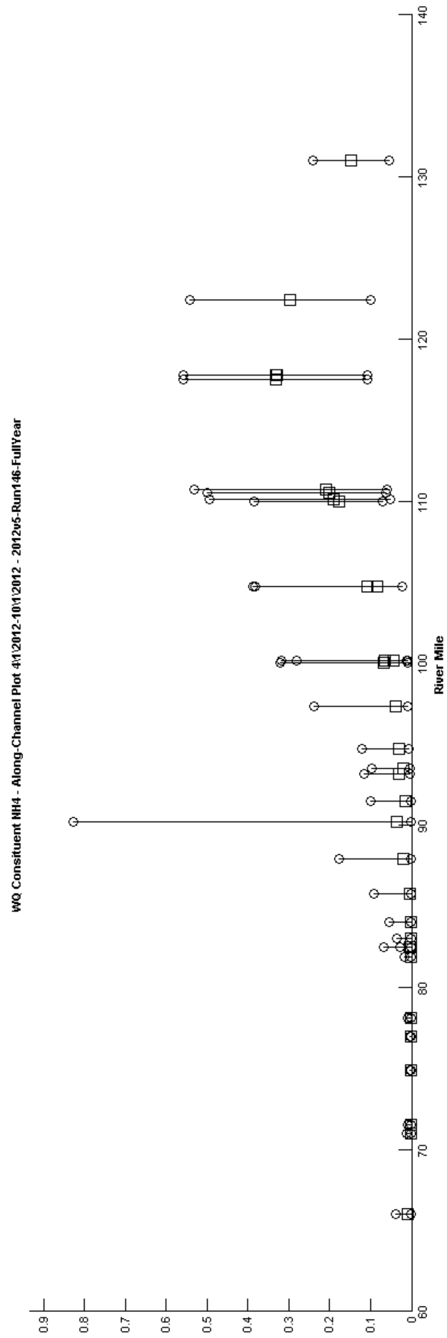

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09023 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR08790 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR08575 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR08400 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR08300 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station UCDR08250 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date

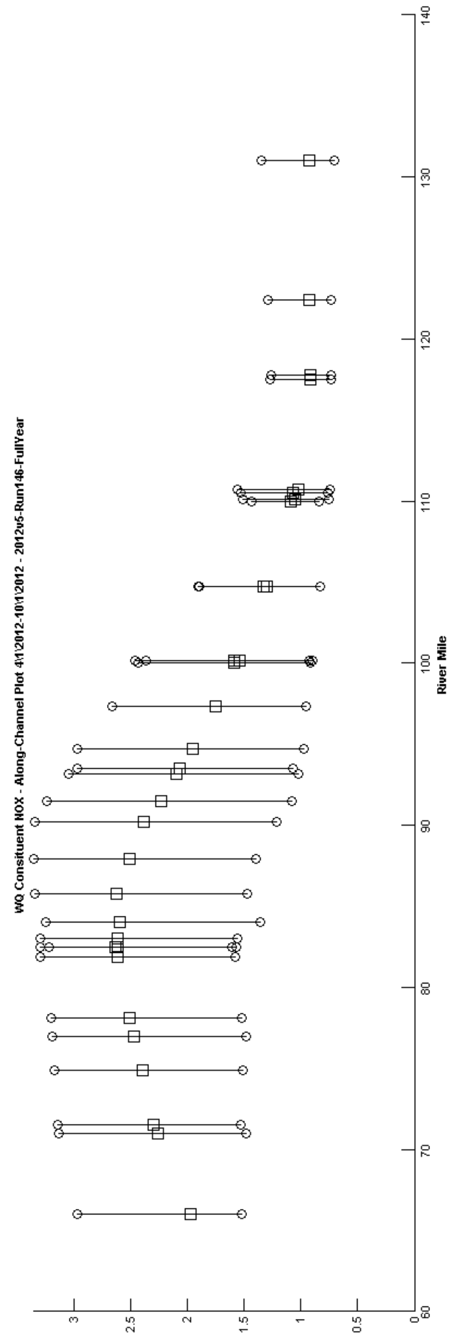

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR08190 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07810 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07490 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12
0
0.5
1
1.5
2
2.5
3
3.5



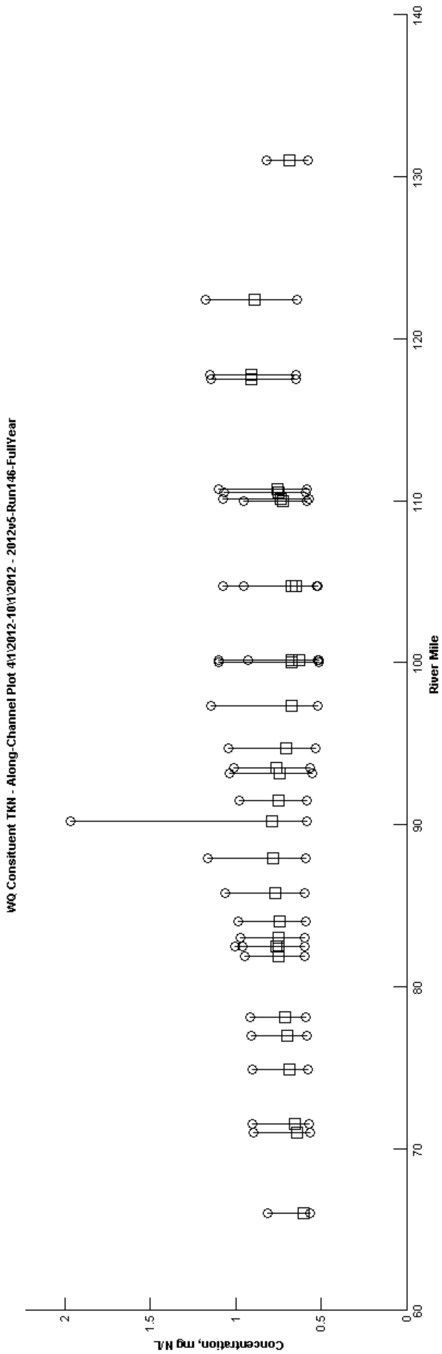
LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR07150 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07100 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR06600 in Simulation 2012v5-Run146-FullYear
mg-N/L
Date

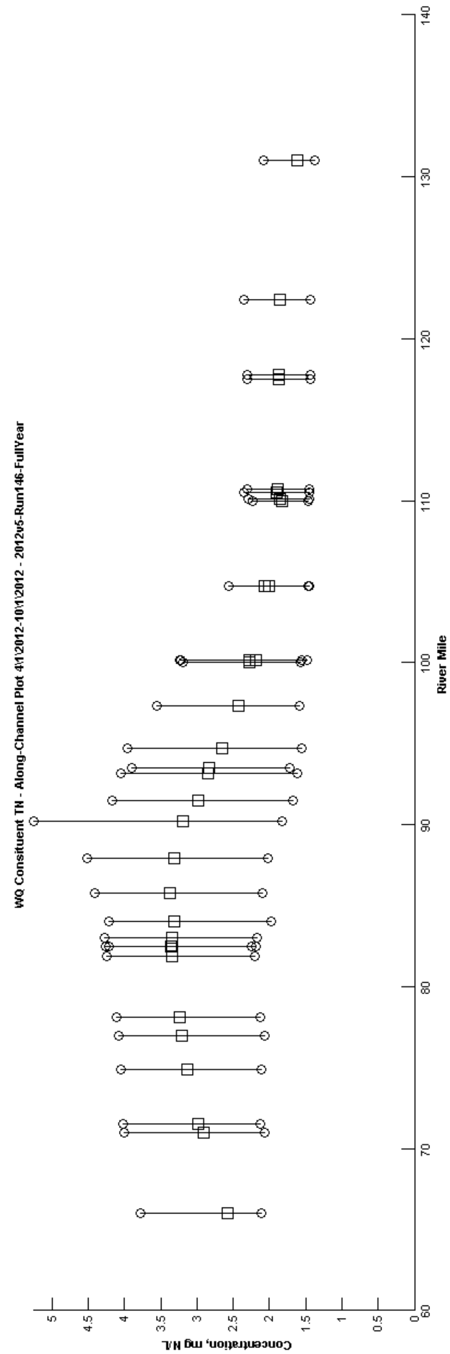


WQ Consituent NH4 - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg N/L
River Mile

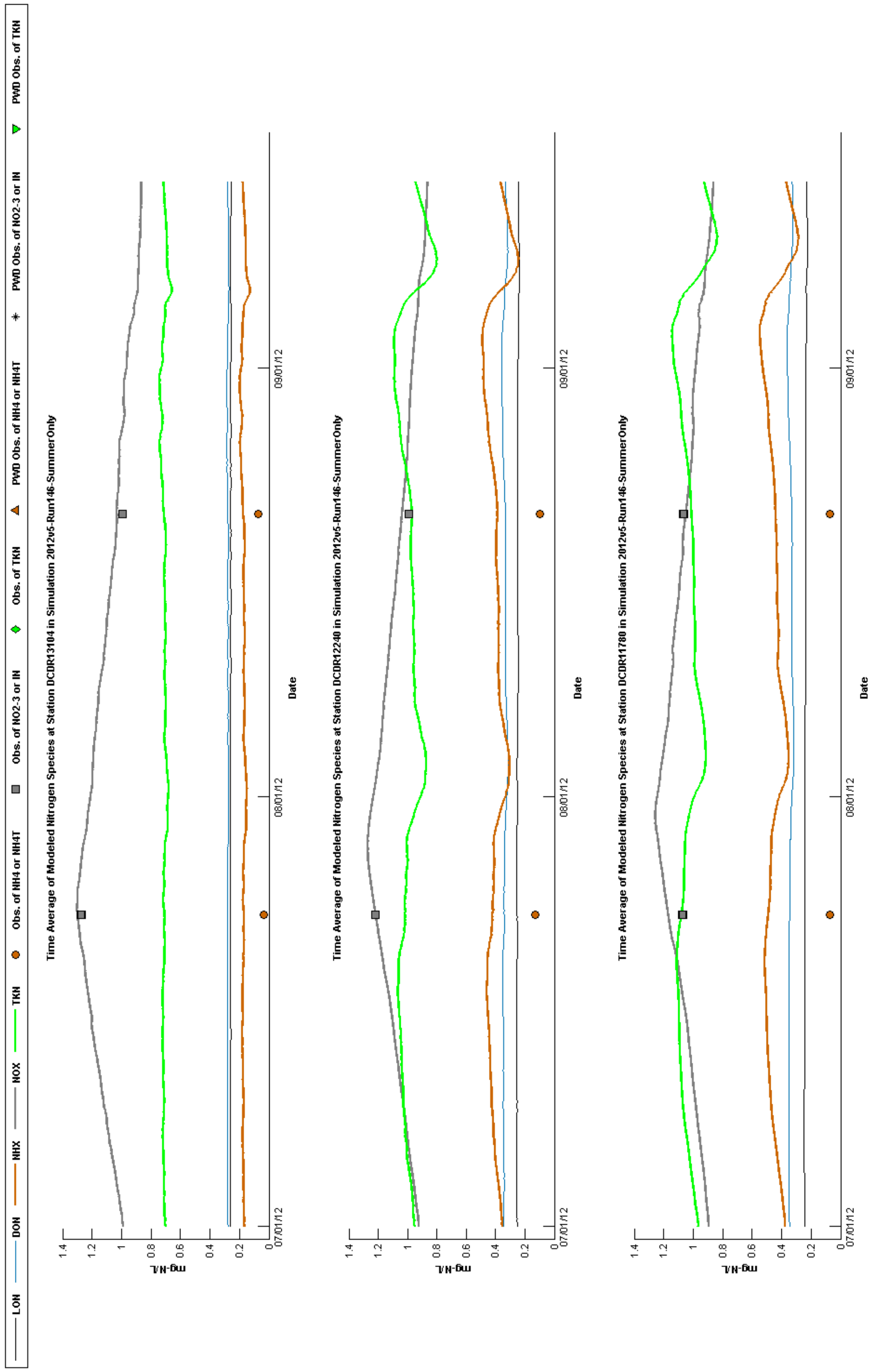


WQ Consituent NOX - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg N/L
River Mile

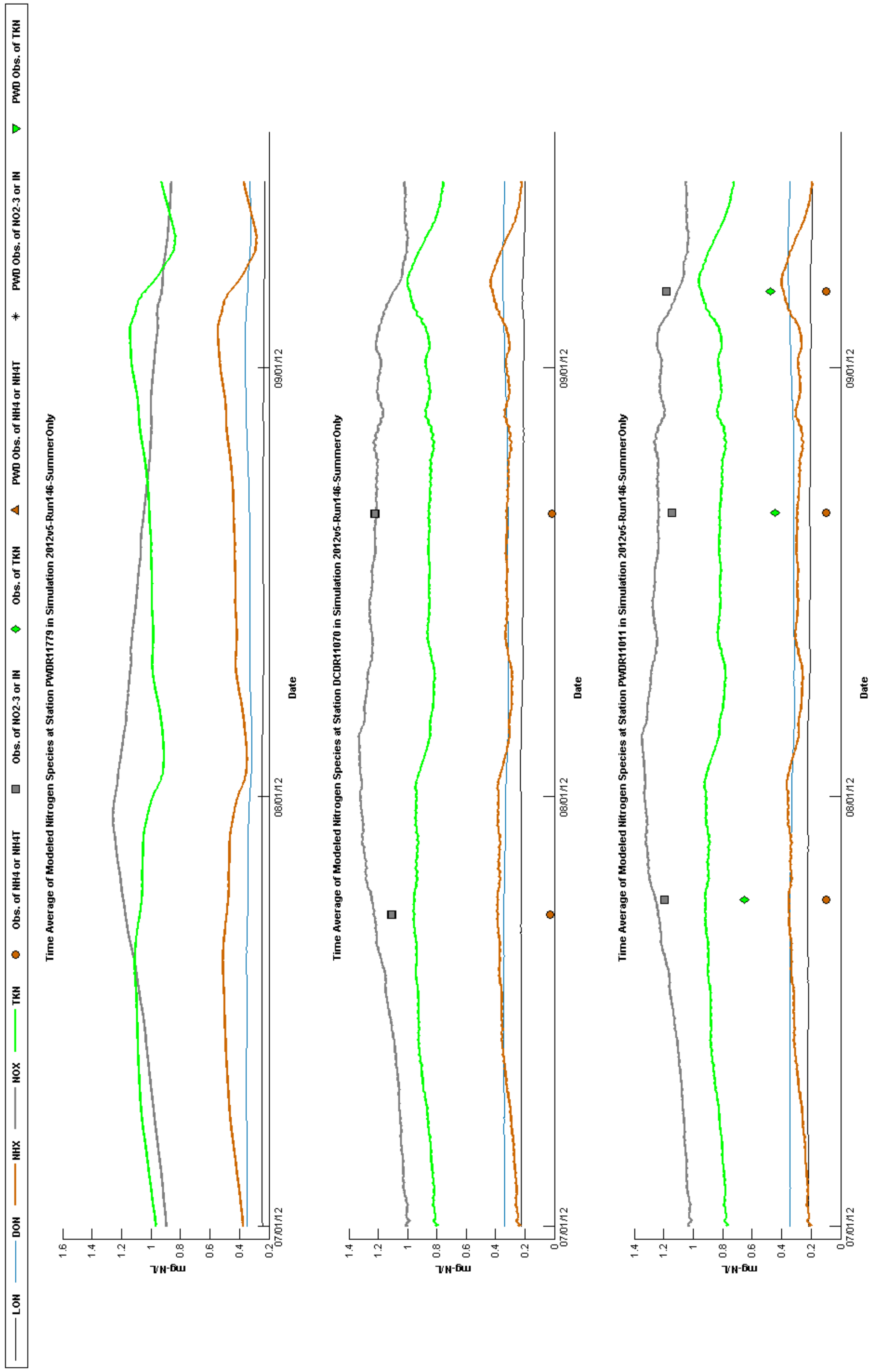

WQ Consituent TKN - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg N/L
River Mile


WQ Consituent TN - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg N/L
River Mile

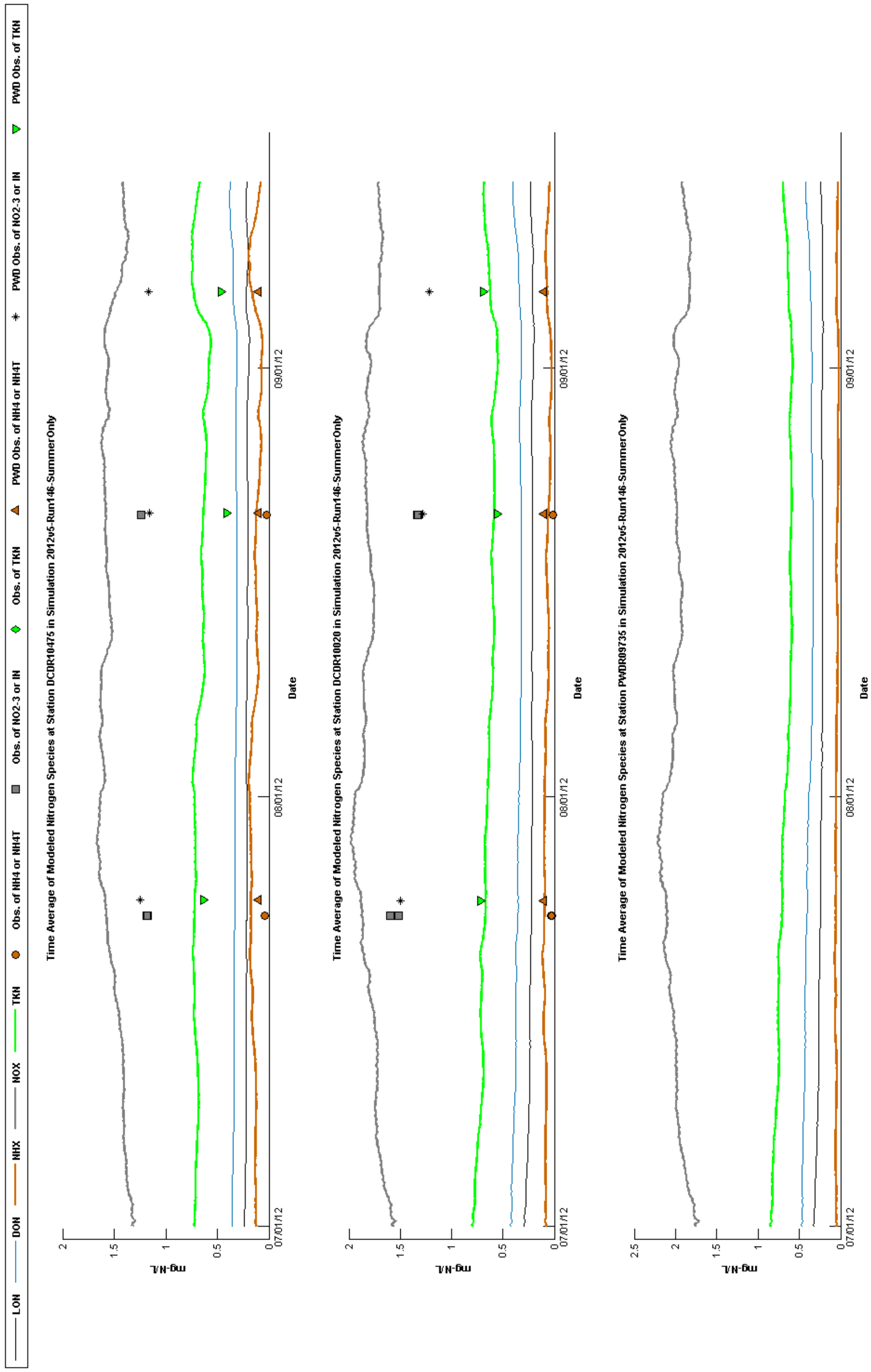
1.5.2. Summer

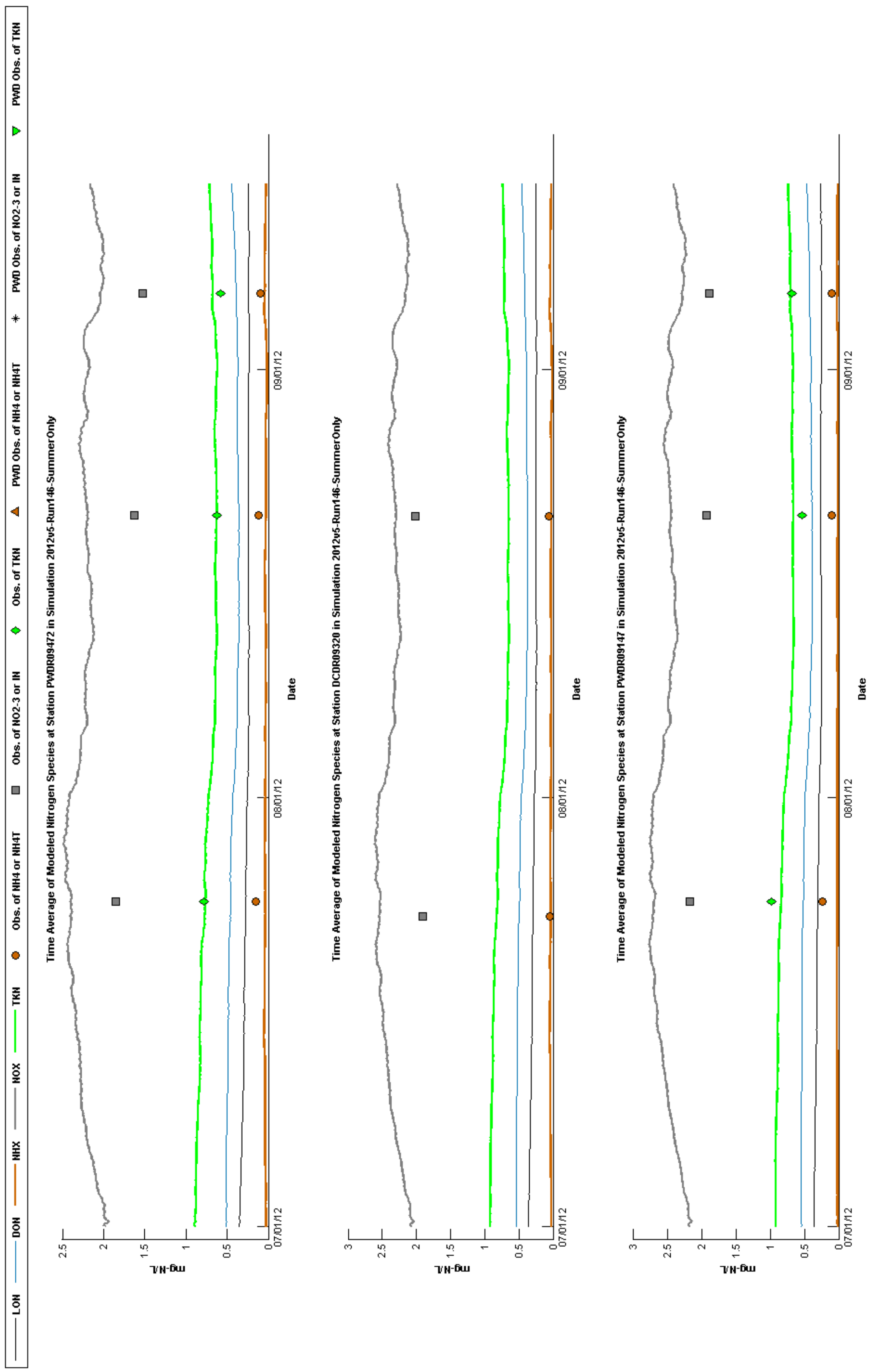


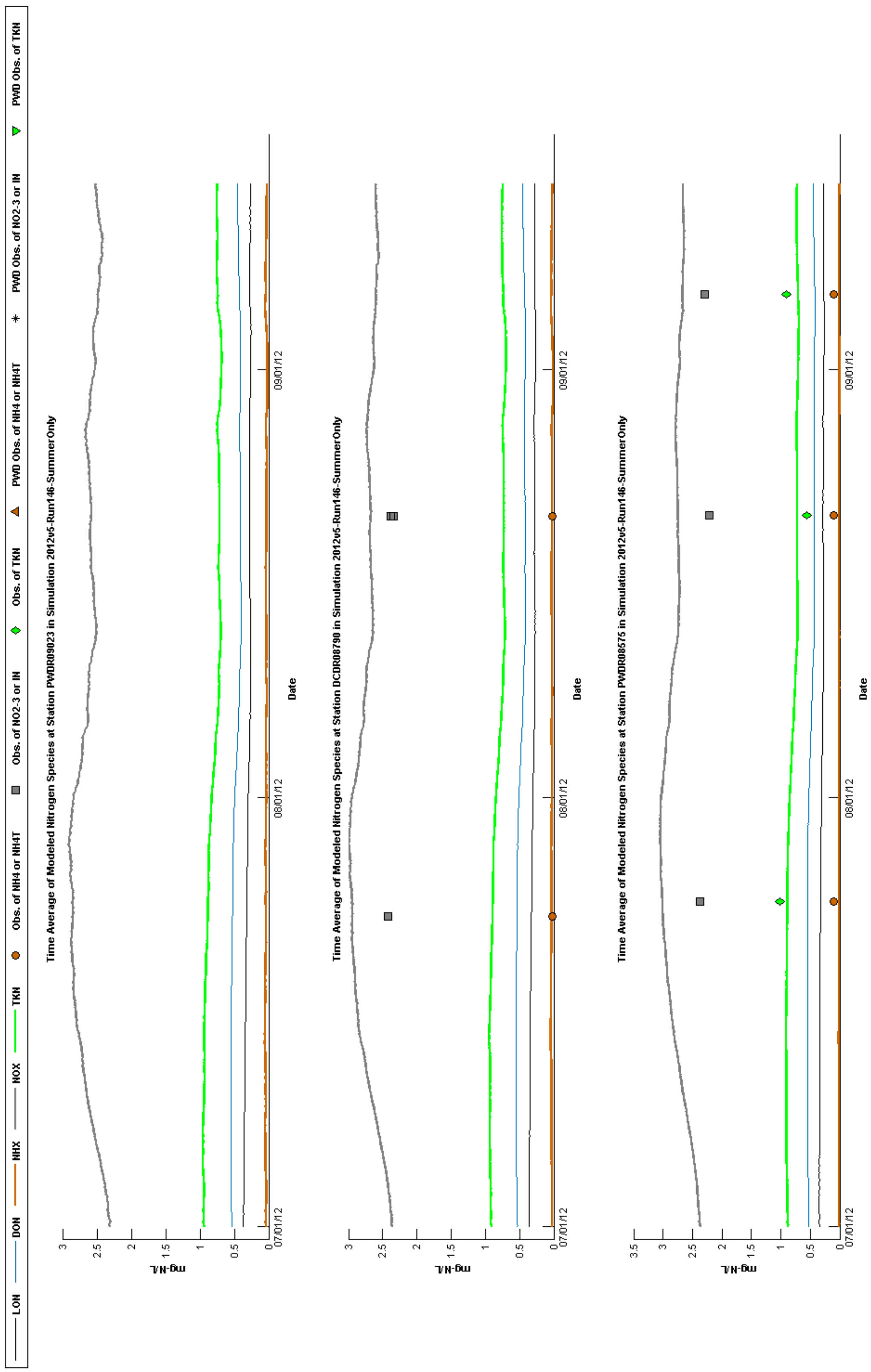
LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR13104 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR12240 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR11780 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12

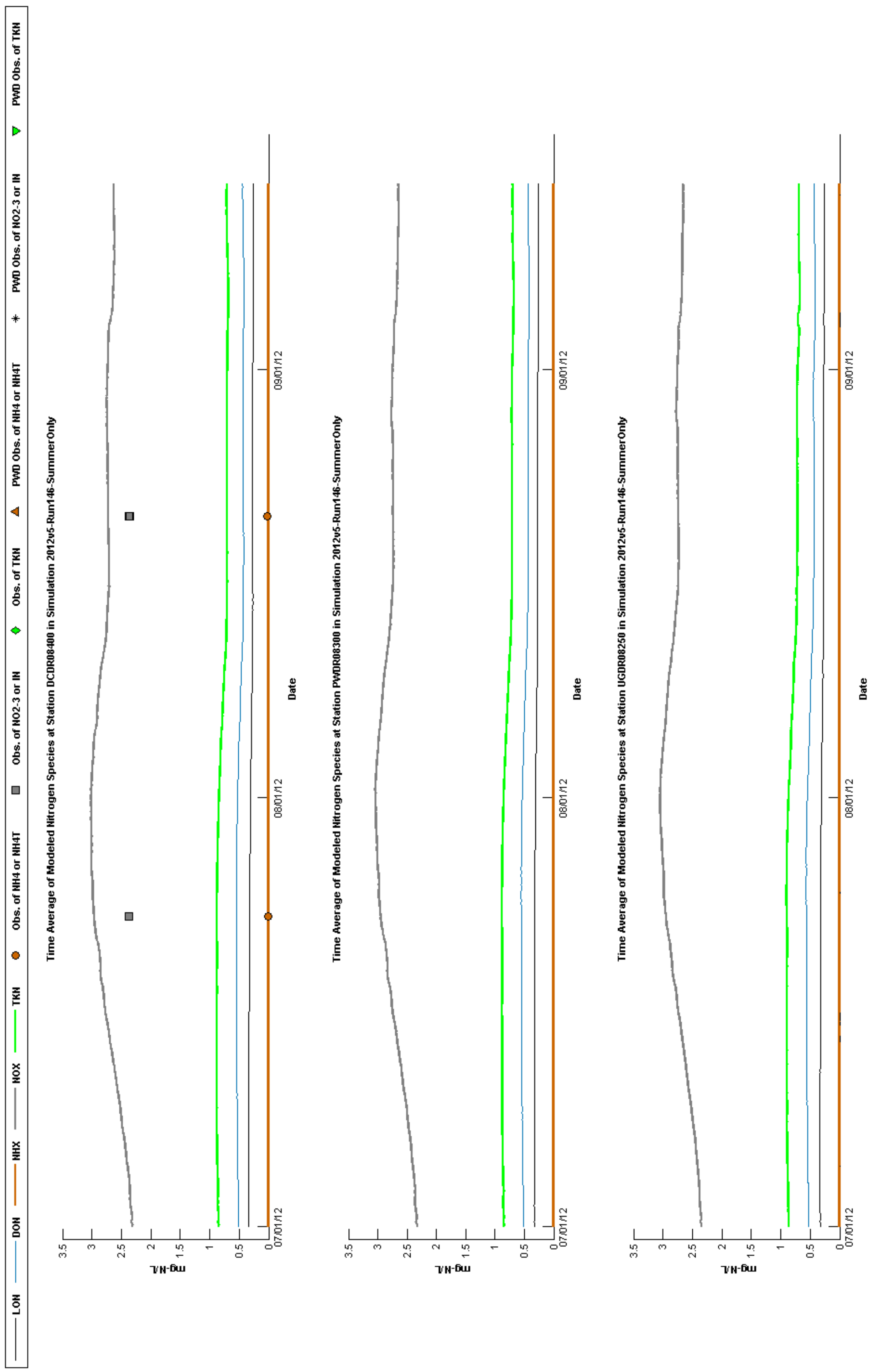


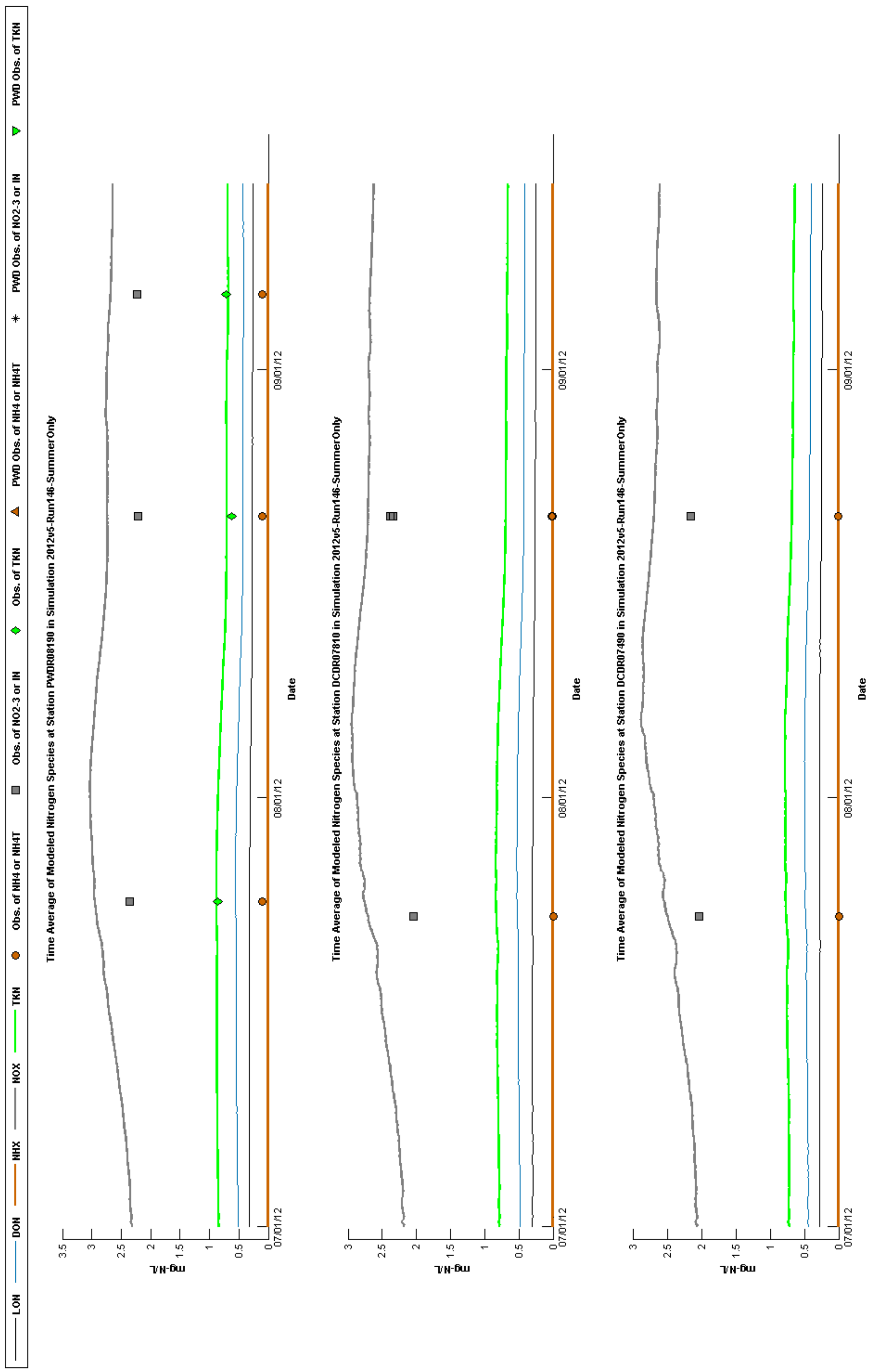
LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR11779 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Nitrogen Species at Station DCDR11070 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Nitrogen Species at Station PWDR11011 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12

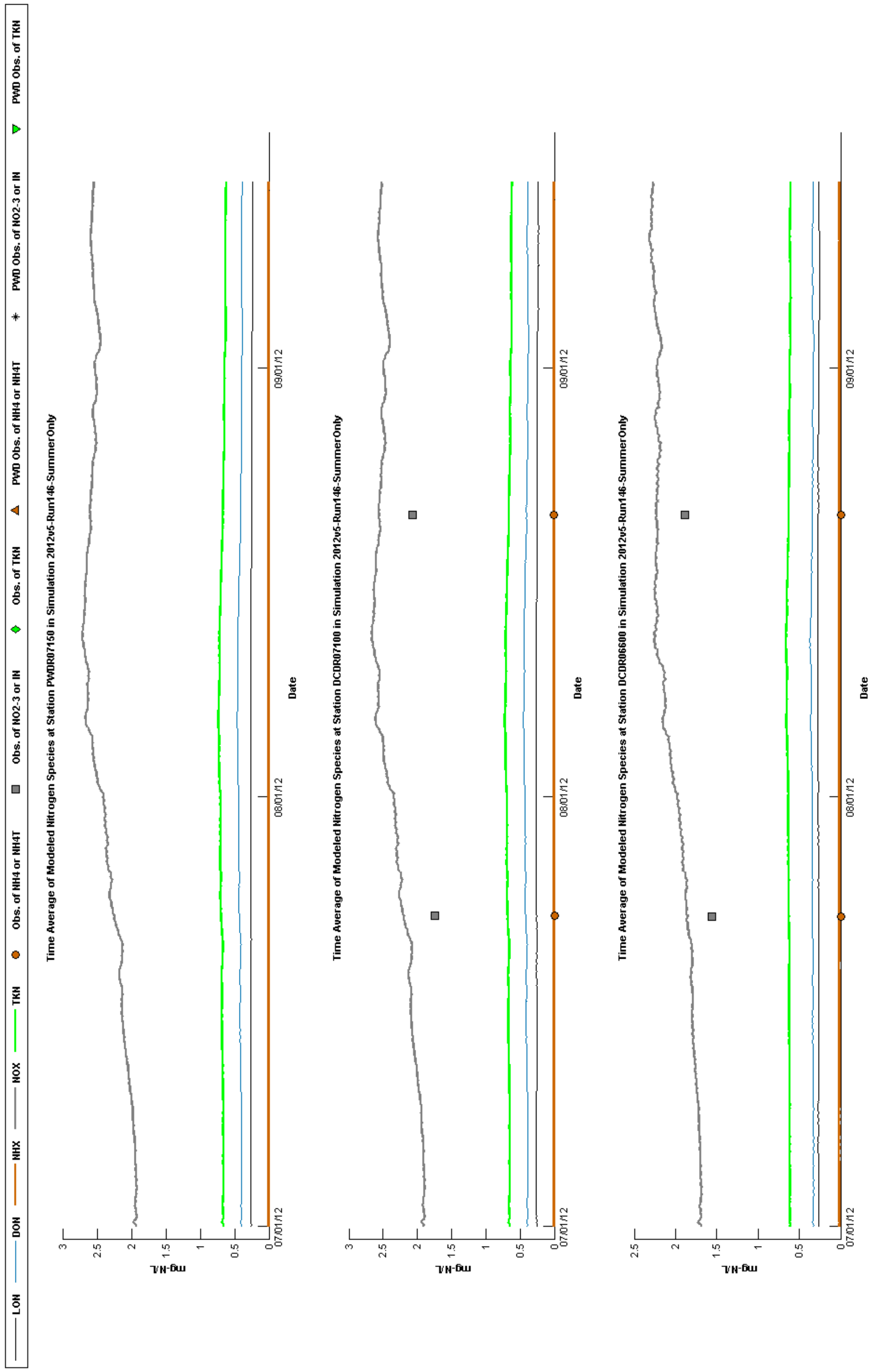

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR10475 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Nitrogen Species at Station DCDR10020 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Nitrogen Species at Station PWDR09735 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12

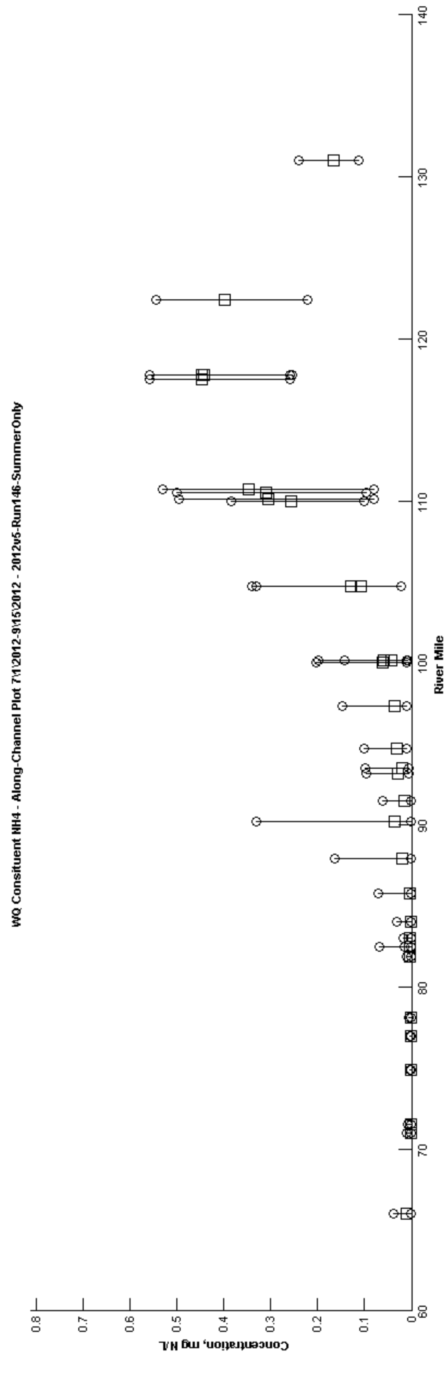

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09472 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR09320 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR09147 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12

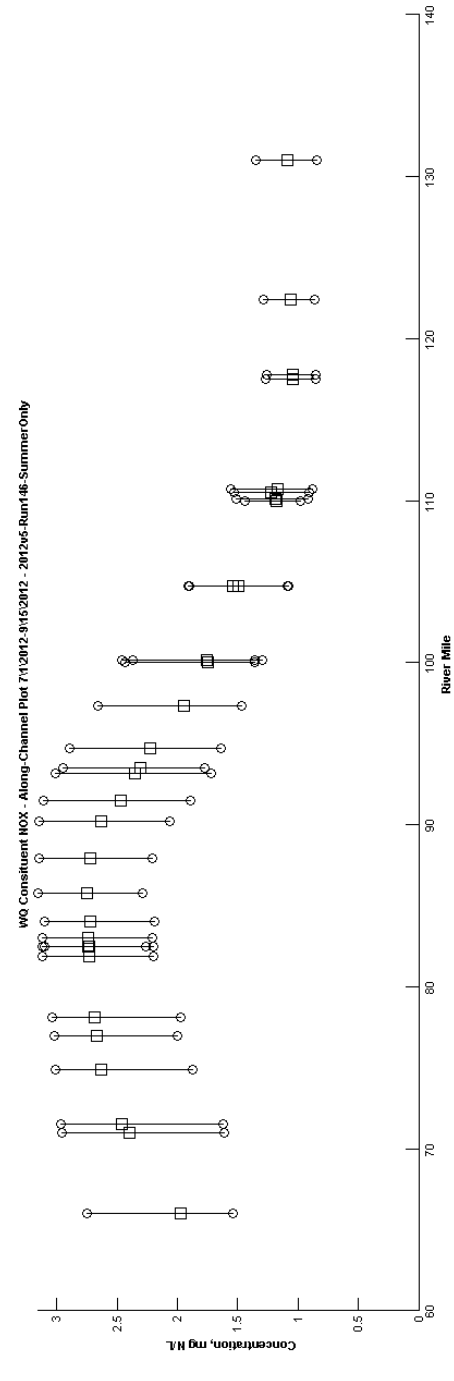

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09023 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR08790 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR08575 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12

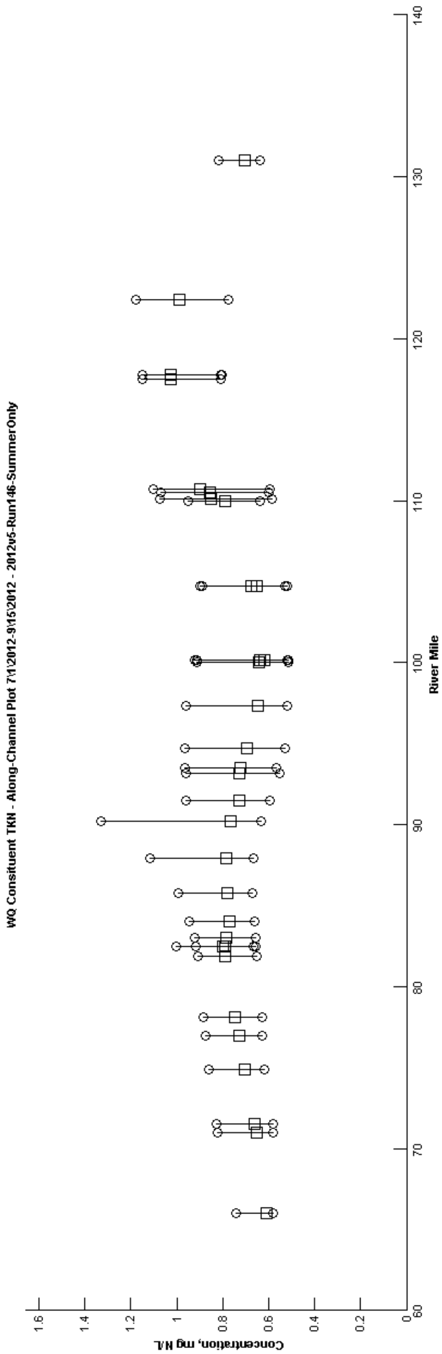

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR08400 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
3.5
3
2.5
2
1.5
1
0.5
0
07/01/12
08/01/12
09/01/12
Date
Time Average of Modeled Nitrogen Species at Station PWDR08300 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
3.5
3
2.5
2
1.5
1
0.5
0
07/01/12
08/01/12
09/01/12
Date
Time Average of Modeled Nitrogen Species at Station UGDR08250 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
3.5
3
2.5
2
1.5
1
0.5
0
07/01/12
08/01/12
09/01/12
Date

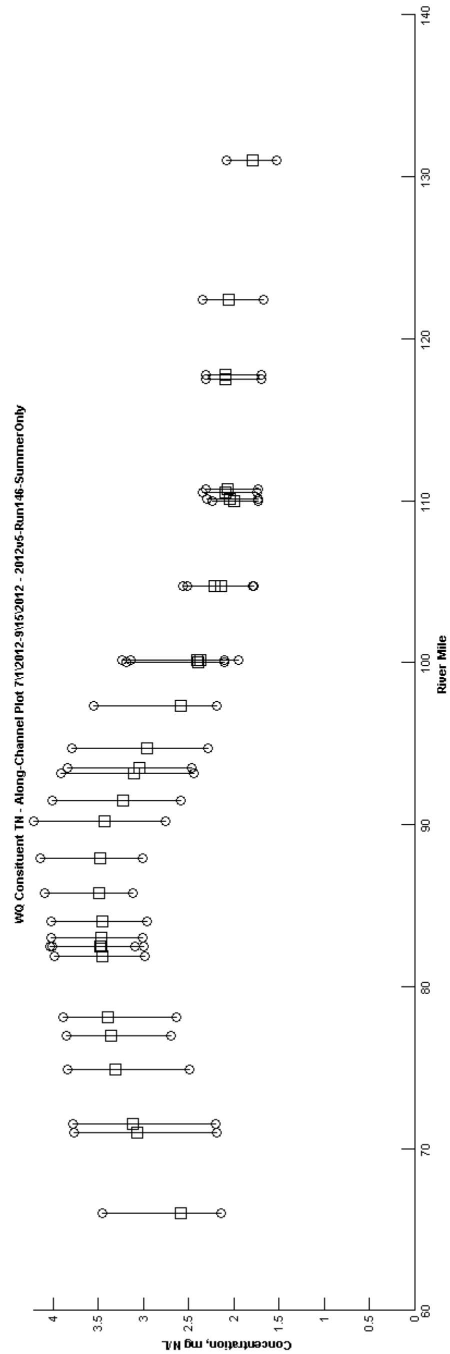

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR08190 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR07810 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR07490 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12


LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR07150 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR07100 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR06600 in Simulation 2012v5-Run146-SummerOnly
mg-N/L
Date
07/01/12
08/01/12
09/01/12


WQ Consituent NH4 - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg N/L
60
70
80
90
100
110
120
130
140
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

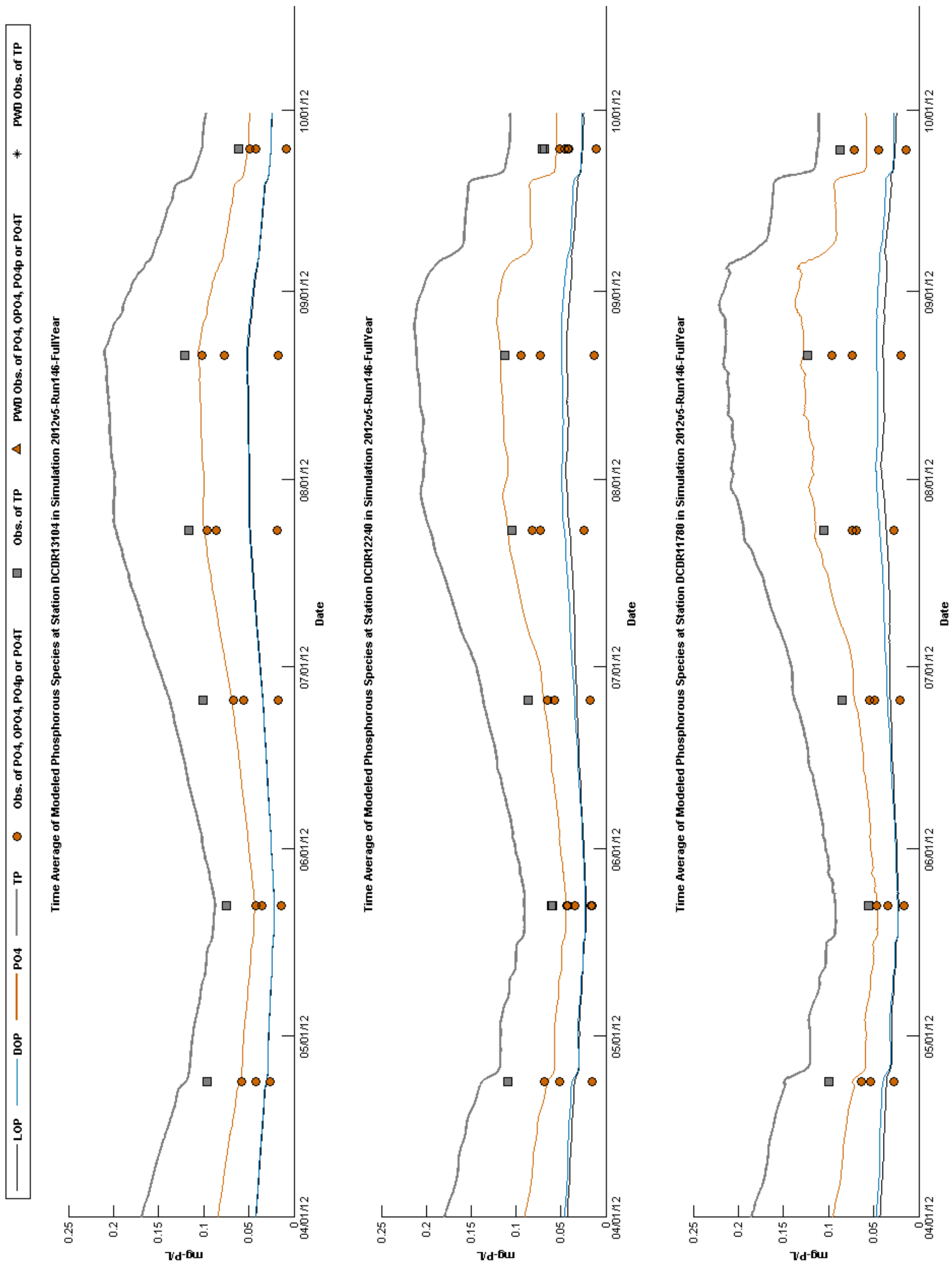

WQ Consituent NOX - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg N/L
60
70
80
90
100
110
120
130
140
0
0.5
1
1.5
2
2.5
3

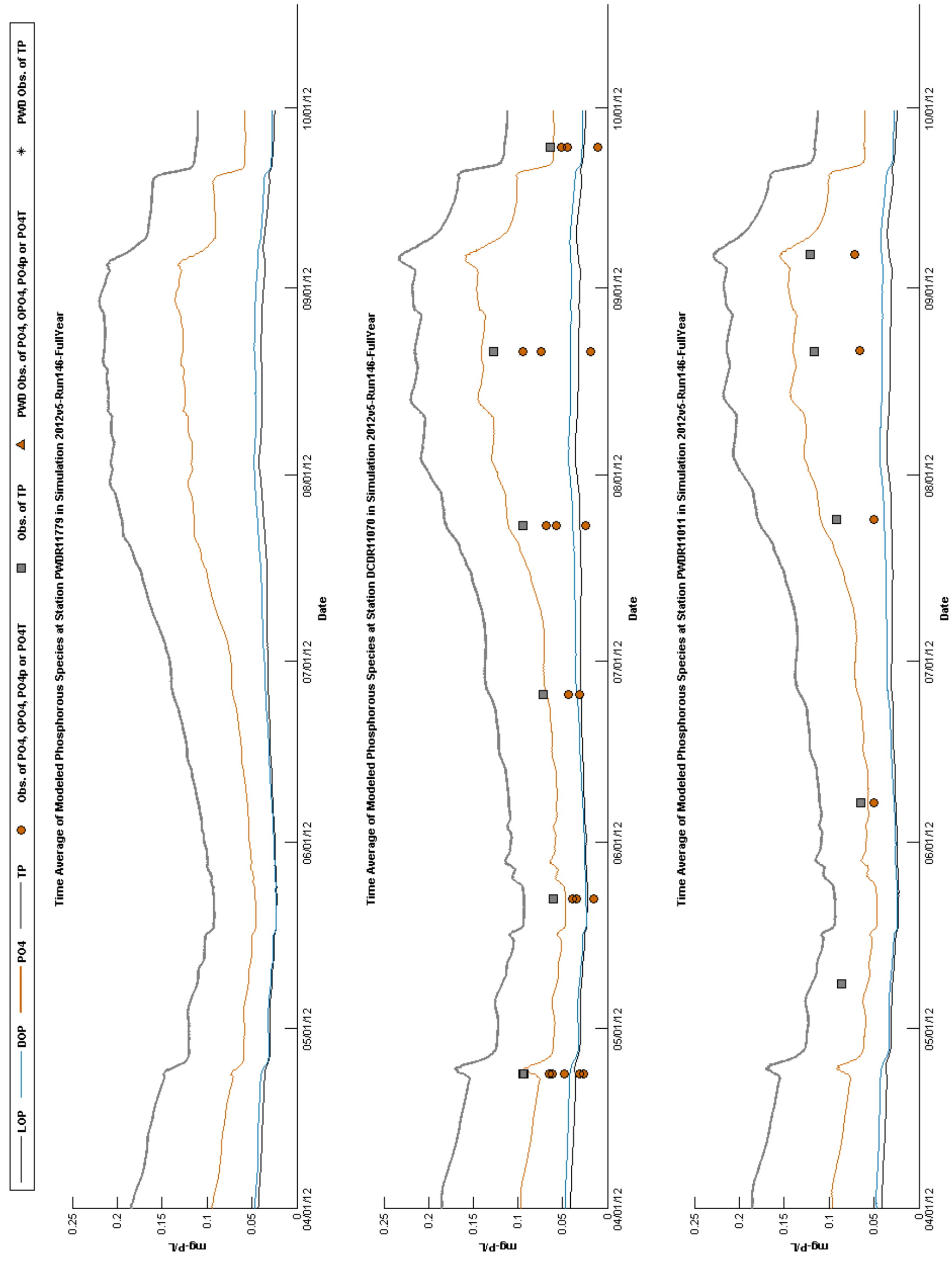

WQ Consitutent TKN - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

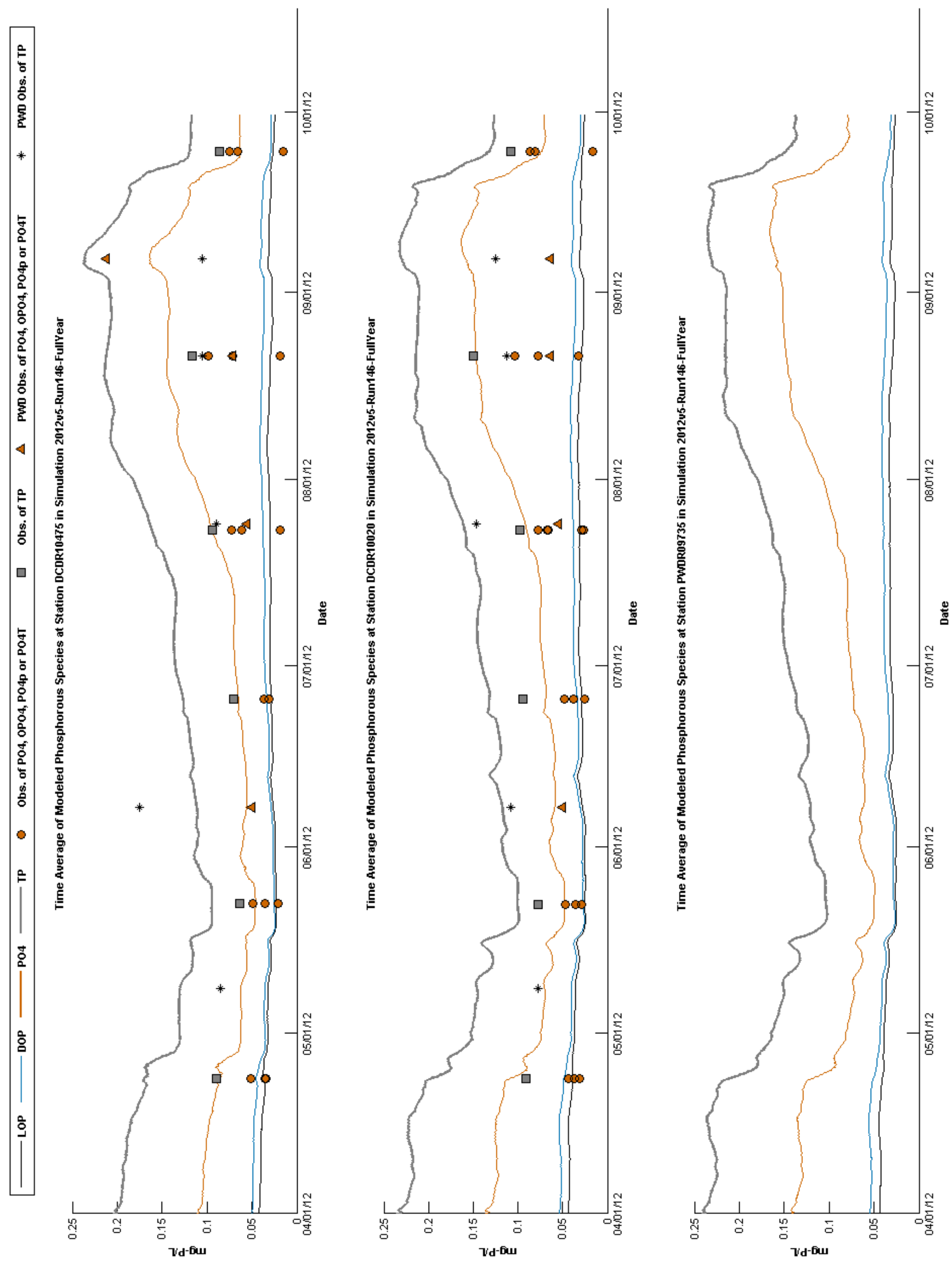

WQ Consitutent TN - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

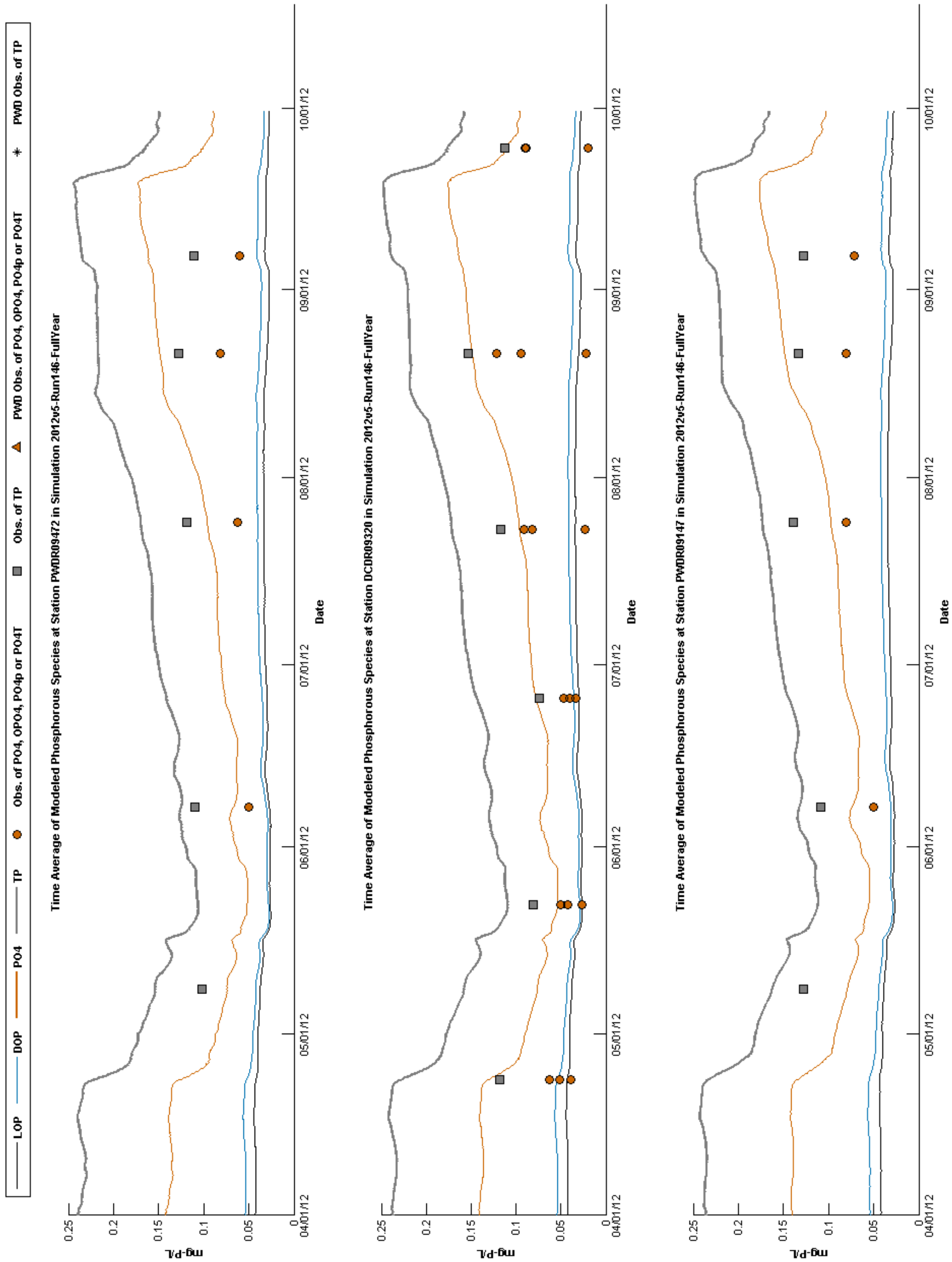
1.6. Phosphorus species

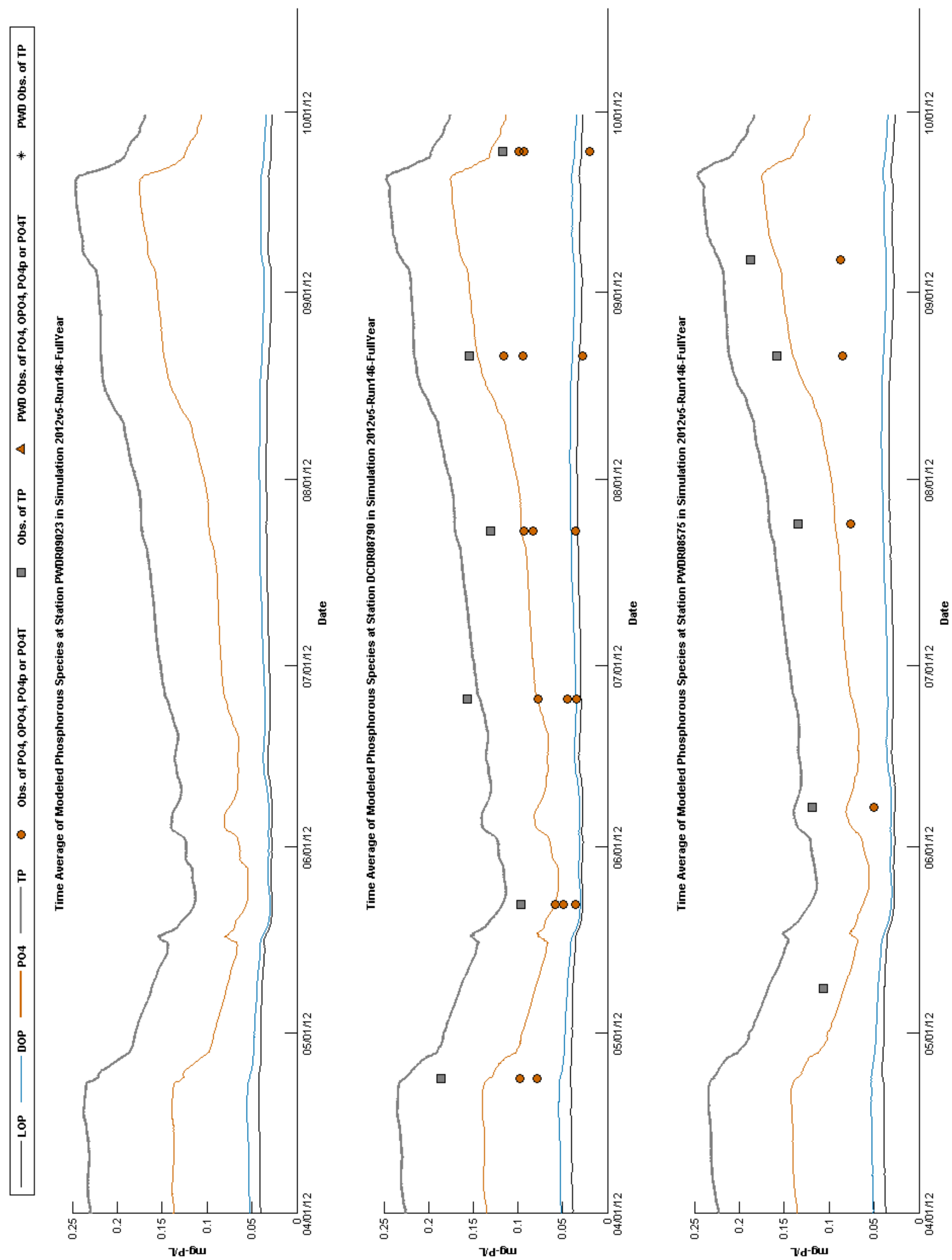
1.6.1. April to October

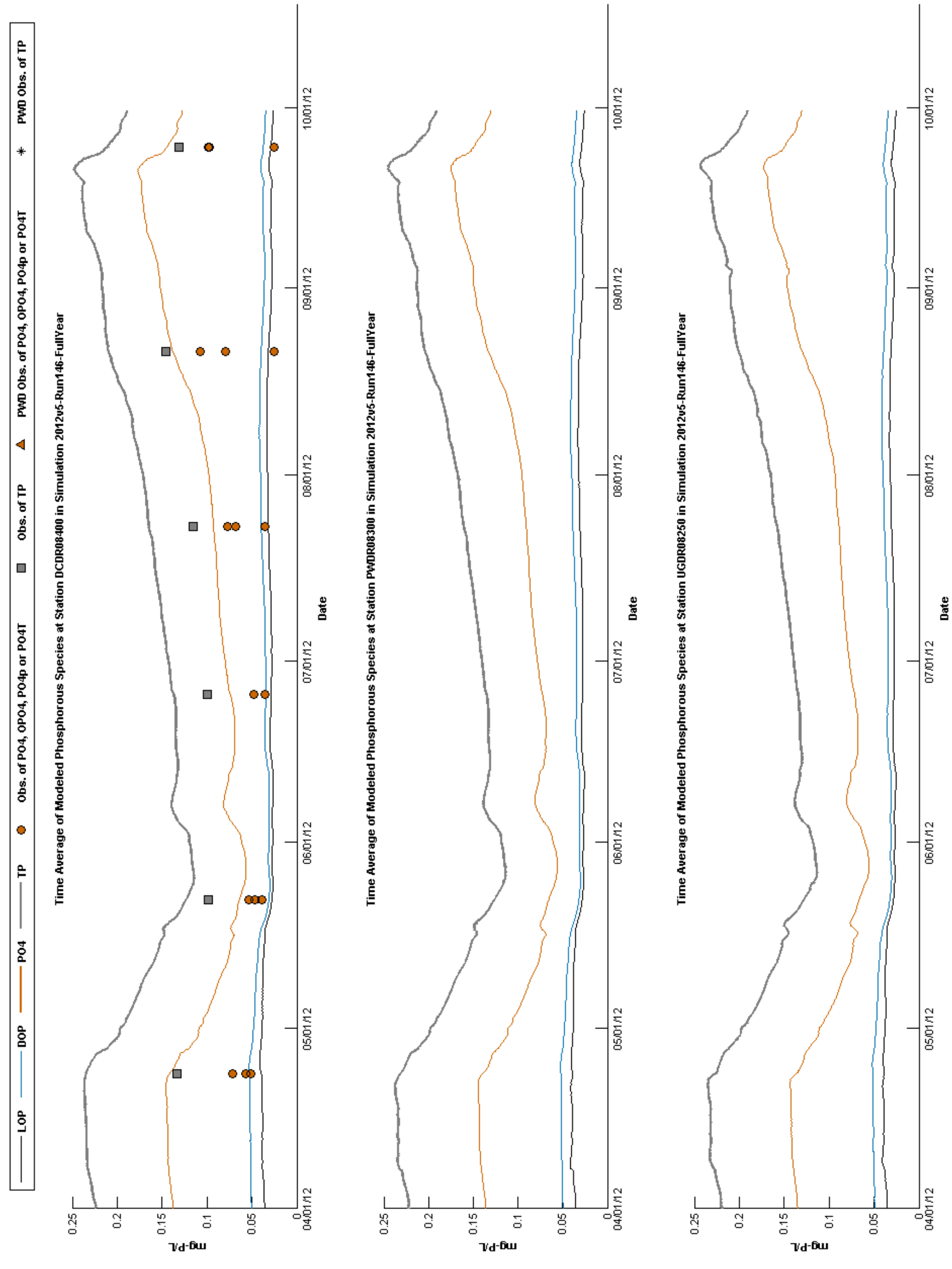


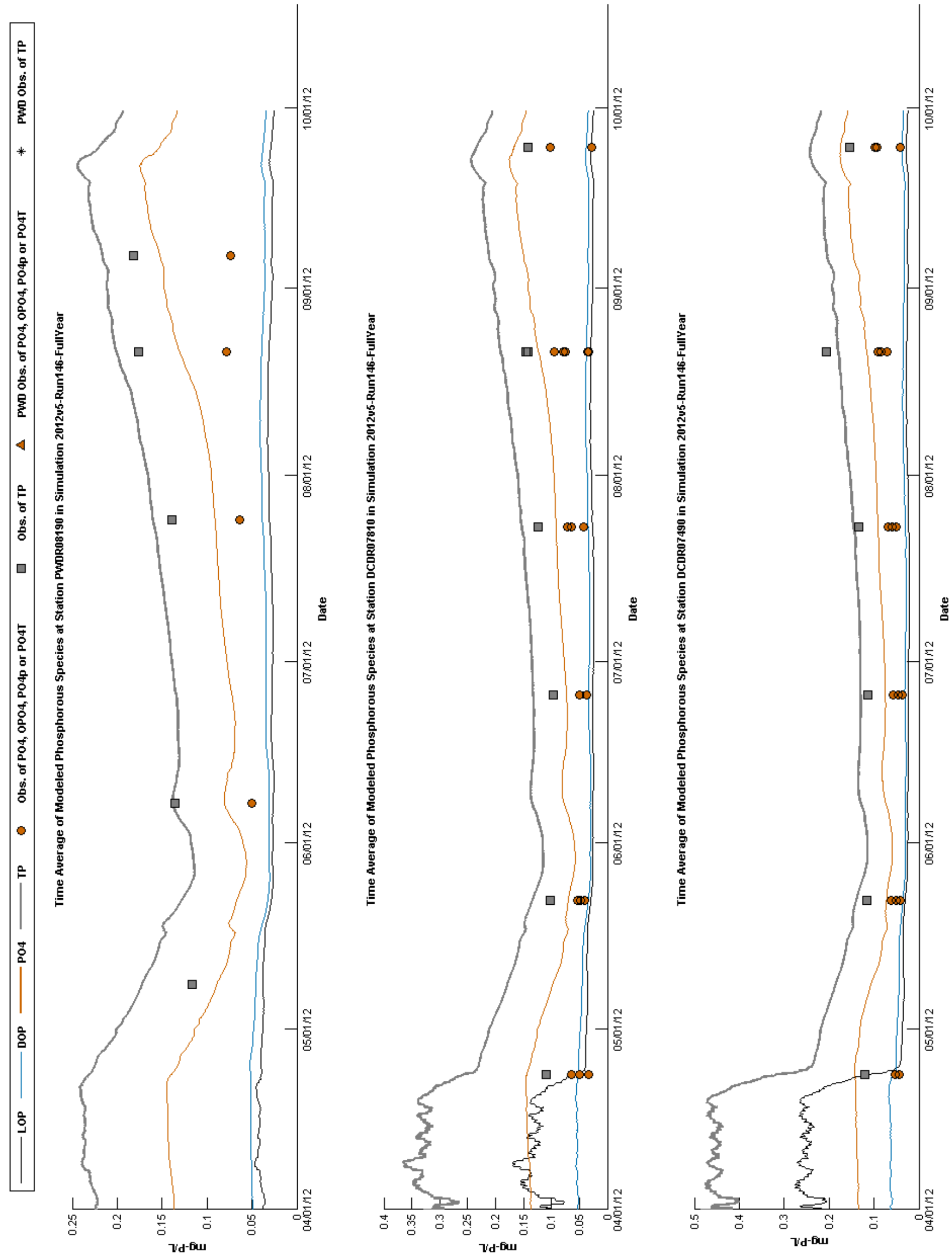

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR11779 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR11070 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR11011 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date
0
0.05
0.1
0.15
0.2
0.25
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

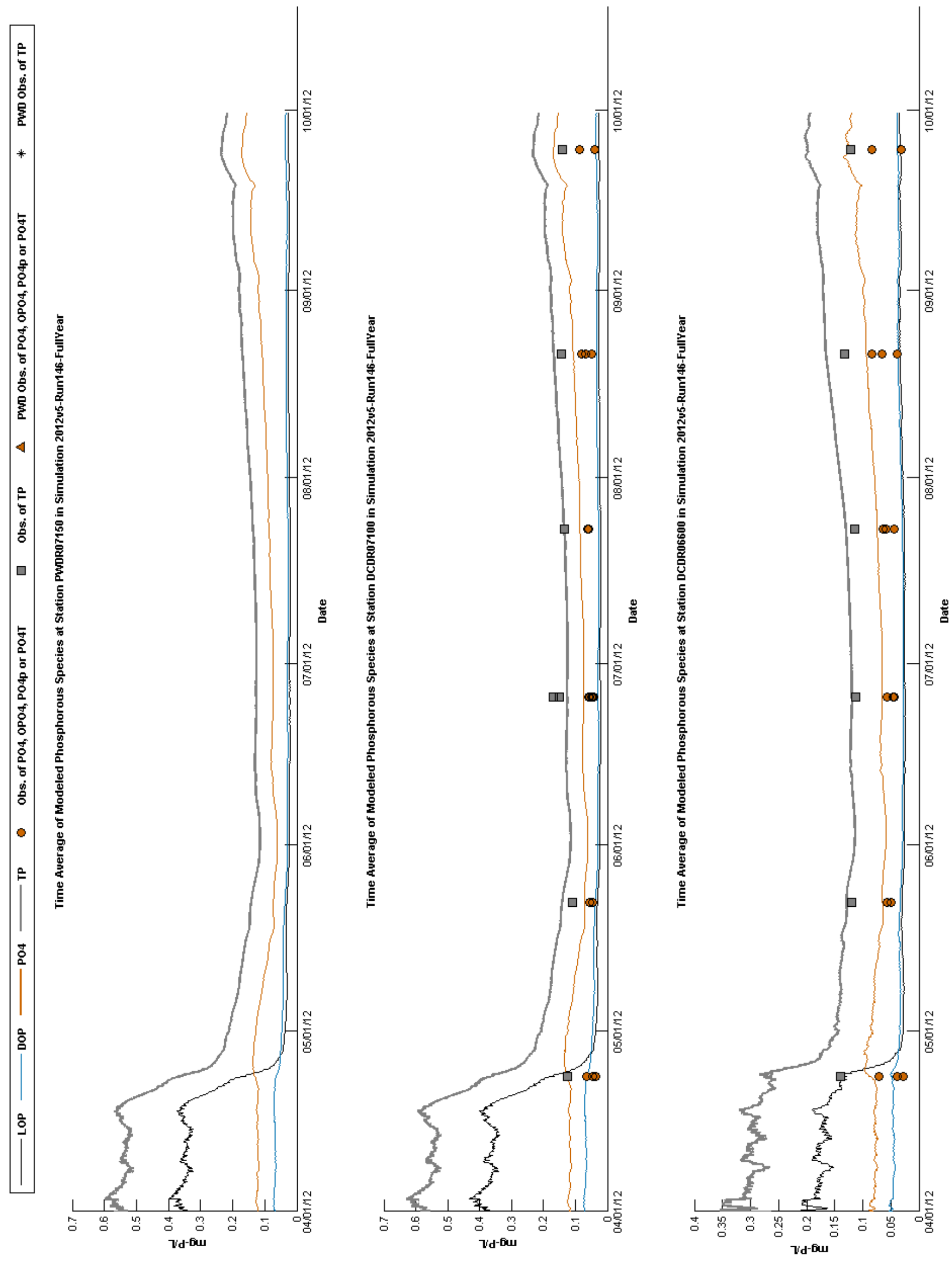

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR10475 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR10020 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR09735 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date

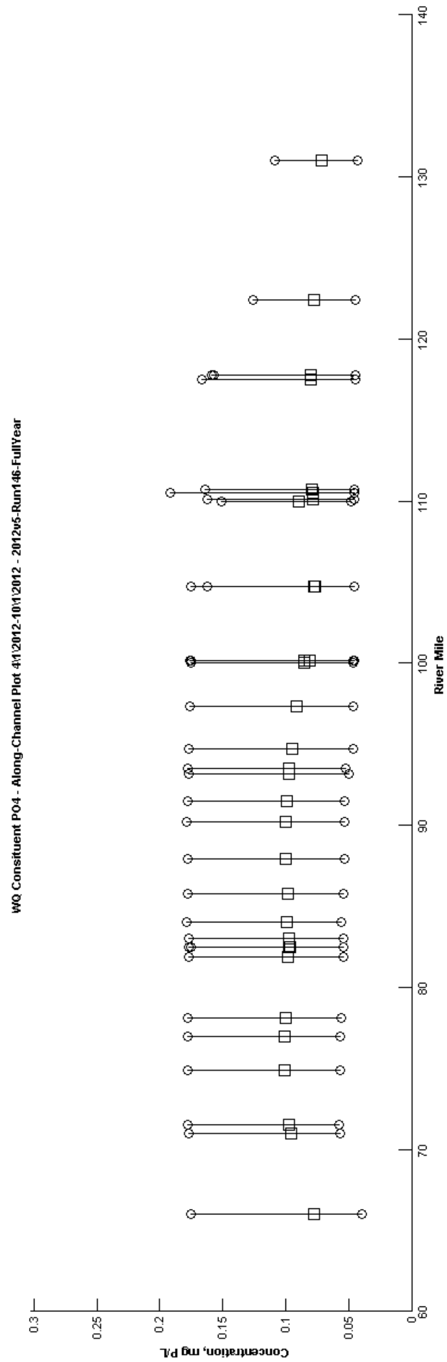

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09472 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR09320 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR09147 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

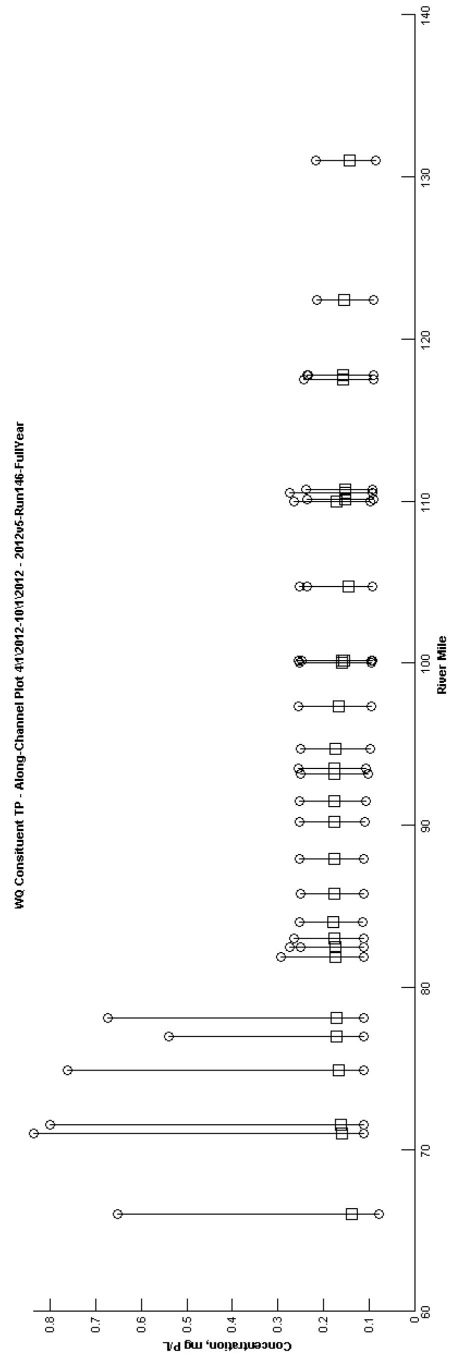

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09023 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR08790 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR08575 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR08400 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR08300 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station UGDR08250 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

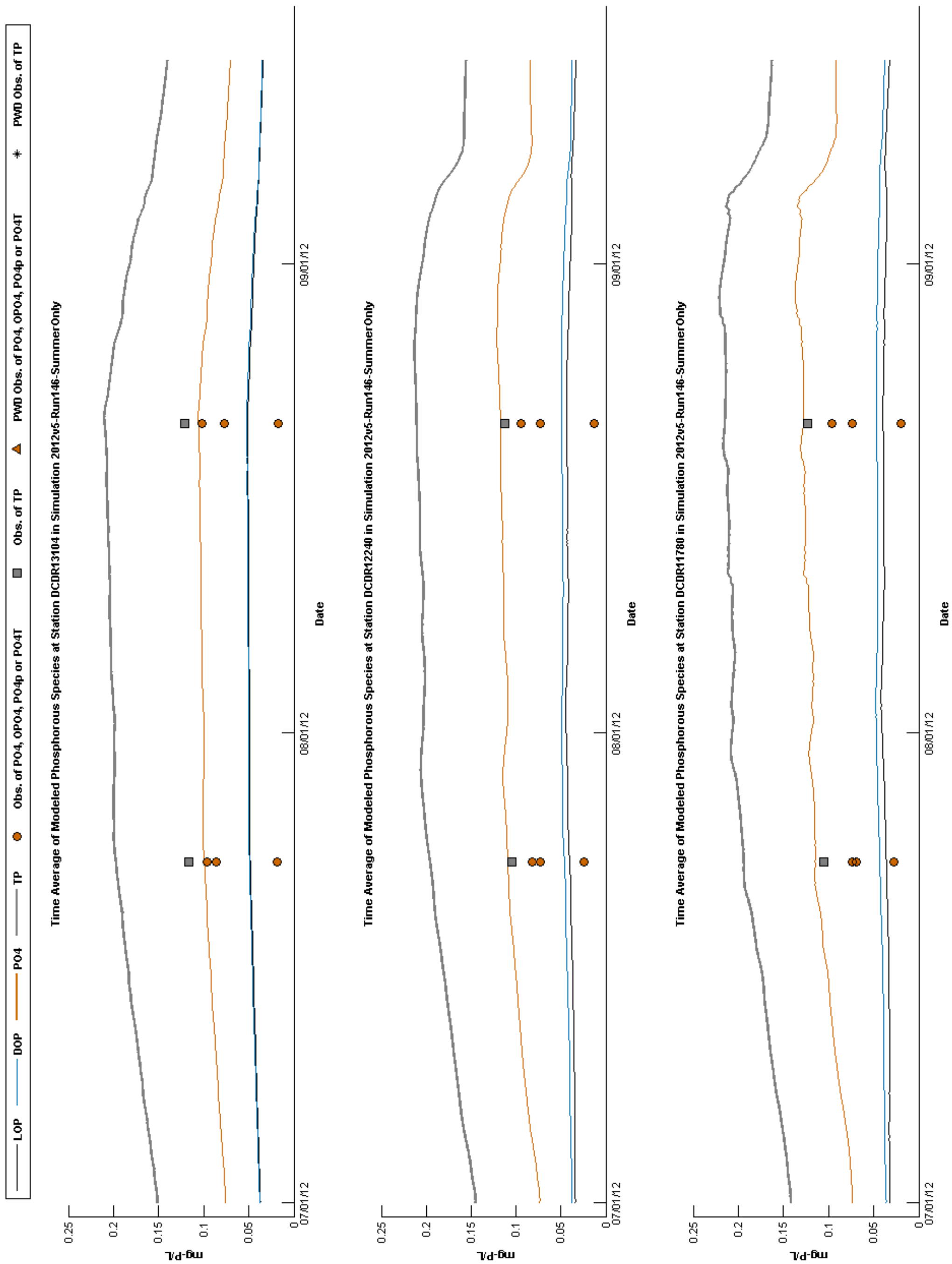

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR08190 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07810 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07490 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date

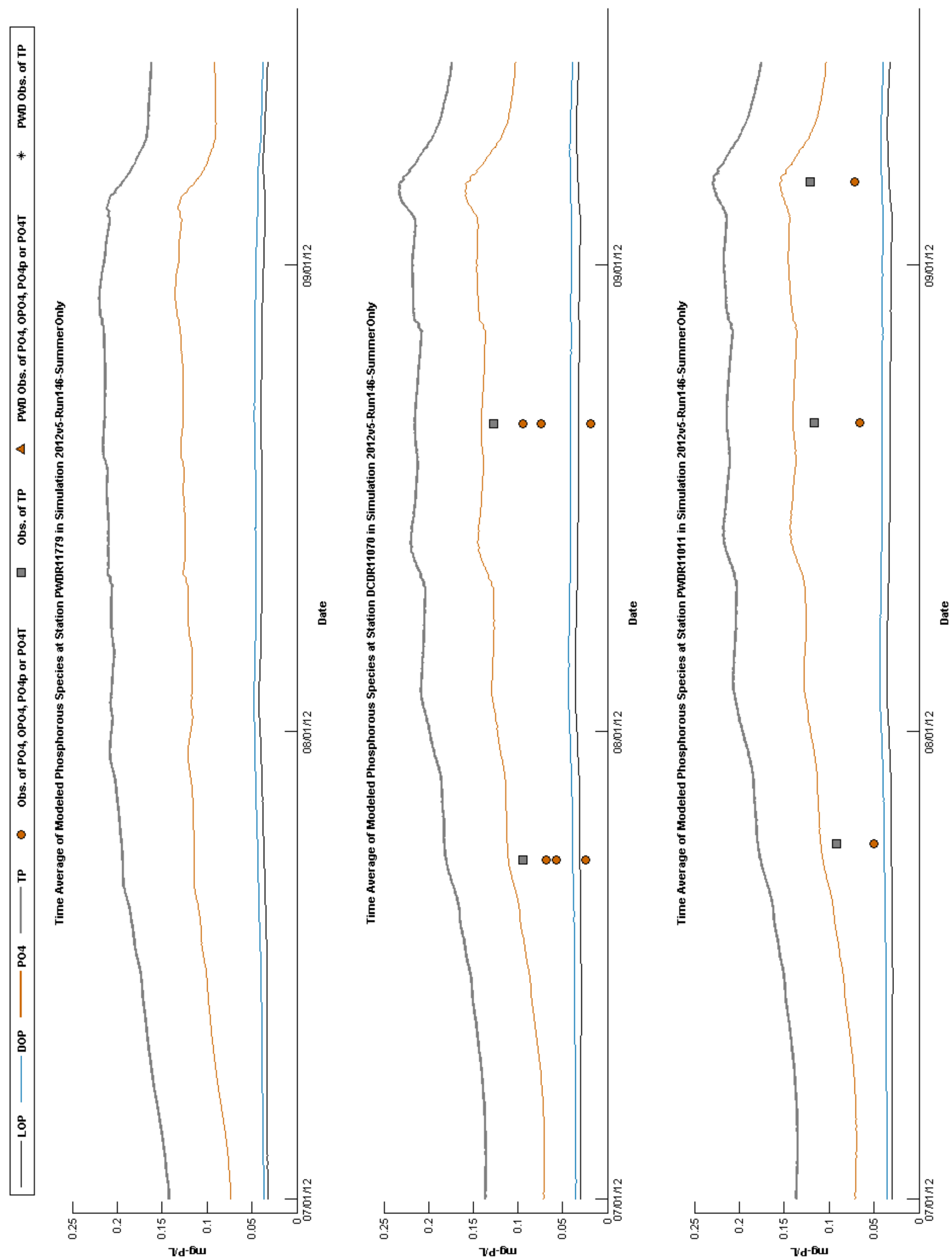

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR07150 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07100 in Simulation 2012v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR06600 in Simulation 2012v5-Run146-FullYear
mg-P/L
Date
04/01/12
05/01/12
06/01/12
07/01/12
08/01/12
09/01/12
10/01/12

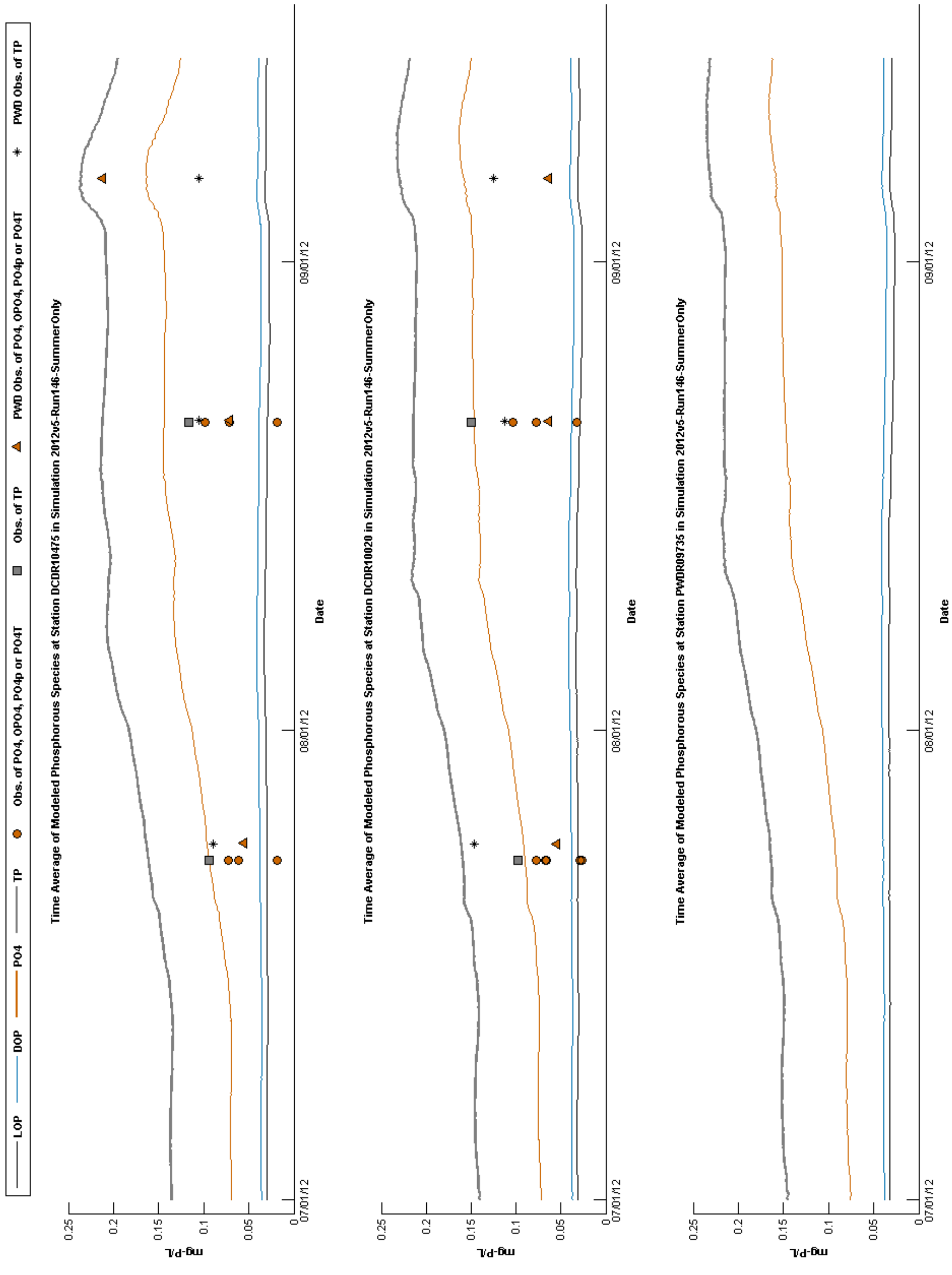

WQ Consituent PO4 - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg P/L
River Mile

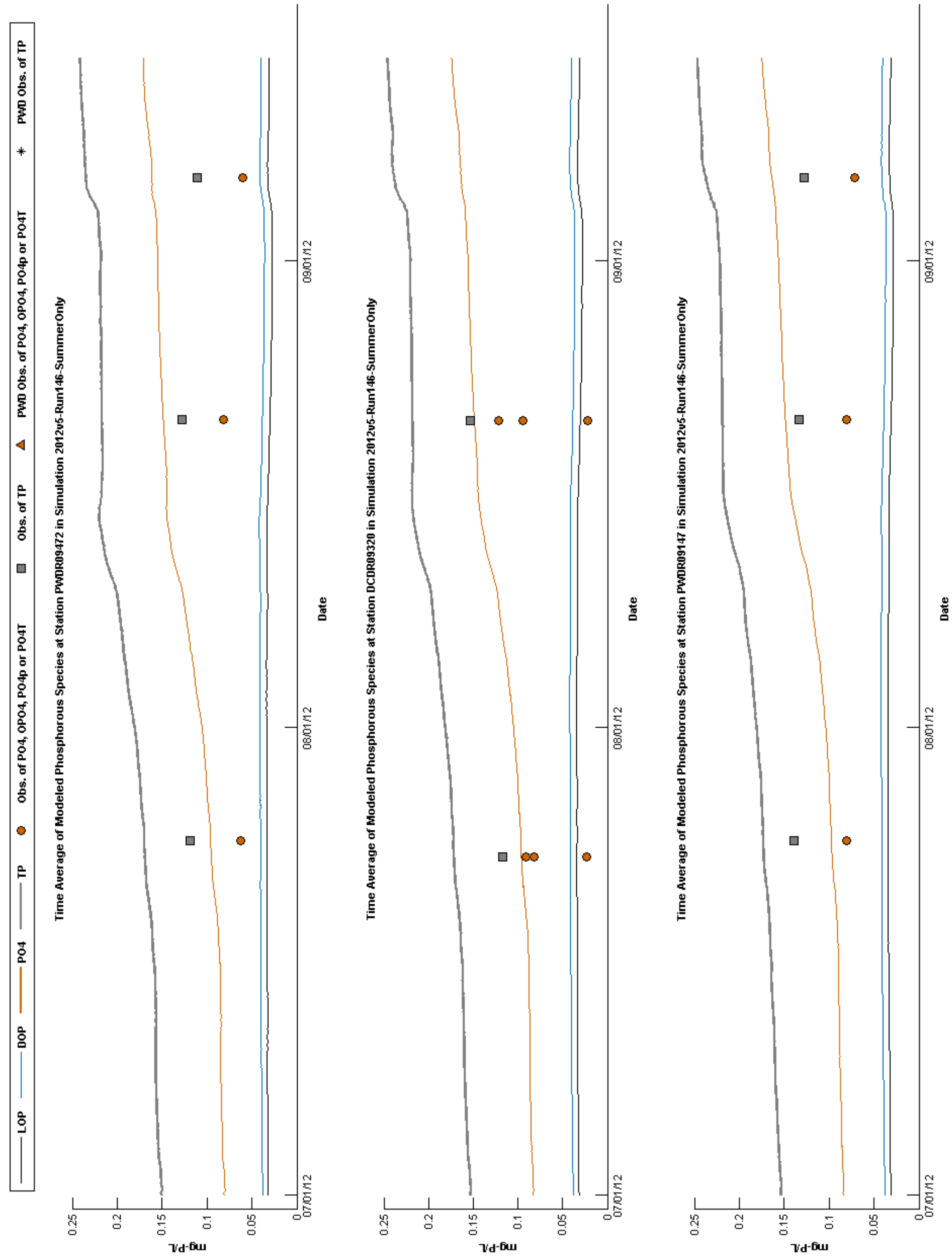

WQ Consituent TP - Along-Channel Plot 4\1\2012-10\1\2012 - 2012v5-Run146-FullYear
Concentration, mg P/L
River Mile

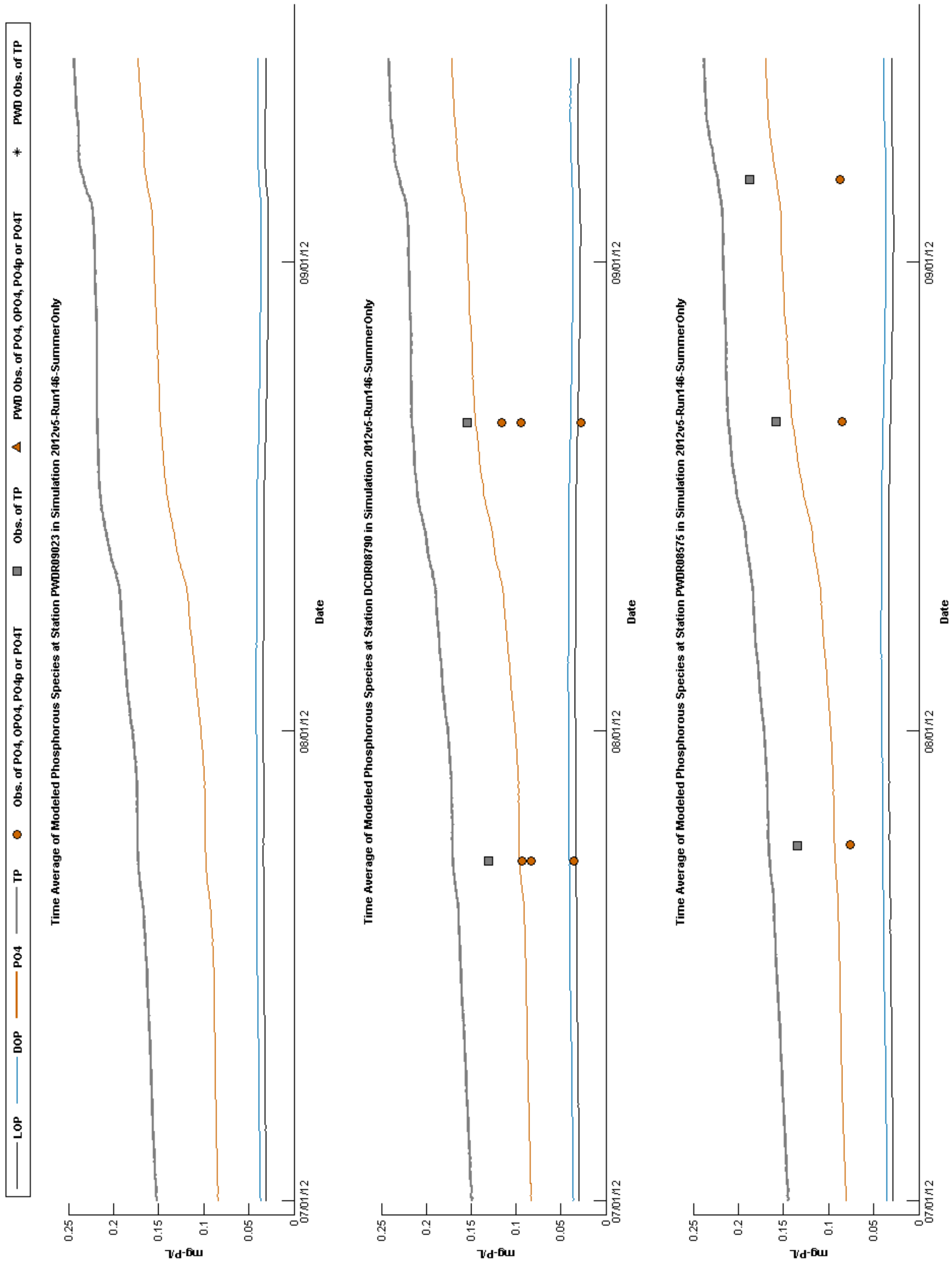
1.6.2. Summer


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR13104 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR12240 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR11780 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12

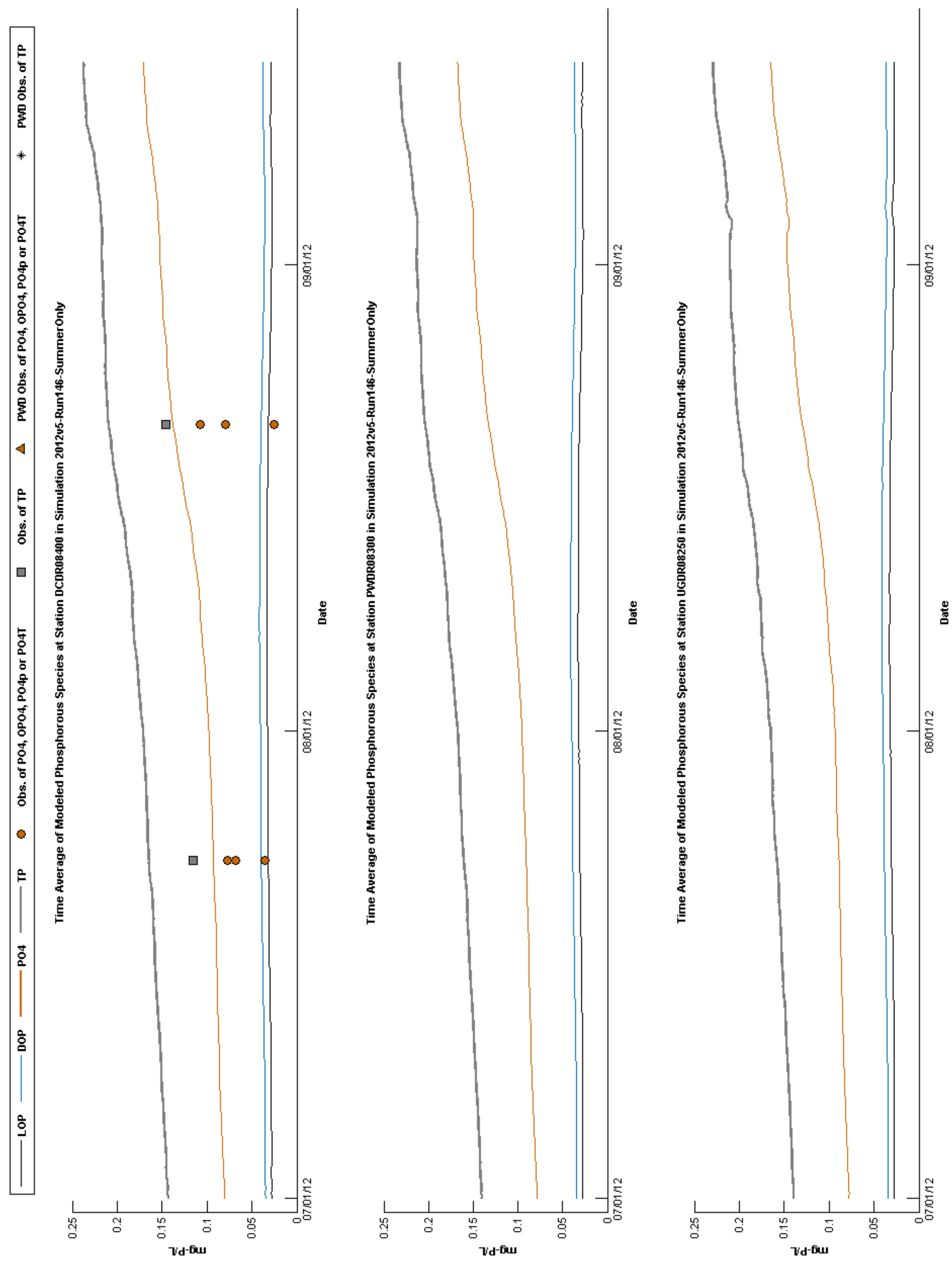

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR11779 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR11070 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR11011 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12
0
0.05
0.1
0.15
0.2
0.25

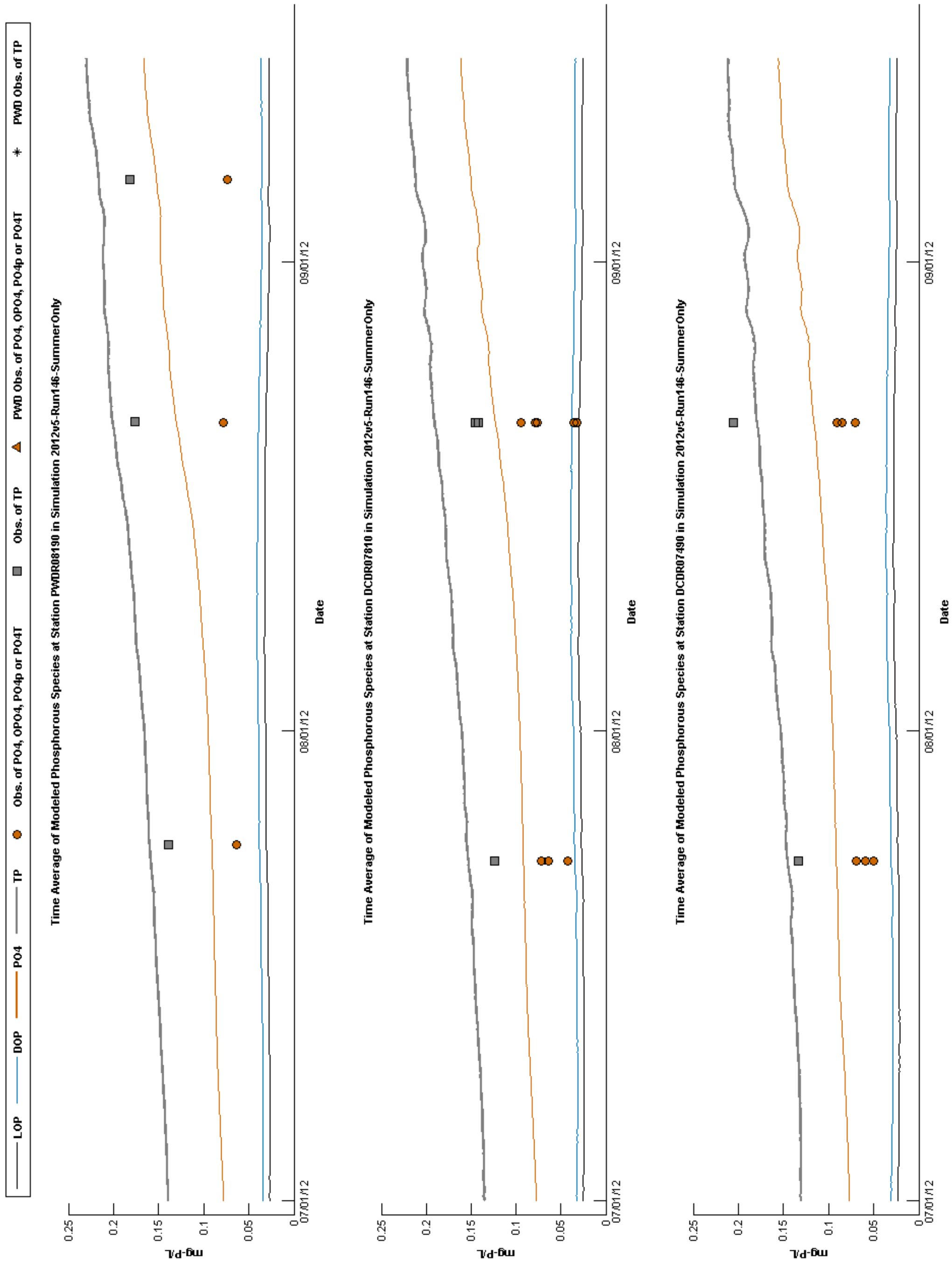

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR10475 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR10020 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR09735 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12

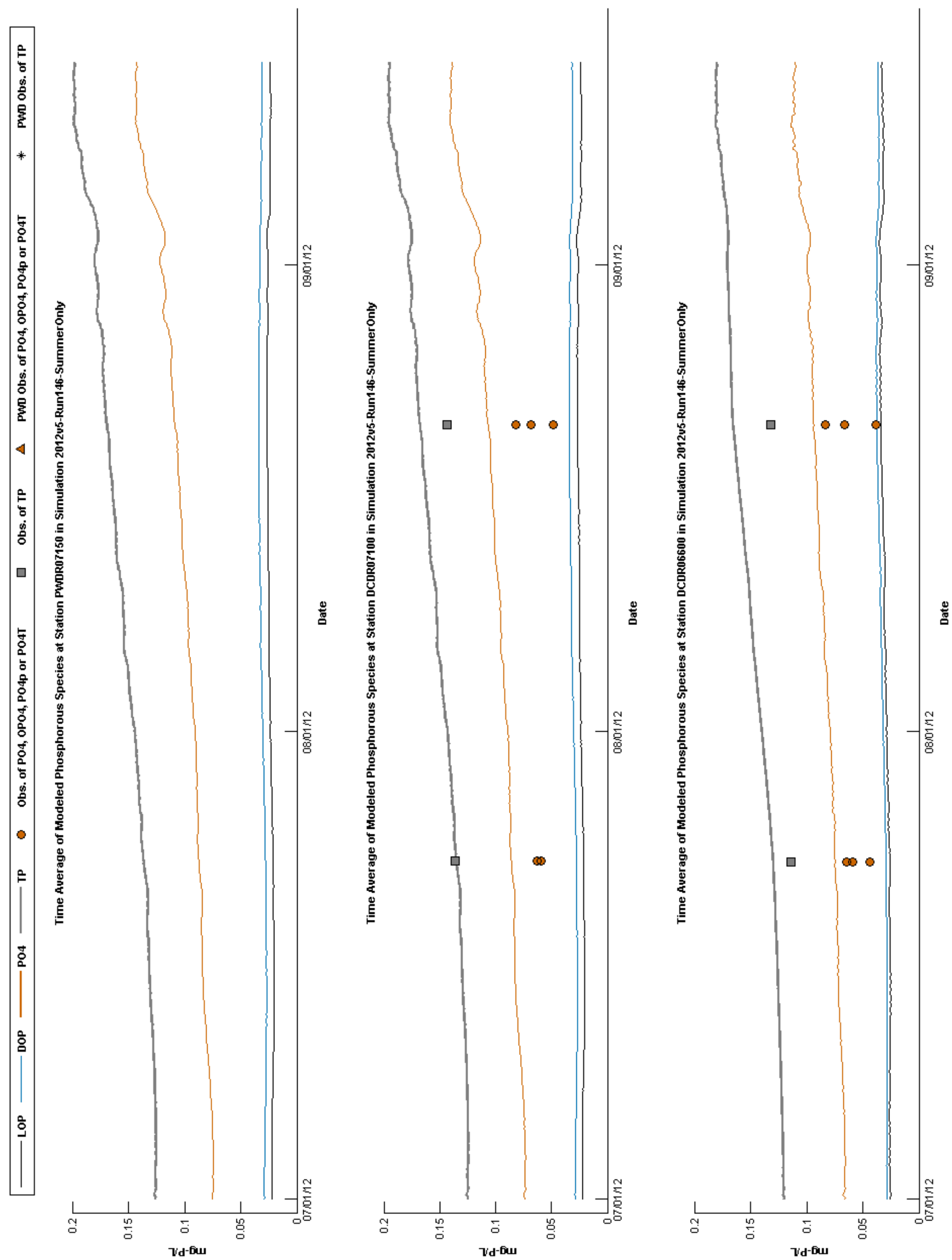

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09472 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR09320 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR09147 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
0
0.05
0.1
0.15
0.2
0.25
07/01/12
08/01/12
09/01/12
Date



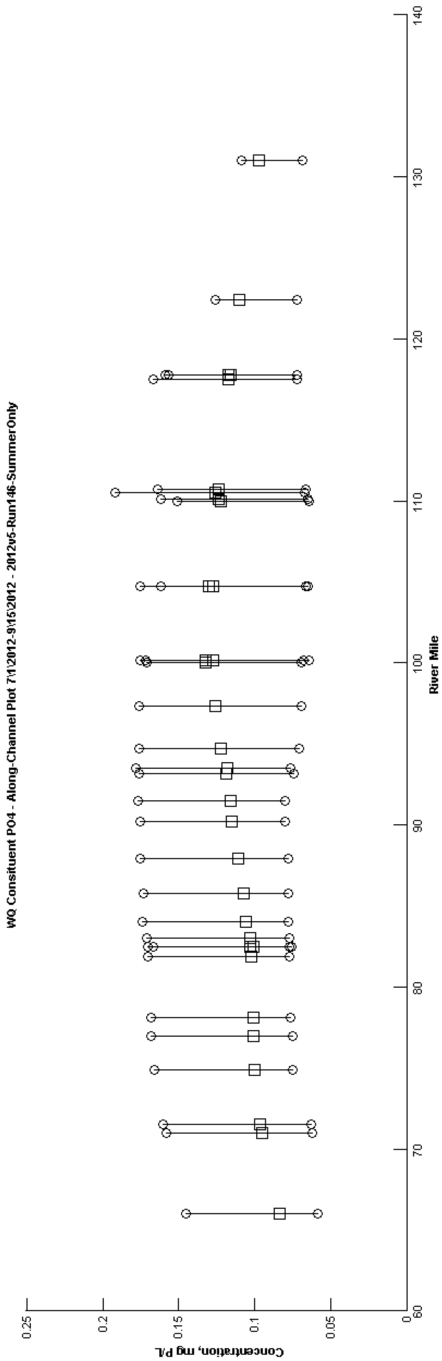
LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09023 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR08790 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR08575 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12

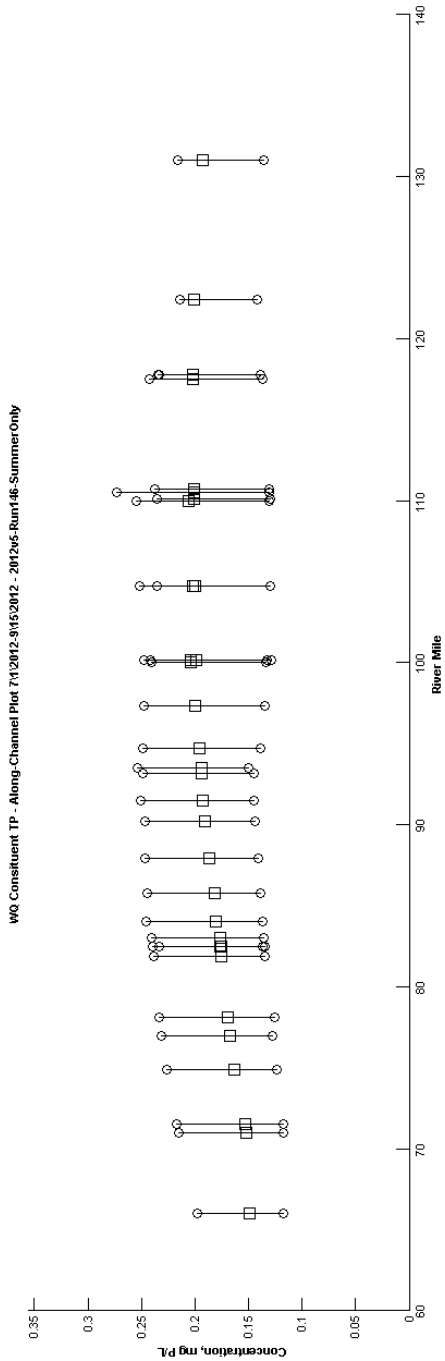

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR08400 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Phosphorous Species at Station PWDR08300 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12
Time Average of Modeled Phosphorous Species at Station UGDR08250 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR08190 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07810 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07490 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12
0
0.05
0.1
0.15
0.2
0.25



LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR07150 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07100 in Simulation 2012v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR06600 in Simulation 2012v5-Run146-SummerOnly
mg-P/L
Date
07/01/12
08/01/12
09/01/12

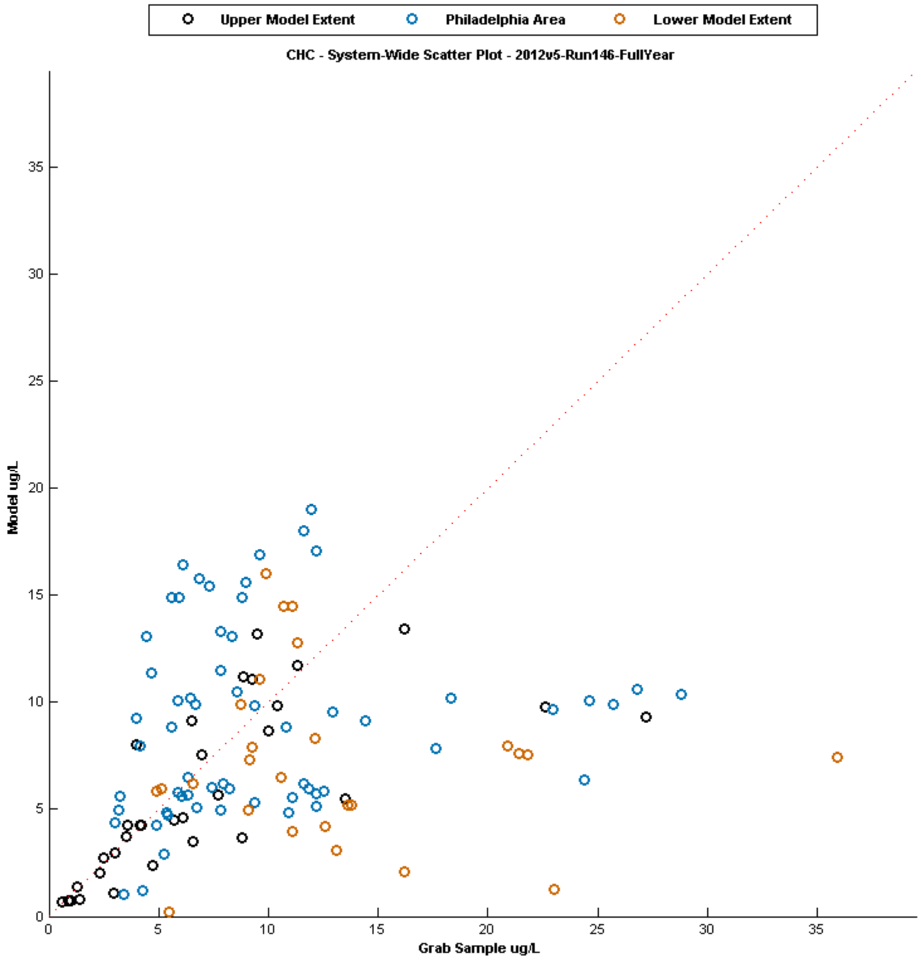

WQ Consituent PO4 - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg P/L
60
70
80
90
100
110
120
130
140
0
0.05
0.1
0.15
0.2
0.25


WQ Consituent TP - Along-Channel Plot 7\1\2012-9\15\2012 - 2012v5-Run146-SummerOnly
River Mile
Concentration, mg P/L
60
70
80
90
100
110
120
130
140
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

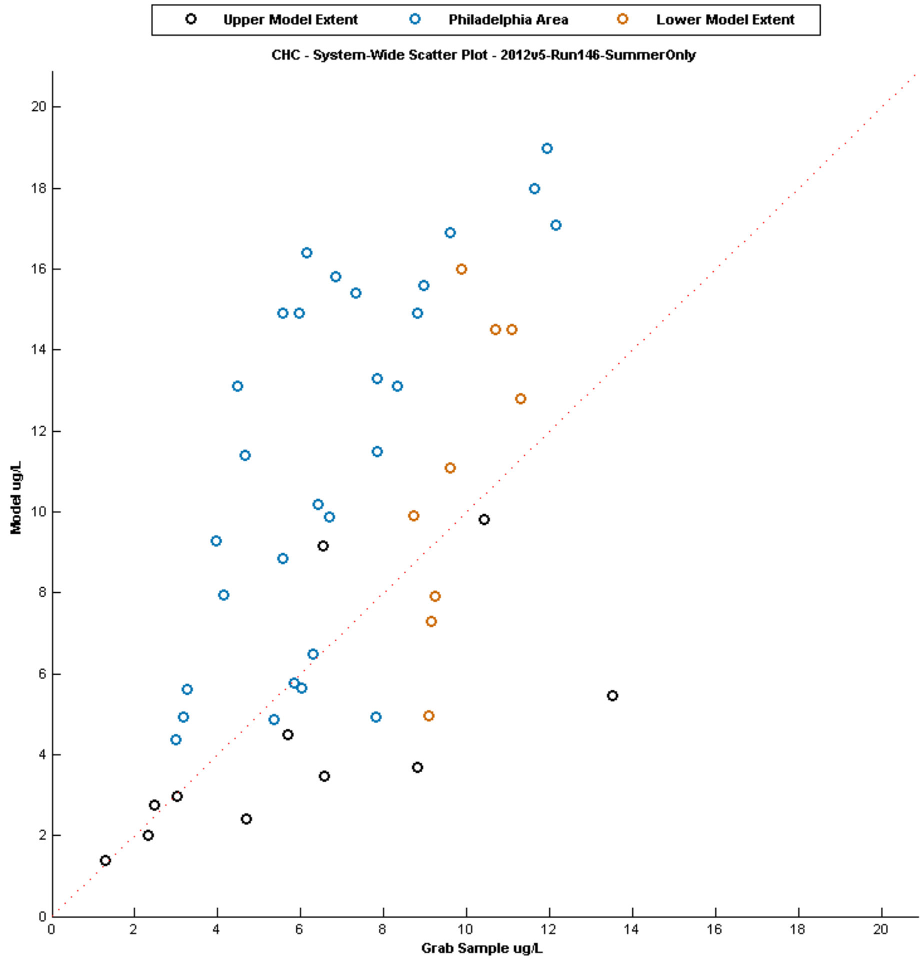
Chapter 2. Scatter Plots

2.1. Biomass - Algae

2.1.1. April to October

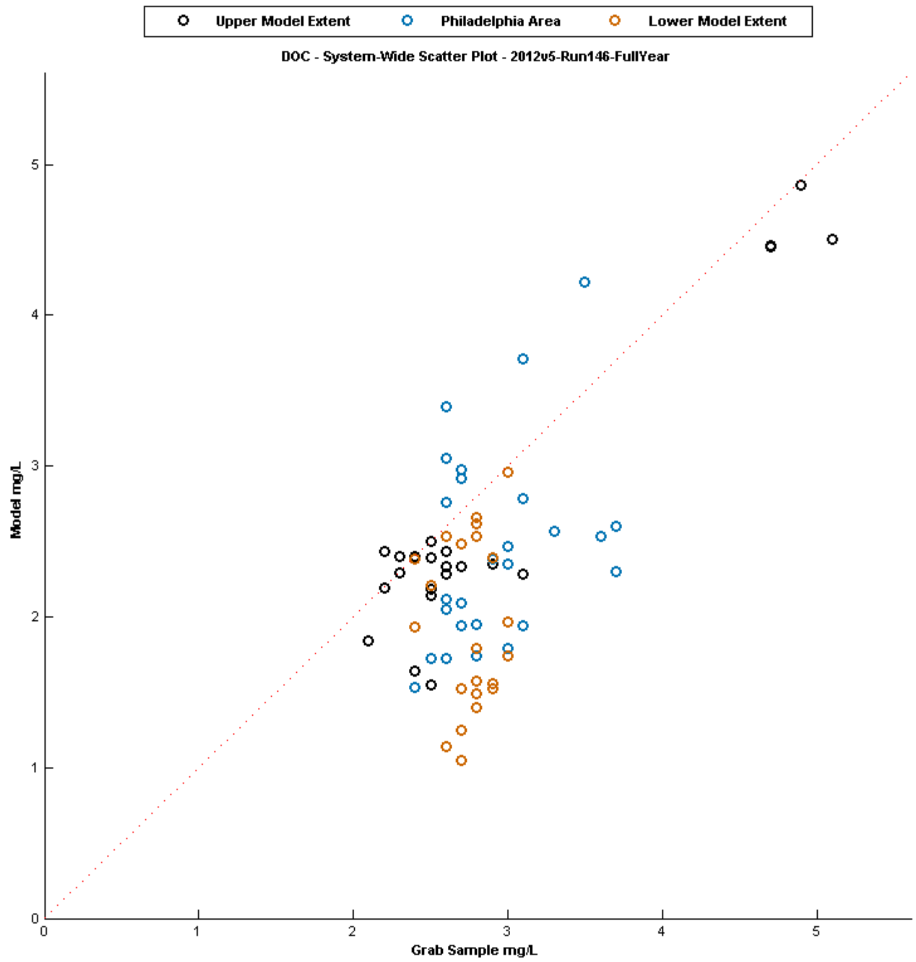


2.1.2. Summer

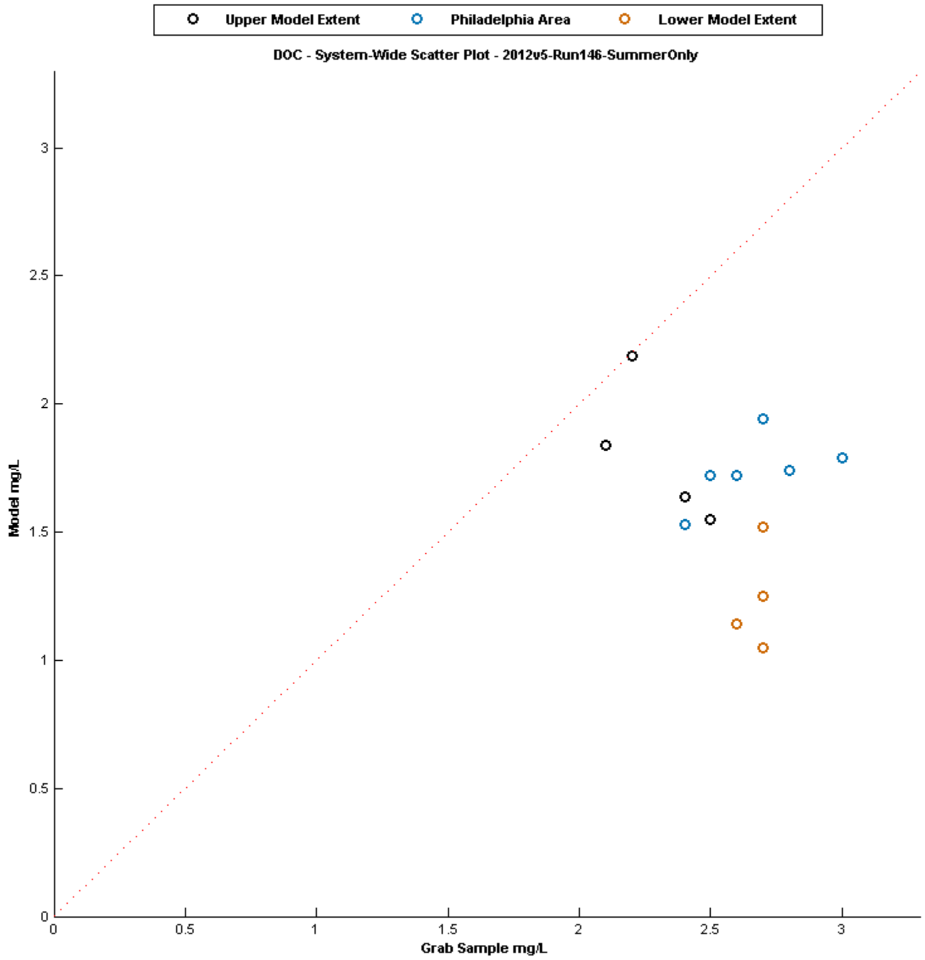

Upper Model Extent
Philadelphia Area
Lower Model Extent
CHC - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model ug/L
Grab Sample ug/L
0
2
4
6
8
10
12
14
16
18
20

2.2. Dissolved Organic Carbon

2.2.1. April to October



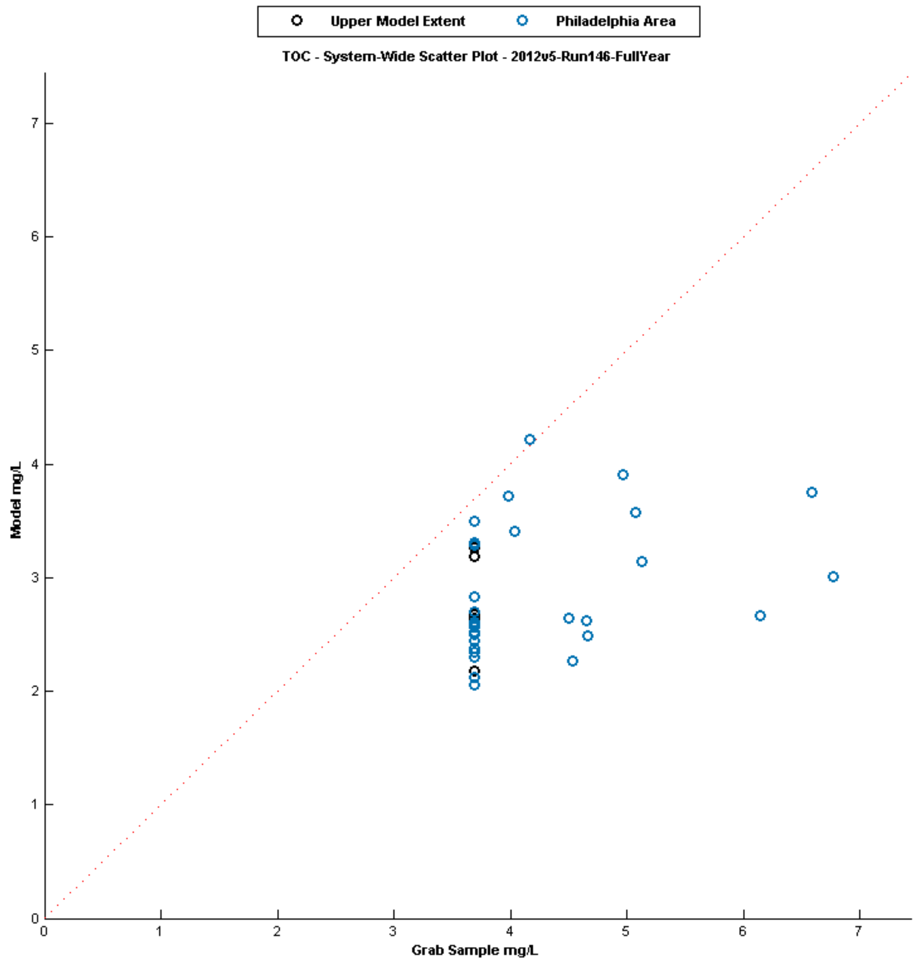
2.2.2. Summer



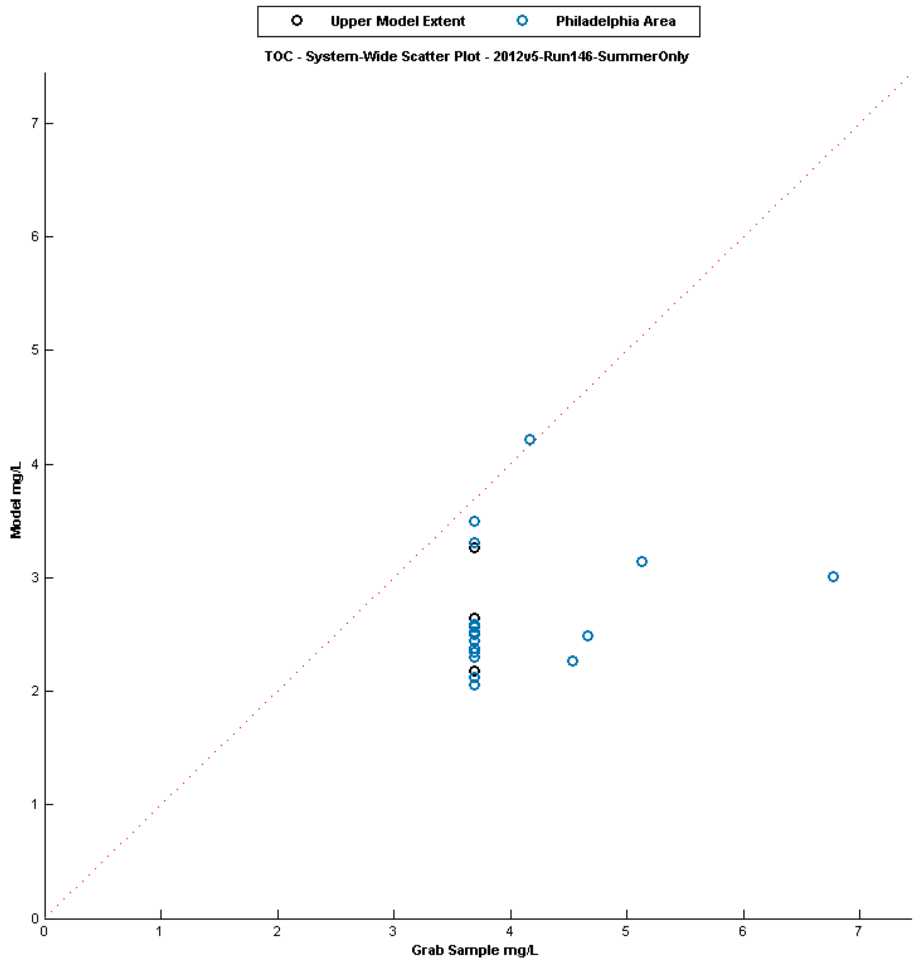
Upper Model Extent
Philadelphia Area
Lower Model Extent
DOC - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg/L
Grab Sample mg/L
0
0.5
1
1.5
2
2.5
3

2.3. Total Organic Carbon

2.3.1. April to October



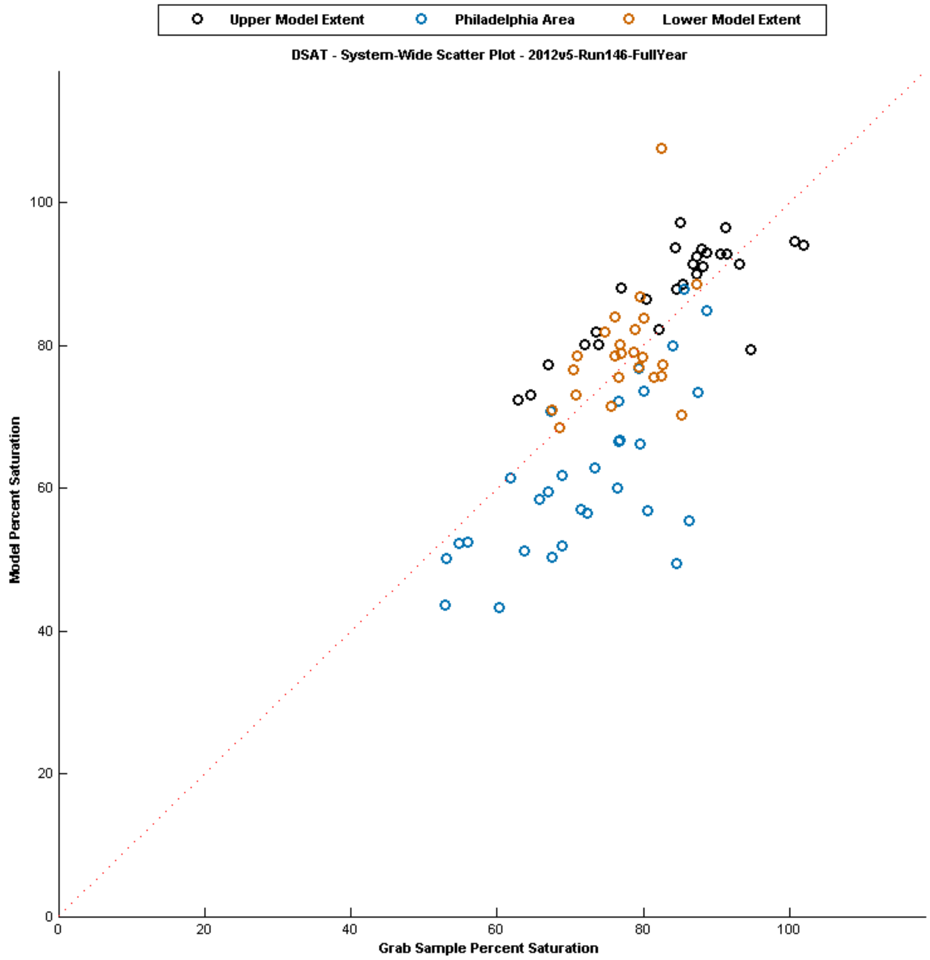
2.3.2. Summer



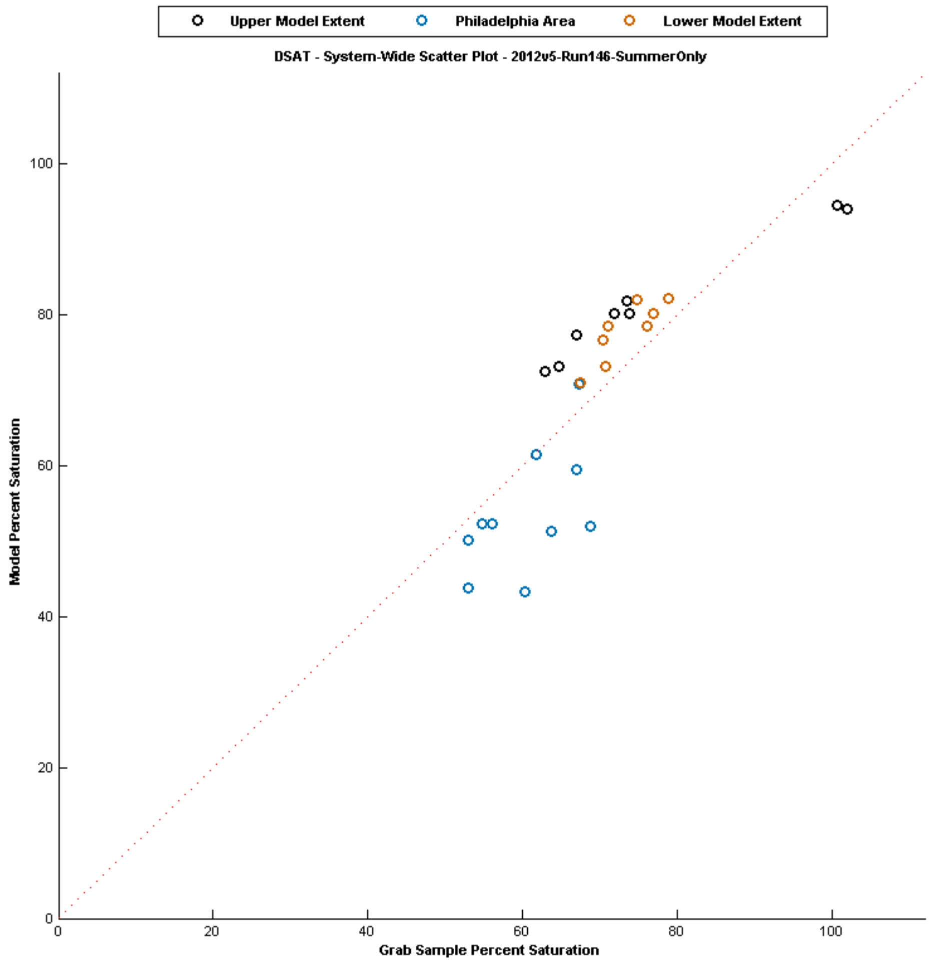
Upper Model Extent
Philadelphia Area
TOC - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg/L
Grab Sample mg/L
0
1
2
3
4
5
6
7

2.4. DO % Saturation

2.4.1. April to October

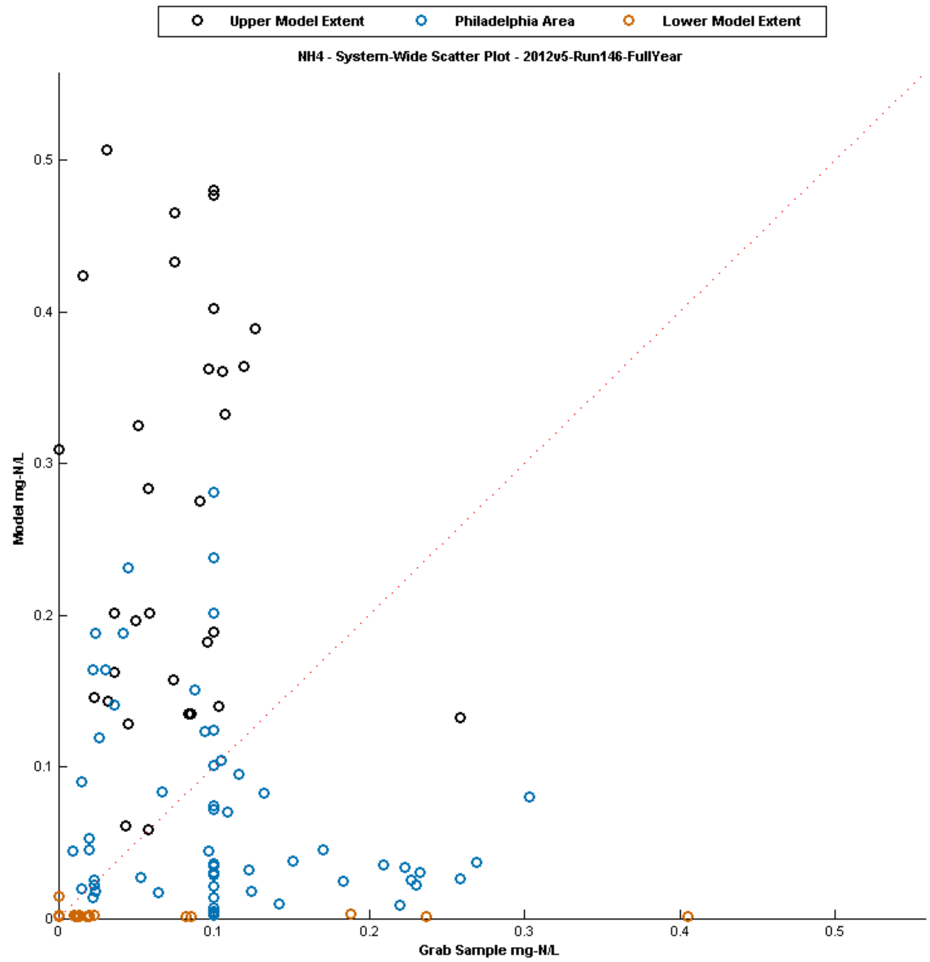


2.4.2. Summer

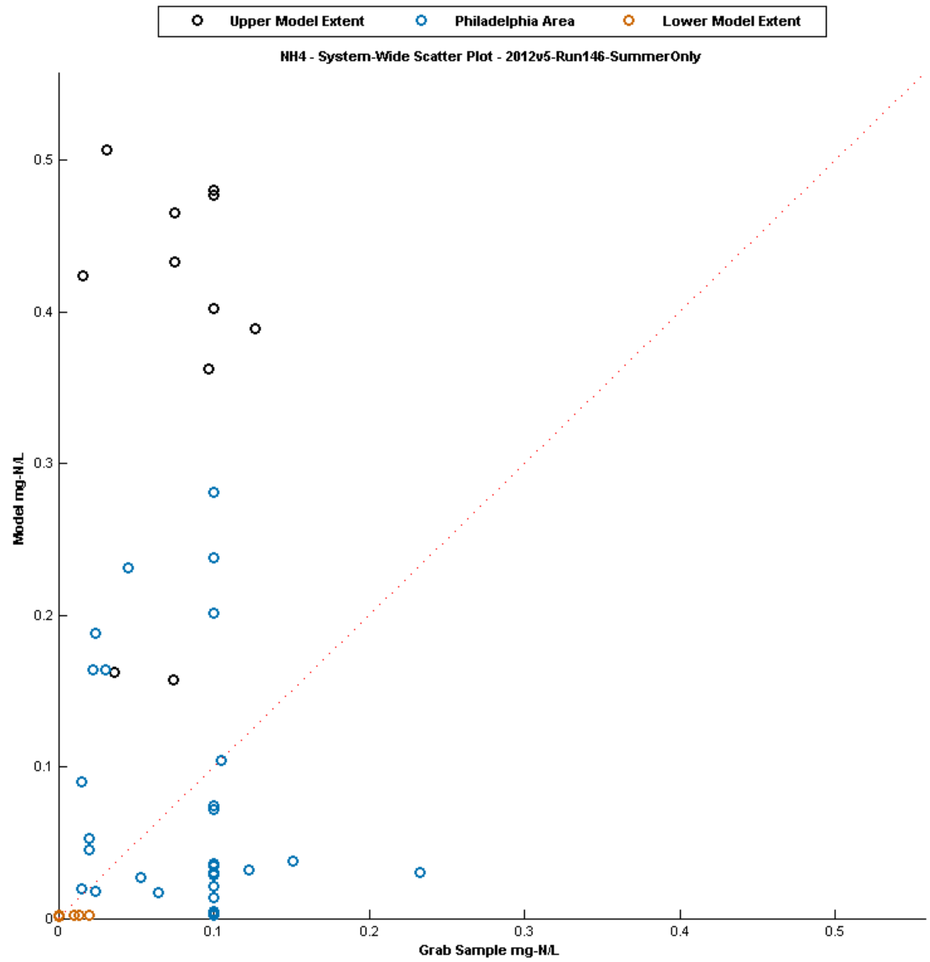

Upper Model Extent
Philadelphia Area
Lower Model Extent
DSAT - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model Percent Saturation
Grab Sample Percent Saturation
0
20
40
60
80
100

2.5. Ammonia Nitrogen

2.5.1. April to October

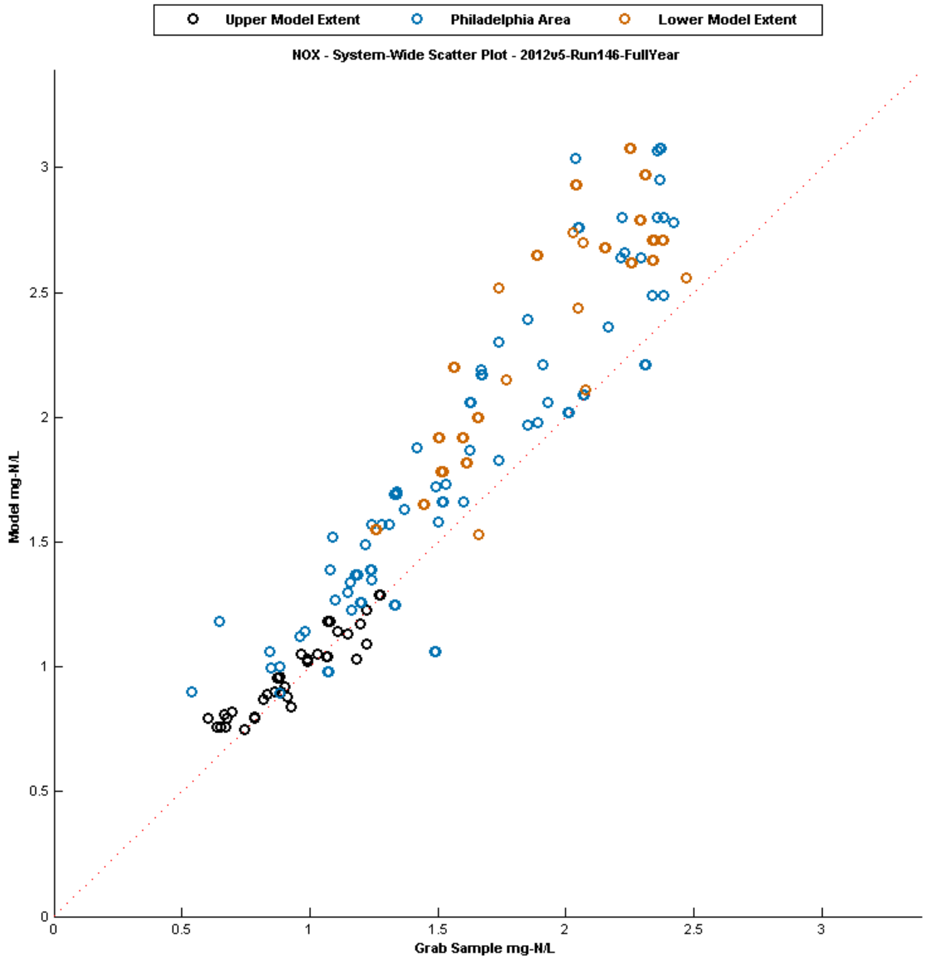


2.5.2. Summer

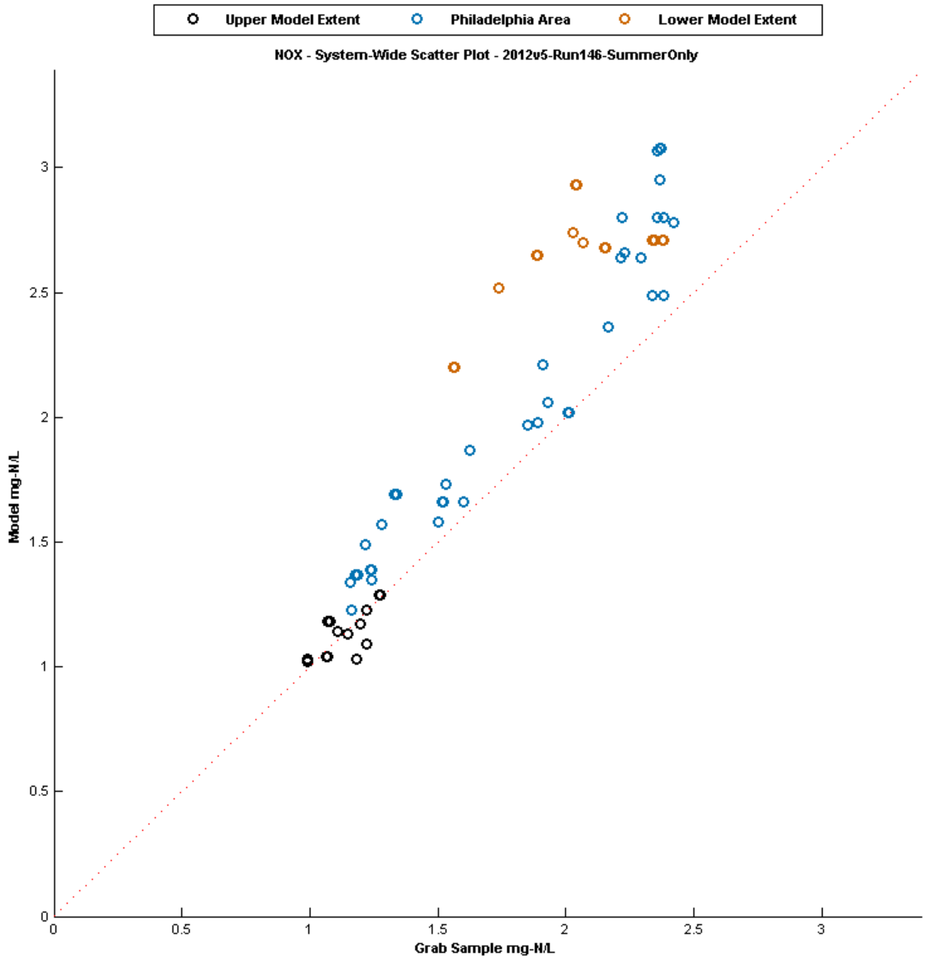

Upper Model Extent
Philadelphia Area
Lower Model Extent
NH4 - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.1
0.2
0.3
0.4
0.5

2.6. Nitrate Nitrogen

2.6.1. April to October



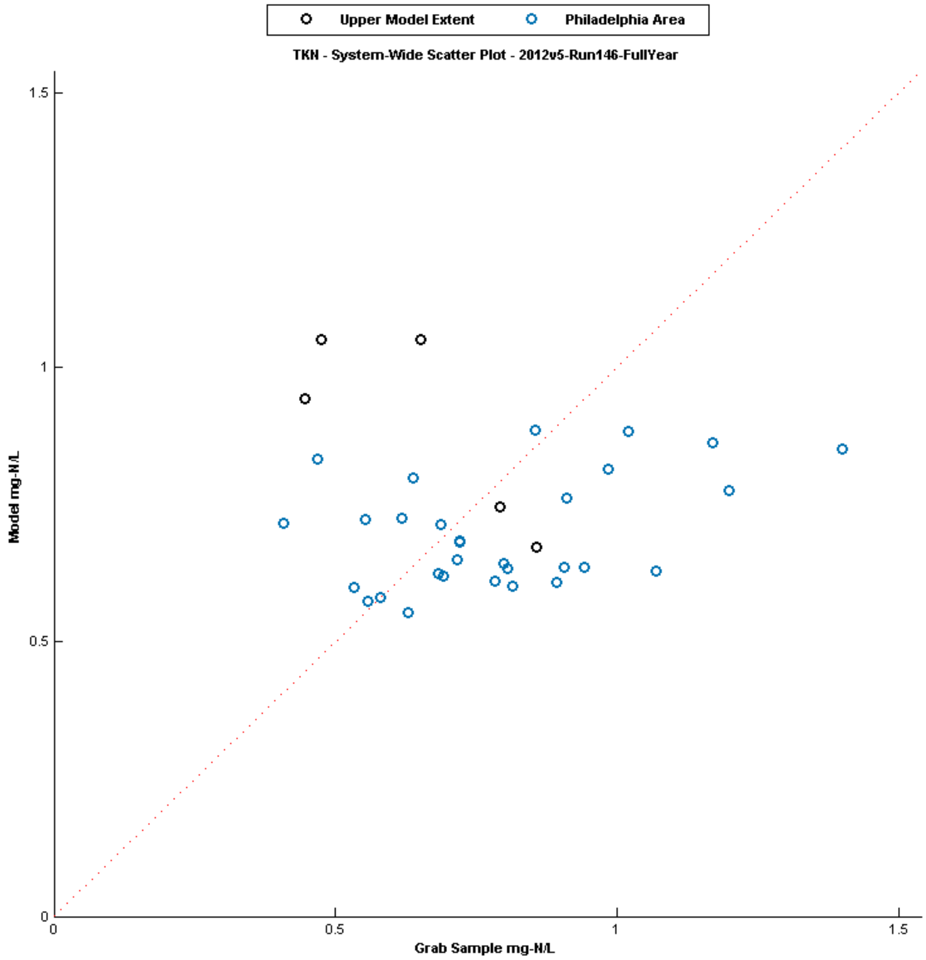
2.6.2. Summer



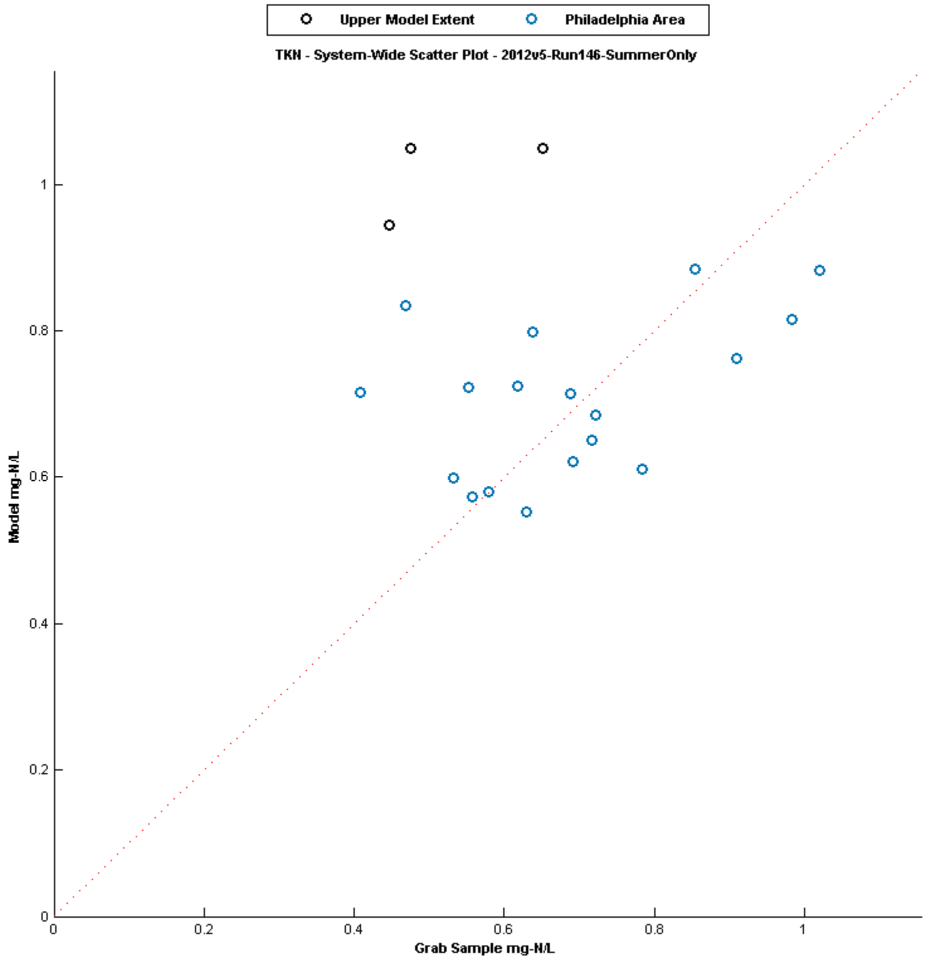
Upper Model Extent
Philadelphia Area
Lower Model Extent
NOX - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.5
1
1.5
2
2.5
3

2.7. Total Kjeldahl Nitrogen

2.7.1. April to October

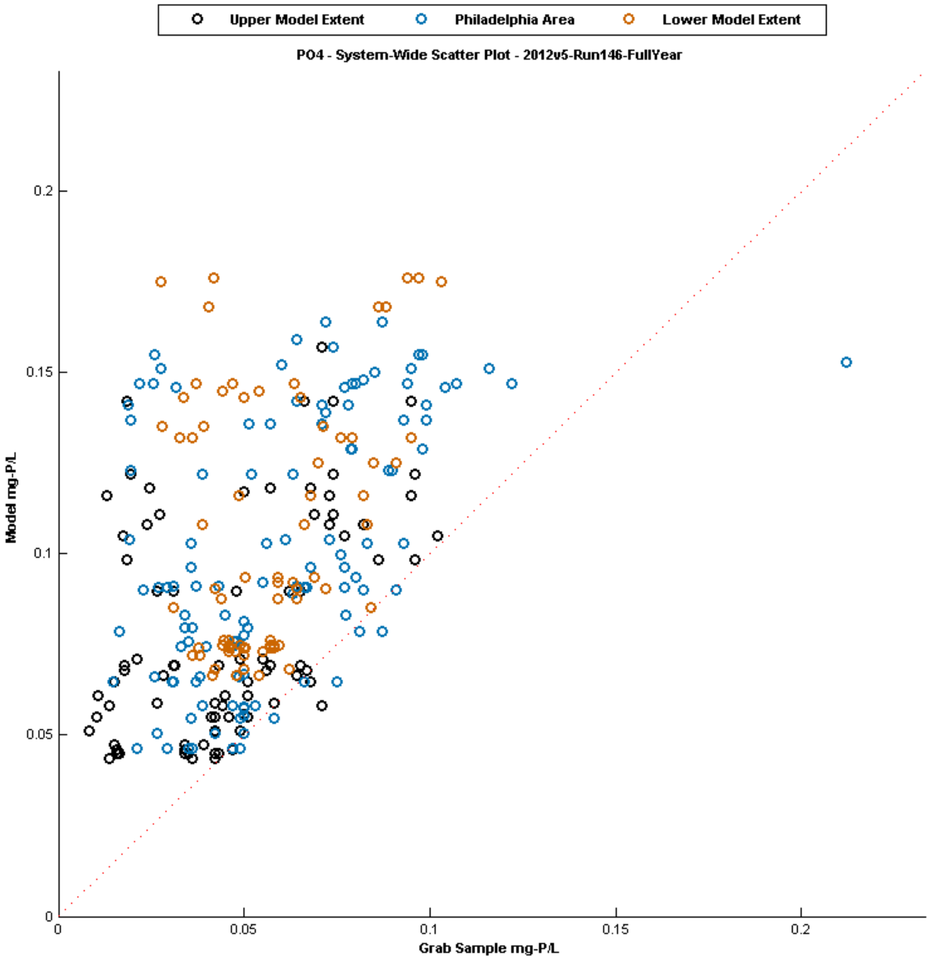


2.7.2. Summer

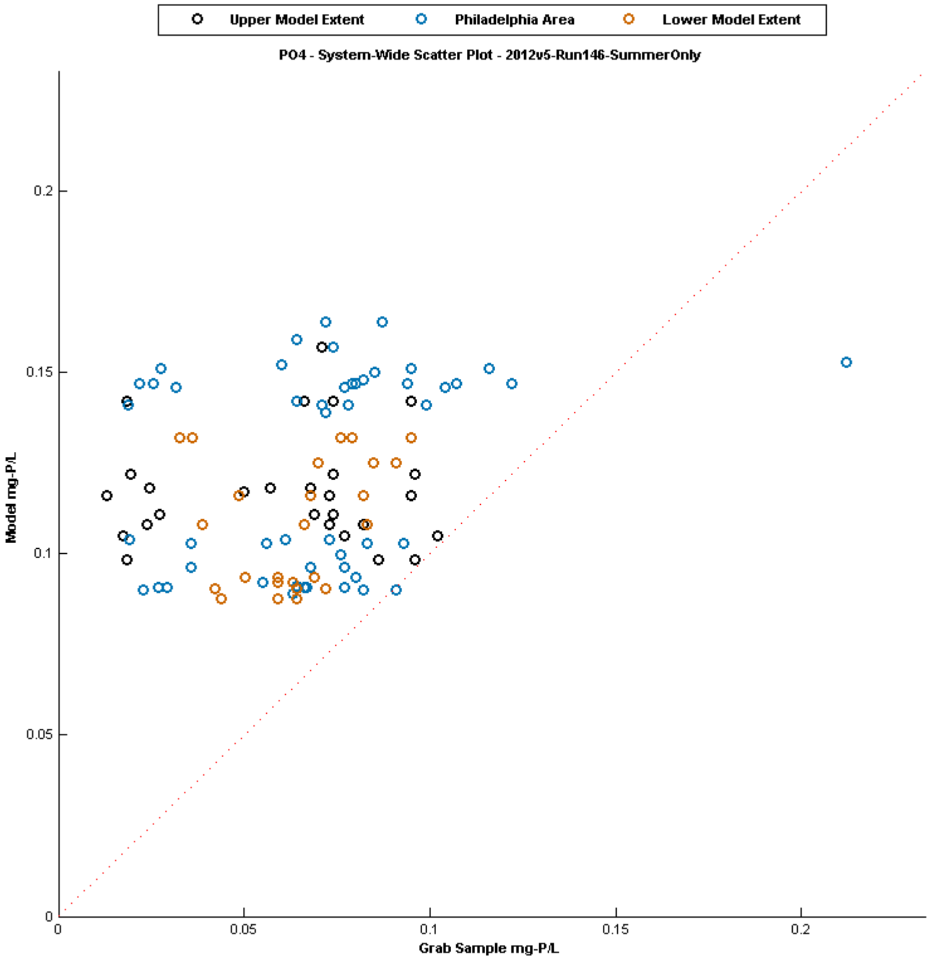

Upper Model Extent
Philadelphia Area
TKN - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.2
0.4
0.6
0.8
1

2.8. Orthophosphate

2.8.1. April to October

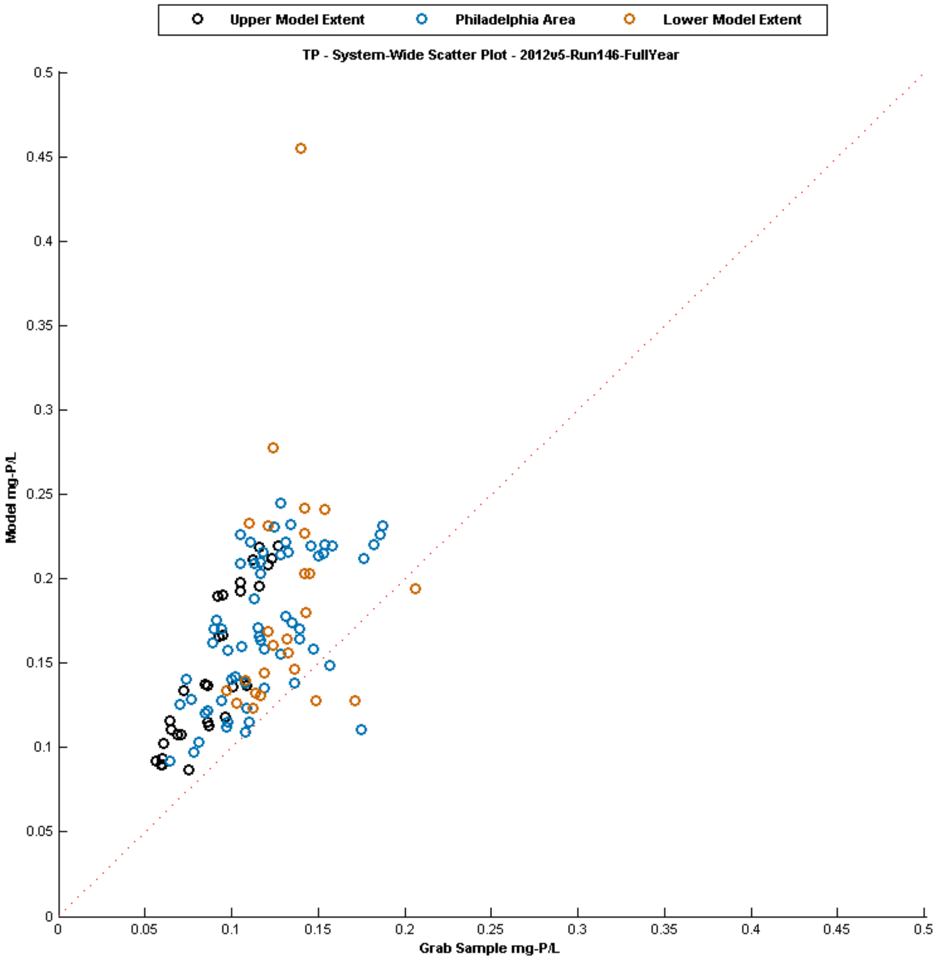


2.8.2. Summer

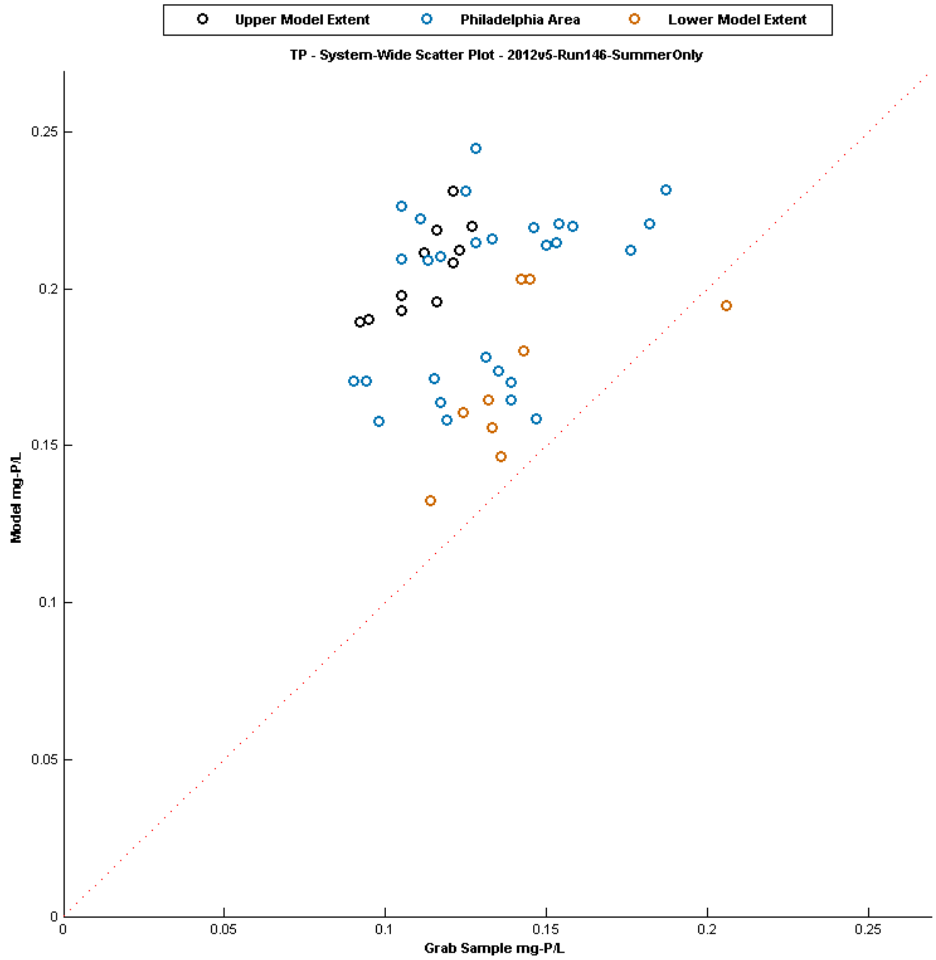

Upper Model Extent
Philadelphia Area
Lower Model Extent
PO4 - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg-P/L
Grab Sample mg-P/L
0
0.05
0.1
0.15
0.2

2.9. Total Phosphorous

2.9.1. April to October

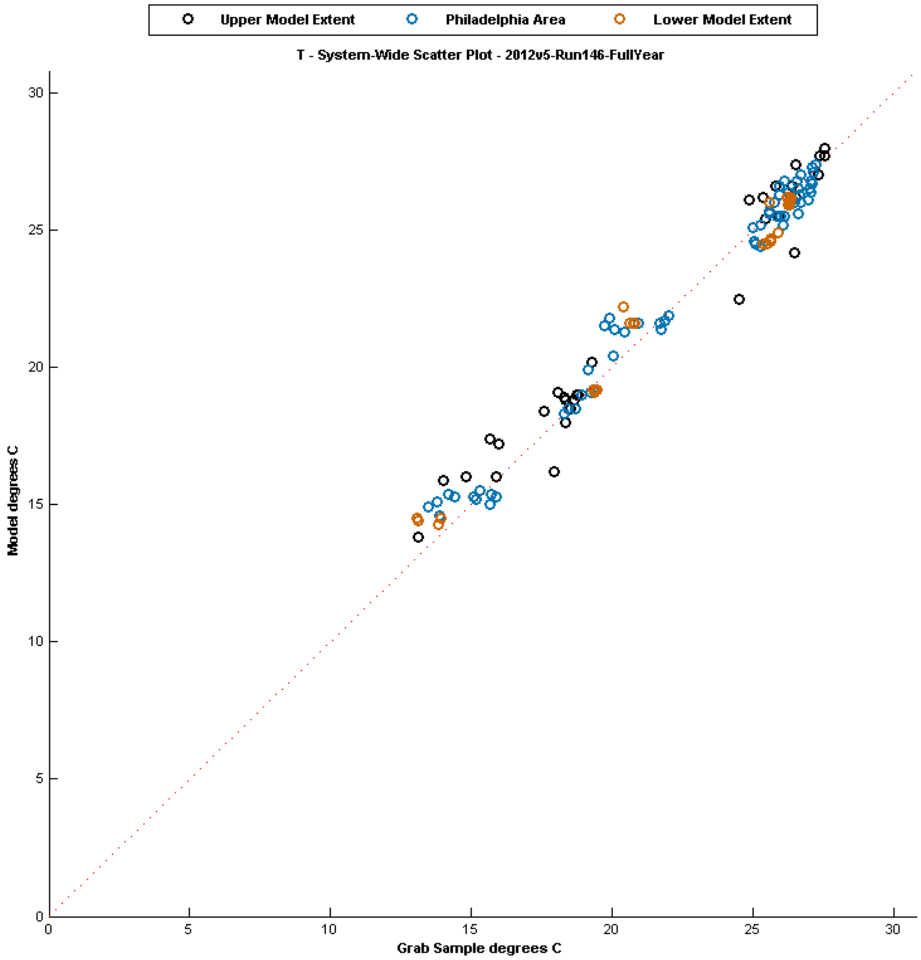


2.9.2. Summer

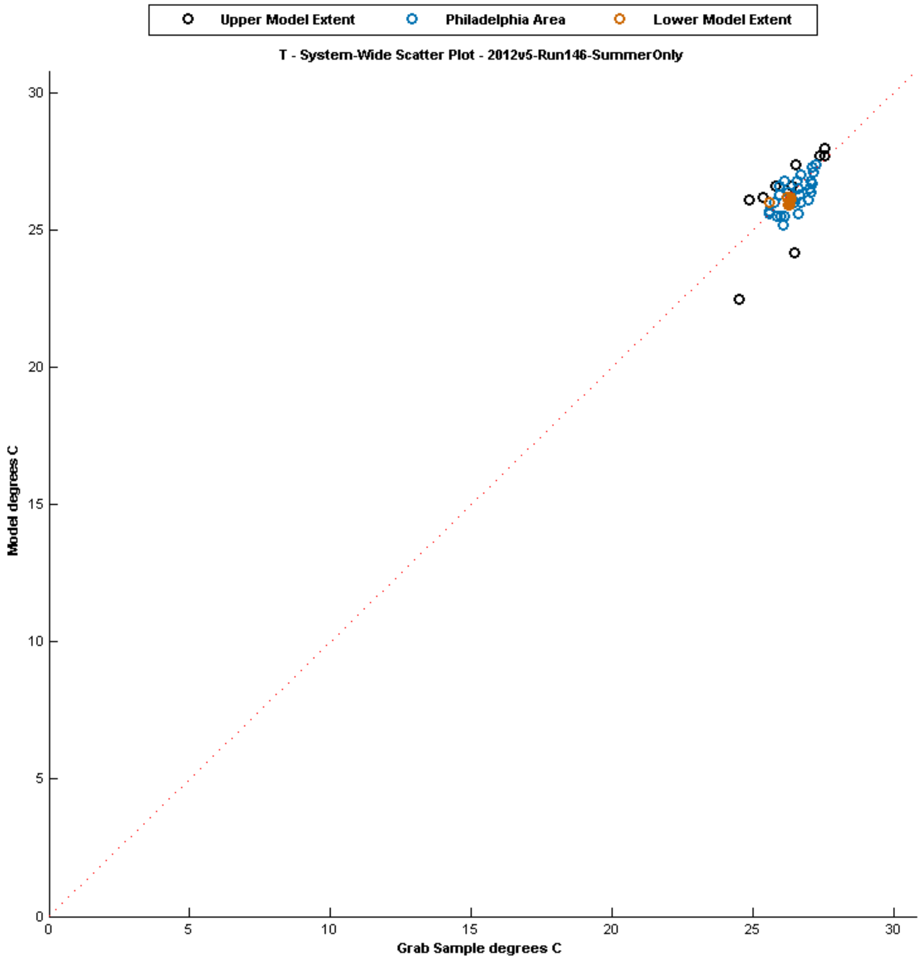

Upper Model Extent
Philadelphia Area
Lower Model Extent
TP - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model mg-P/L
Grab Sample mg-P/L
0
0.05
0.1
0.15
0.2
0.25

2.10. Temperature

2.10.1. April to October



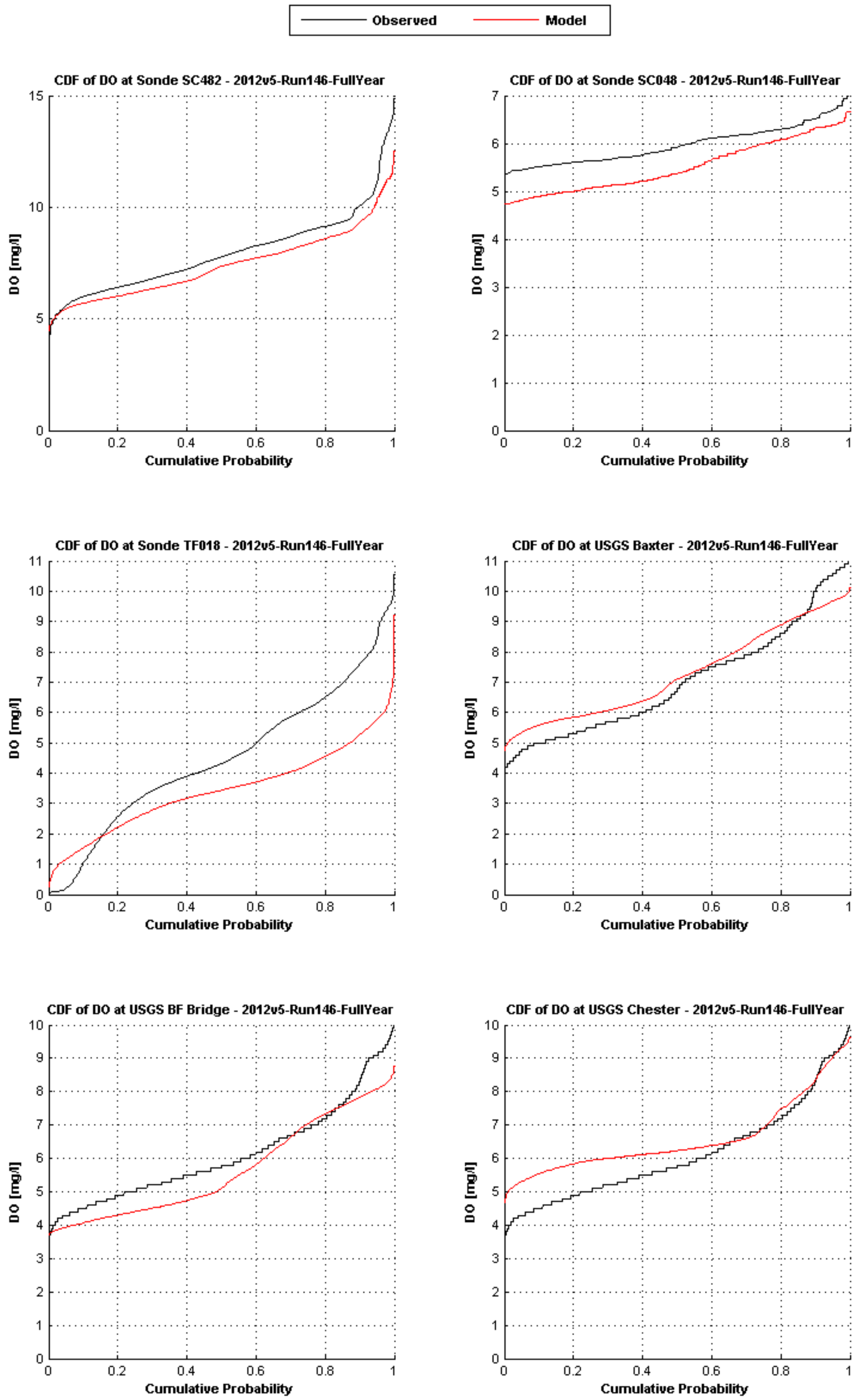
2.10.2. Summer


Upper Model Extent
Philadelphia Area
Lower Model Extent
T - System-Wide Scatter Plot - 2012v5-Run146-SummerOnly
Model degrees C
Grab Sample degrees C
0
5
10
15
20
25
30

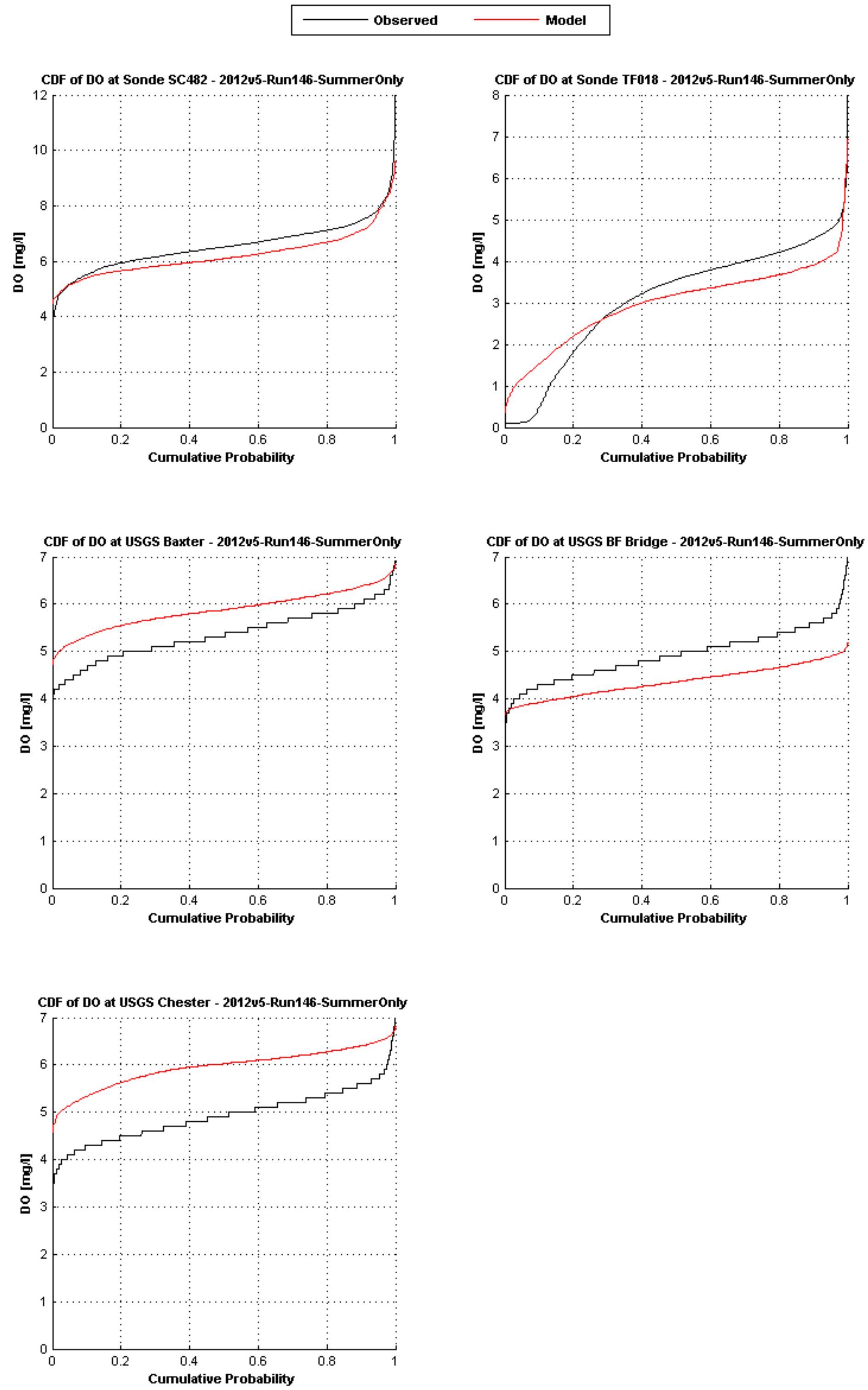
Chapter 3. CDF Plots

3.1. Dissolved Oxygen

3.1.1. April to October



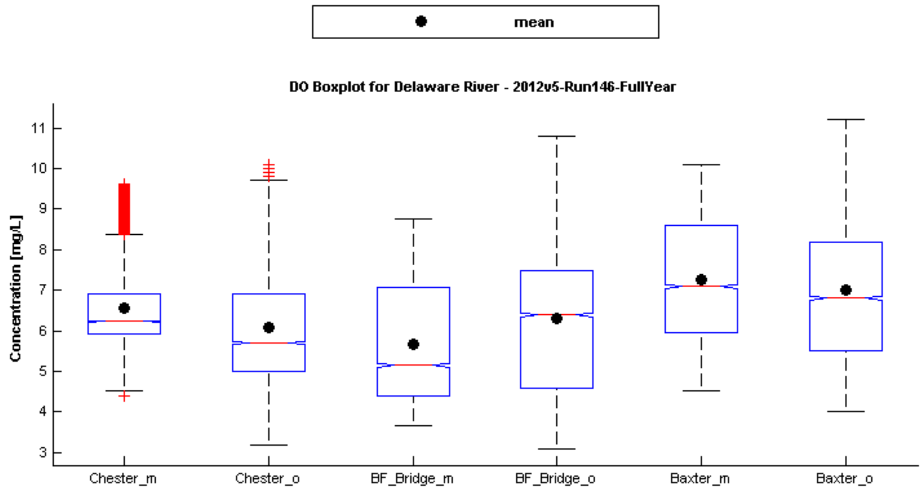
3.1.2. Summer


Observed
Model
CDF of DO at Sonde SC482 - 2012v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability
CDF of DO at Sonde TF018 - 2012v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability
CDF of DO at USGS Baxter - 2012v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability
CDF of DO at USGS BF Bridge - 2012v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability
CDF of DO at USGS Chester - 2012v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability

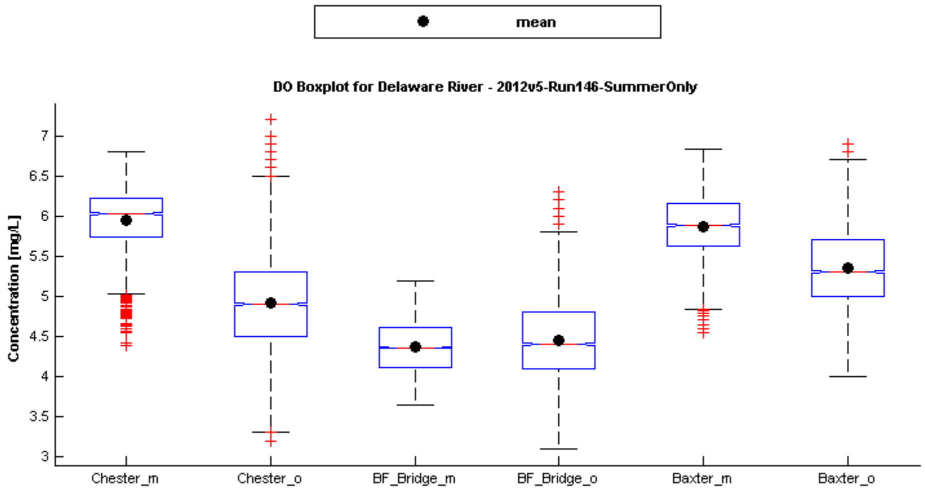
Chapter 4. Box Plots

4.1. Dissolved Oxygen

4.1.1. April to October

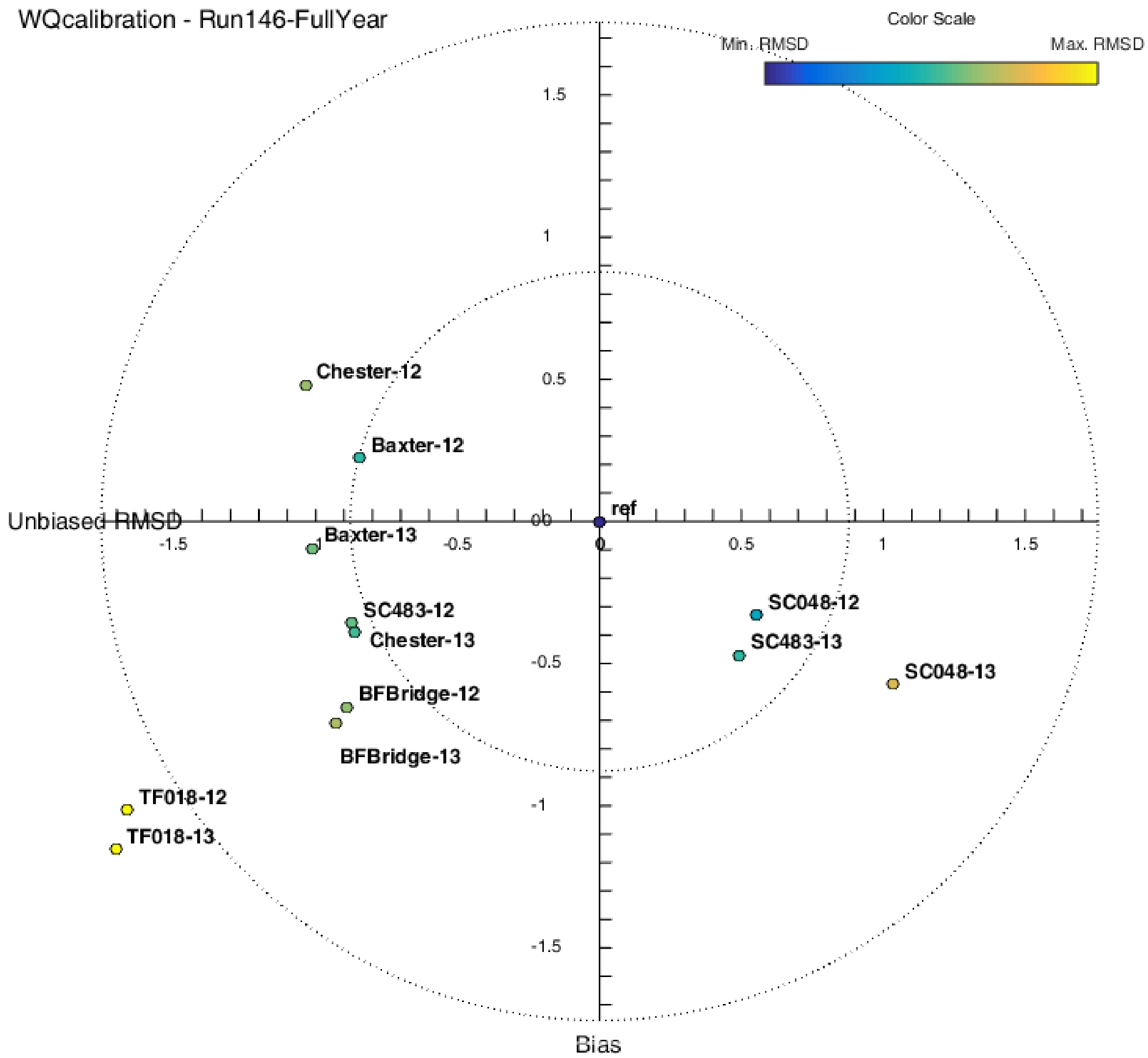


4.1.2. Summer

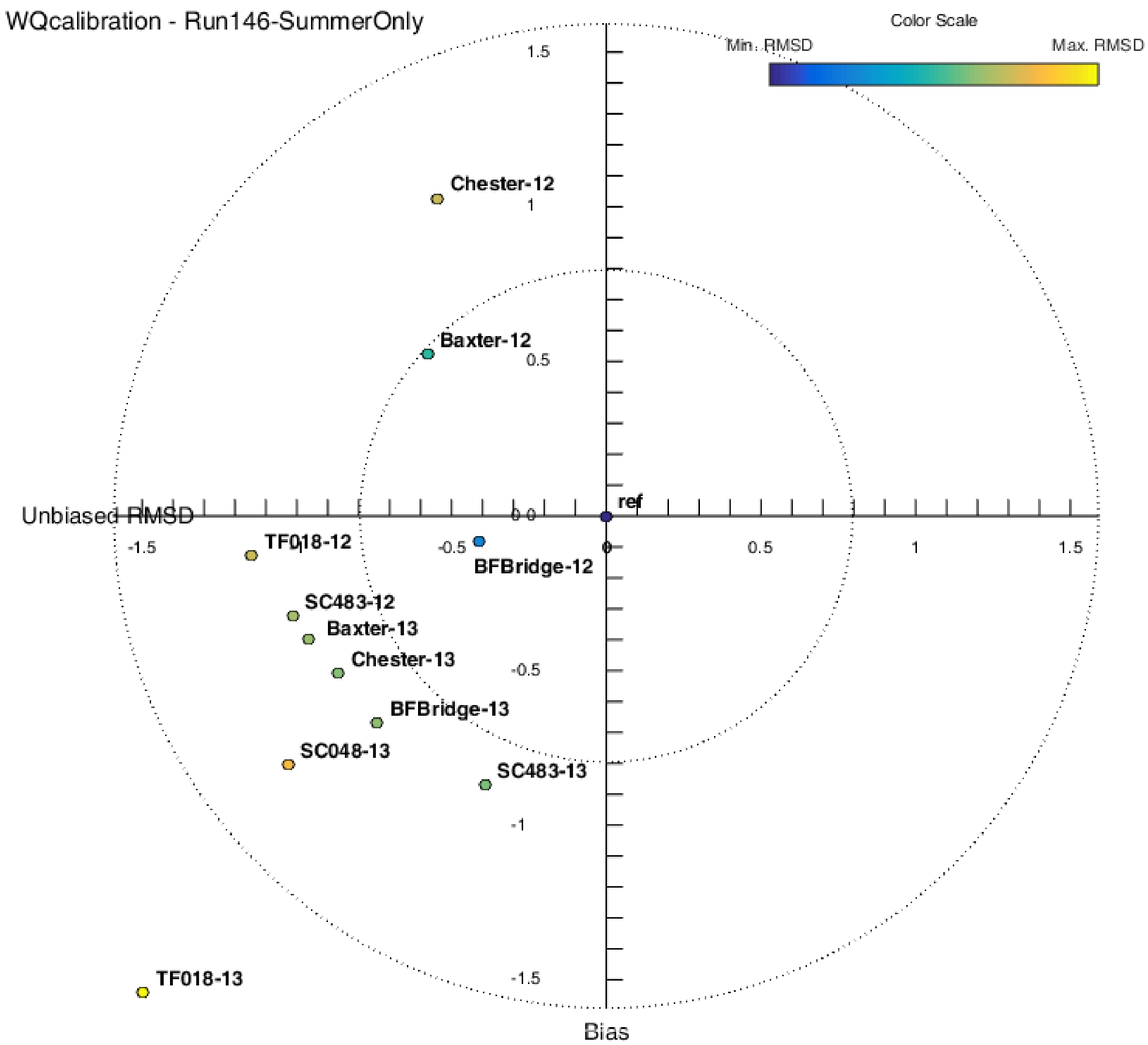

mean
DO Boxplot for Delaware River - 2012v5-Run146-SummerOnly
Concentration [mg/L]
7
6.5
6
5.5
5
4.5
4
3.5
3
Chester_m
Chester_o
BF_Bridge_m
BF_Bridge_o
Baxter_m
Baxter_o

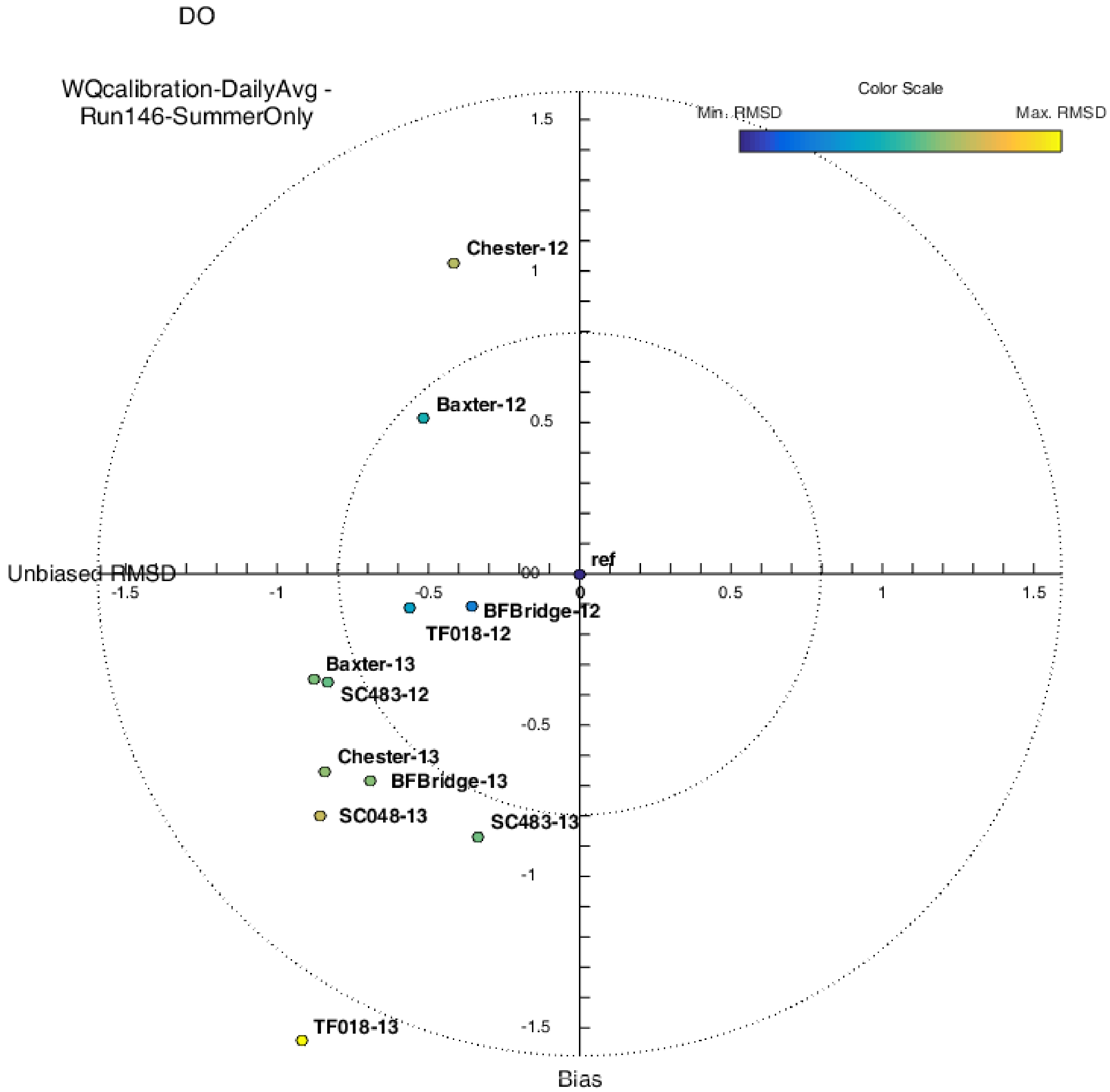
Chapter 5. Target Diagrams

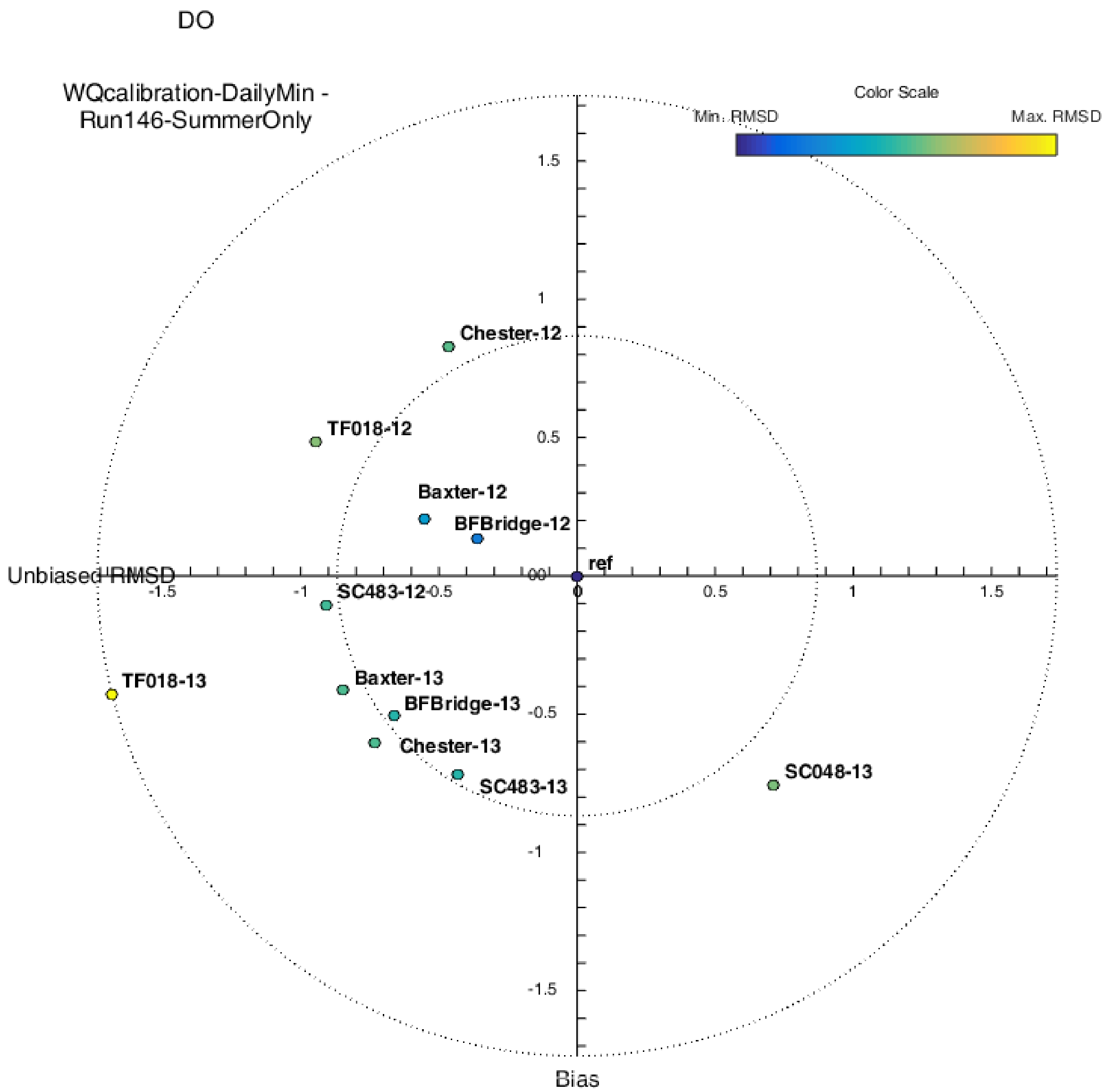
DO



DO


WQcalibration - Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
Chester-12
Baxter-12
ref
Unbiased RMSD
TF018-12
BFBridge-12
SC483-12
Baxter-13
Chester-13
BFBridge-13
SC048-13
SC483-13
TF018-13
Bias


DO
WQcalibration-DailyAvg - Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
Unbiased RMSD
Bias
ref
Chester-12
Baxter-12
BFBridge-12
TF018-12
Baxter-13
SC483-12
Chester-13
BFBridge-13
SC048-13
SC483-13
TF018-13
-1.5
-1
-0.5
0
0.5
1
1.5


DO
WQcalibration-DailyMin - Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
1.5
1
0.5
-0.5
-1
-1.5
0
0.5
1
1.5
Unbiased RMSD
Bias
ref
Chester-12
TF018-12
Baxter-12
BFBridge-12
SC483-12
TF018-13
Baxter-13
BFBridge-13
Chester-13
SC483-13
SC048-13

Appendix B

2013v5 Run146

2013v5 Run146

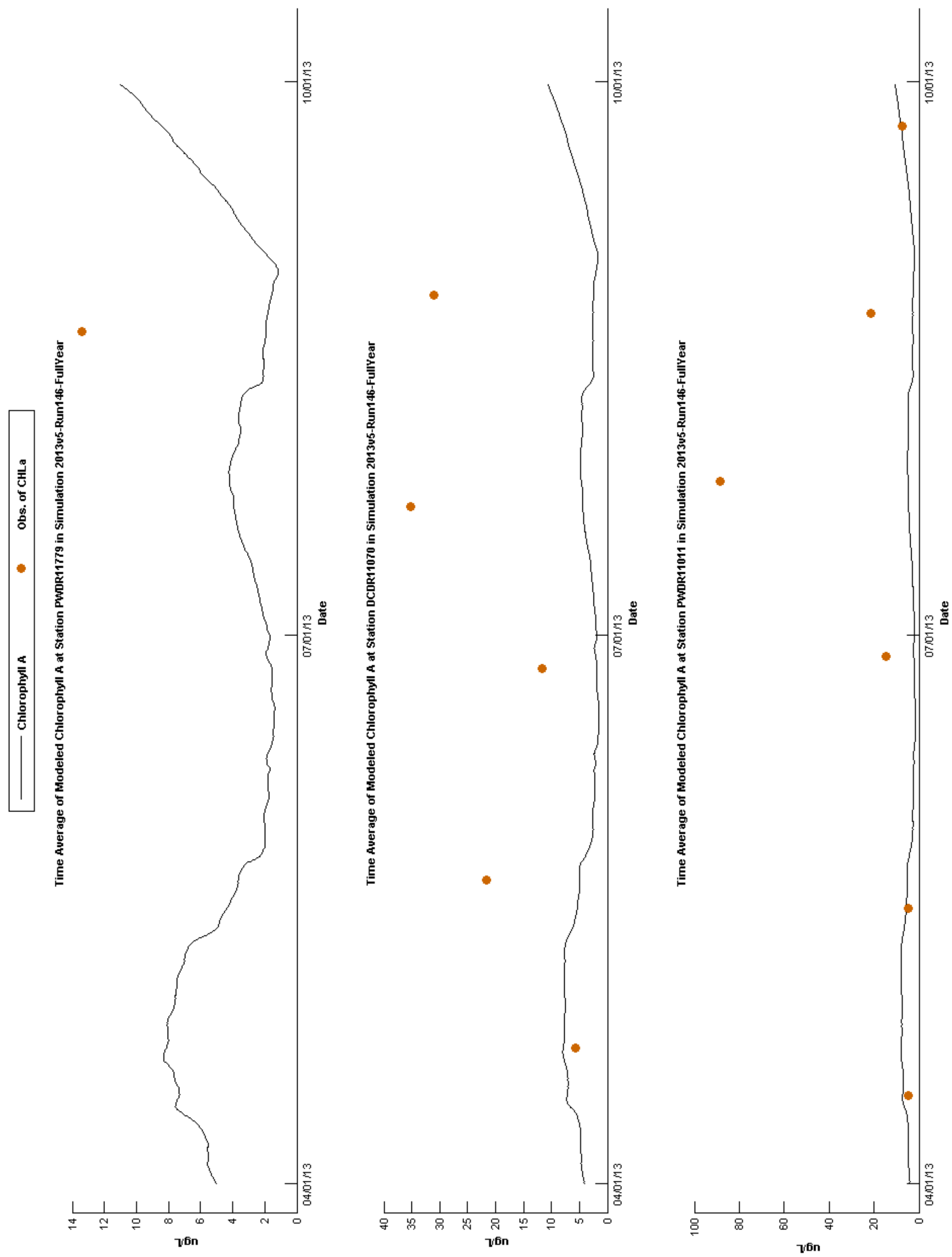
2013v5 Run146:

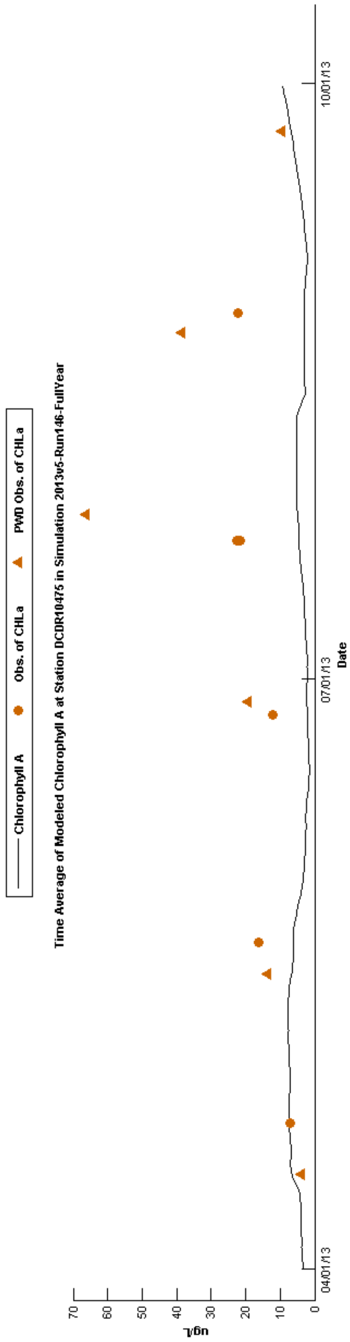
Table of Contents

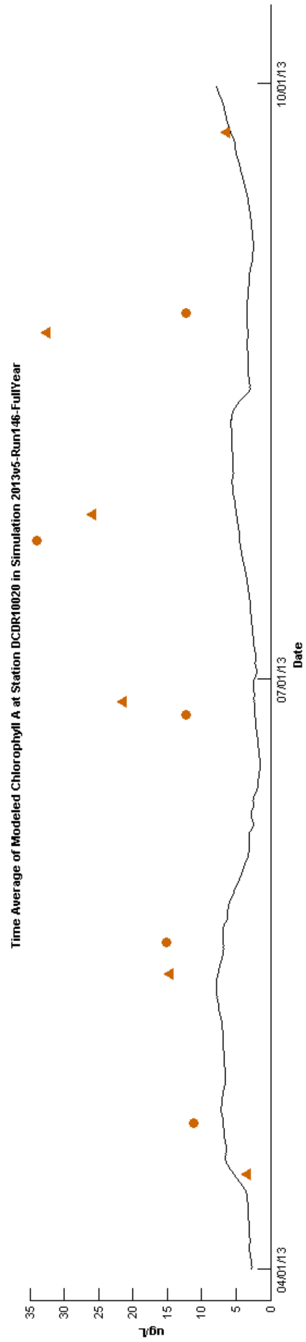
Chapter 1. Time series plots

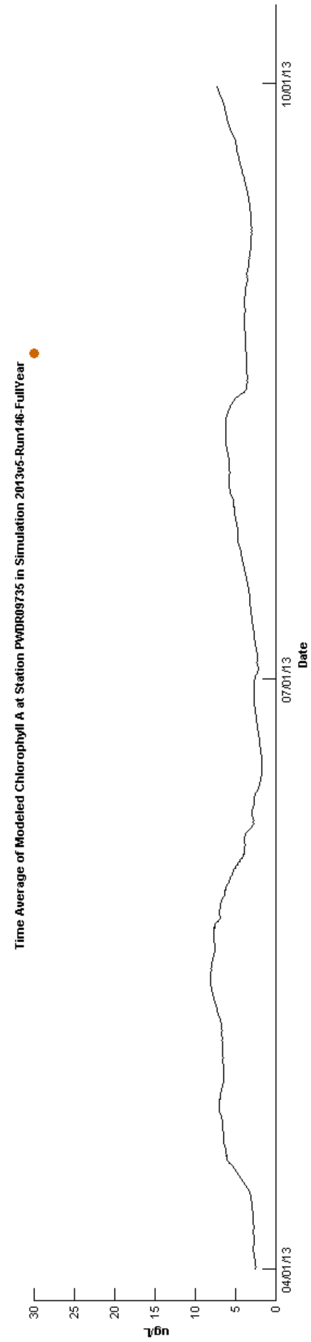
1.1. Biomass - Algae

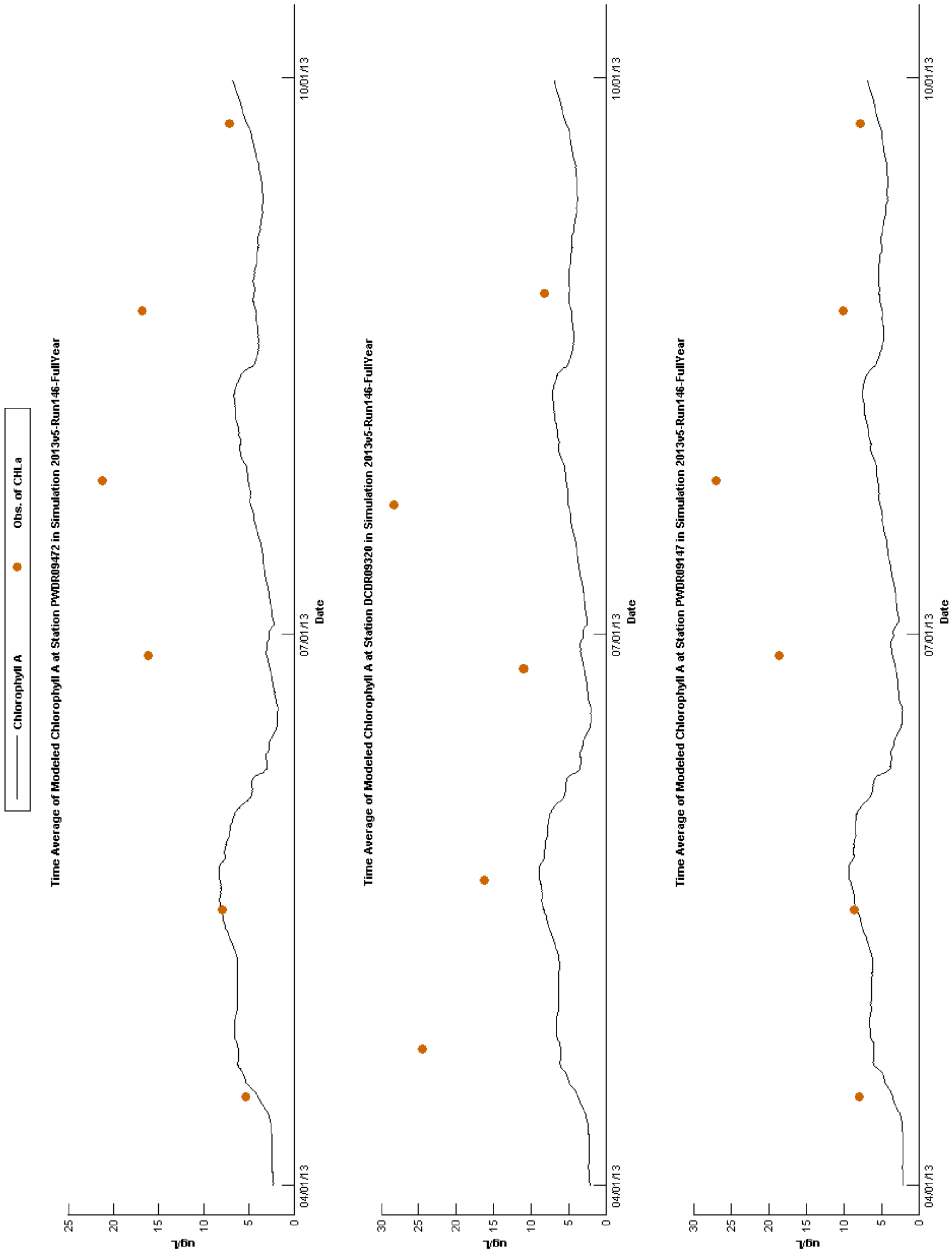
1.1.1. April to October

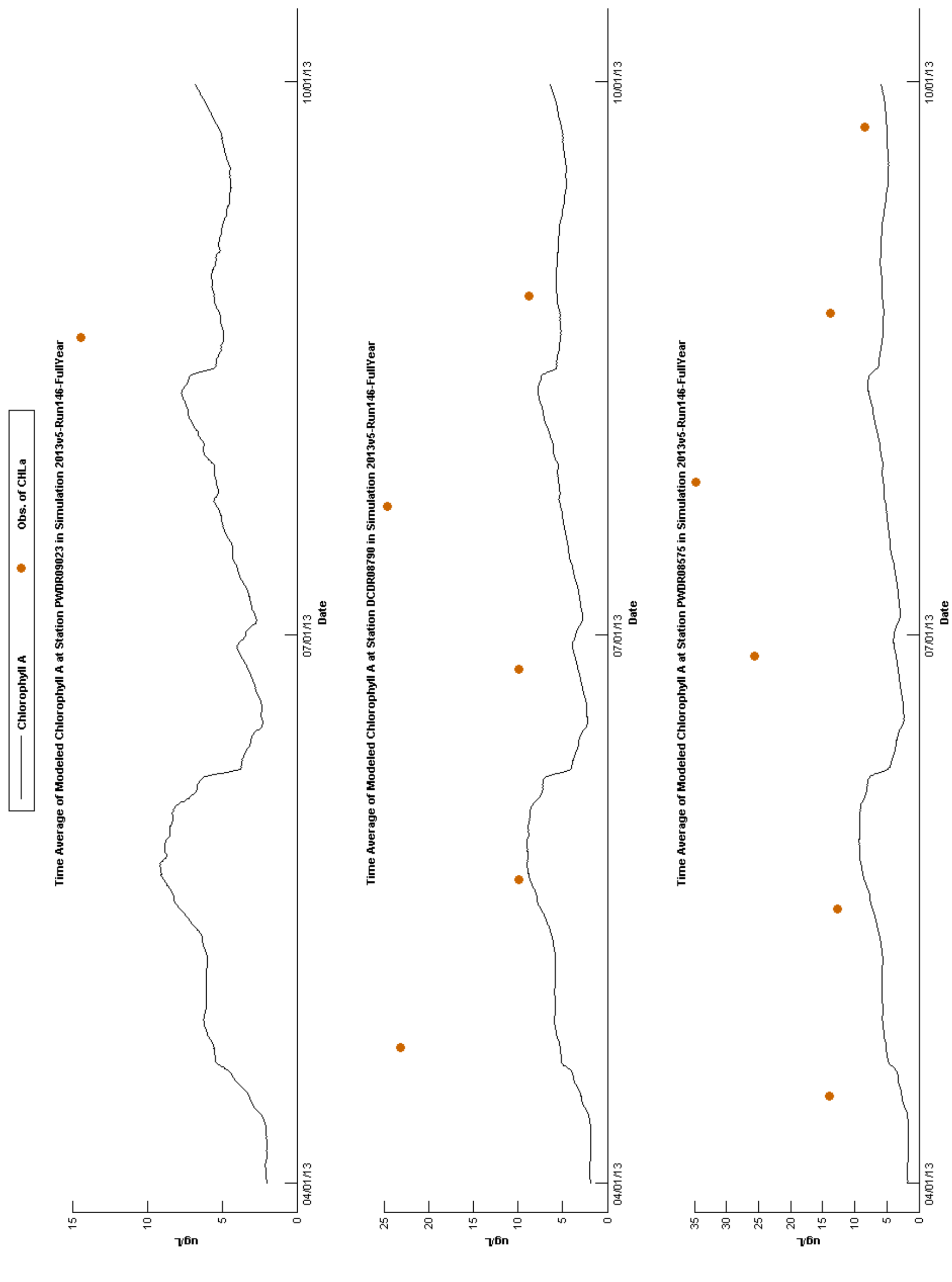

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR11779 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR11070 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station PWDR11011 in Simulation 2013v5-Run146-FullYear
ug/L
Date
04/01/13
07/01/13
10/01/13

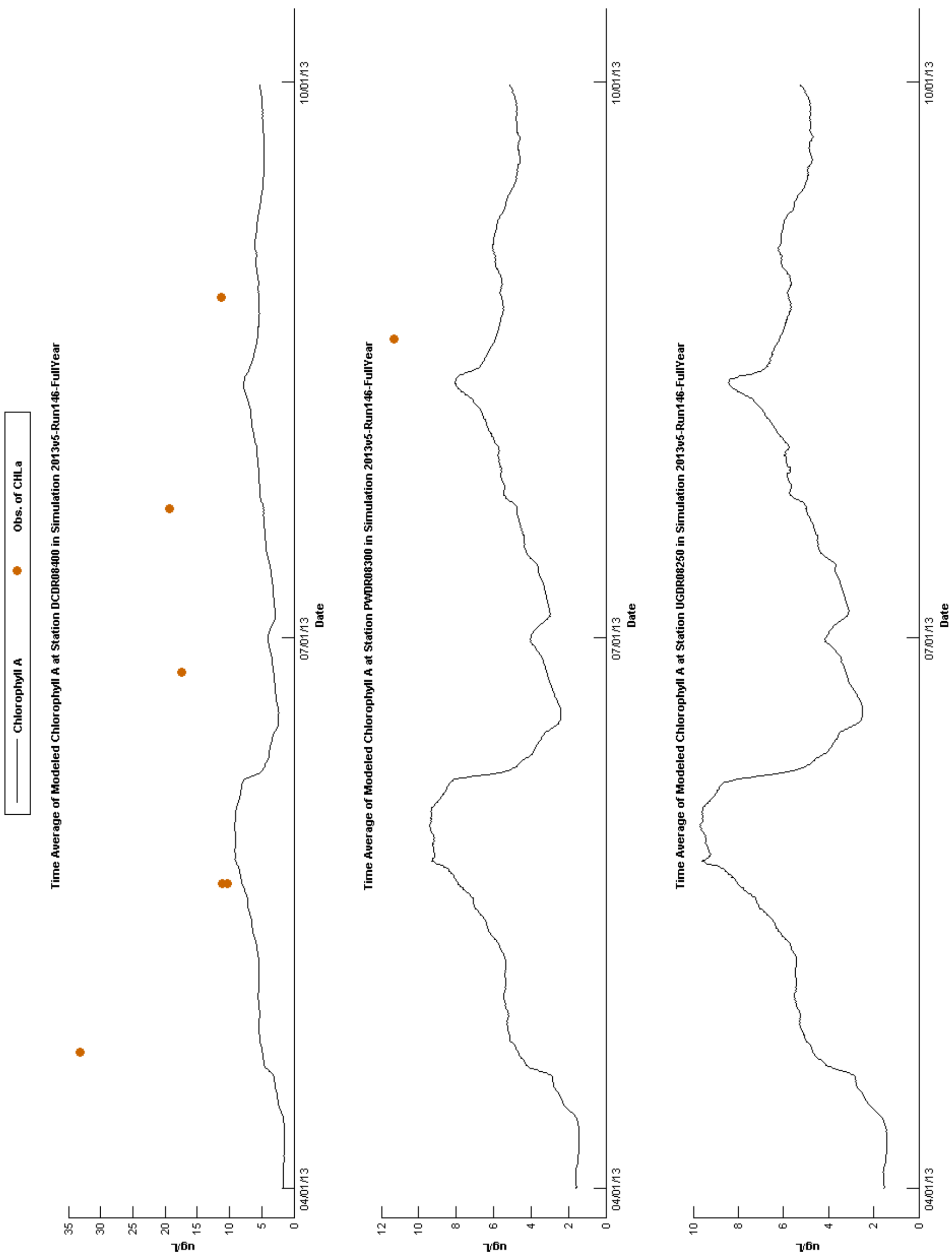

Time Average of Modeled Chlorophyll A at Station DCDR10475 in Simulation 2013v5-Run146-FullYear
Chlorophyll A
Obs. of CHLa
PWD Obs. of CHLa
ug/L
70
60
50
40
30
20
10
0
04/01/13
07/01/13
10/01/13
Date

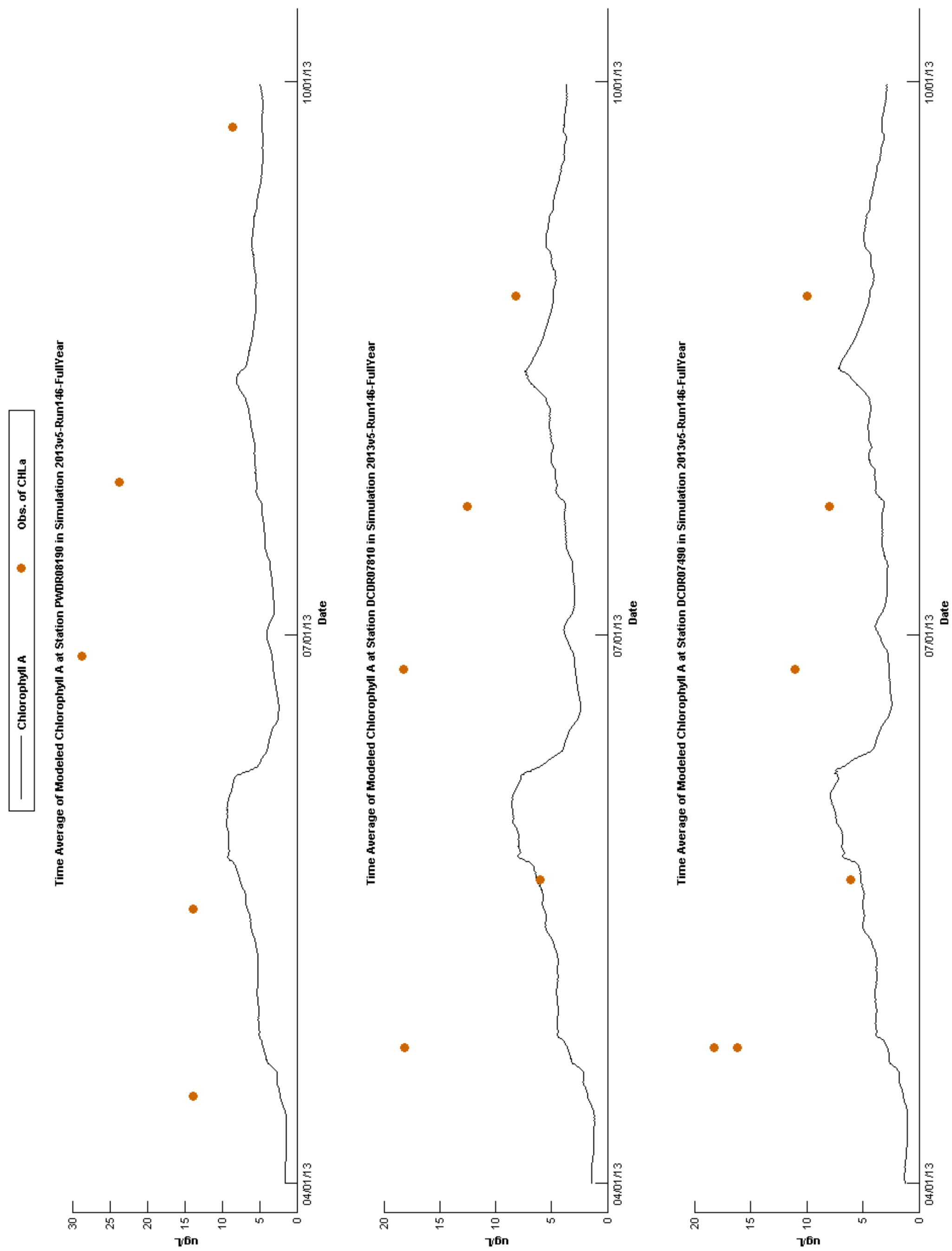

Time Average of Modeled Chlorophyll A at Station DCDR10020 in Simulation 2013v5-Run146-FullYear
ug/L
35
30
25
20
15
10
5
0
04/01/13
07/01/13
10/01/13
Date

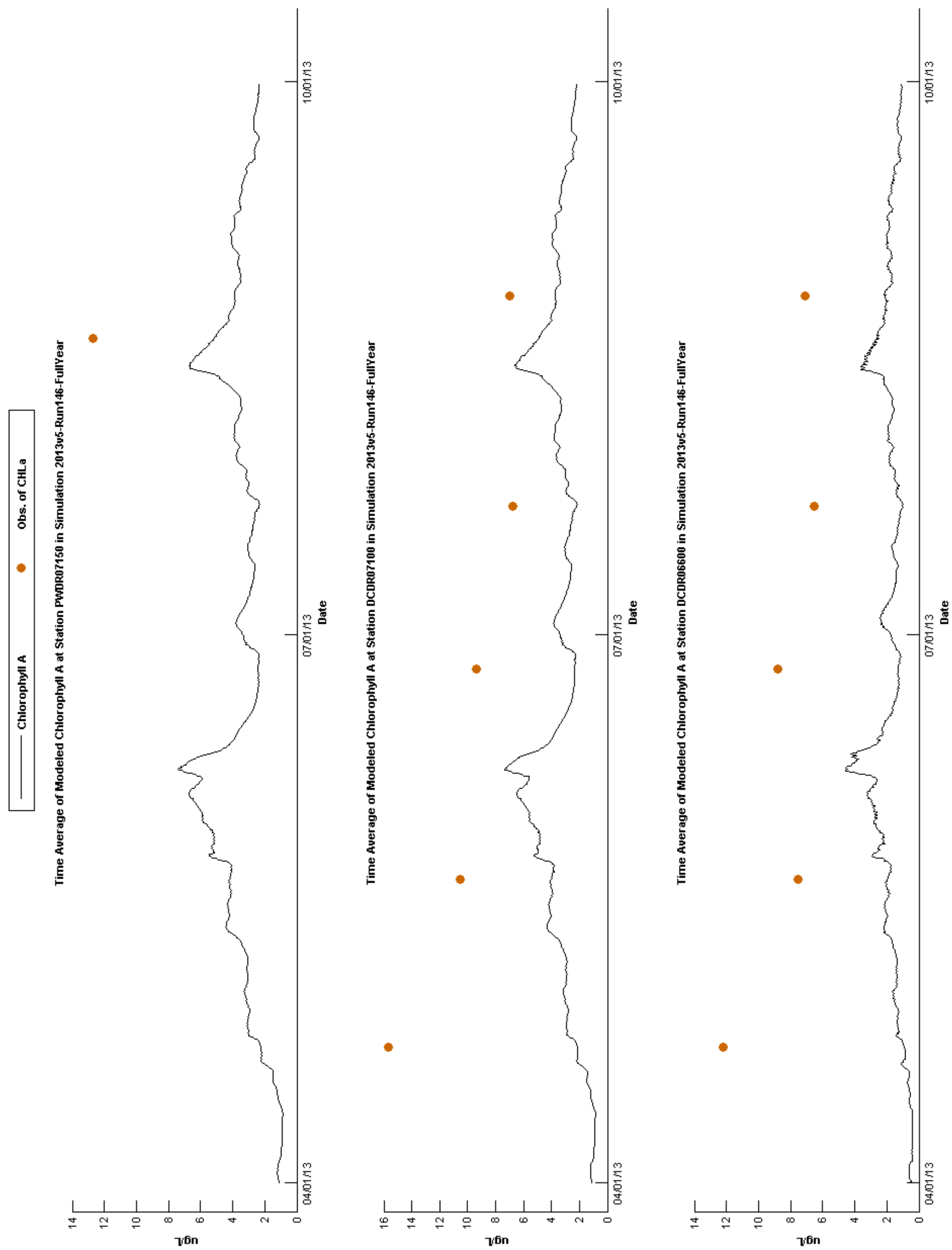

Time Average of Modeled Chlorophyll A at Station PWDR09735 in Simulation 2013v5-Run146-FullYear
ug/L
30
25
20
15
10
5
0
04/01/13
07/01/13
10/01/13
Date

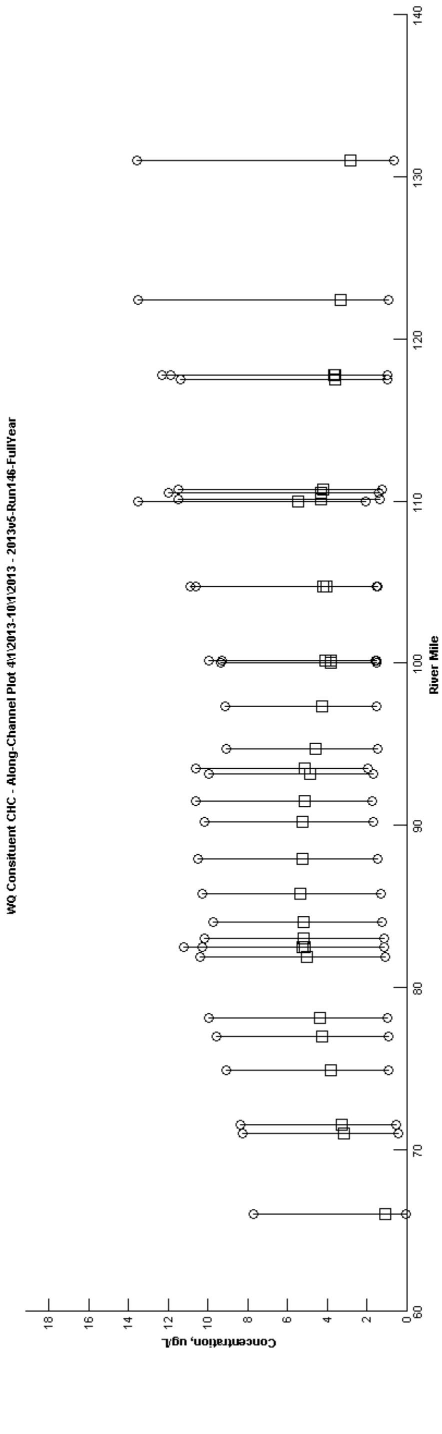

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR09472 in Simulation 2013v5-Run146-FullYear
ug/L
25
20
15
10
5
0
04/01/13
07/01/13
10/01/13
Date
Time Average of Modeled Chlorophyll A at Station DCDR09320 in Simulation 2013v5-Run146-FullYear
ug/L
30
25
20
15
10
5
0
04/01/13
07/01/13
10/01/13
Date
Time Average of Modeled Chlorophyll A at Station PWDR09147 in Simulation 2013v5-Run146-FullYear
ug/L
30
25
20
15
10
5
0
04/01/13
07/01/13
10/01/13
Date


Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR09023 in Simulation 2013v5-Run146-FullYear
ug/L
Date
04/01/13
07/01/13
10/01/13
Time Average of Modeled Chlorophyll A at Station DCDR08790 in Simulation 2013v5-Run146-FullYear
ug/L
Date
Time Average of Modeled Chlorophyll A at Station PWDR08575 in Simulation 2013v5-Run146-FullYear
ug/L
Date

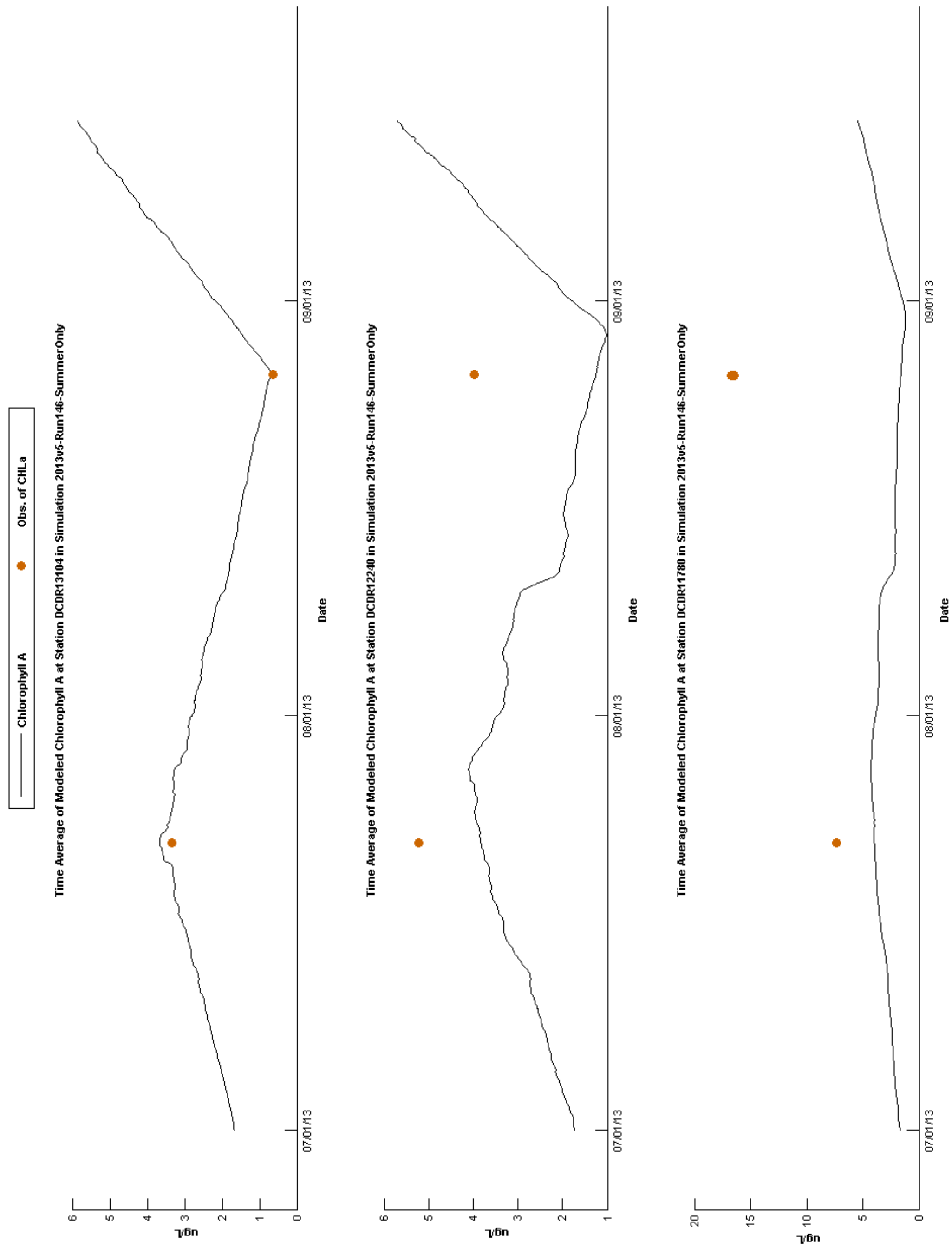

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR08400 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station PWDR08300 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station UGDR08250 in Simulation 2013v5-Run146-FullYear
ug/L
Date
04/01/13
07/01/13
10/01/13

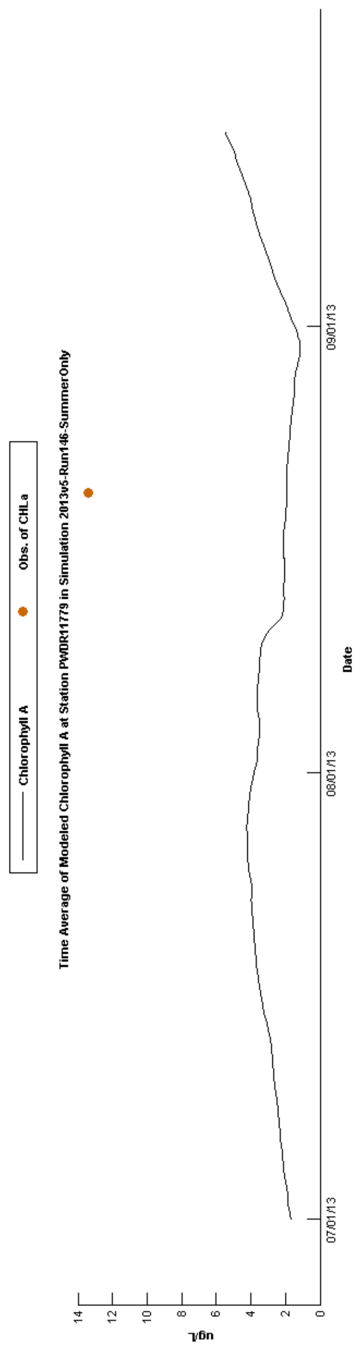

Time Average of Modeled Chlorophyll A at Station PWDR08190 in Simulation 2013v5-Run146-FullYear
Chlorophyll A
Obs. of CHLa
ug/L
Date
04/01/13
07/01/13
10/01/13
Time Average of Modeled Chlorophyll A at Station DCDR07810 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR07490 in Simulation 2013v5-Run146-FullYear

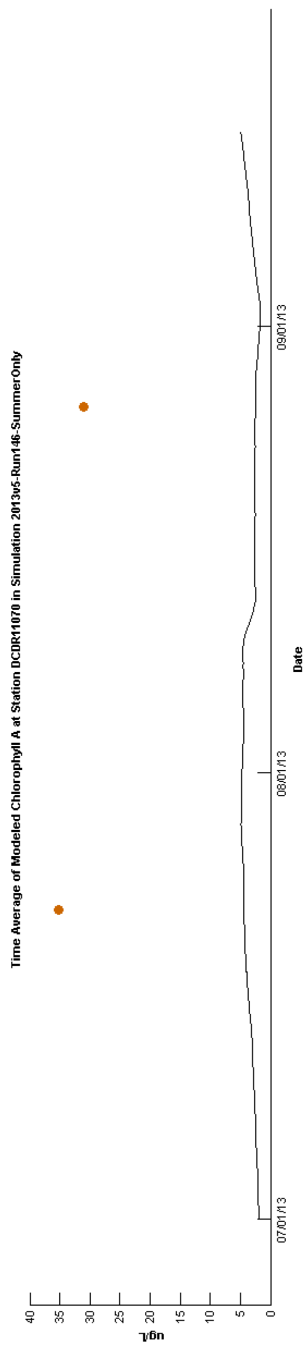

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR07150 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR07100 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Chlorophyll A at Station DCDR06600 in Simulation 2013v5-Run146-FullYear
ug/L
Date
04/01/13
07/01/13
10/01/13

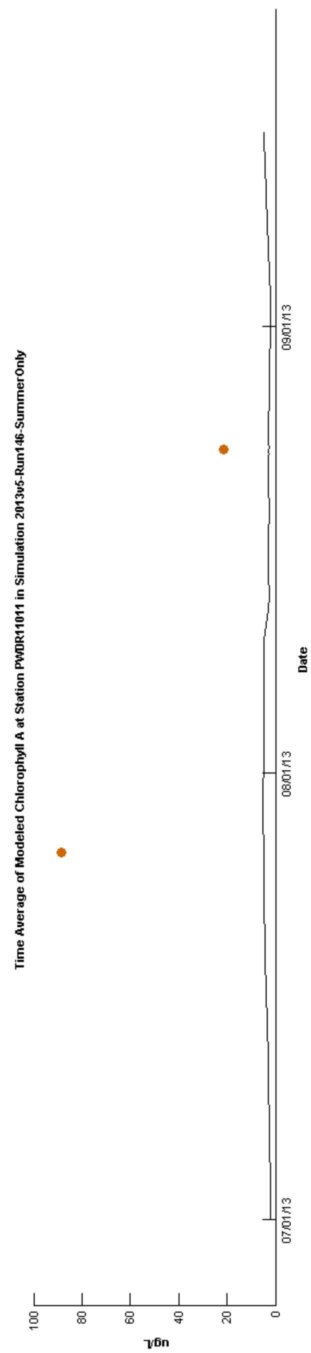

WQ Consituent CHC - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
River Mile
Concentration, ug/L

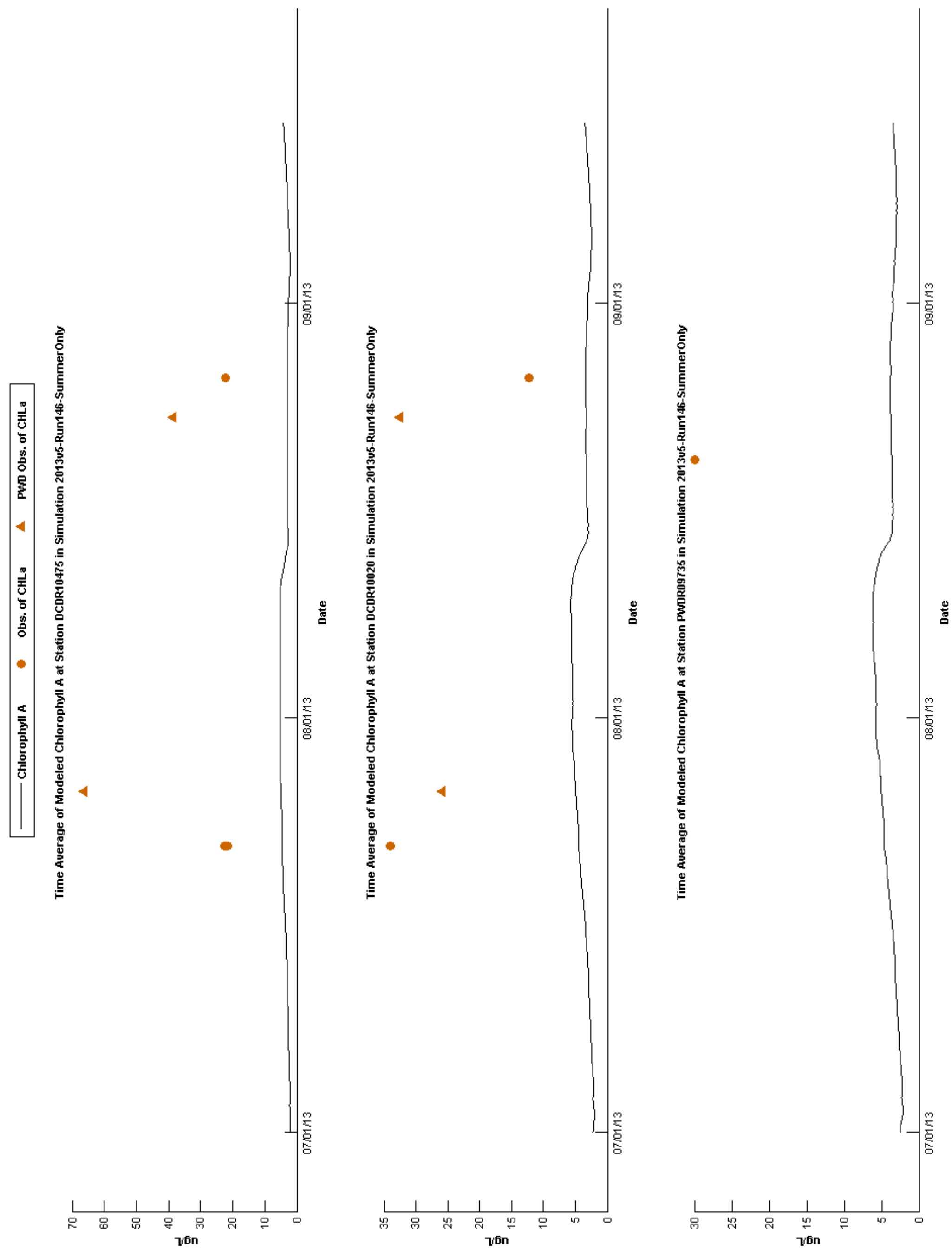
1.1.2. Summer

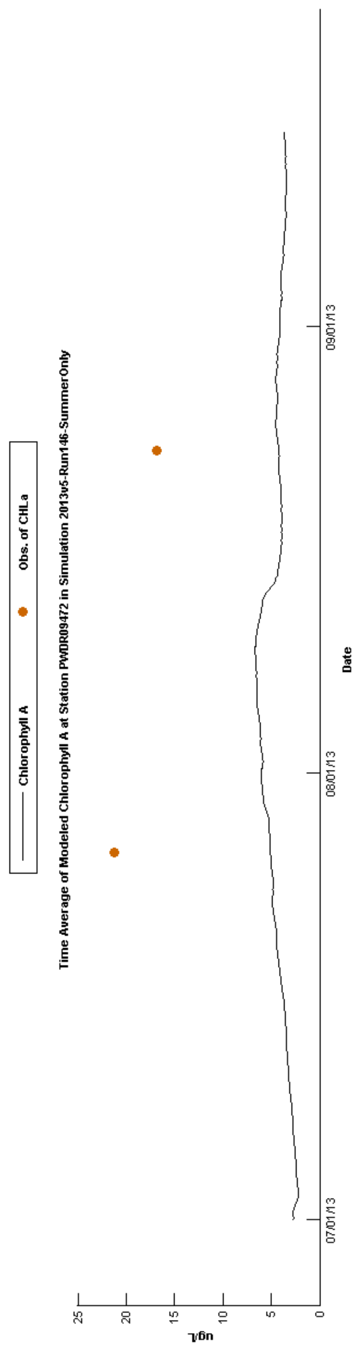

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR13104 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR12240 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR11780 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

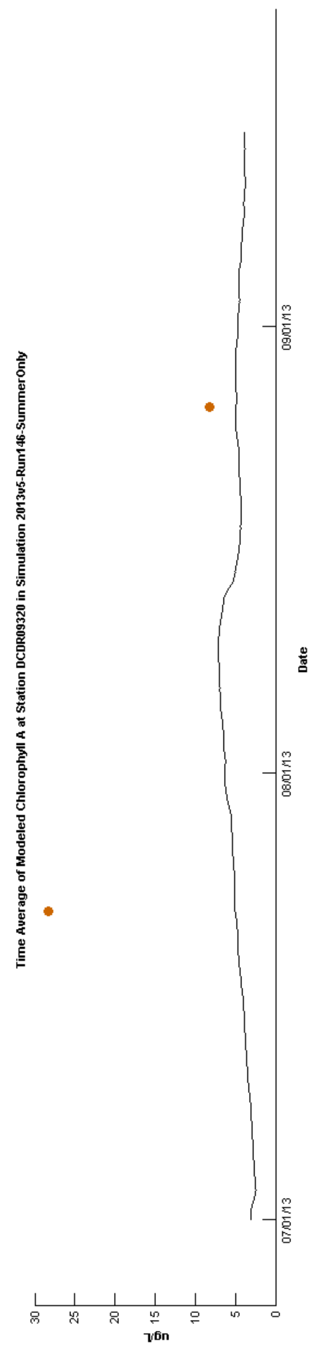

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR11779 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

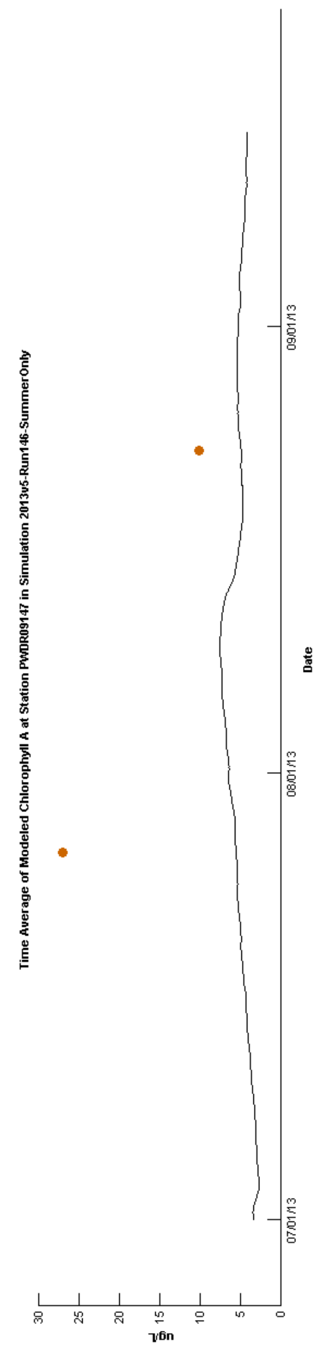

Time Average of Modeled Chlorophyll A at Station DCDR11070 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

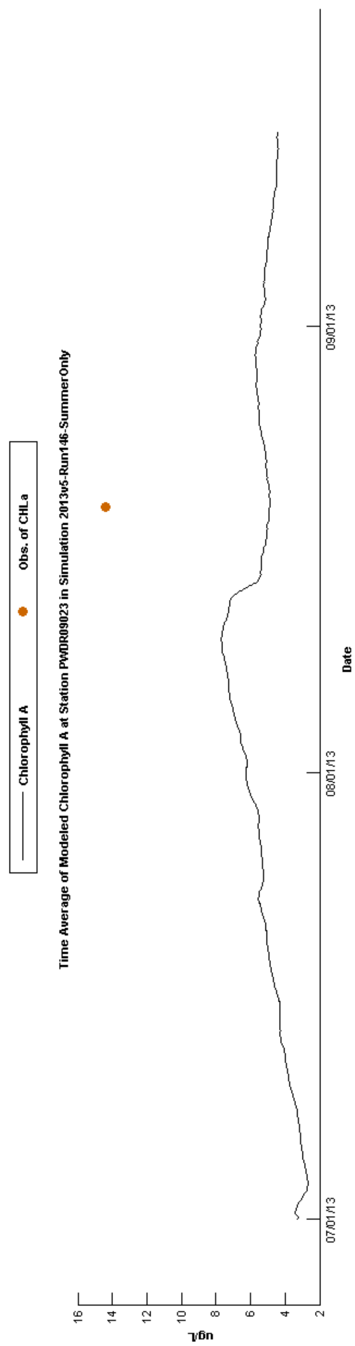

Time Average of Modeled Chlorophyll A at Station PWDR11011 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

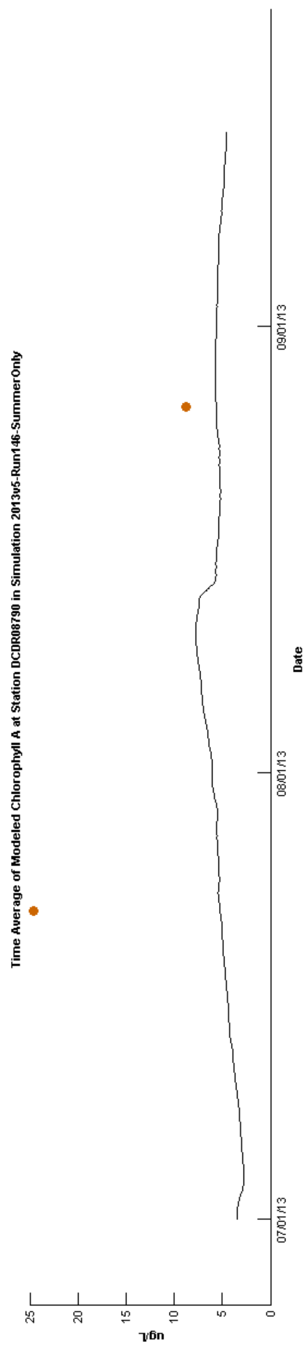

Chlorophyll A
Obs. of CHLa
PWD Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR10475 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Chlorophyll A at Station DCDR10020 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Chlorophyll A at Station PWDR09735 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

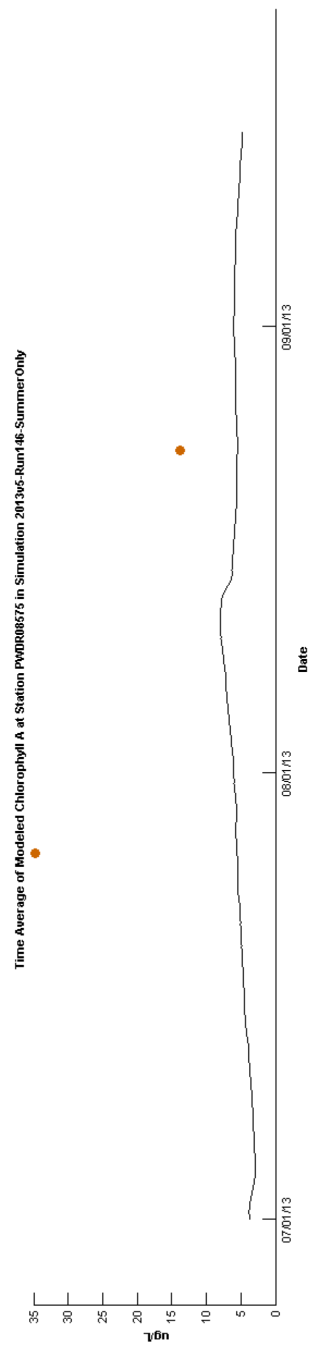

Time Average of Modeled Chlorophyll A at Station PWDR09472 in Simulation 2013v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
0
5
10
15
20
25
07/01/13
08/01/13
09/01/13
Date

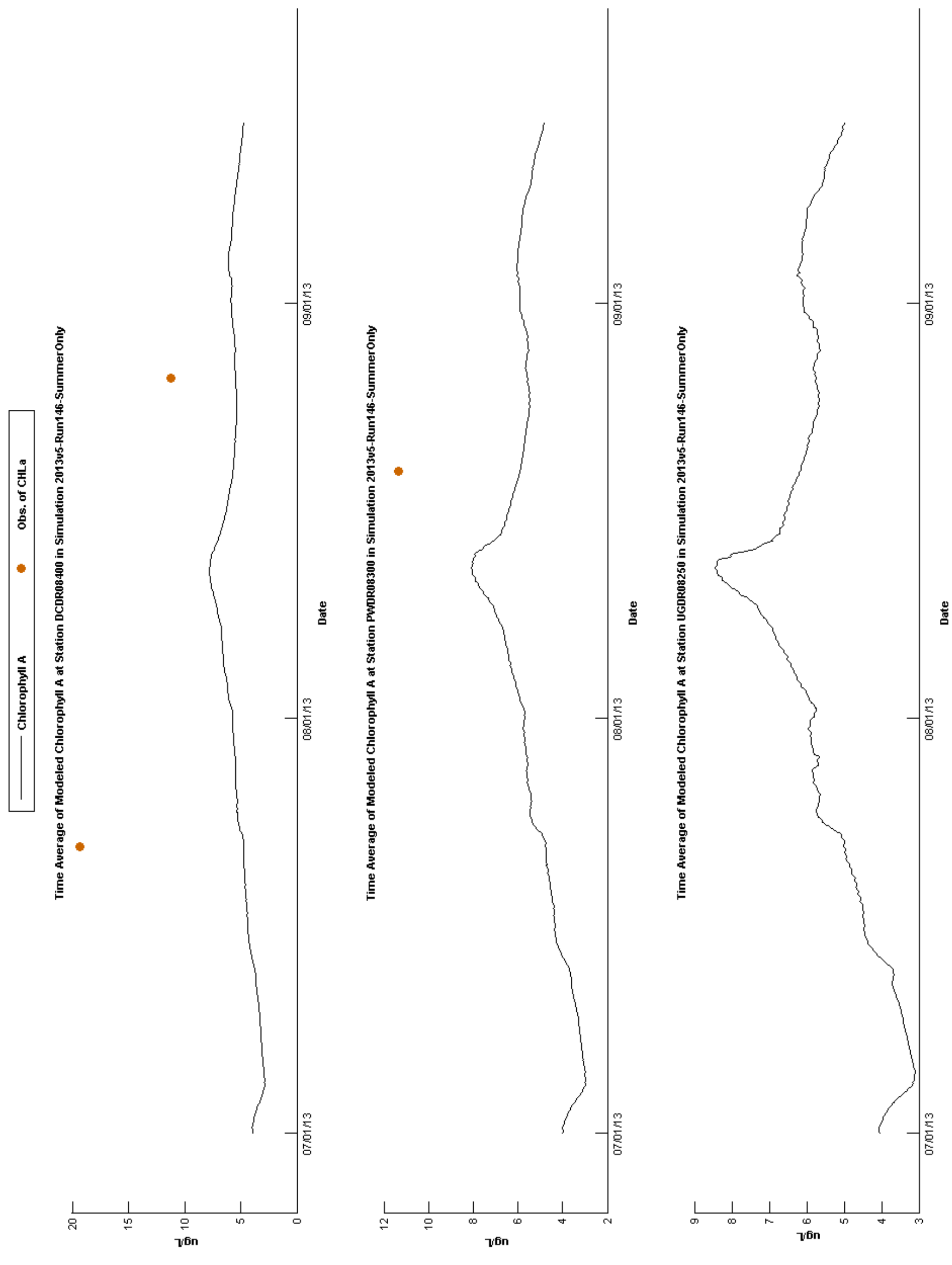

Time Average of Modeled Chlorophyll A at Station DCDR09320 in Simulation 2013v5-Run146-SummerOnly
ug/L
0
5
10
15
20
25
30
07/01/13
08/01/13
09/01/13
Date

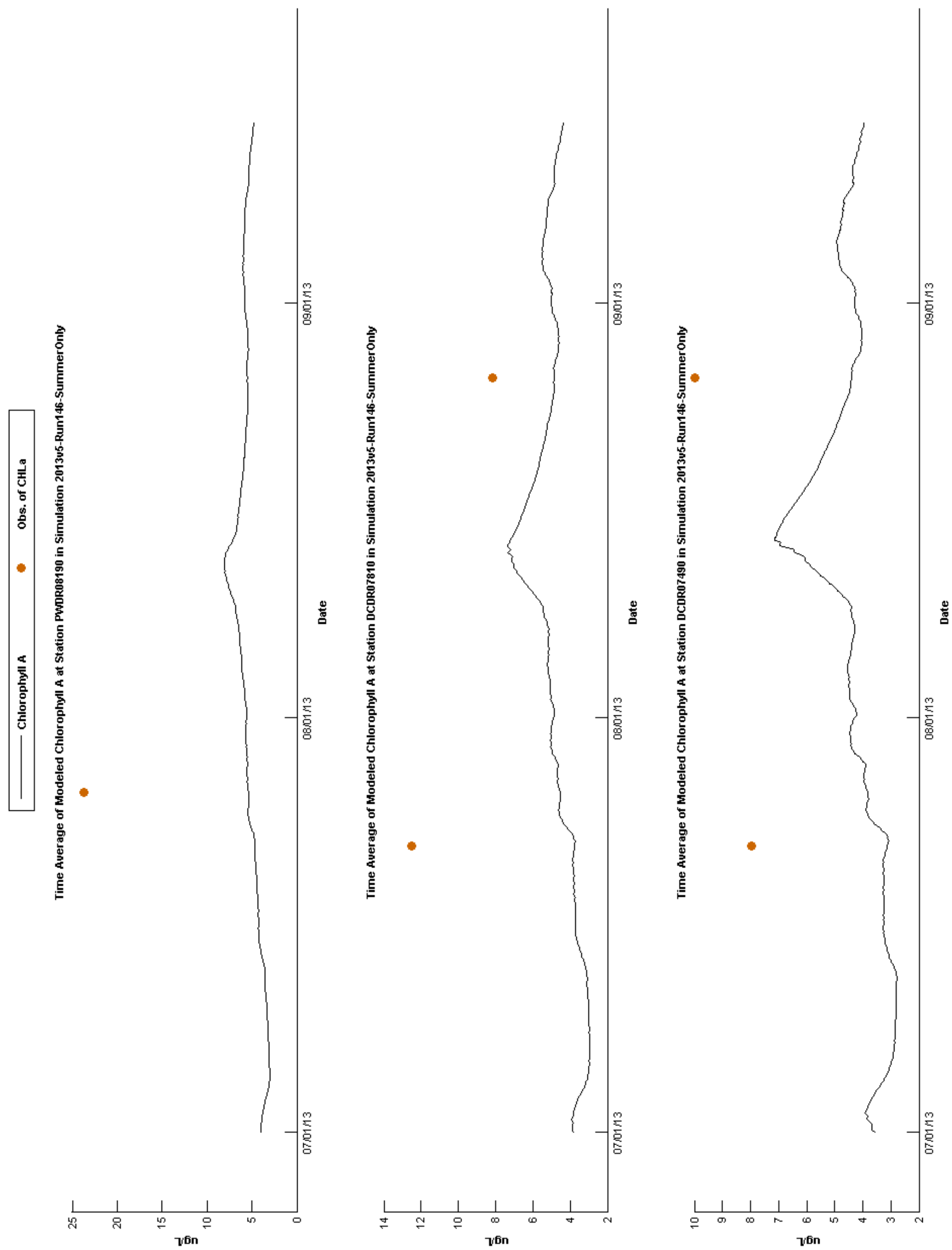

Time Average of Modeled Chlorophyll A at Station PWDR09147 in Simulation 2013v5-Run146-SummerOnly
ug/L
0
5
10
15
20
25
30
07/01/13
08/01/13
09/01/13
Date

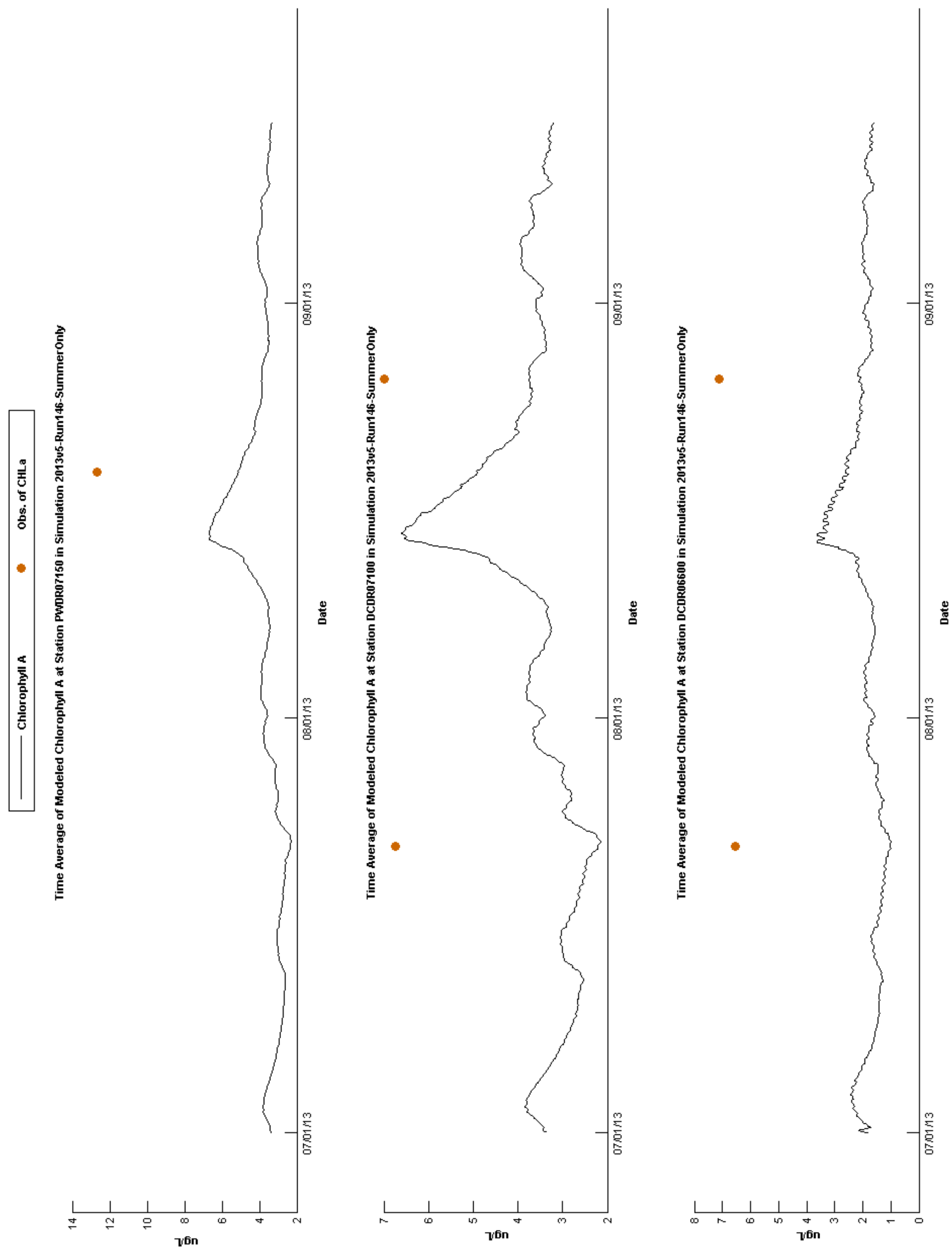

Time Average of Modeled Chlorophyll A at Station PWDR09023 in Simulation 2013v5-Run146-SummerOnly
Chlorophyll A
Obs. of CHLa
ug/L
16
14
12
10
8
6
4
2
07/01/13
08/01/13
09/01/13
Date

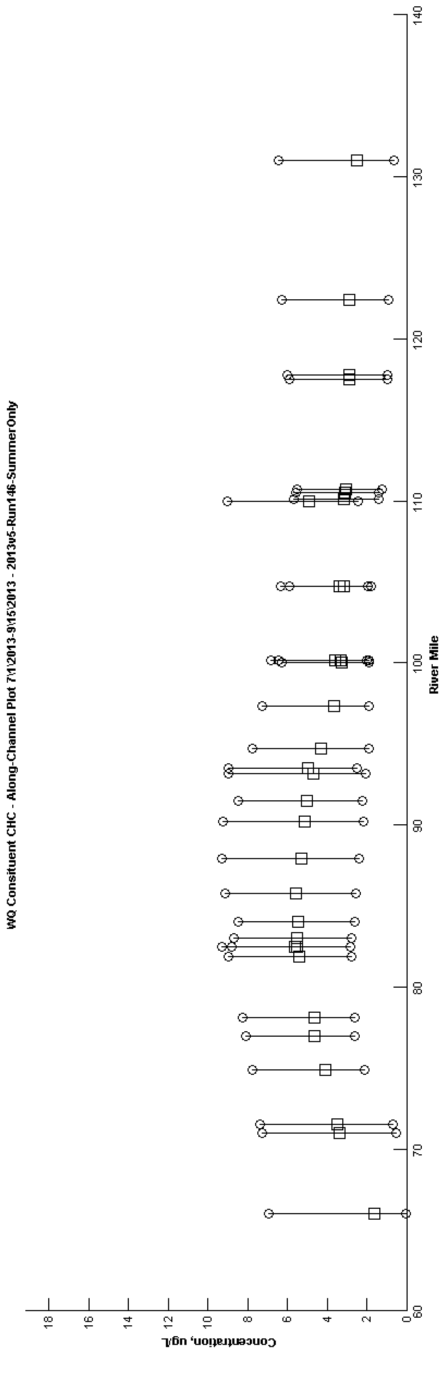

Time Average of Modeled Chlorophyll A at Station DCDR08790 in Simulation 2013v5-Run146-SummerOnly
ug/L
25
20
15
10
5
0
07/01/13
08/01/13
09/01/13
Date


Time Average of Modeled Chlorophyll A at Station PWDR08575 in Simulation 2013v5-Run146-SummerOnly
ug/L
35
30
25
20
15
10
5
0
07/01/13
08/01/13
09/01/13
Date


Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station DCDR08400 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station PWDR08300 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station UGDR08250 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13

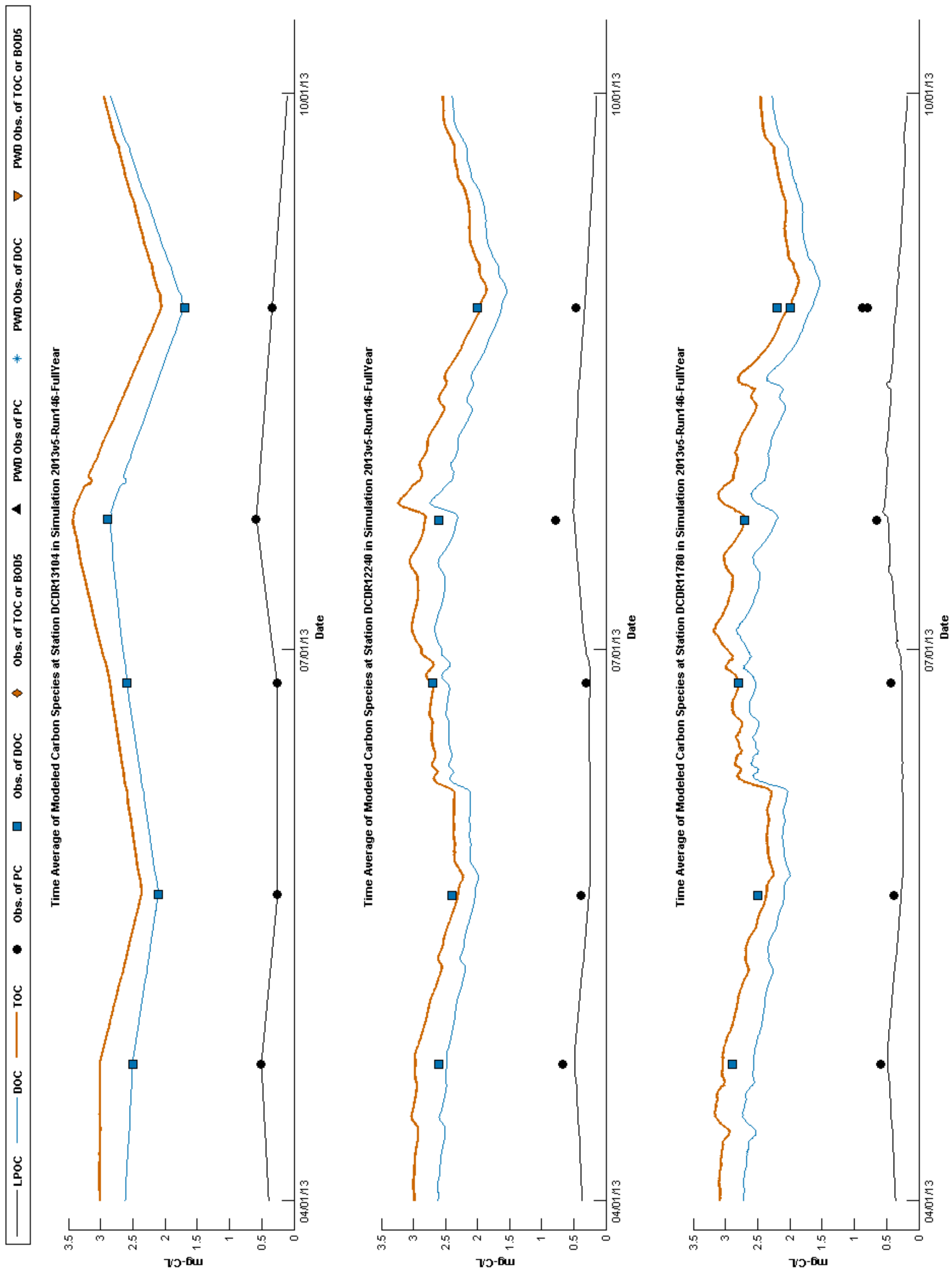

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR08190 in Simulation 2013v5-Run146-SummerOnly
ug/L
25
20
15
10
5
0
07/01/13
08/01/13
09/01/13
Date
Time Average of Modeled Chlorophyll A at Station DCDR07810 in Simulation 2013v5-Run146-SummerOnly
ug/L
14
12
10
8
6
4
2
07/01/13
08/01/13
09/01/13
Date
Time Average of Modeled Chlorophyll A at Station DCDR07490 in Simulation 2013v5-Run146-SummerOnly
ug/L
10
9
8
7
6
5
4
3
2
07/01/13
08/01/13
09/01/13
Date

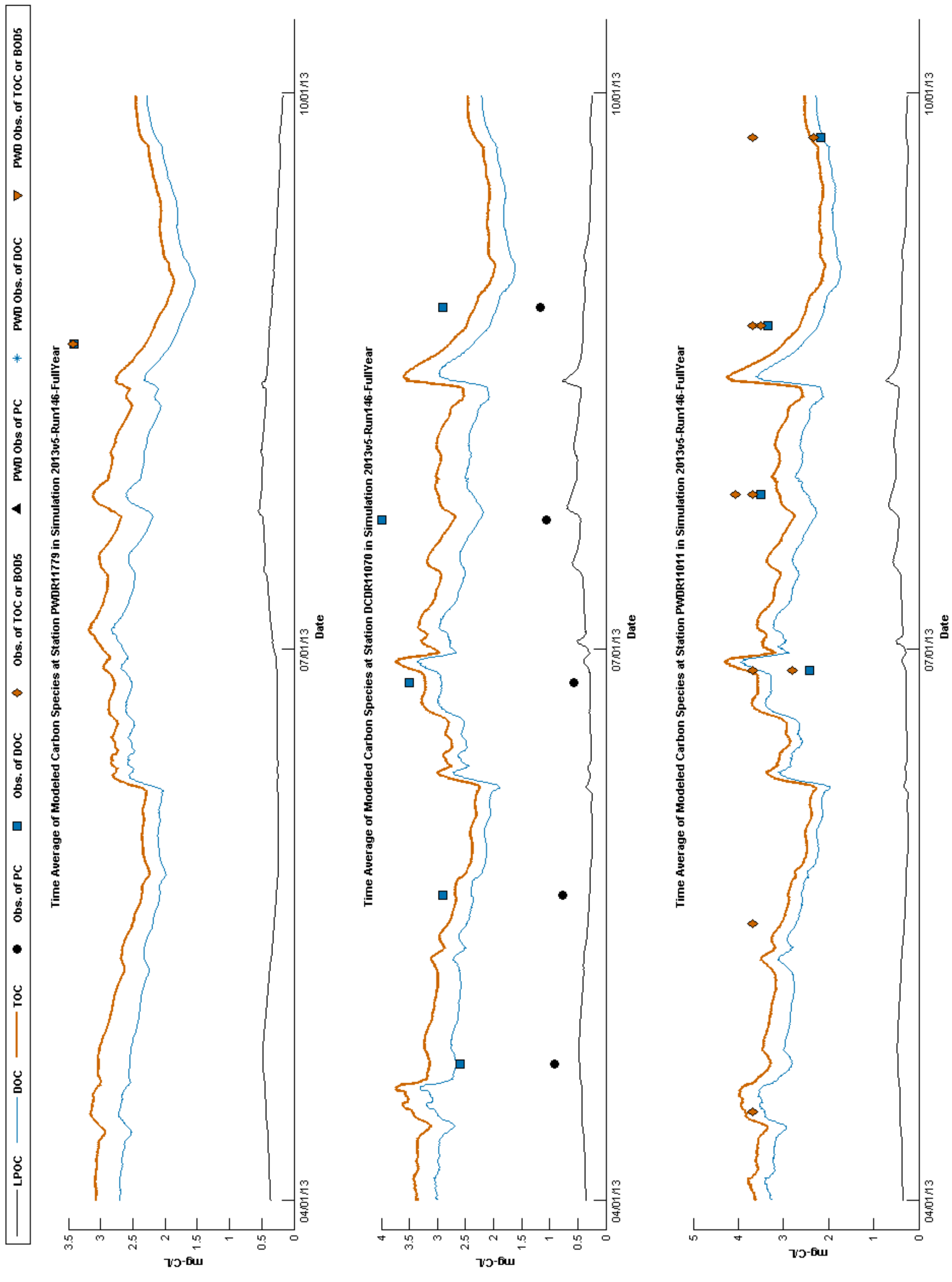

Chlorophyll A
Obs. of CHLa
Time Average of Modeled Chlorophyll A at Station PWDR07150 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR07100 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Chlorophyll A at Station DCDR06600 in Simulation 2013v5-Run146-SummerOnly
ug/L
Date
07/01/13
08/01/13
09/01/13


WQ Consituent CHC - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
60
70
80
90
100
110
120
130
140
Concentration, ug/L
0
2
4
6
8
10
12
14
16
18

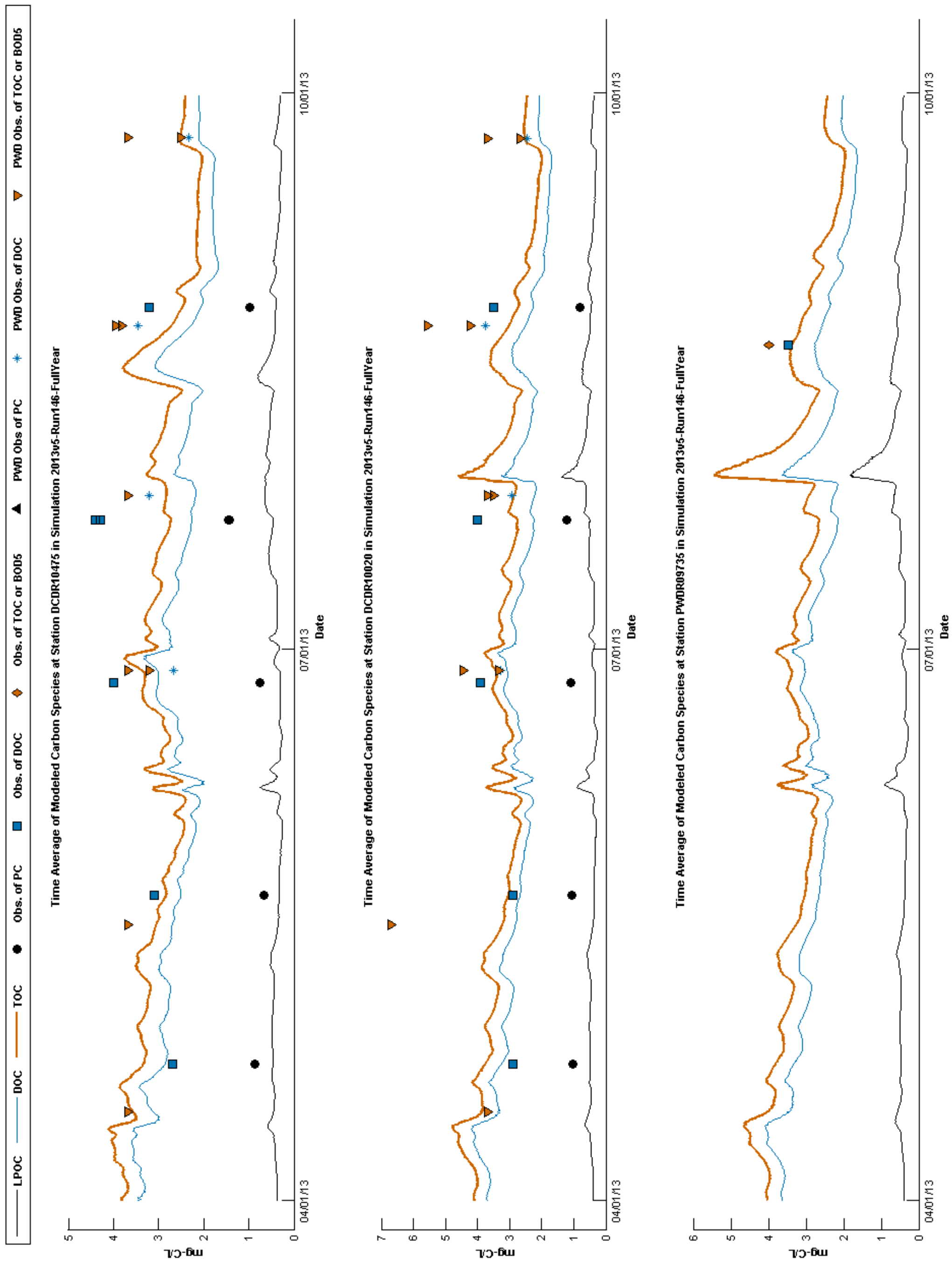
1.2. Carbon Species

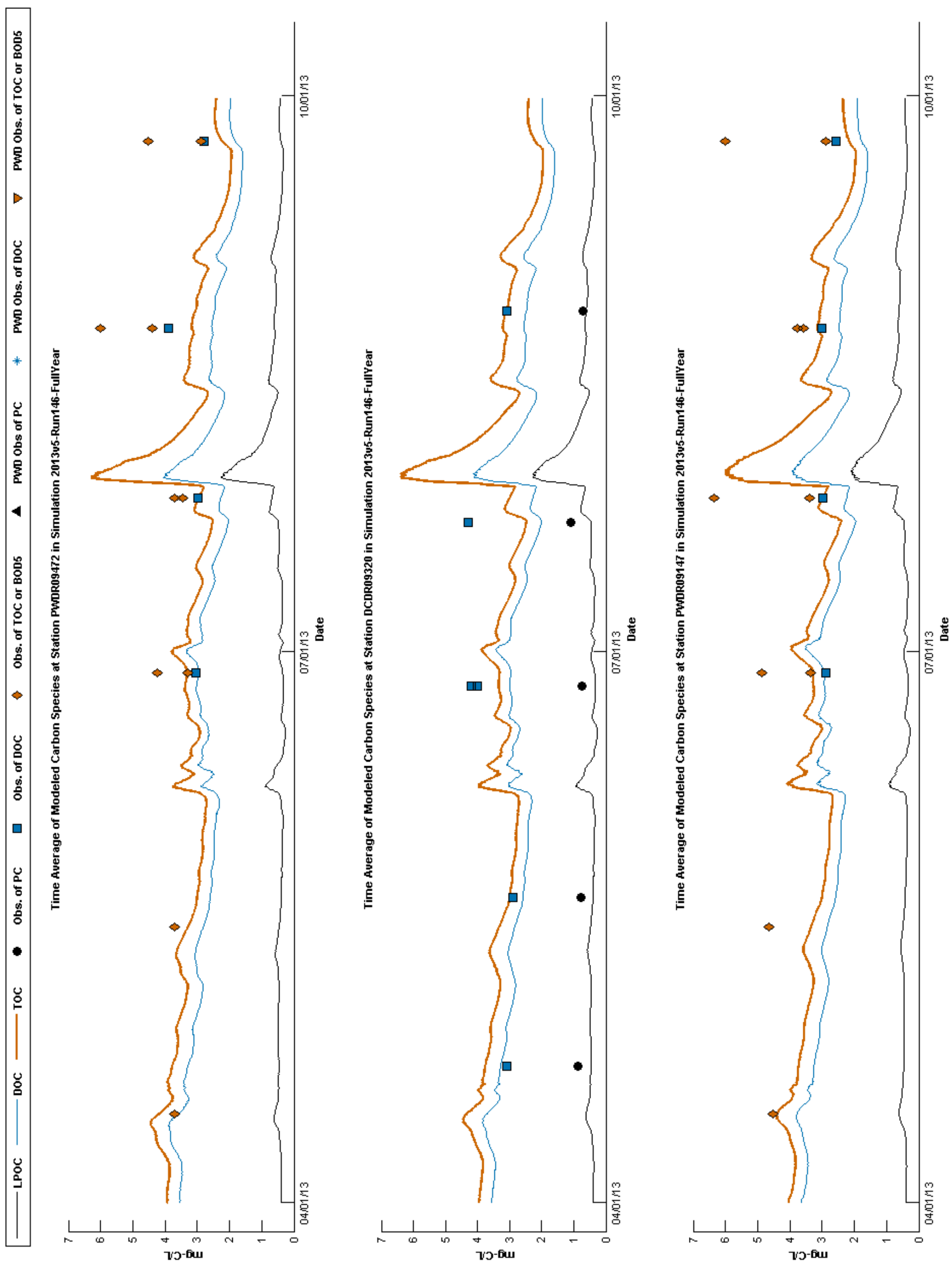
1.2.1. April to October





LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR11779 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13
Time Average of Modeled Carbon Species at Station DCDR11070 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13
Time Average of Modeled Carbon Species at Station PWDR11011 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR10475 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR10020 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR09735 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13



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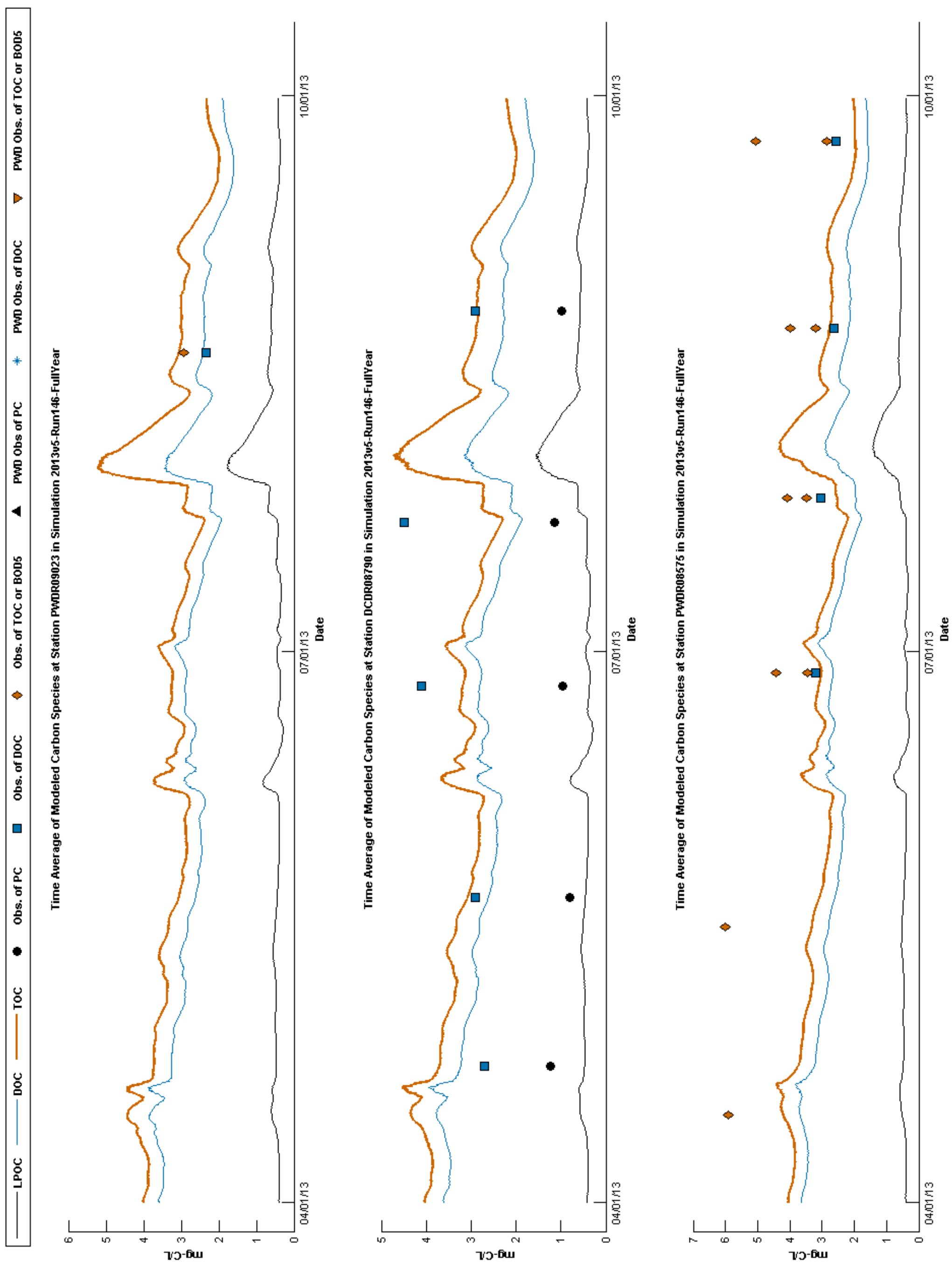
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09472 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR09320 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR09147 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13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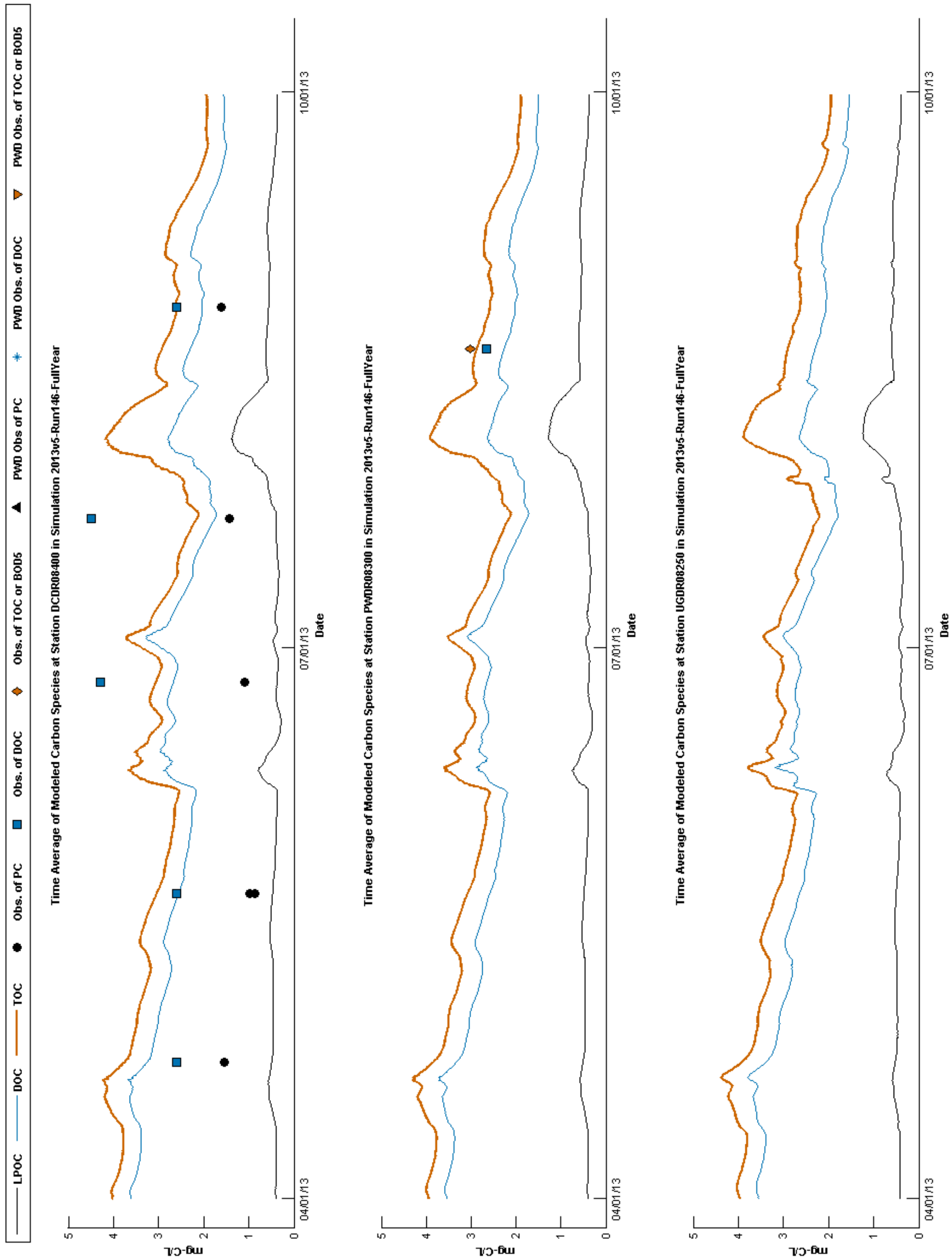
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09023 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR08790 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR08575 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13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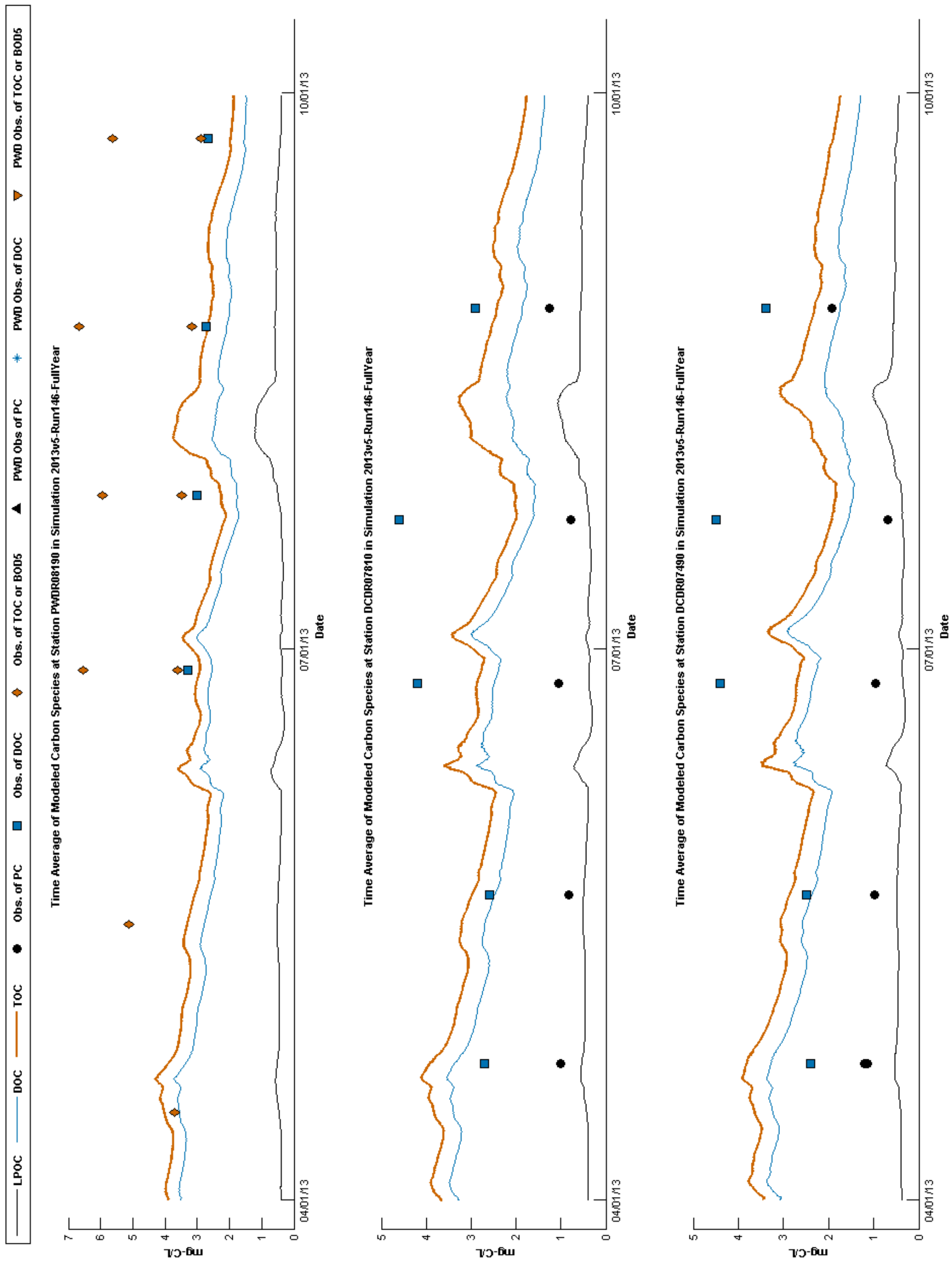
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR08400 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station PWDR08300 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station UGDR08250 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13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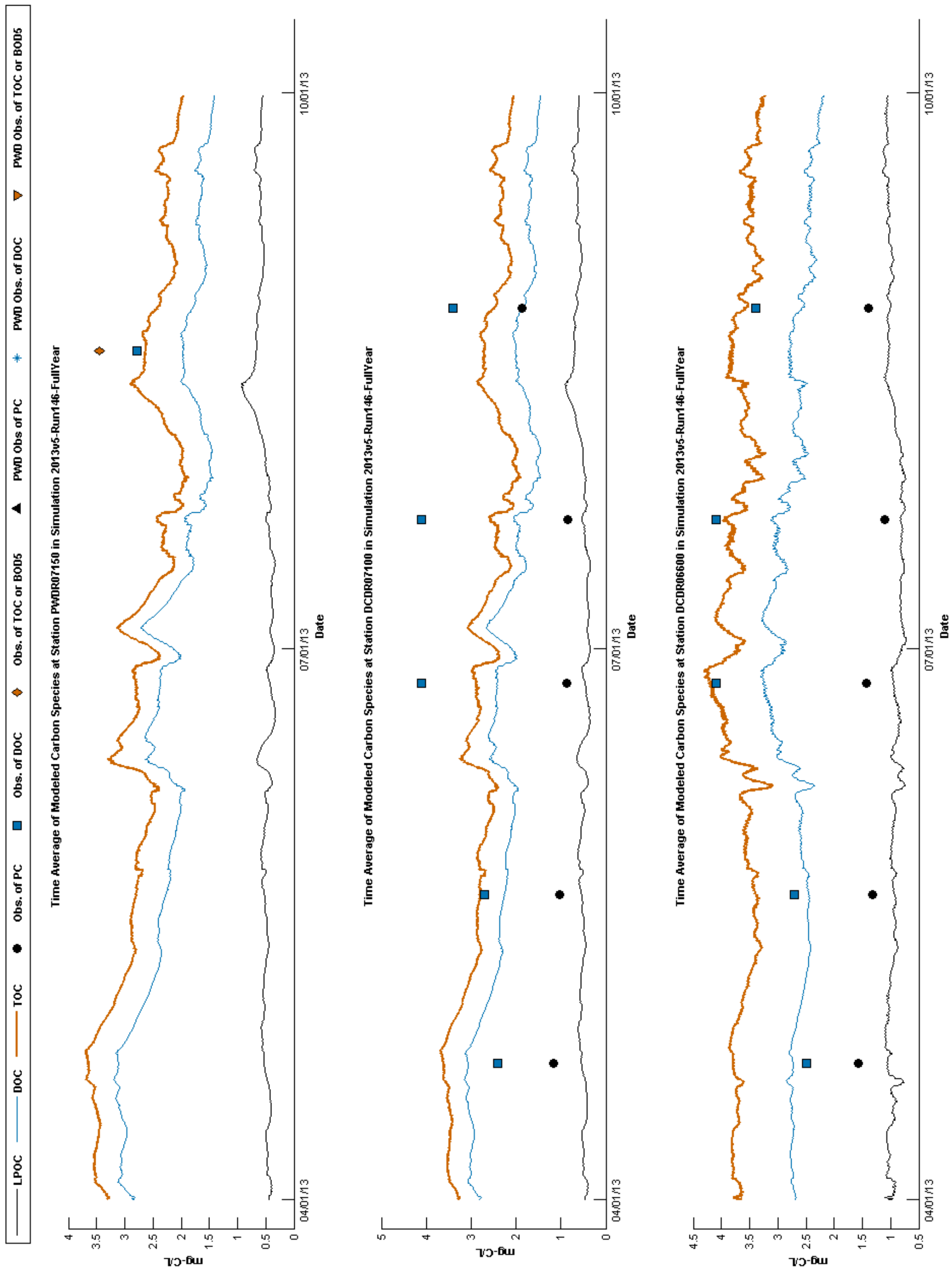
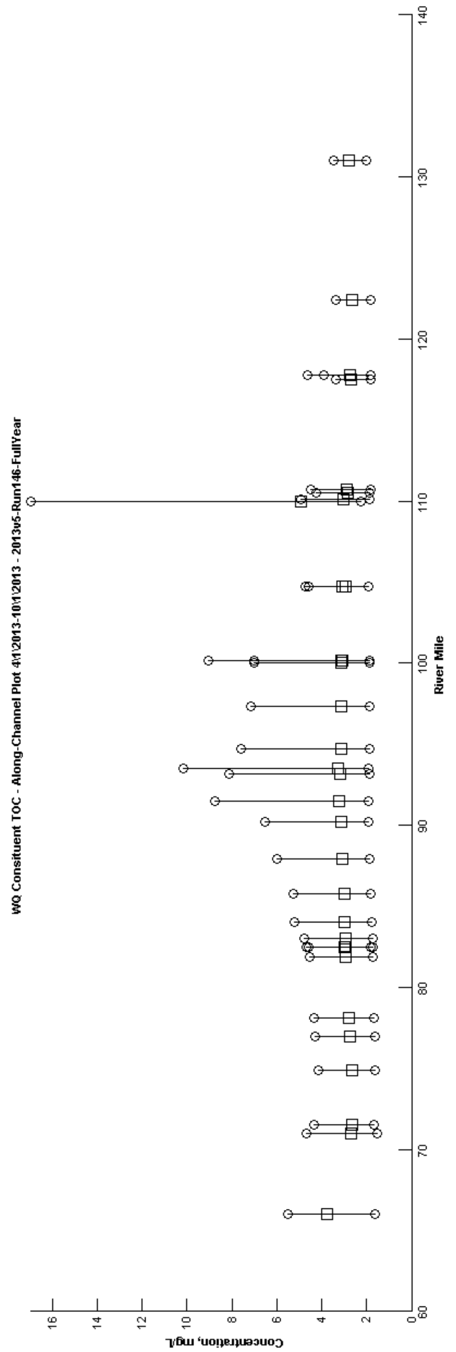
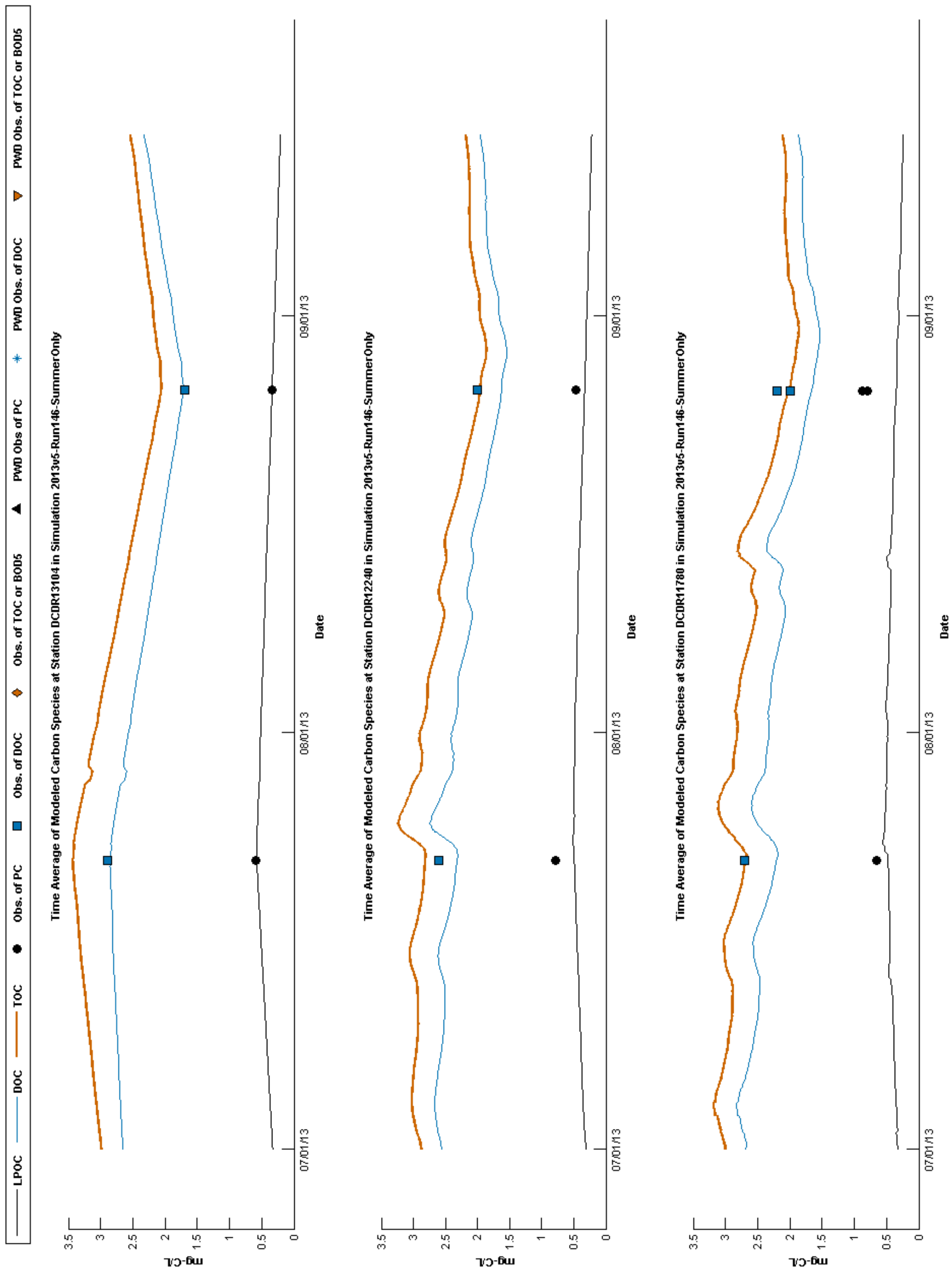
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR08190 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07810 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07490 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR07150 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR07100 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Carbon Species at Station DCDR06600 in Simulation 2013v5-Run146-FullYear
mg-C/L
Date
04/01/13
07/01/13
10/01/13


WQ Consituent TOC - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
Concentration, mg/L
River Mile
16
14
12
10
8
6
4
2
0
60
70
80
90
100
110
120
130
140

1.2.2. Summer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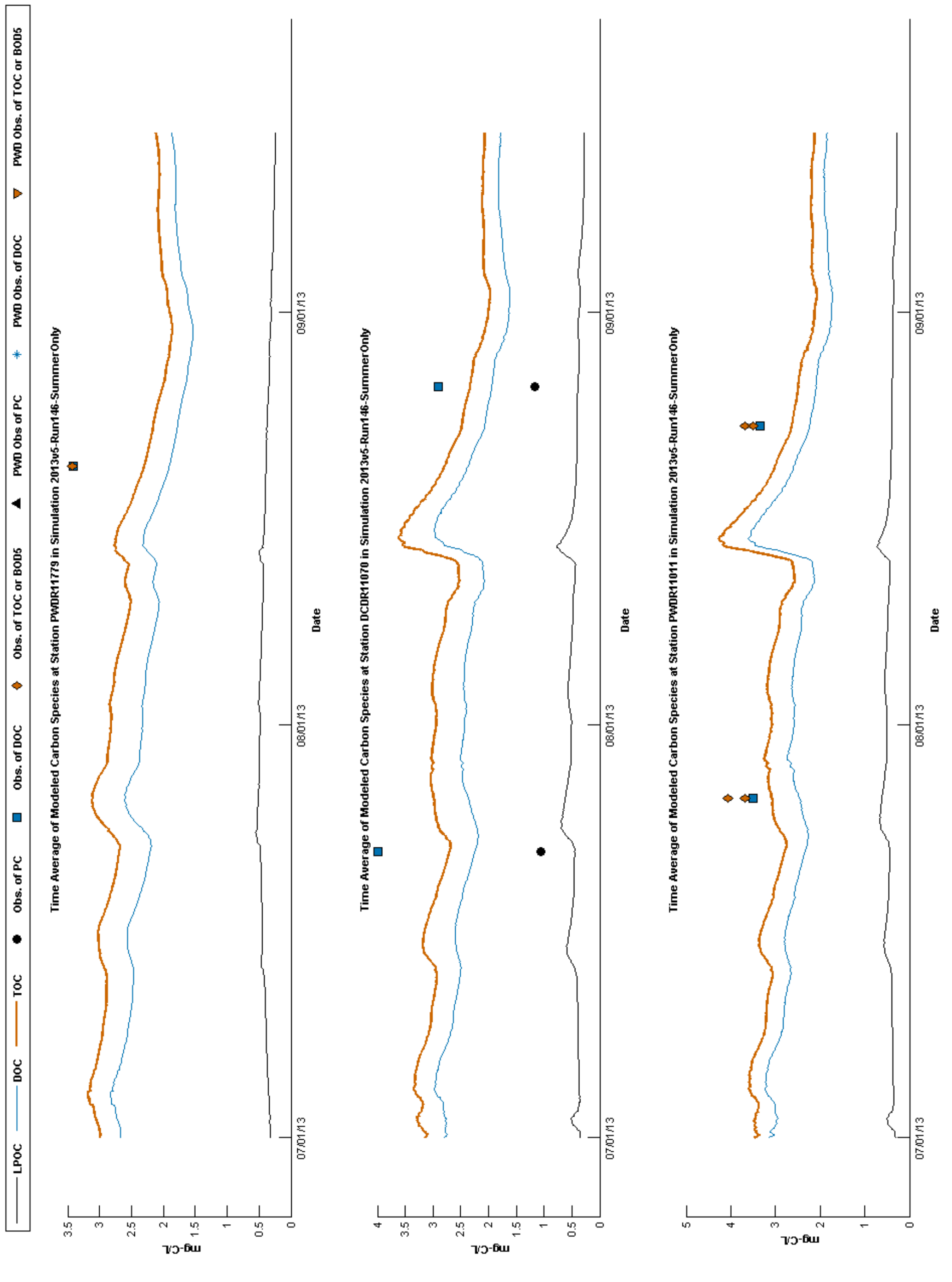
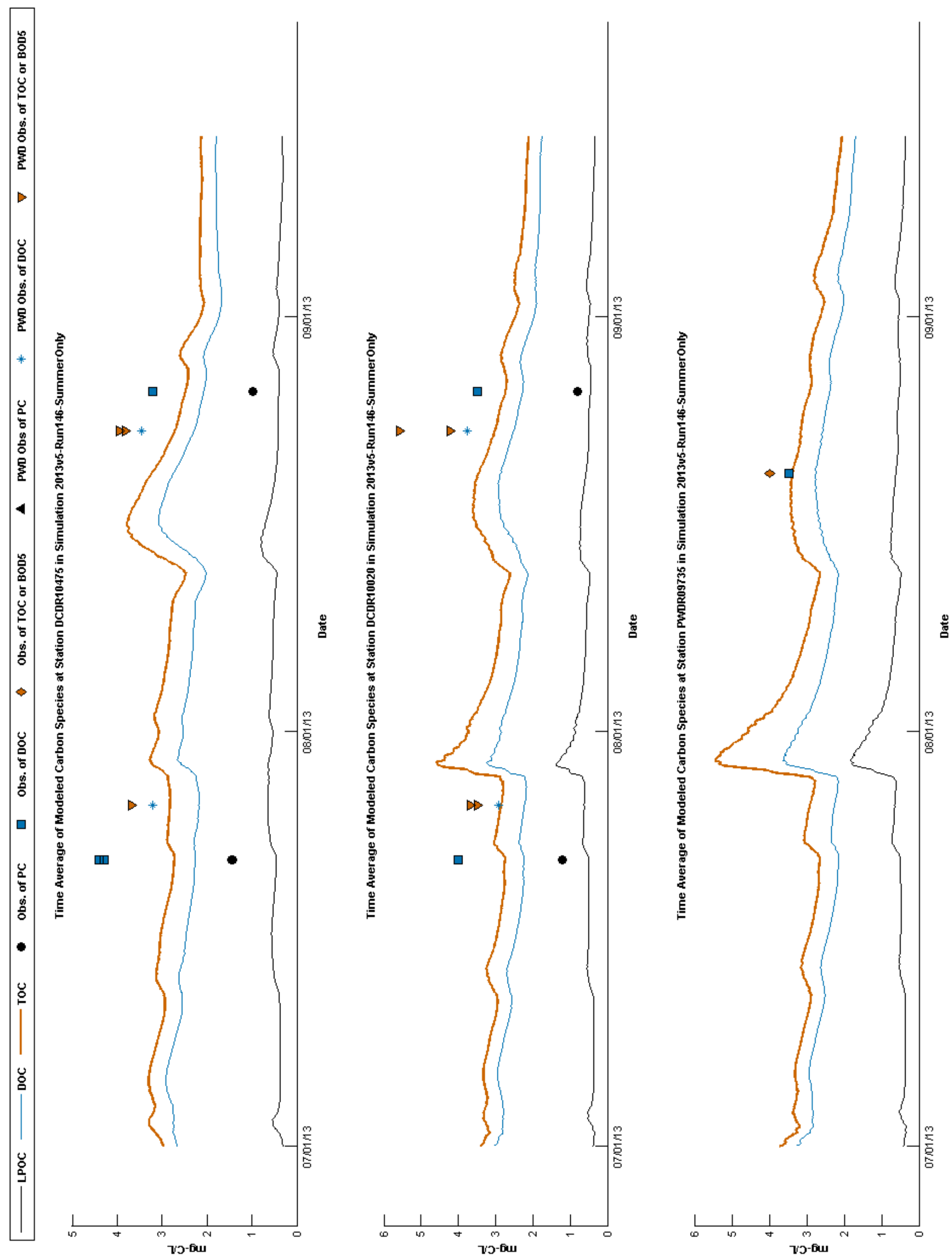
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR13104 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR12240 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR11780 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR11779 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station DCDR11070 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station PWDR11011 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13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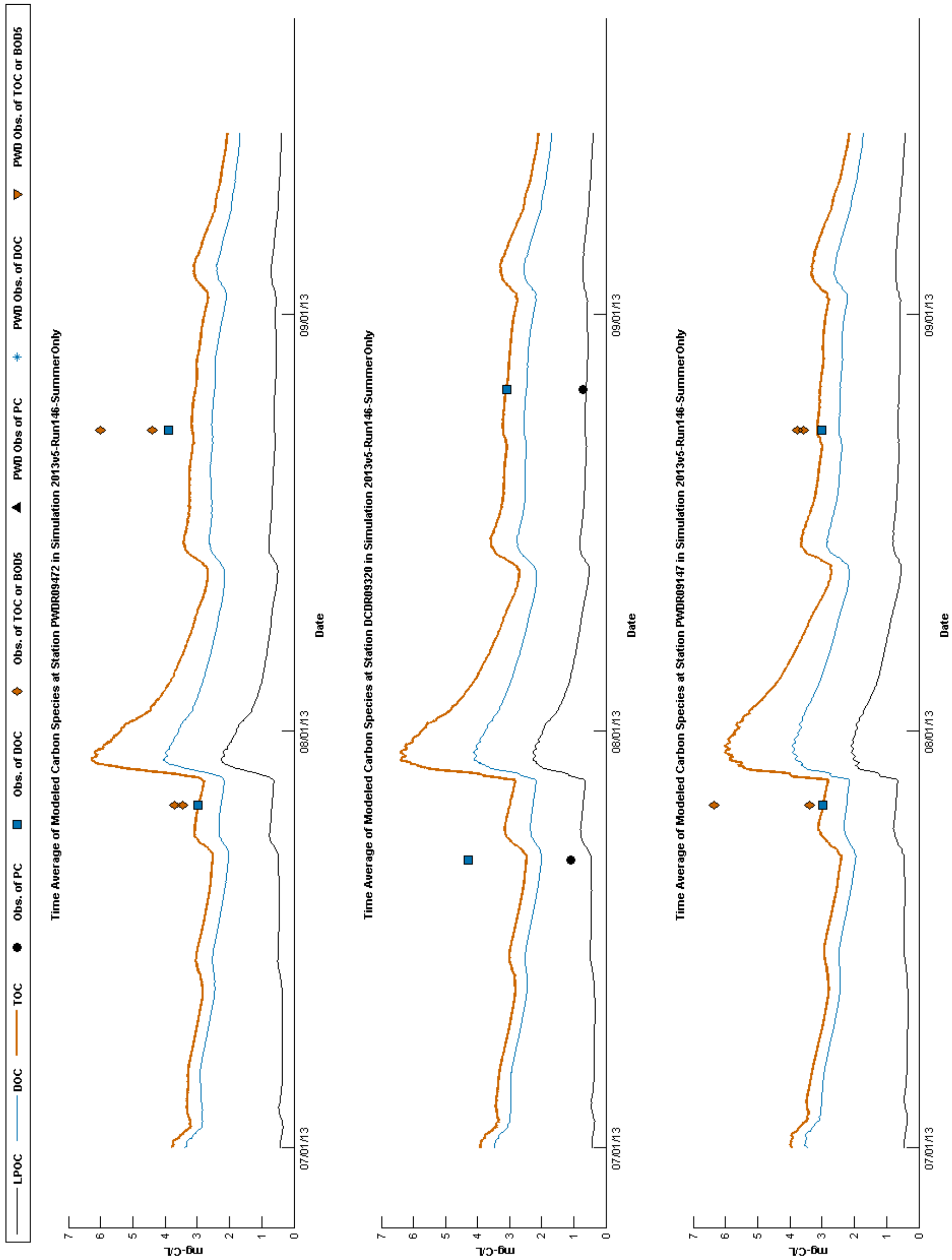
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR10475 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR10020 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR09735 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09472 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station DCDR09320 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station PWDR09147 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
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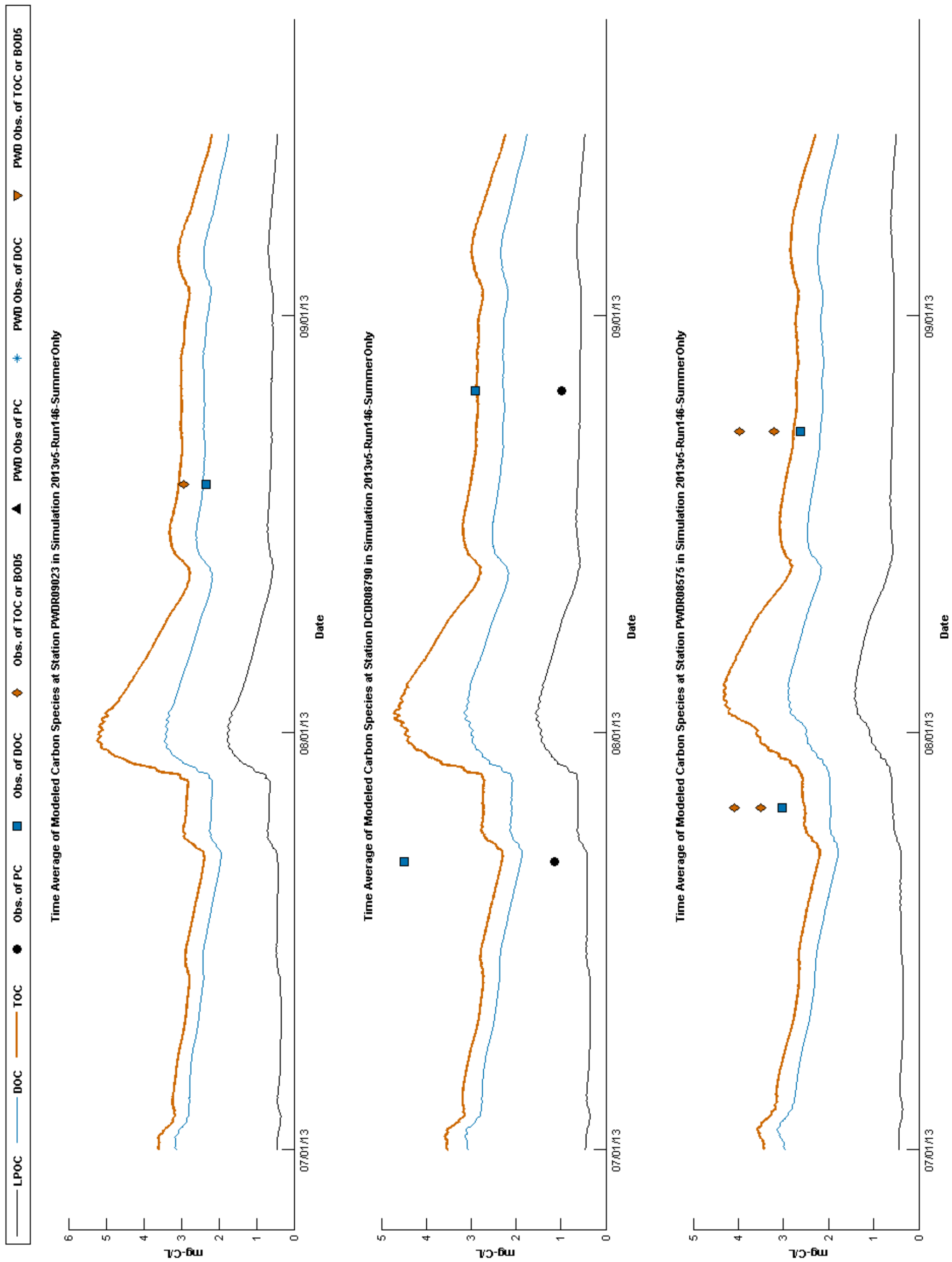
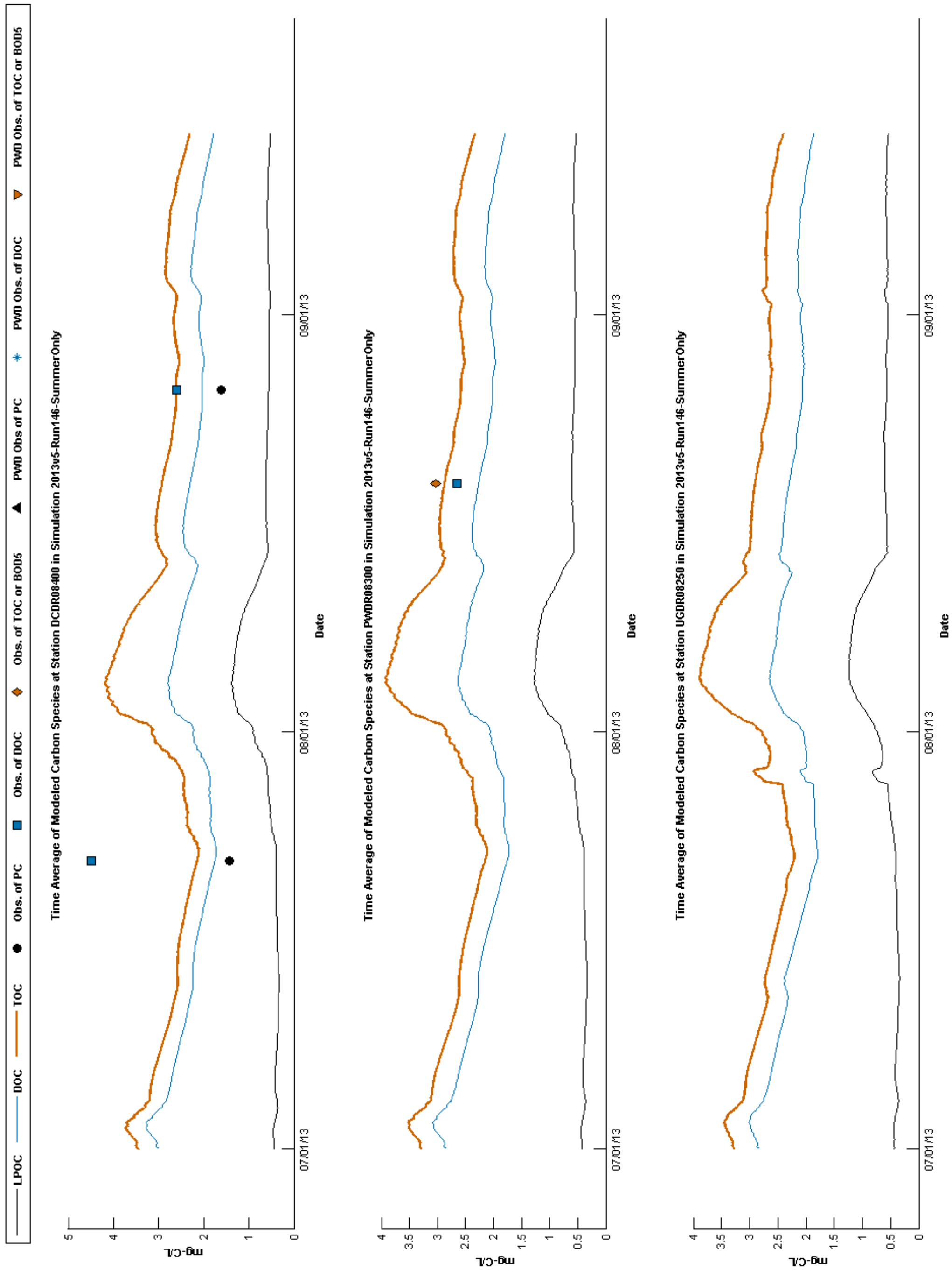
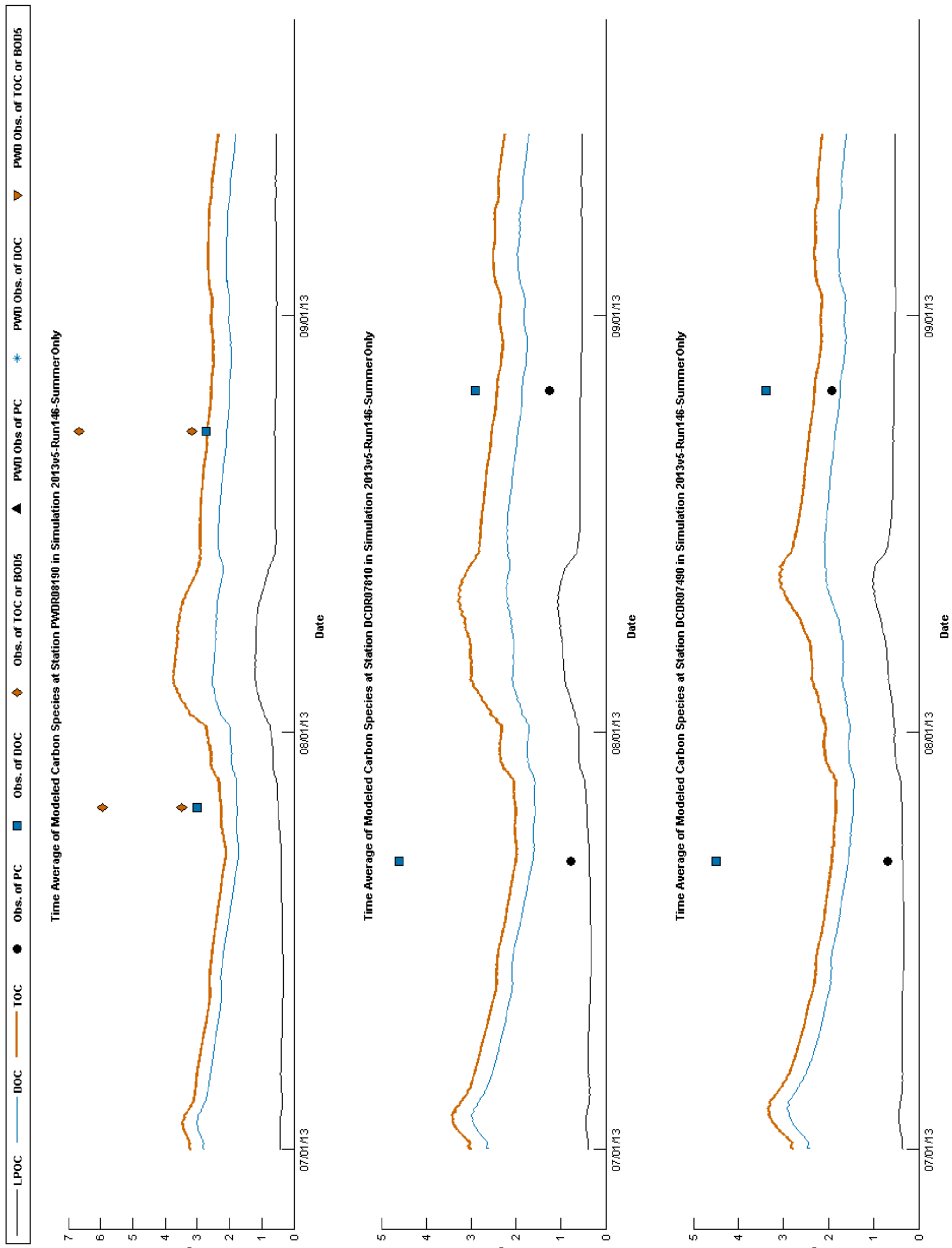
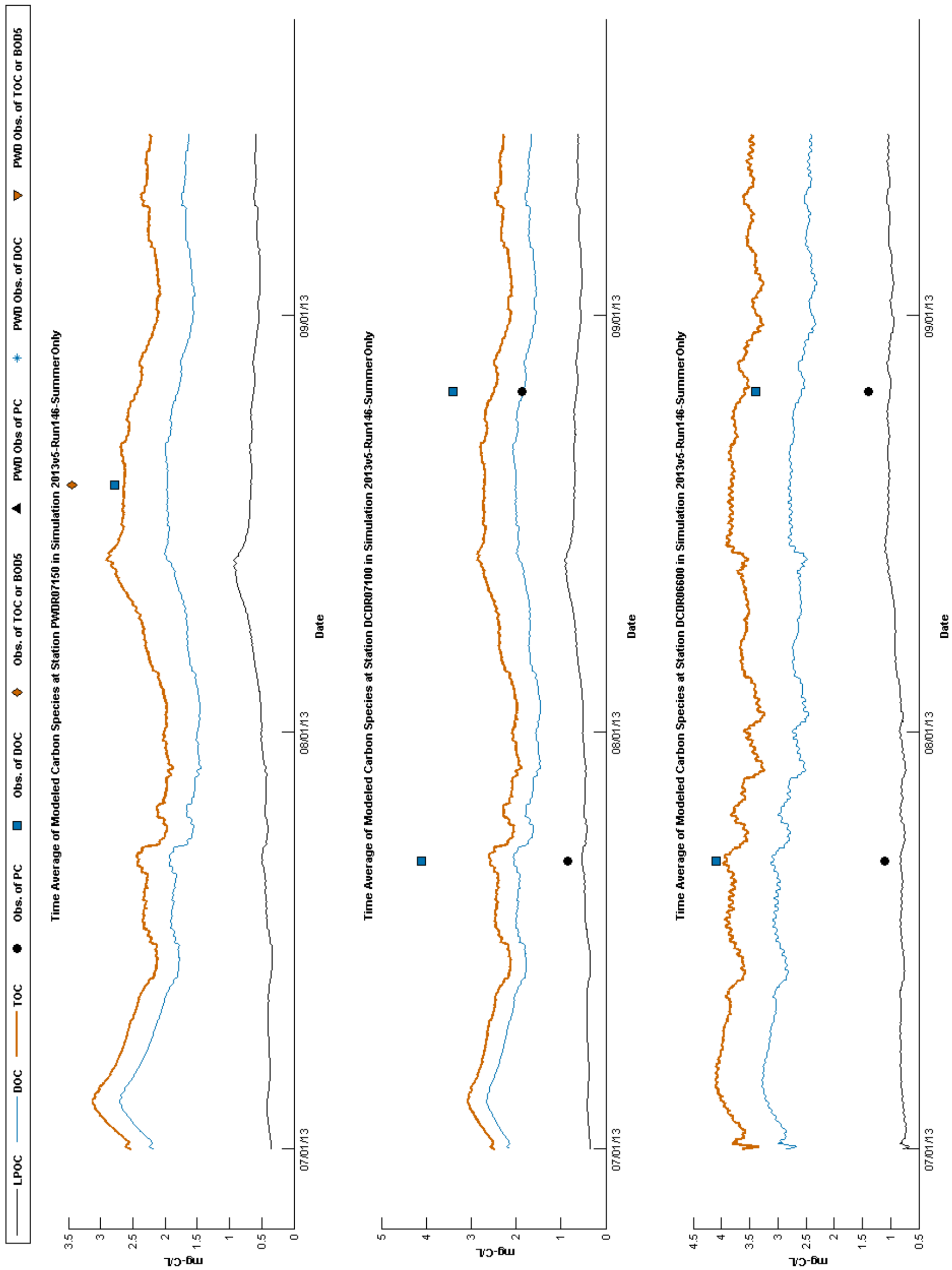
08/01/13
09/01/13

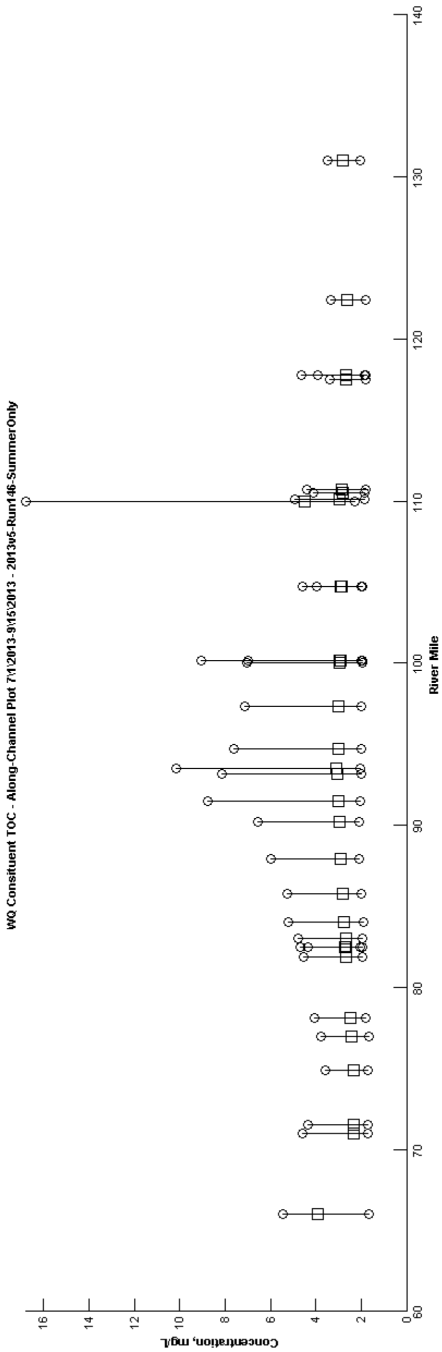

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR09023 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR08790 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station PWDR08575 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13


LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station DCDR08400 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station PWDR08300 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Carbon Species at Station UGDR08250 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13



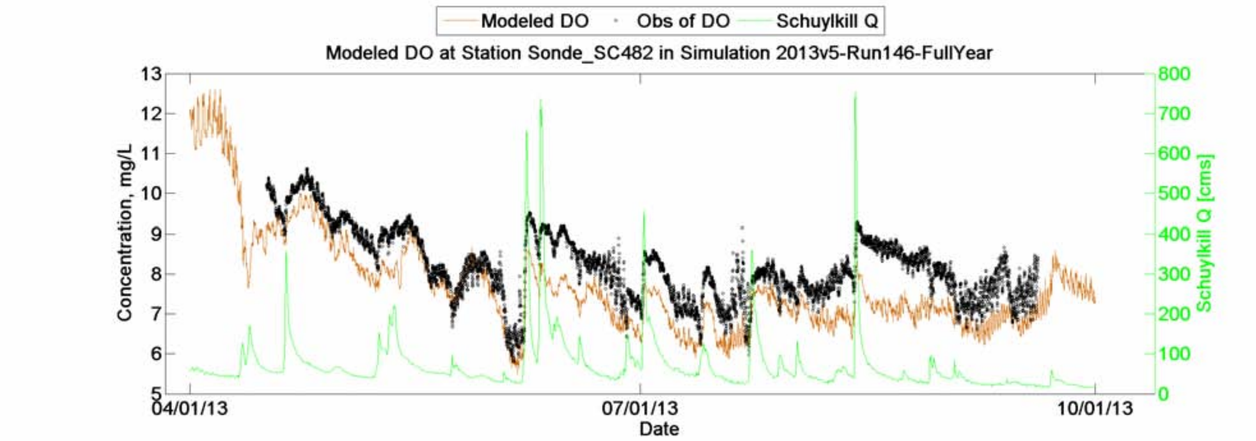
LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR08190 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07810 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07490 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13

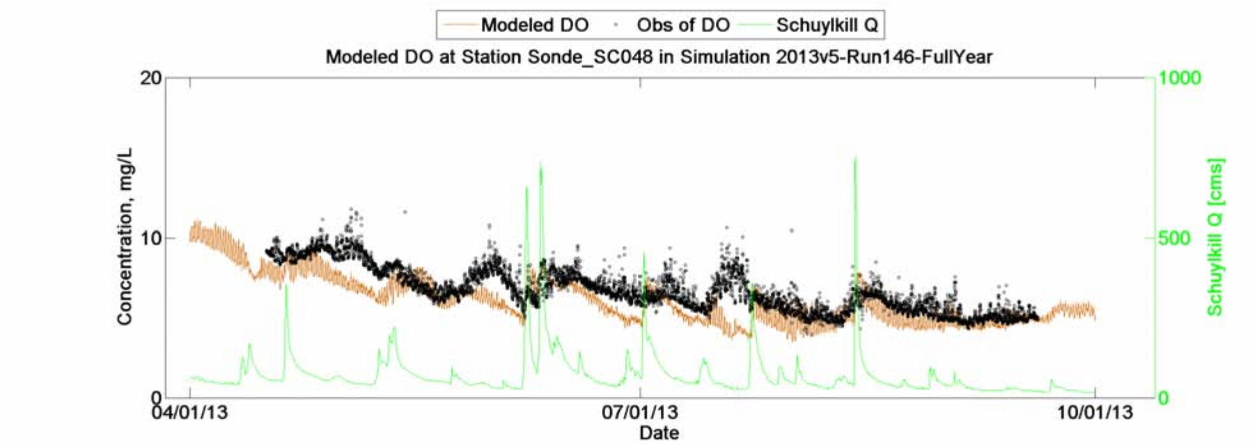

LPOC
DOC
TOC
Obs. of PC
Obs. of DOC
Obs. of TOC or BOD5
PWD Obs of PC
PWD Obs. of DOC
PWD Obs. of TOC or BOD5
Time Average of Modeled Carbon Species at Station PWDR07150 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR07100 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Carbon Species at Station DCDR06600 in Simulation 2013v5-Run146-SummerOnly
mg-C/L
Date
07/01/13
08/01/13
09/01/13

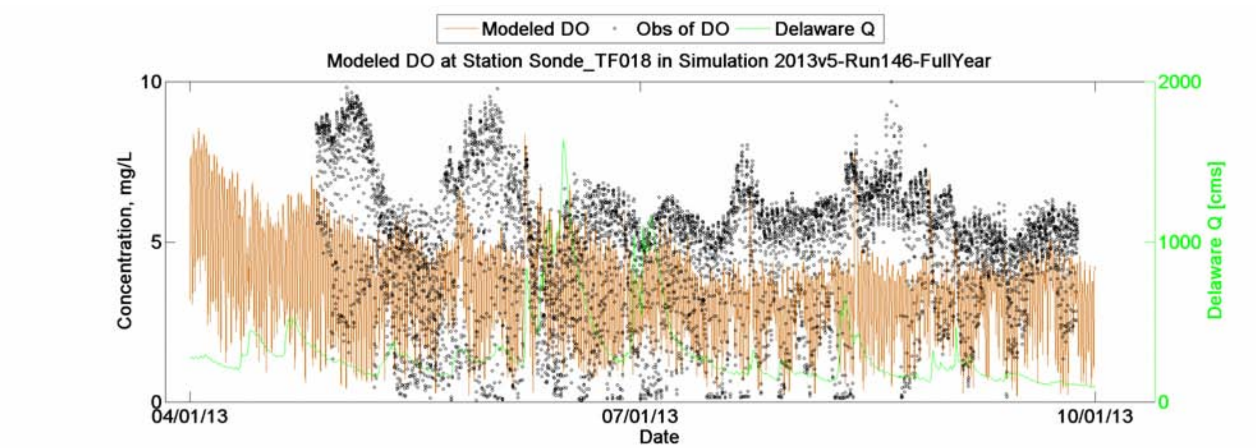

WQ Consituent TOC - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg/L
60
70
80
90
100
110
120
130
140
0
2
4
6
8
10
12
14
16

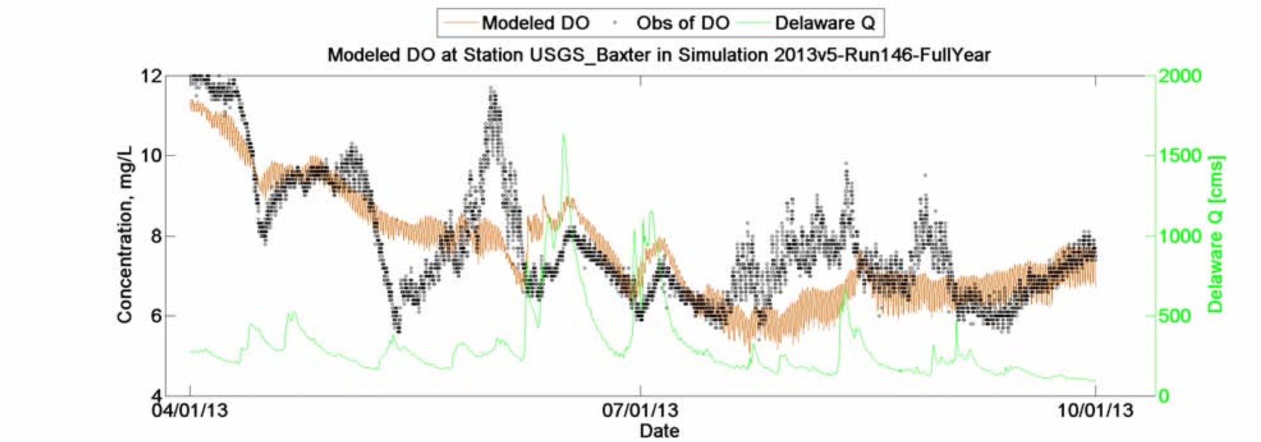
1.3. Dissolved Oxygen

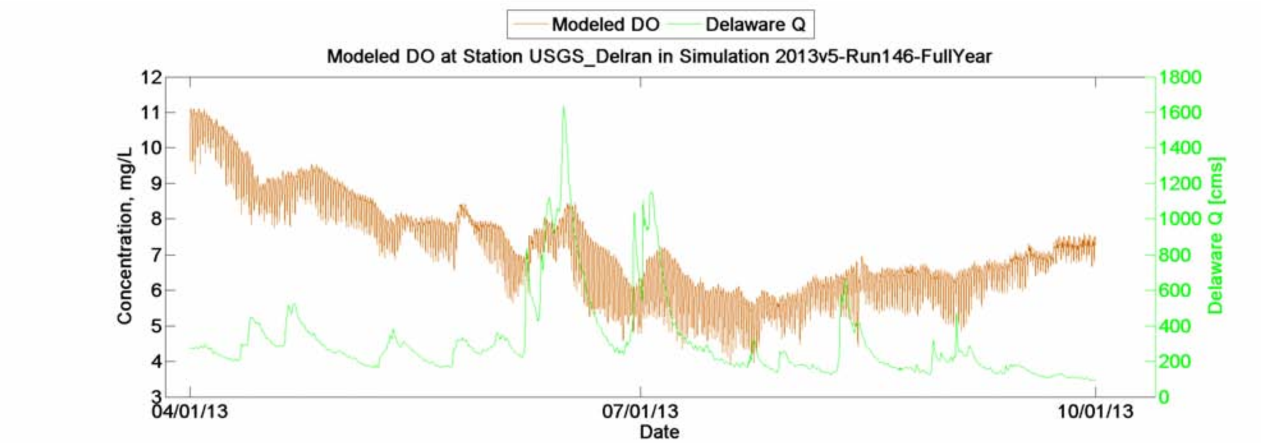
1.3.1. April to October

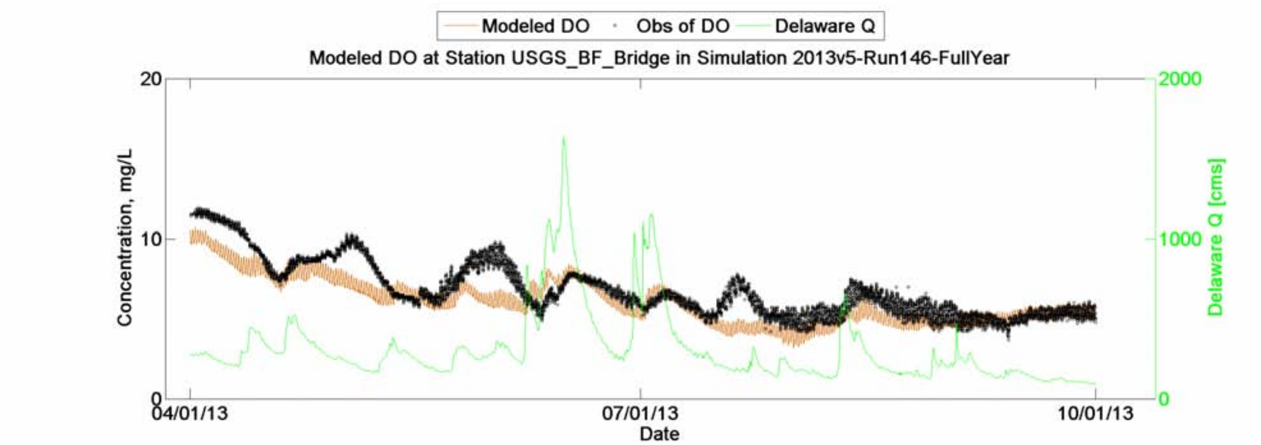


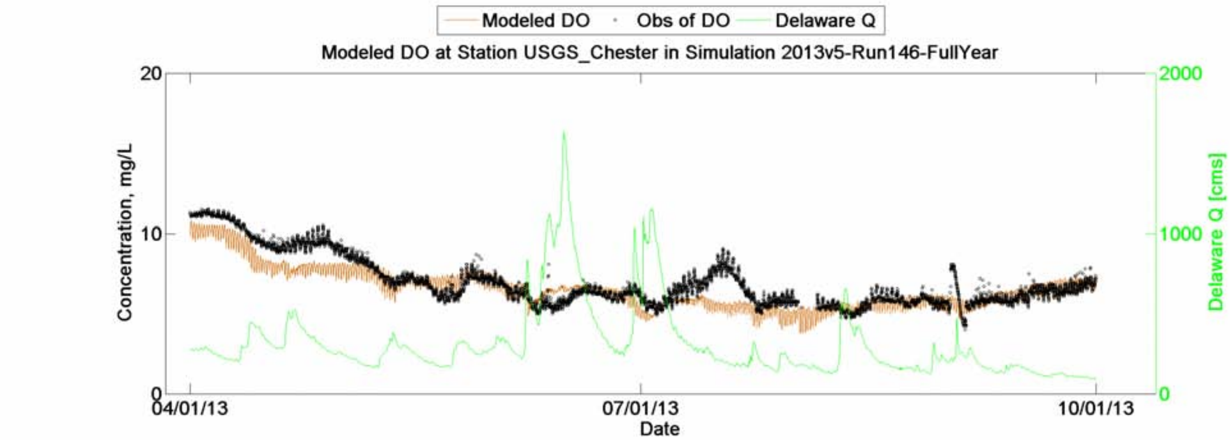


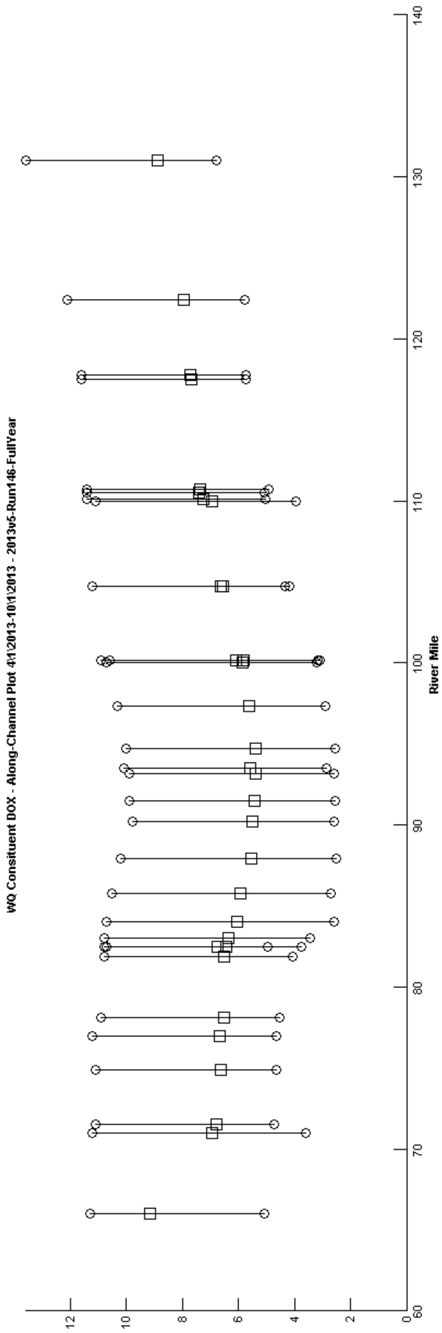



Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Baxter in Simulation 2013v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/13
07/01/13
10/01/13

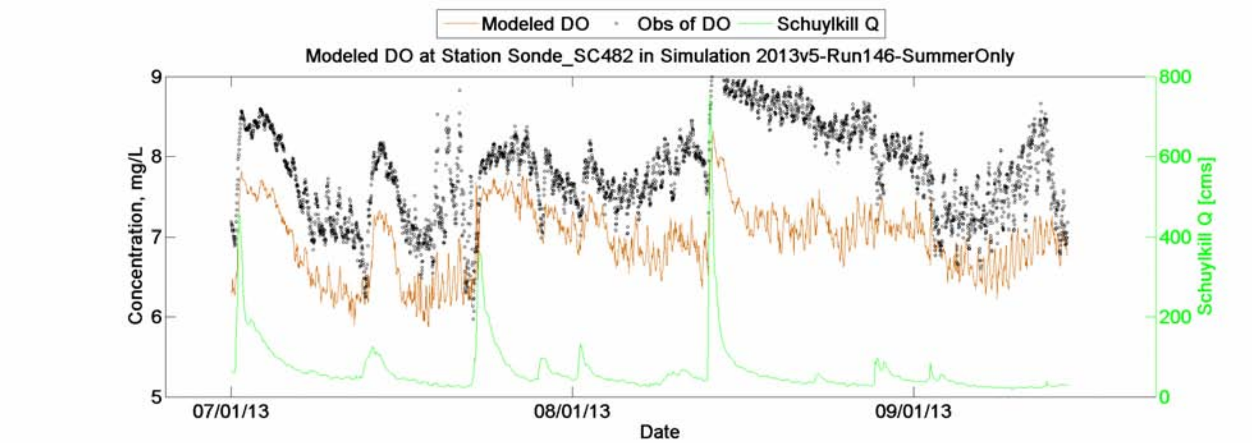

Modeled DO
Delaware Q
Modeled DO at Station USGS_Delran in Simulation 2013v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/13
07/01/13
10/01/13

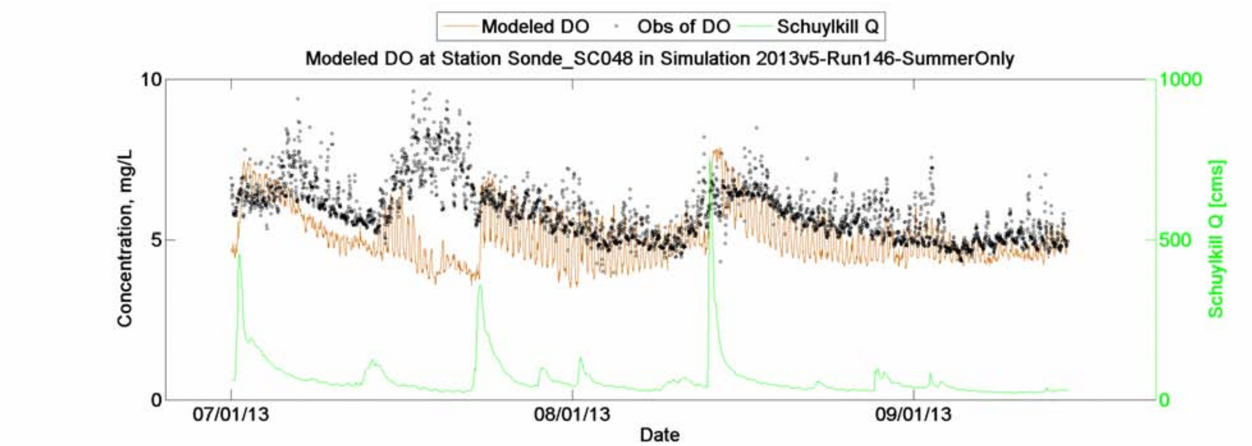

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_BF_Bridge in Simulation 2013v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/13
07/01/13
10/01/13

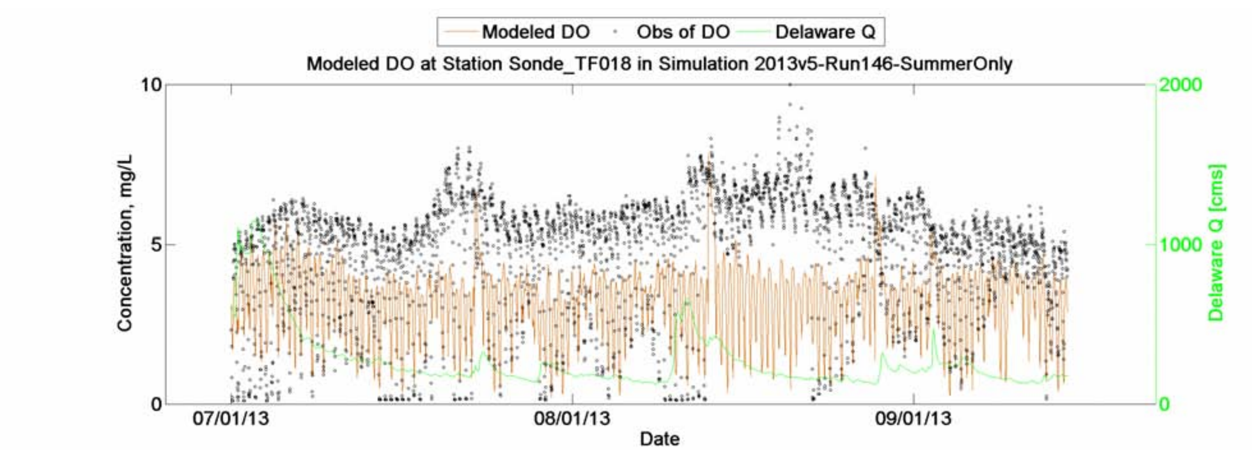

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Chester in Simulation 2013v5-Run146-FullYear
Concentration, mg/L
Delaware Q [cms]
Date
04/01/13
07/01/13
10/01/13
0
10
20
0
1000
2000

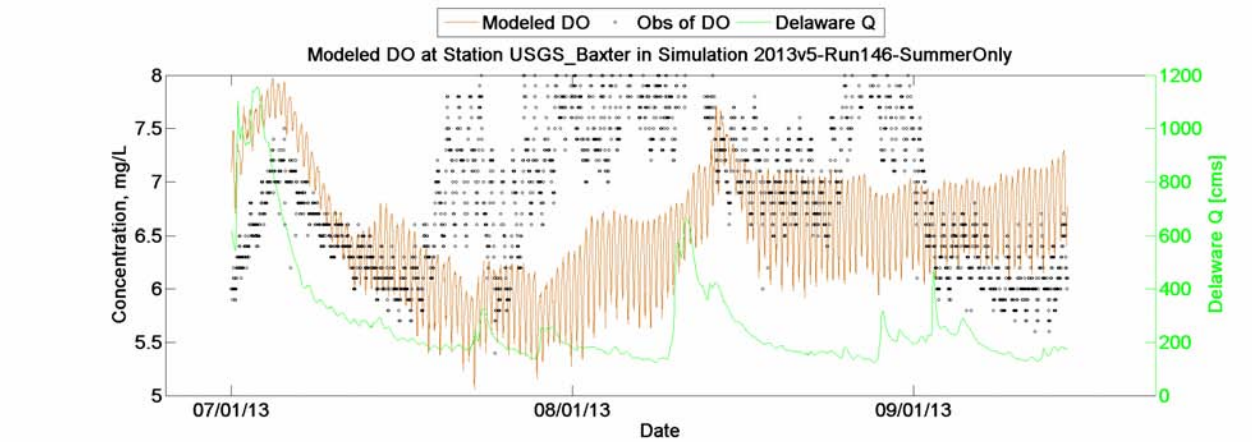

WQ Consituent DOX - Along-Channel Plot 4/1/2013-10/1/2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg/L
60
70
80
90
100
110
120
130
140
0
2
4
6
8
10
12

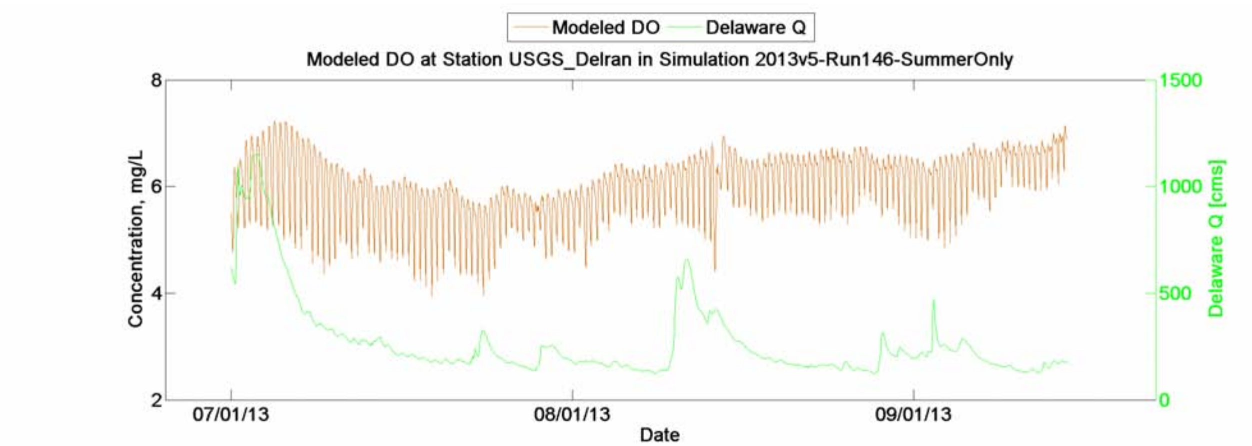
1.3.2. Summer

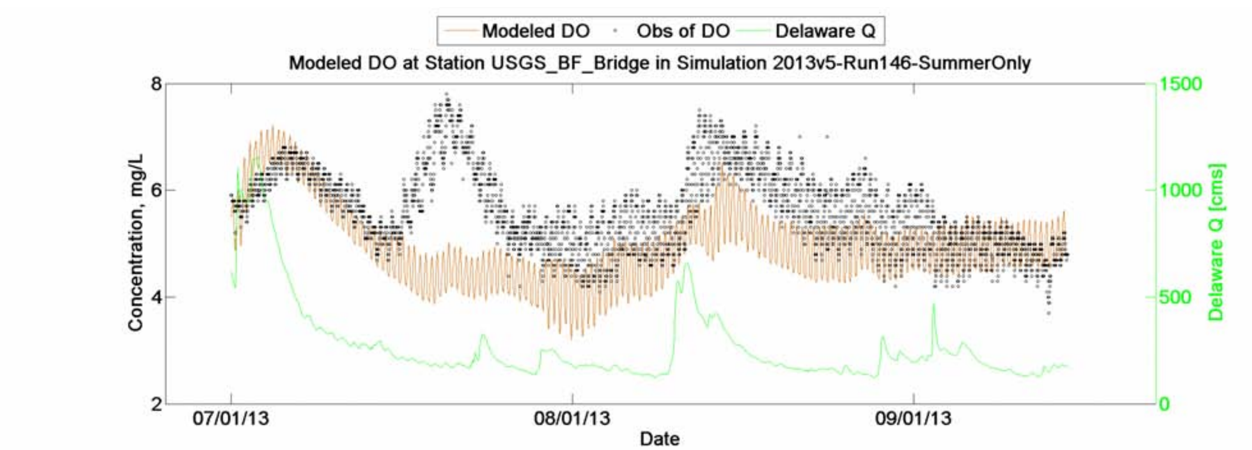

Modeled DO
Obs of DO
Schuylkill Q
Modeled DO at Station Sonde_SC482 in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Schuylkill Q [cms]
Date
07/01/13
08/01/13
09/01/13

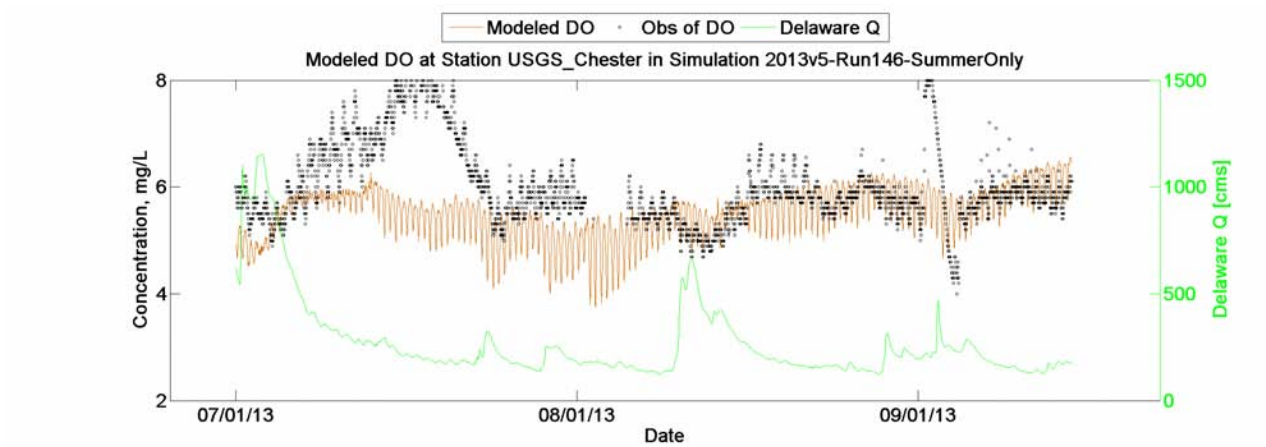

Modeled DO
Obs of DO
Schuylkill Q
Modeled DO at Station Sonde_SC048 in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Schuylkill Q [cms]
Date
07/01/13
08/01/13
09/01/13

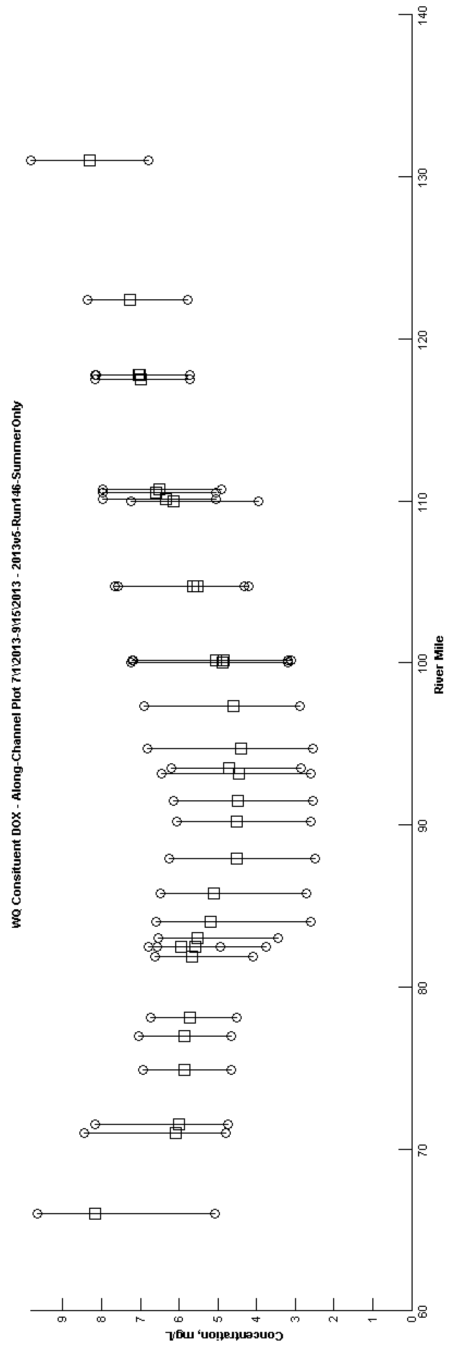

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station Sonde_TF018 in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/13
08/01/13
09/01/13


Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Baxter in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/13
08/01/13
09/01/13


Modeled DO
Delaware Q
Modeled DO at Station USGS_Delran in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/13
08/01/13
09/01/13

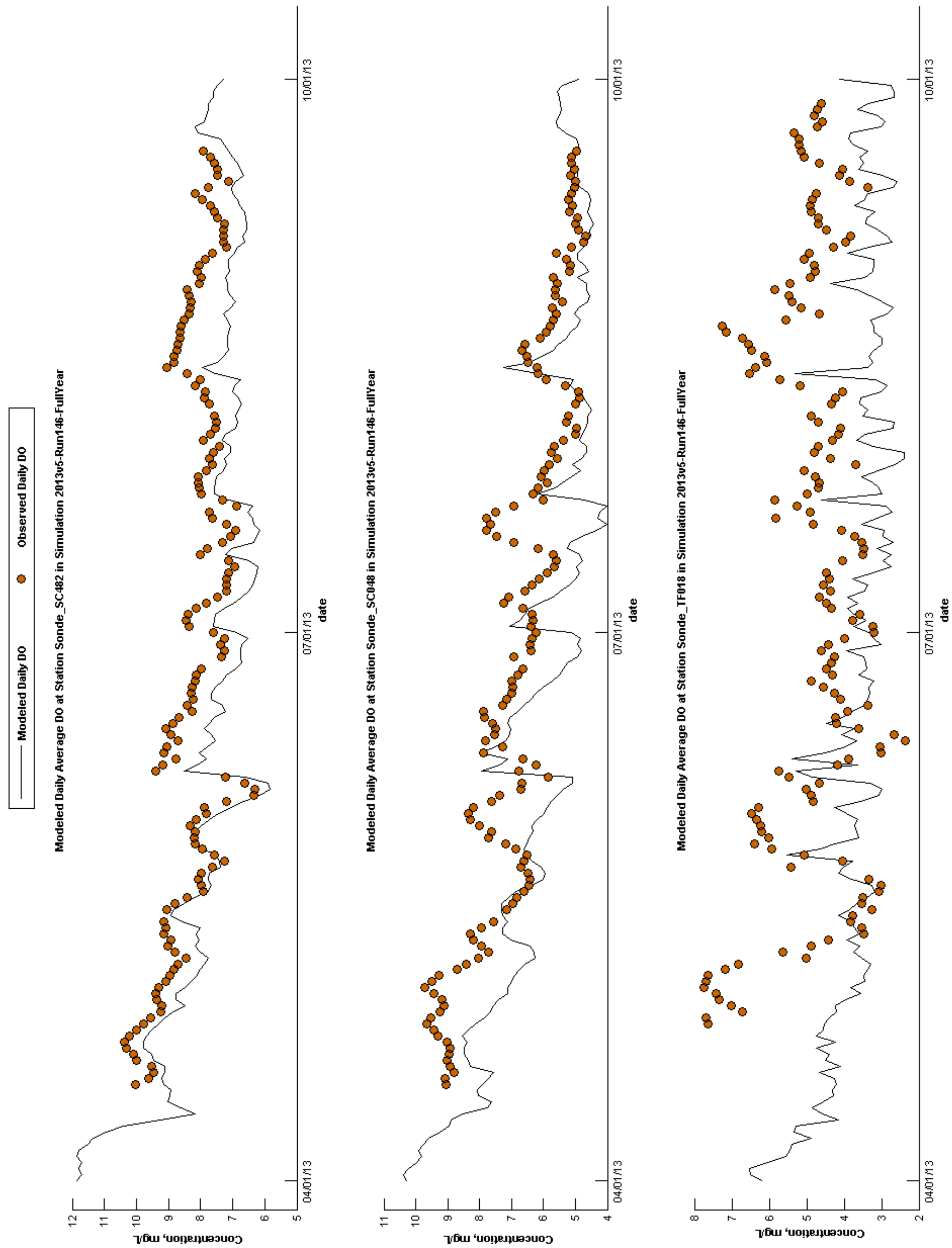

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_BF_Bridge in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
Date
07/01/13
08/01/13
09/01/13

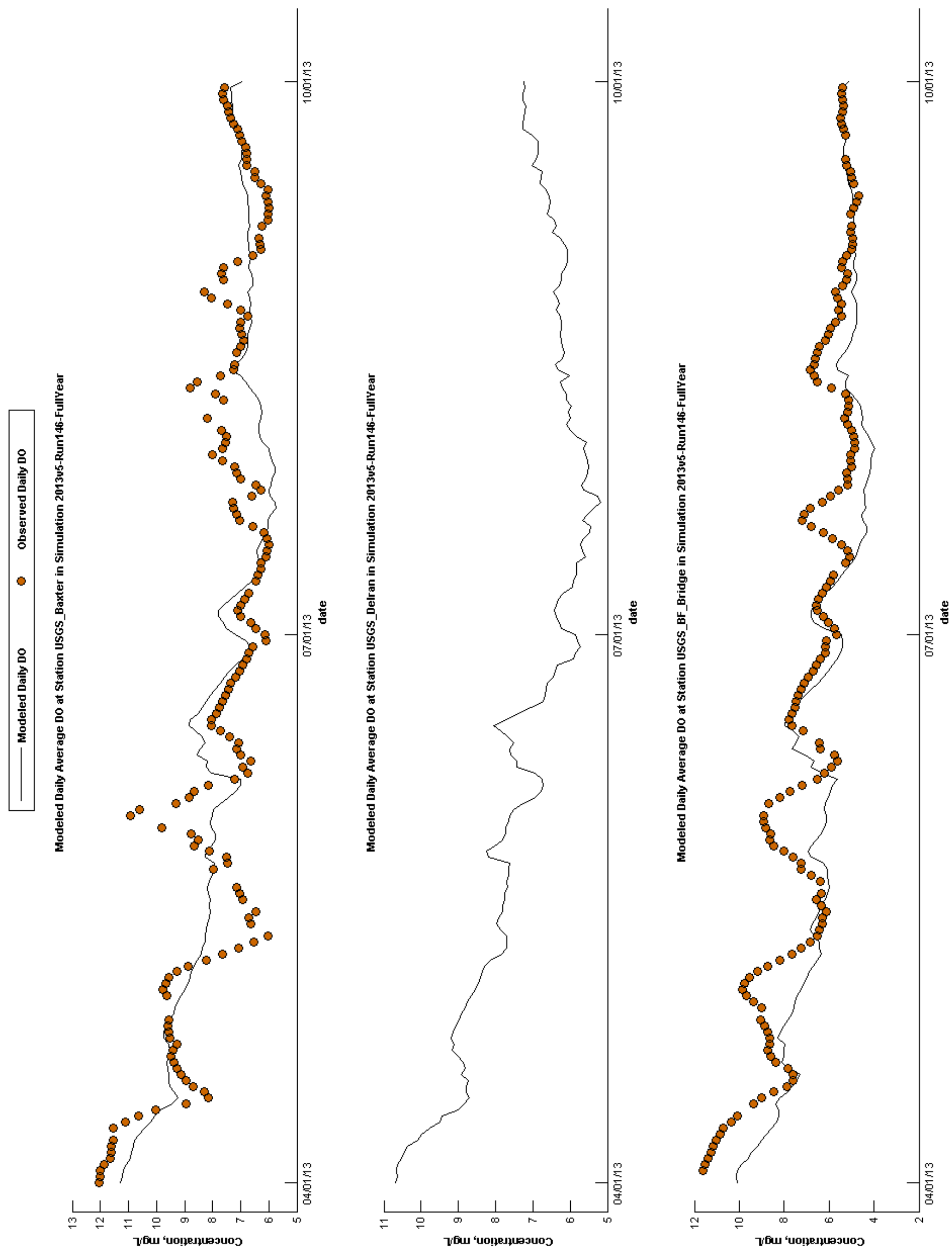

Modeled DO
Obs of DO
Delaware Q
Modeled DO at Station USGS_Chester in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
Delaware Q [cms]
8
6
4
2
1500
1000
500
0
07/01/13
08/01/13
09/01/13
Date

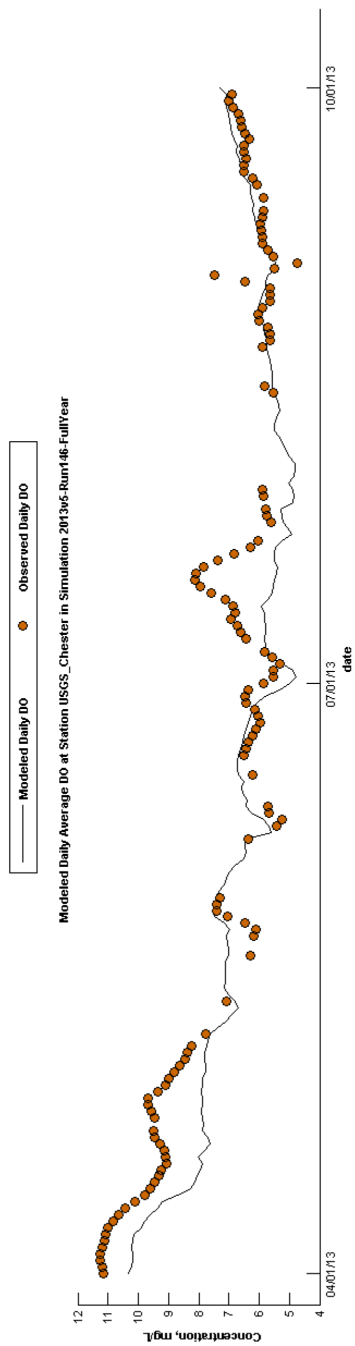

WQ Consituent DOX - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg/L

1.4. Daily Average Dissolved Oxygen

1.4.1. April to October

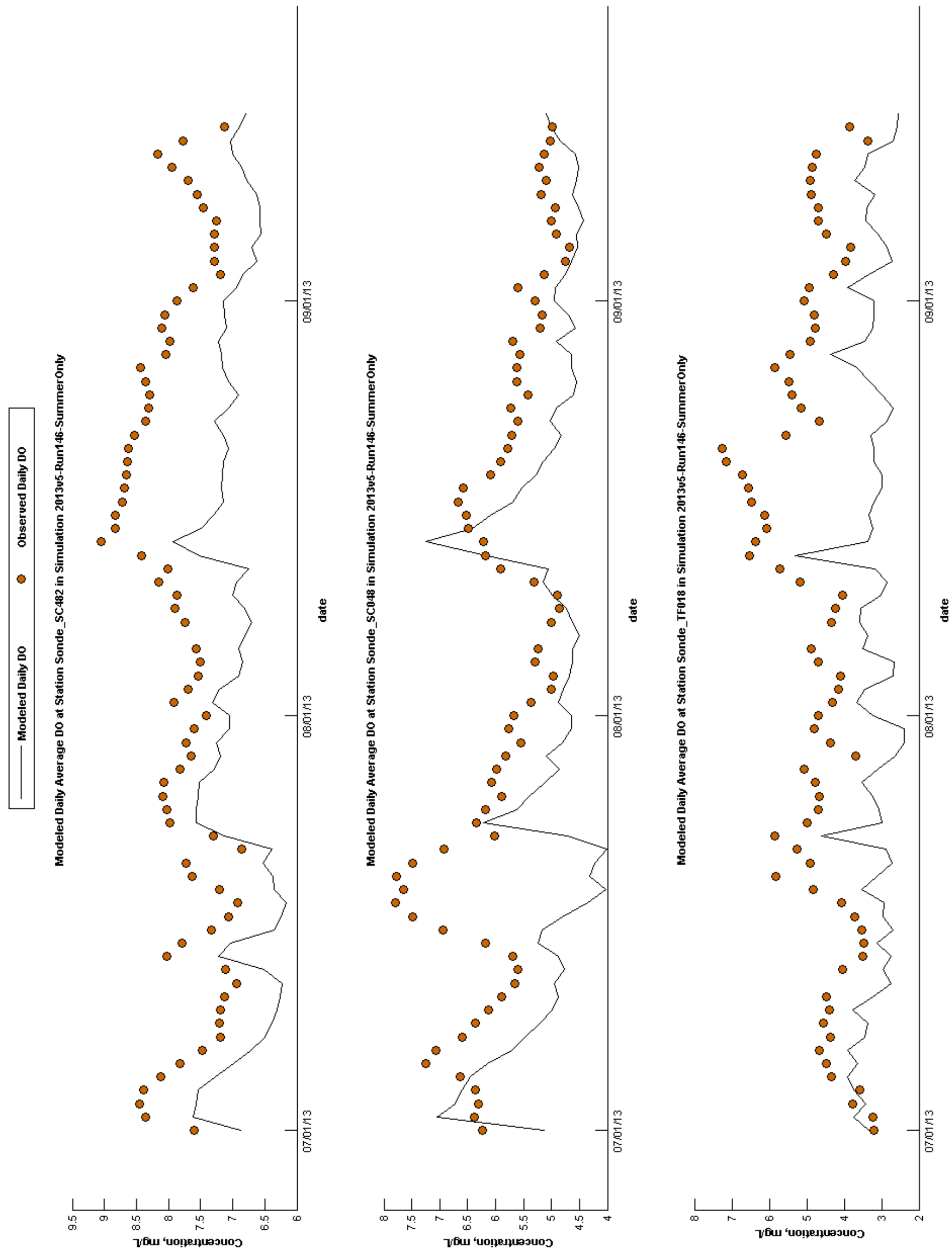


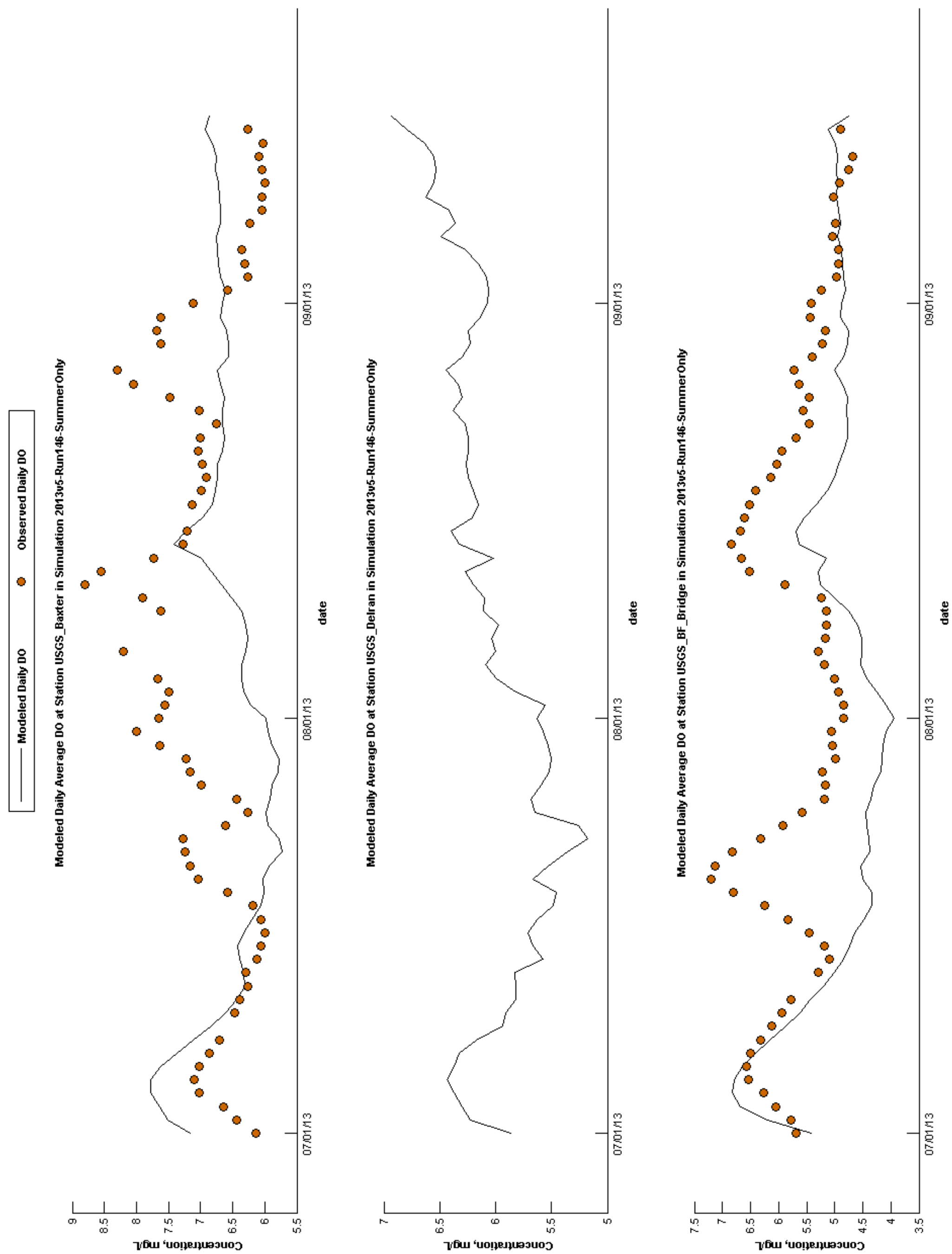

Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station USGS_Baxter in Simulation 2013v5-Run146-FullYear
Modeled Daily Average DO at Station USGS_Delran in Simulation 2013v5-Run146-FullYear
Modeled Daily Average DO at Station USGS_BF_Bridge in Simulation 2013v5-Run146-FullYear
Concentration, mg/L
date
04/01/13
07/01/13
10/01/13

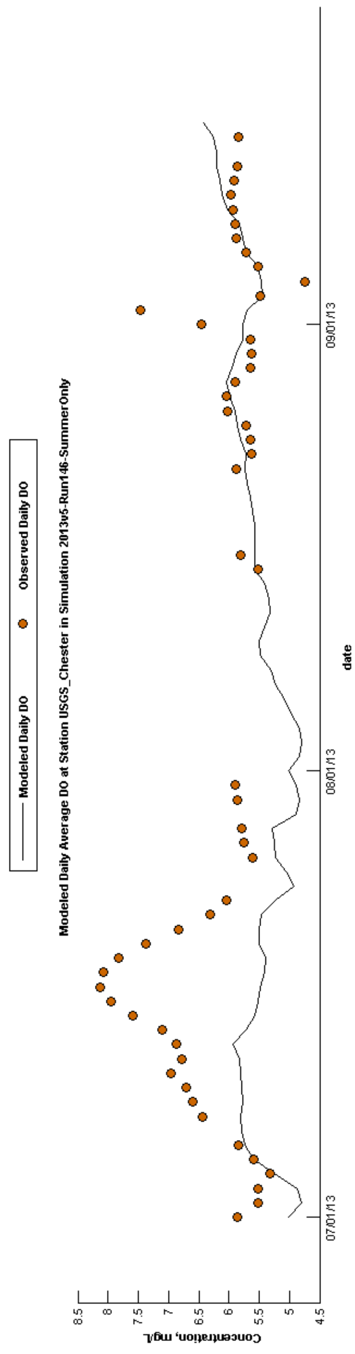


Modeled Daily Average DO at Station USGS_Chester in Simulation 2013v5-Run146-FullYear
Modeled Daily DO
Observed Daily DO
Concentration, mg/L
12
11
10
9
8
7
6
5
4
04/01/13
07/01/13
10/01/13
date

1.4.2. Summer

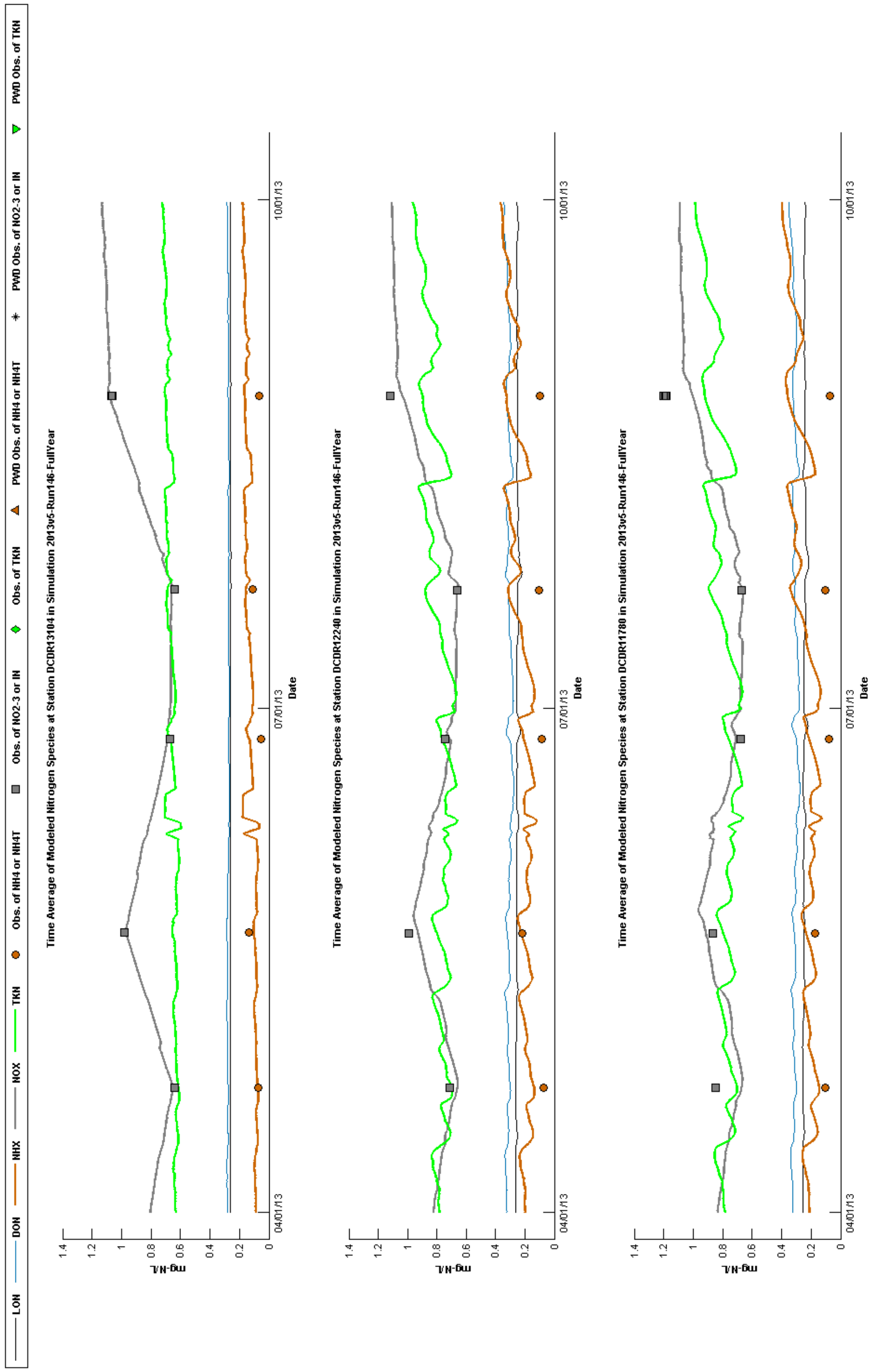

Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station Sonde_SC482 in Simulation 2013v5-Run146-SummerOnly
Modeled Daily Average DO at Station Sonde_SC048 in Simulation 2013v5-Run146-SummerOnly
Modeled Daily Average DO at Station Sonde_TF018 in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/13
08/01/13
09/01/13

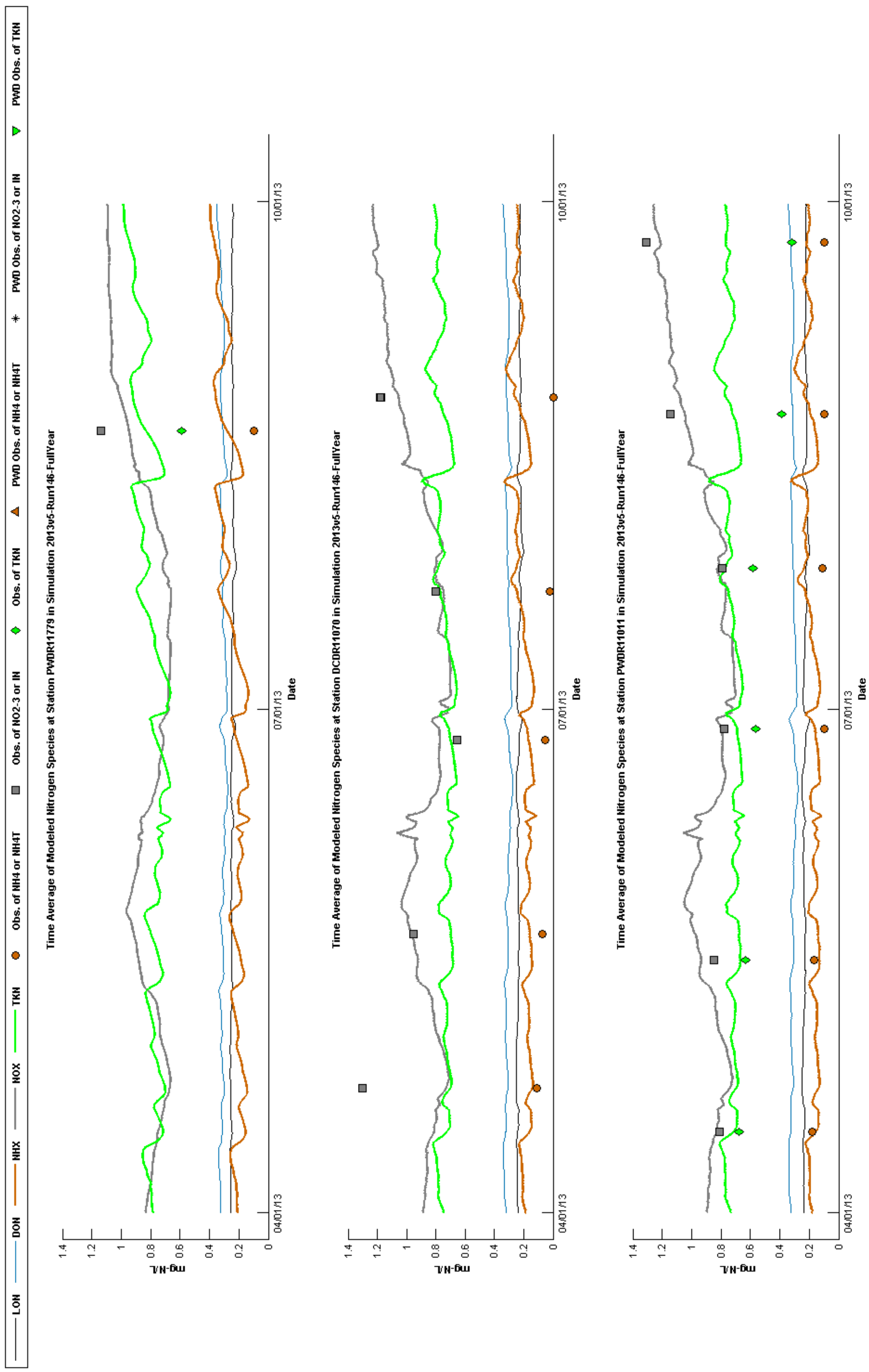

Modeled Daily DO
Observed Daily DO
Modeled Daily Average DO at Station USGS_Baxter in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/13
08/01/13
09/01/13
Modeled Daily Average DO at Station USGS_Delran in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/13
08/01/13
09/01/13
Modeled Daily Average DO at Station USGS_BF_Bridge in Simulation 2013v5-Run146-SummerOnly
Concentration, mg/L
date
07/01/13
08/01/13
09/01/13

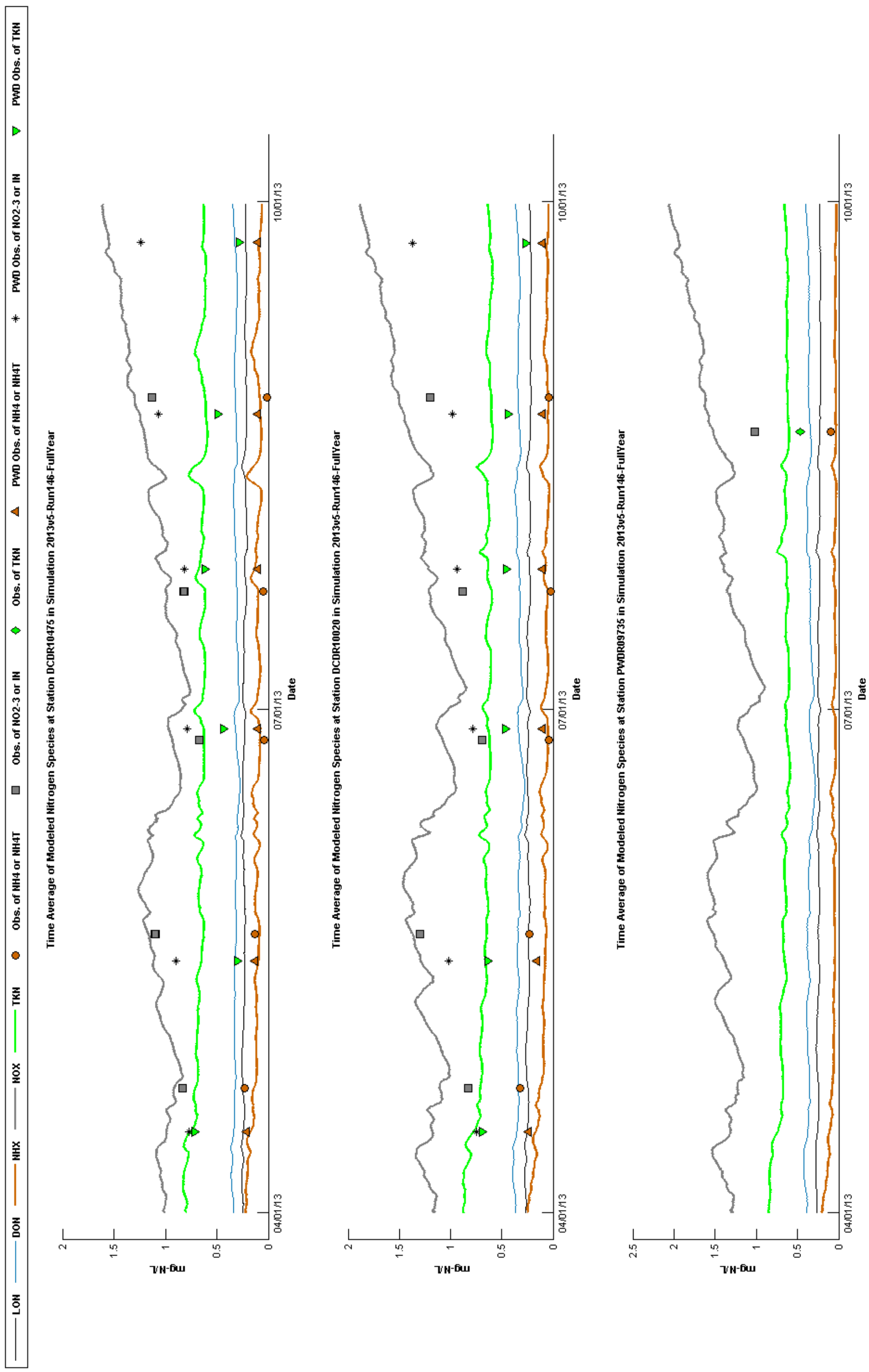

Modeled Daily Average DO at Station USGS_Chester in Simulation 2013v5-Run146-SummerOnly
Modeled Daily DO
Observed Daily DO
Concentration, mg/L
8.5
8
7.5
7
6.5
6
5.5
5
4.5
07/01/13
08/01/13
09/01/13
date

1.5. Nitrogen Species

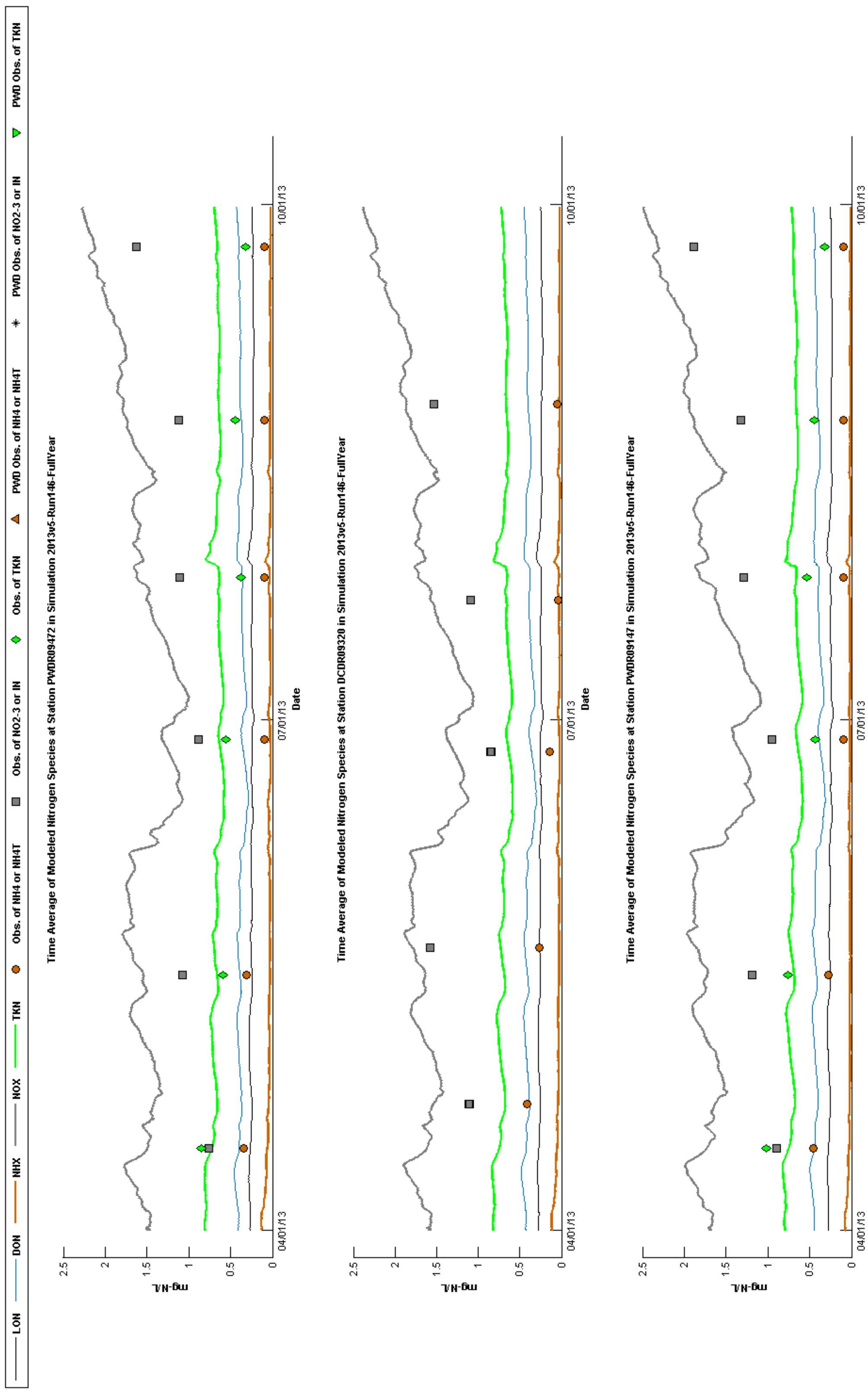
1.5.1. April to October

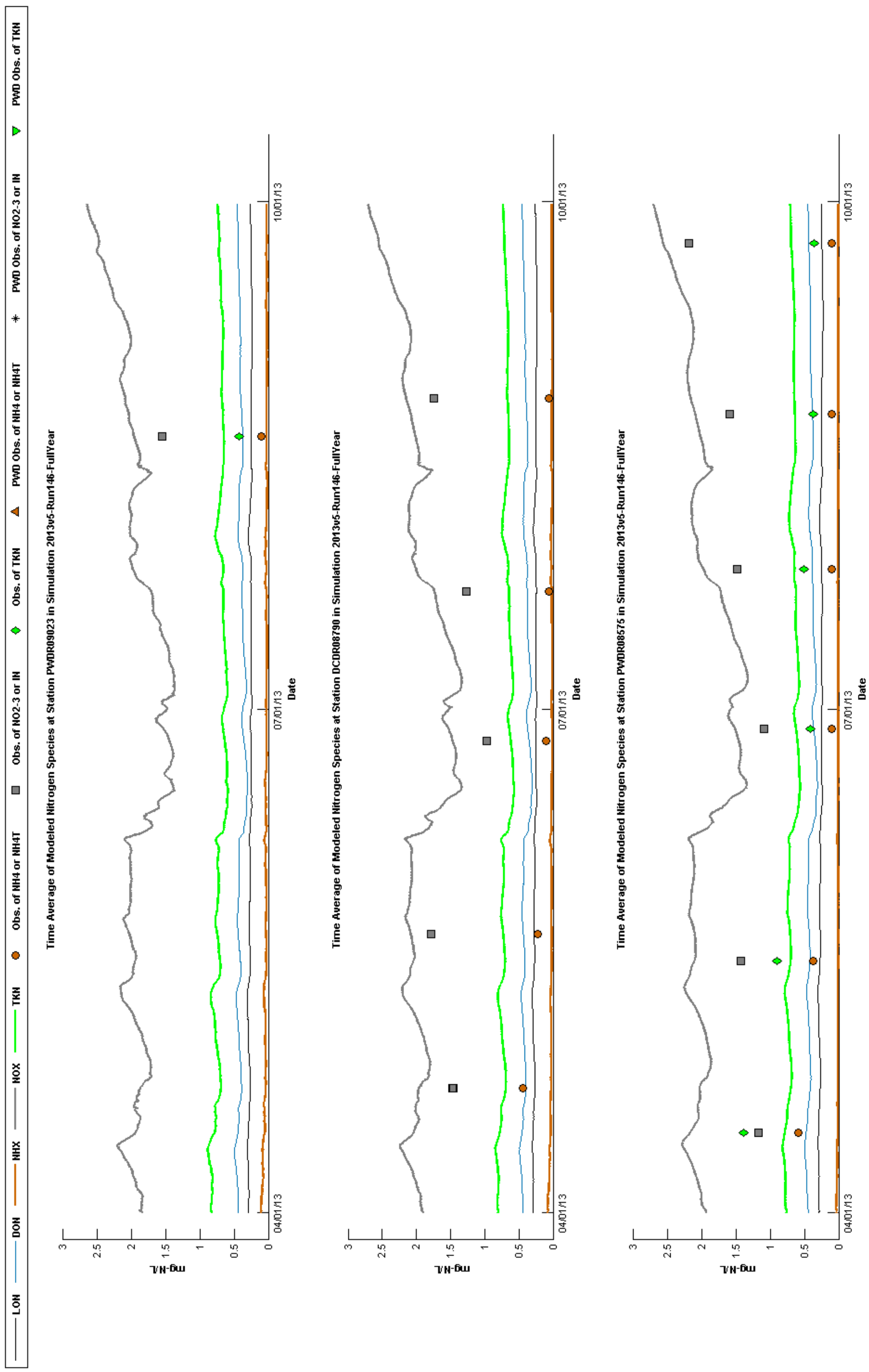


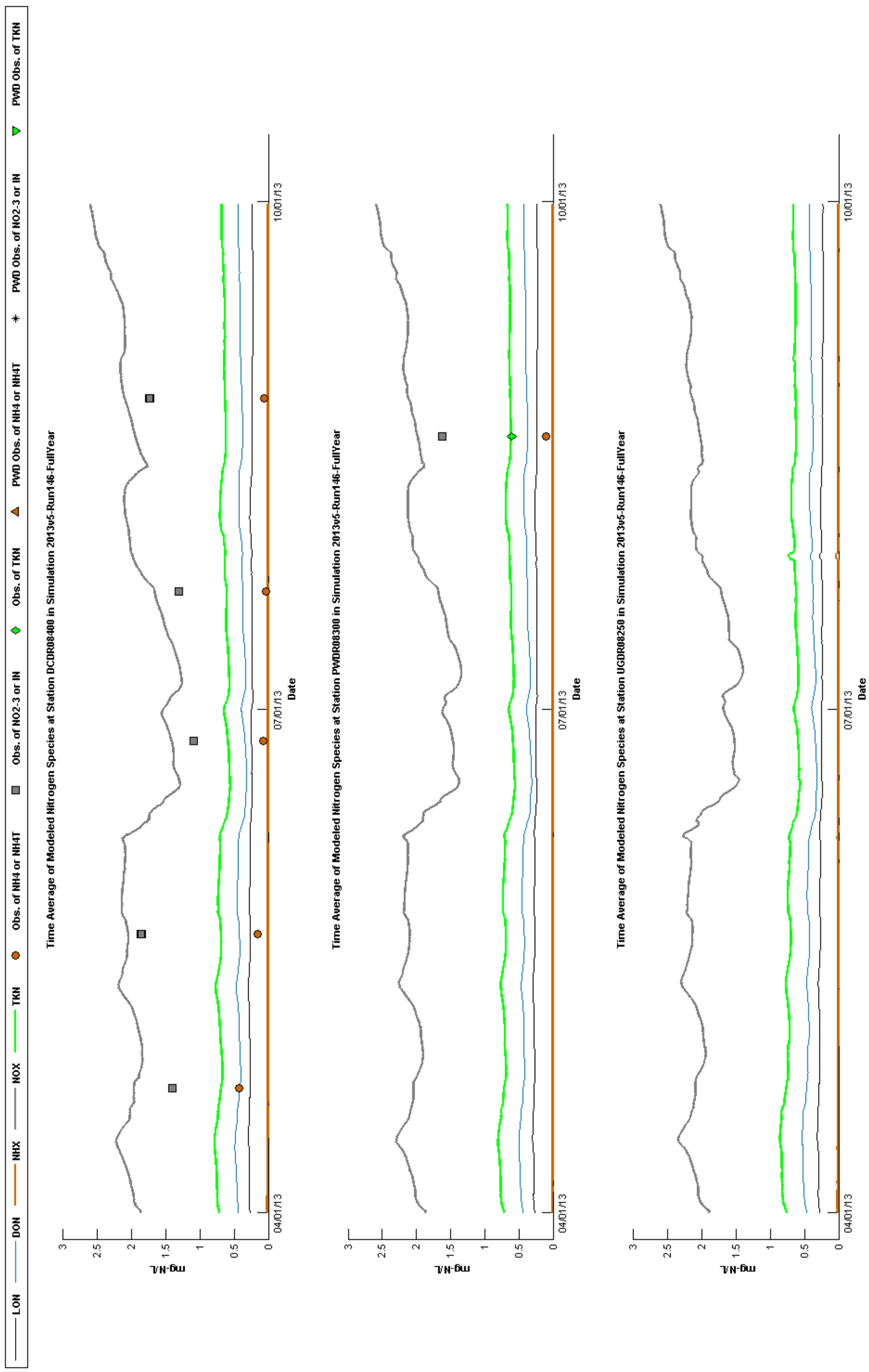

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR11779 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR11070 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR11011 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

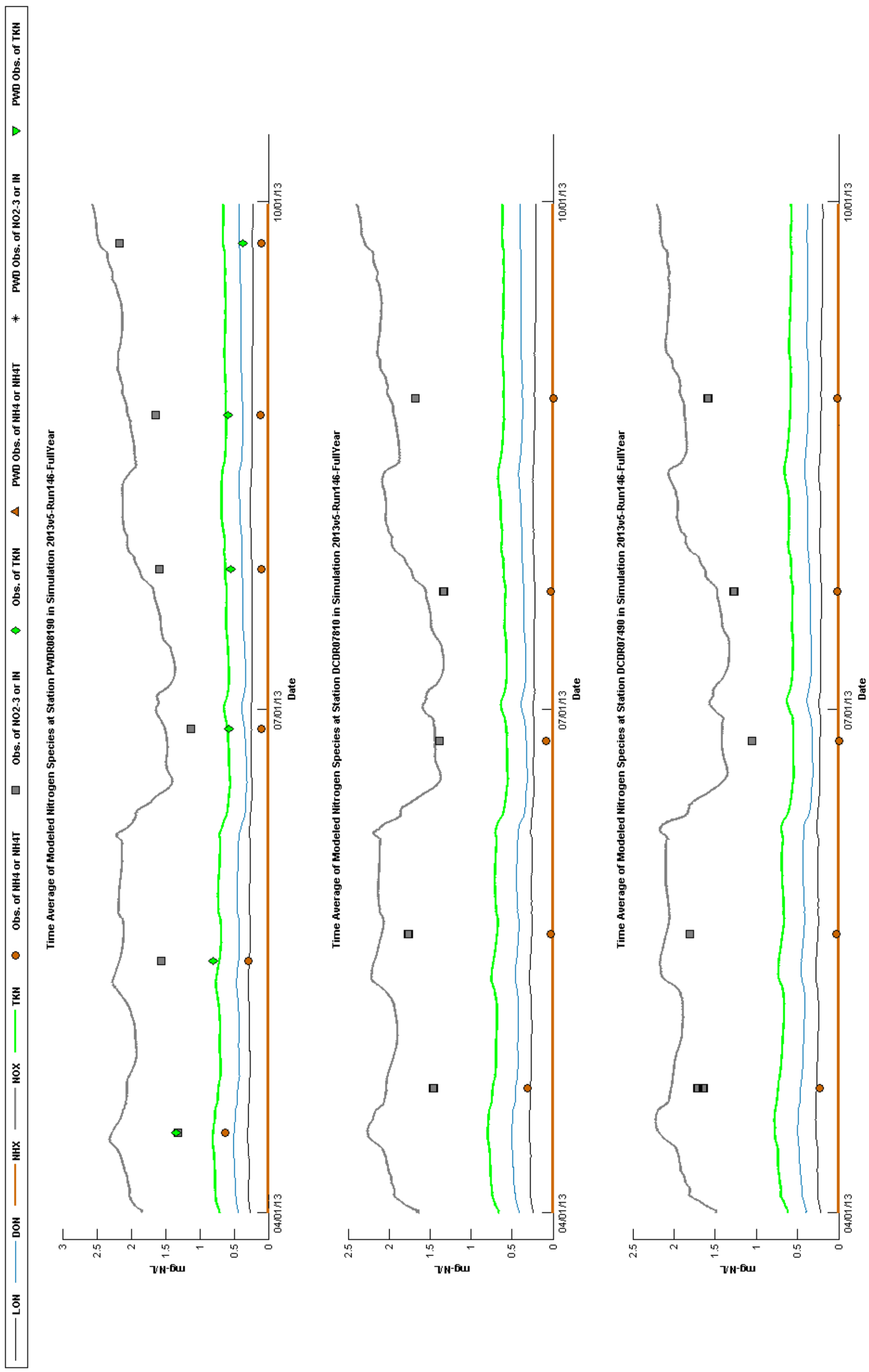


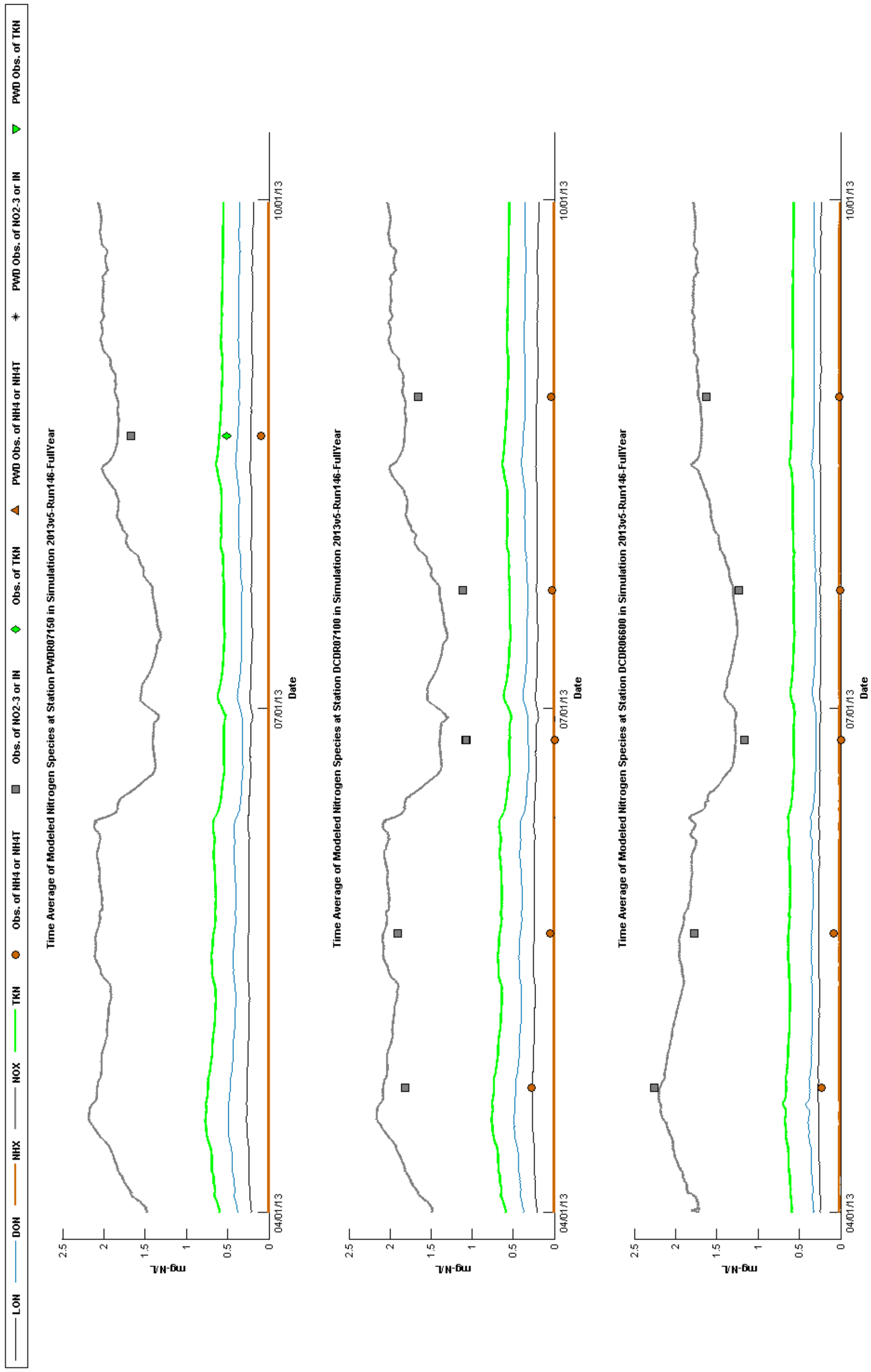
LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR10475 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR10020 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR09735 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

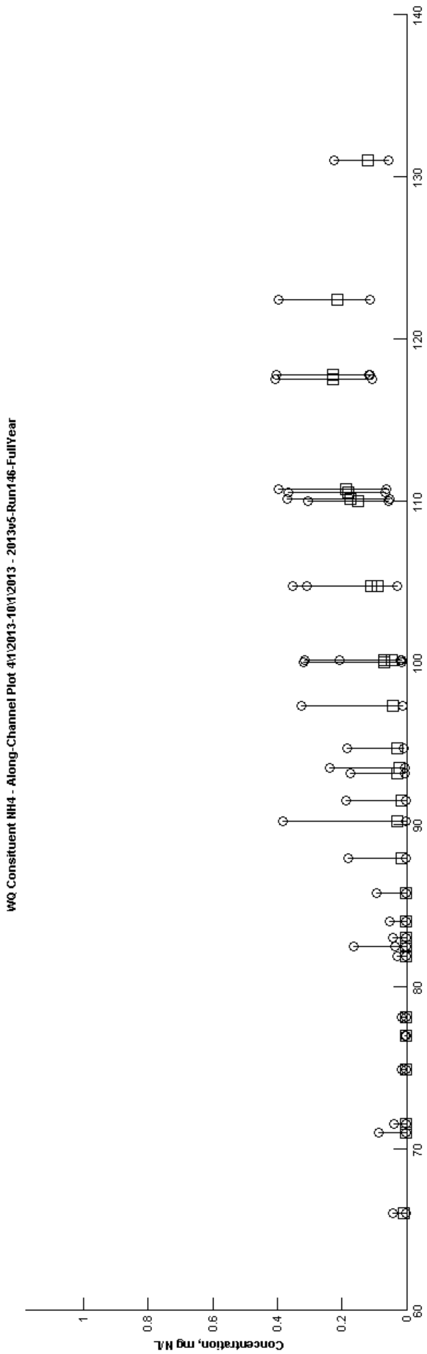

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09472 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR09320 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR09147 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

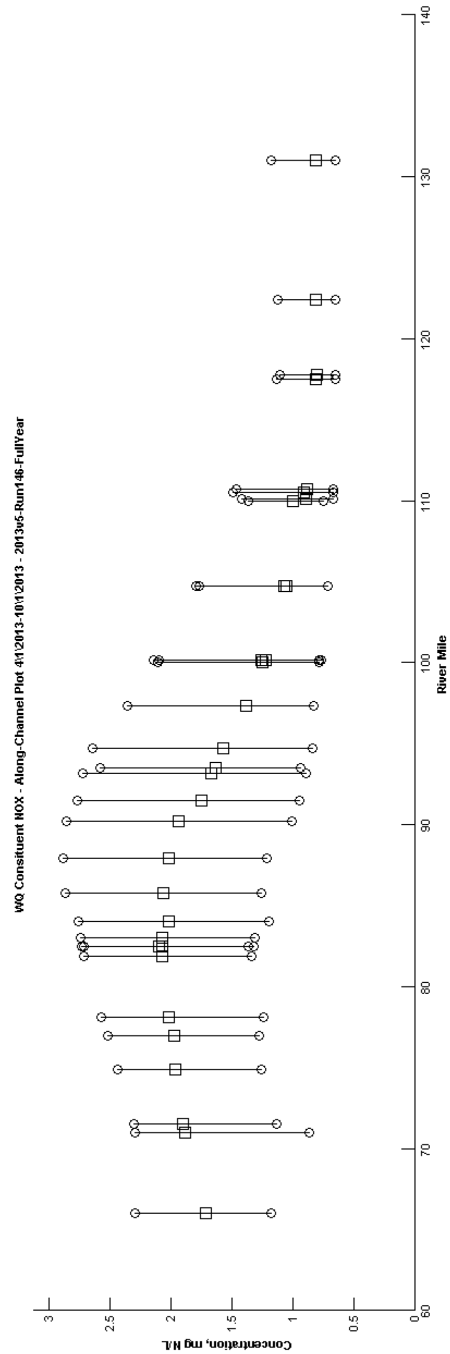

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09023 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR08790 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR08575 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

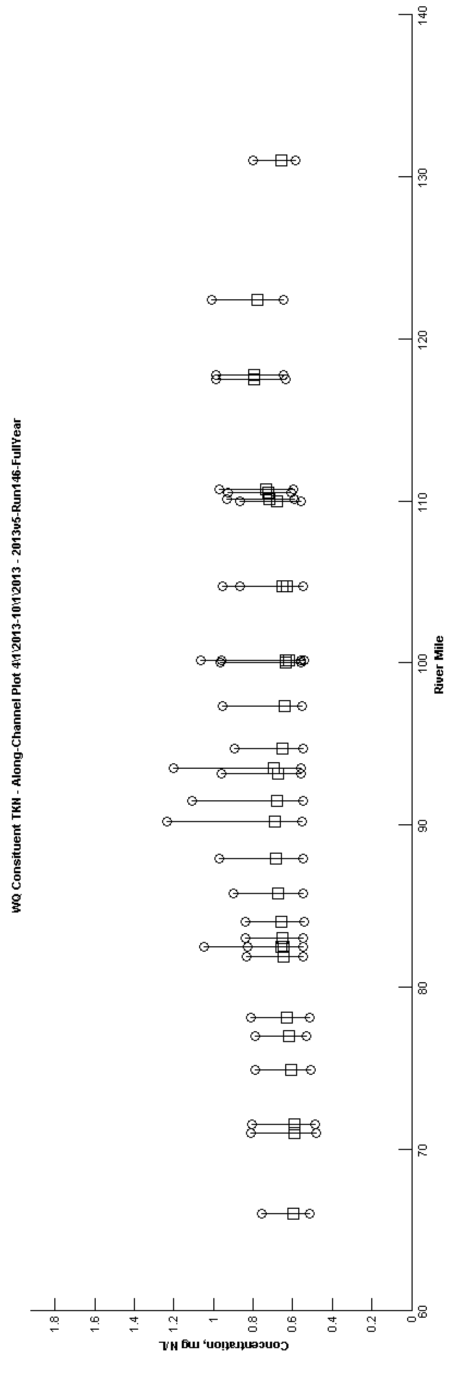

TON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR08400 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station PWDR08300 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station UCDR08250 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

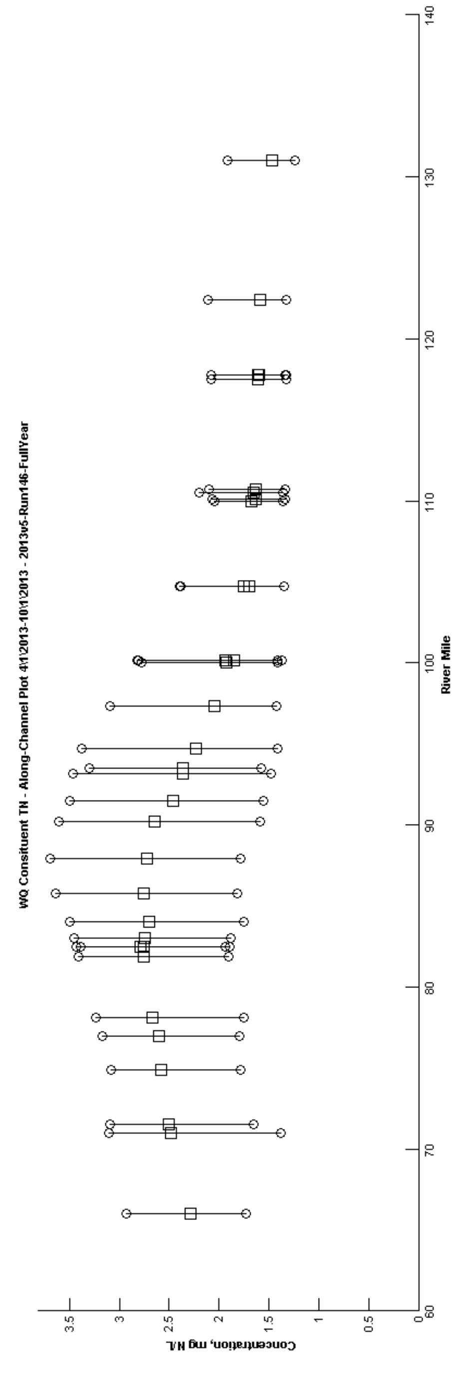

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR08190 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07810 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07490 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13


LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR07150 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR07100 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Nitrogen Species at Station DCDR06600 in Simulation 2013v5-Run146-FullYear
mg-N/L
Date
04/01/13
07/01/13
10/01/13

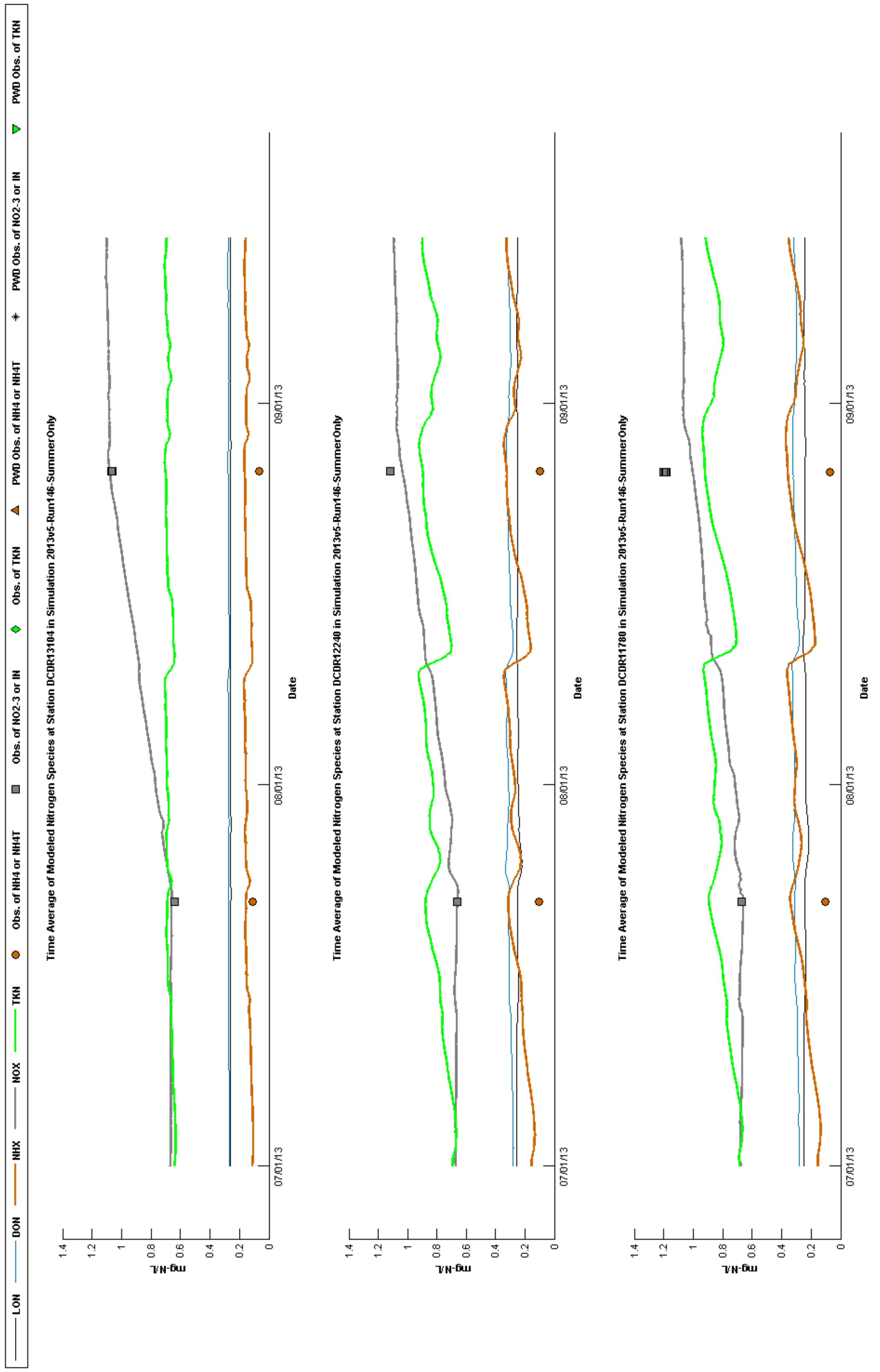

WQ Consituent NH4 - Along-Channel Plot 4/1/2013-10/1/2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg N/L

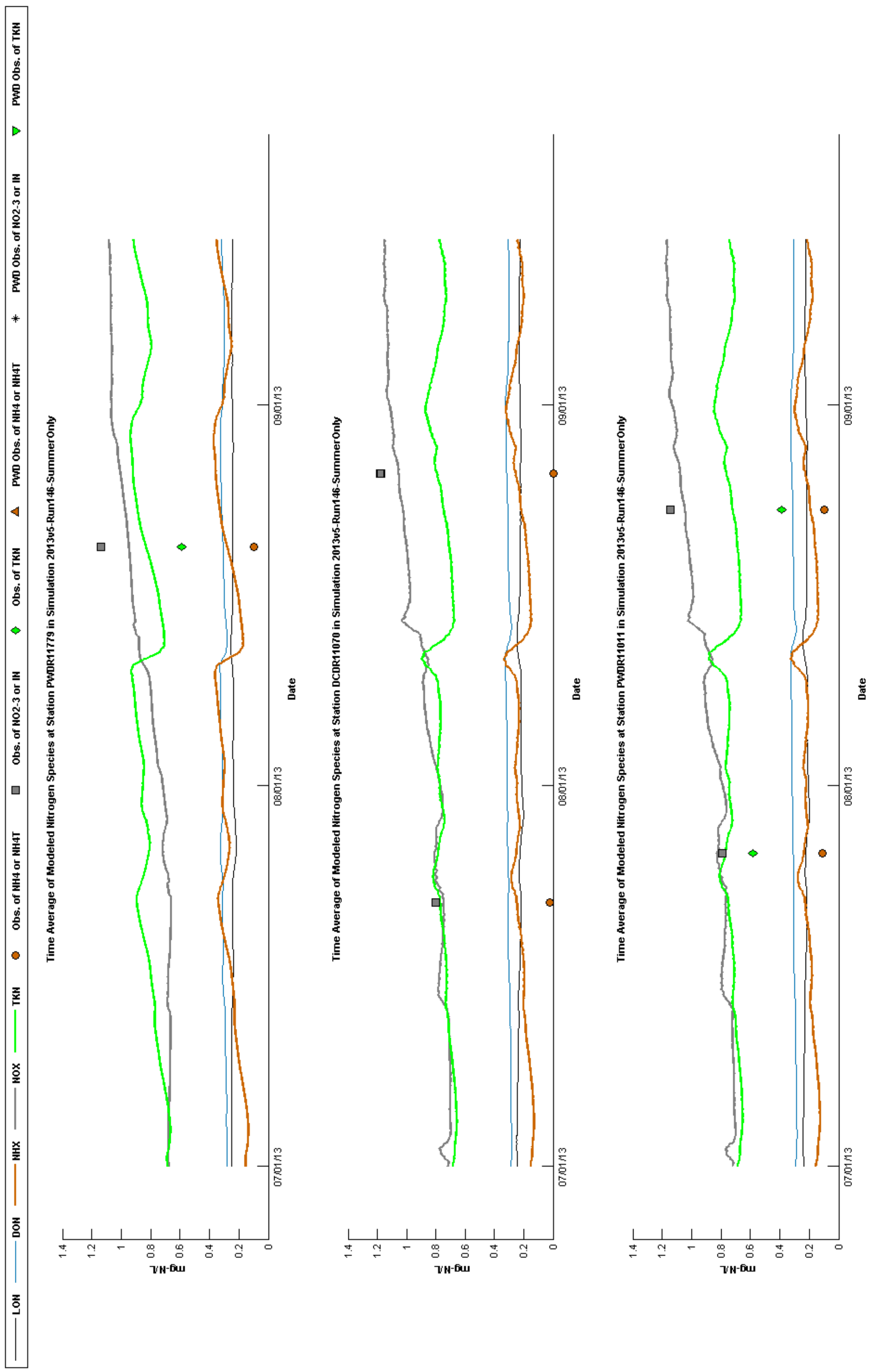

WQ Consituent NOX - Along-Channel Plot 4/1/2013-10/1/2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg N/L

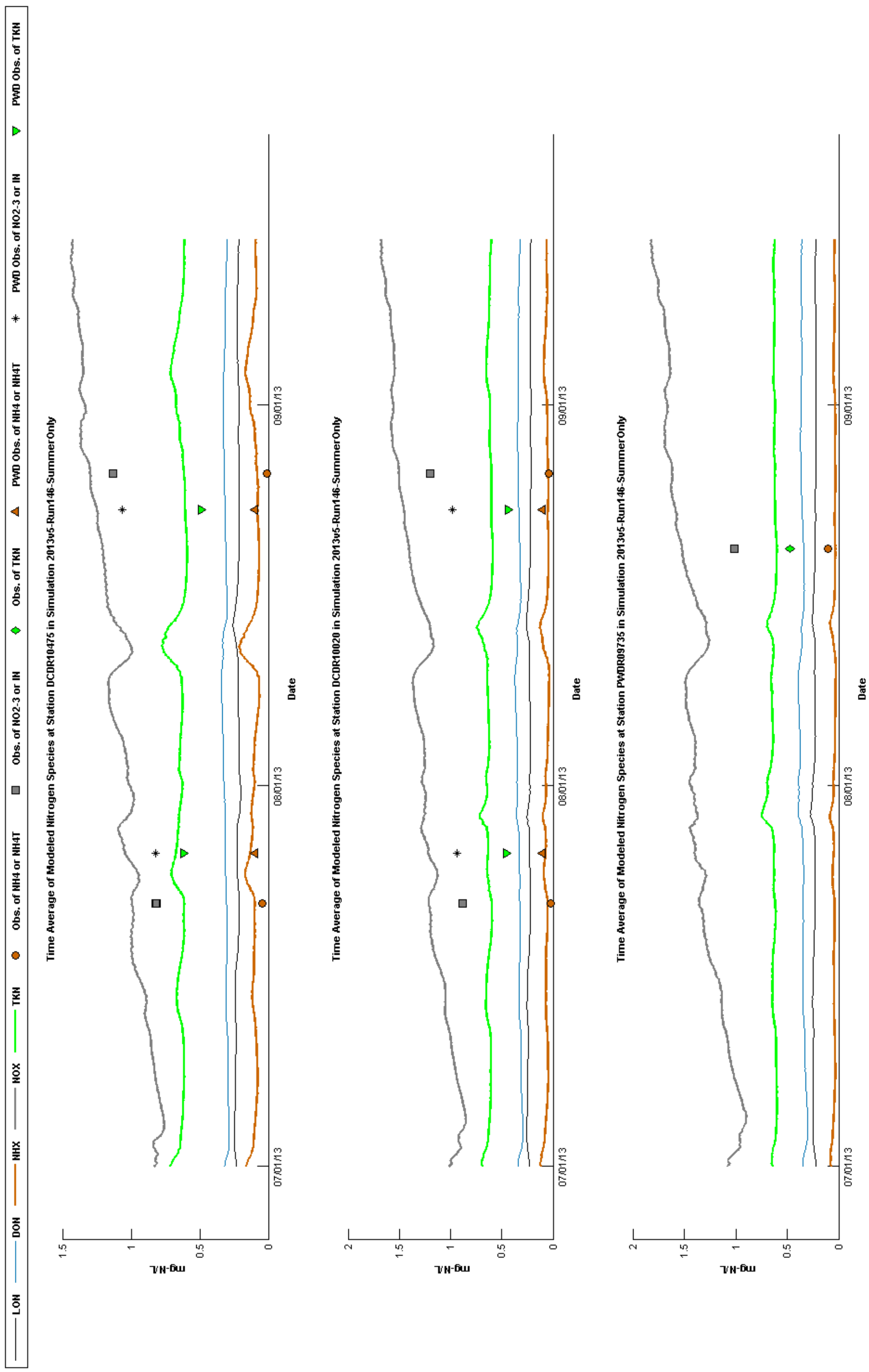

WQ Consituent TKN - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg N/L

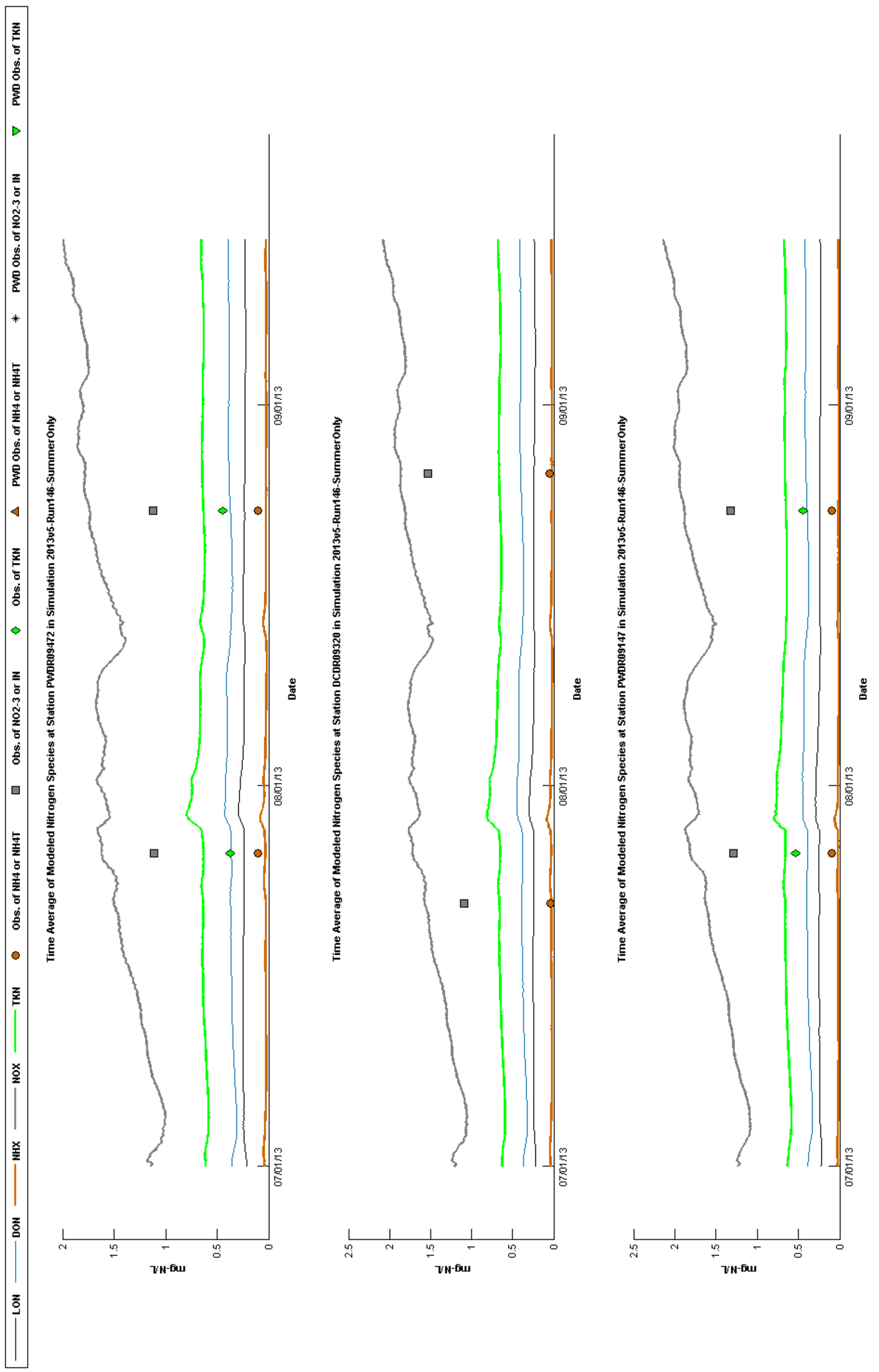

WQ Consituent TN - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg N/L

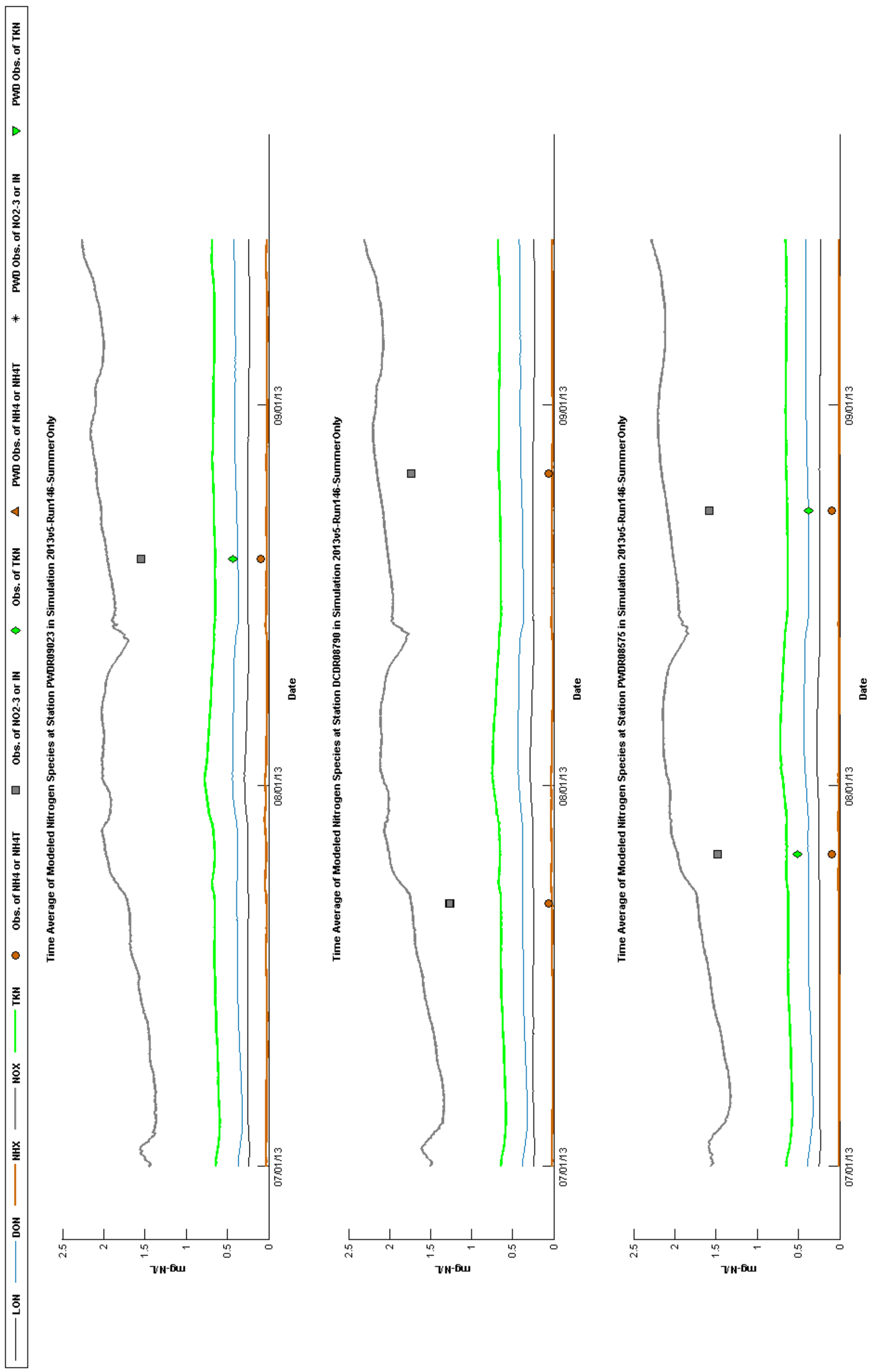
1.5.2. Summer

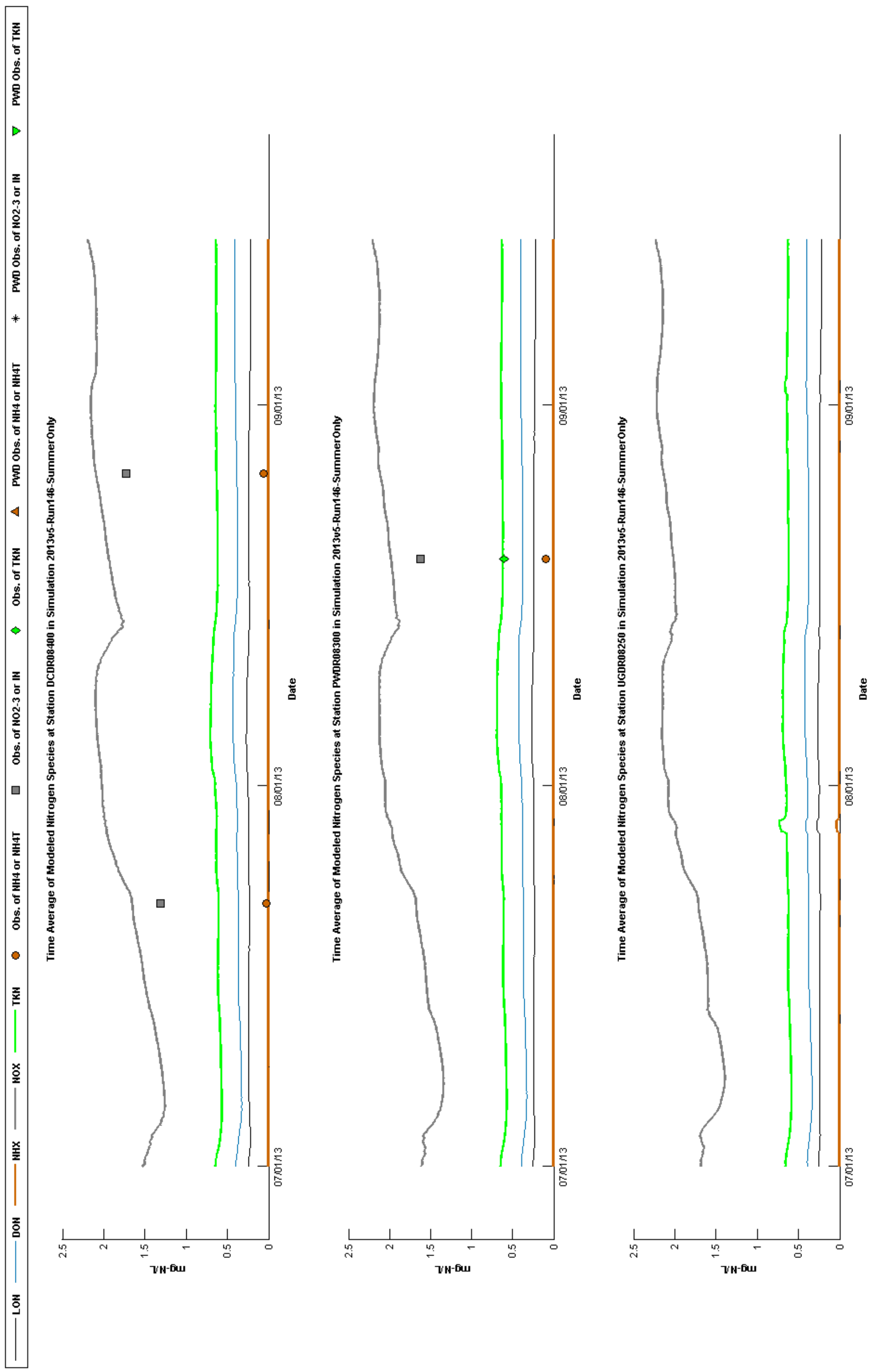

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR13104 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR12240 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR11780 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
1.4
1.2
1
0.8
0.6
0.4
0.2
0
07/01/13
08/01/13
09/01/13
Date

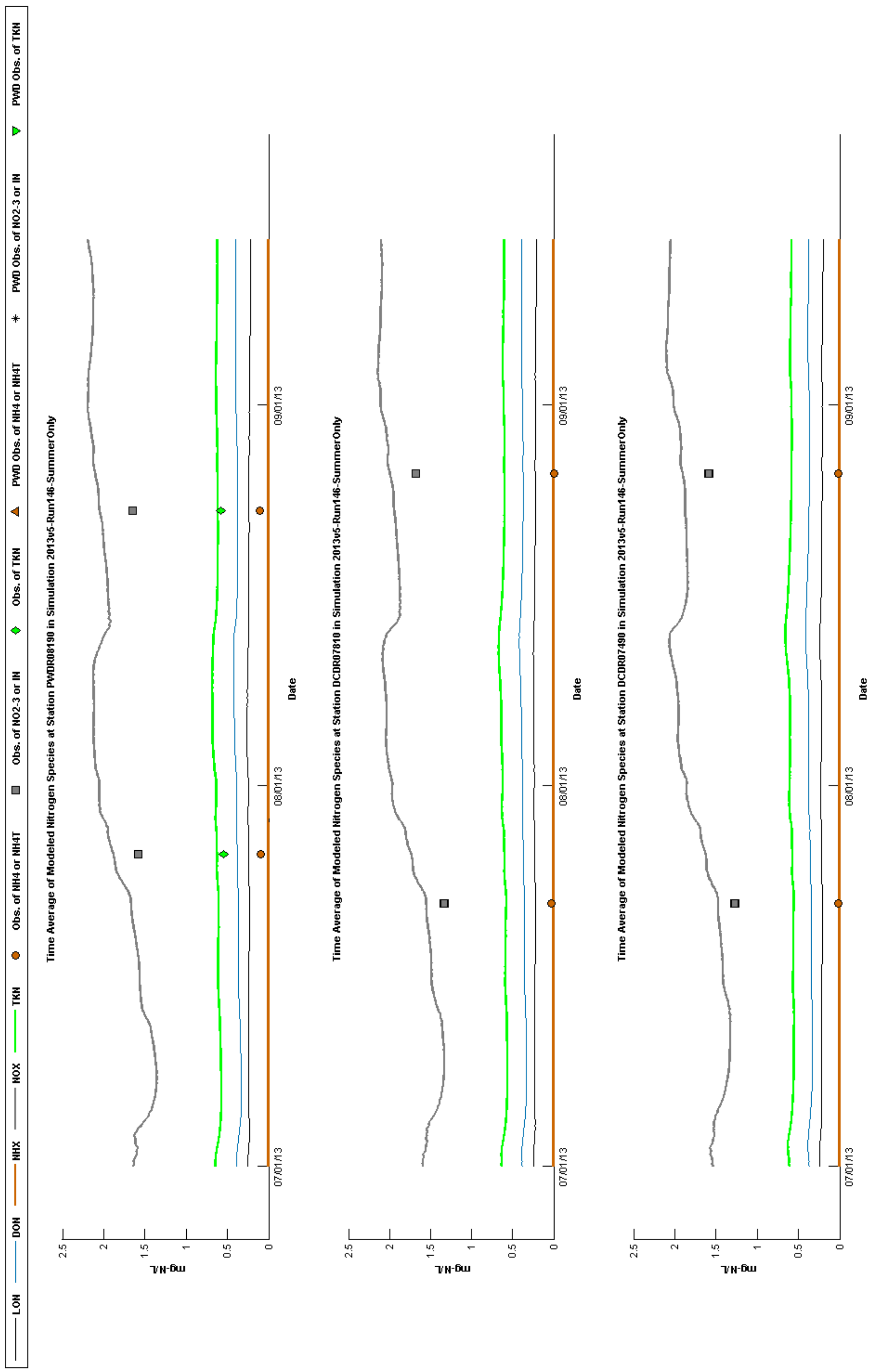

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR11779 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR11070 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR11011 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
0
0.2
0.4
0.6
0.8
1
1.2
1.4
07/01/13
08/01/13
09/01/13
Date

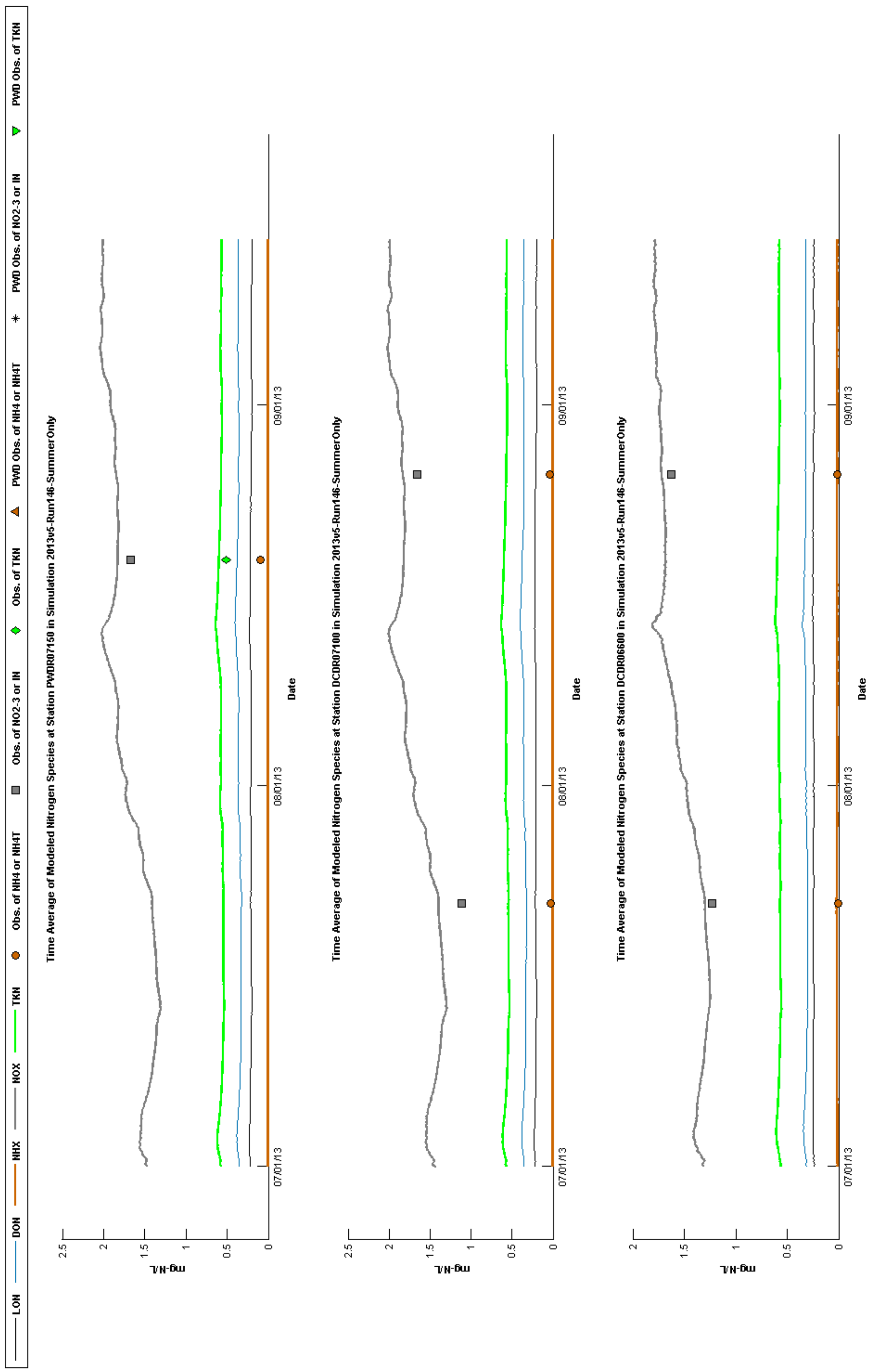

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR10475 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Nitrogen Species at Station DCDR10020 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Nitrogen Species at Station PWDR09735 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13

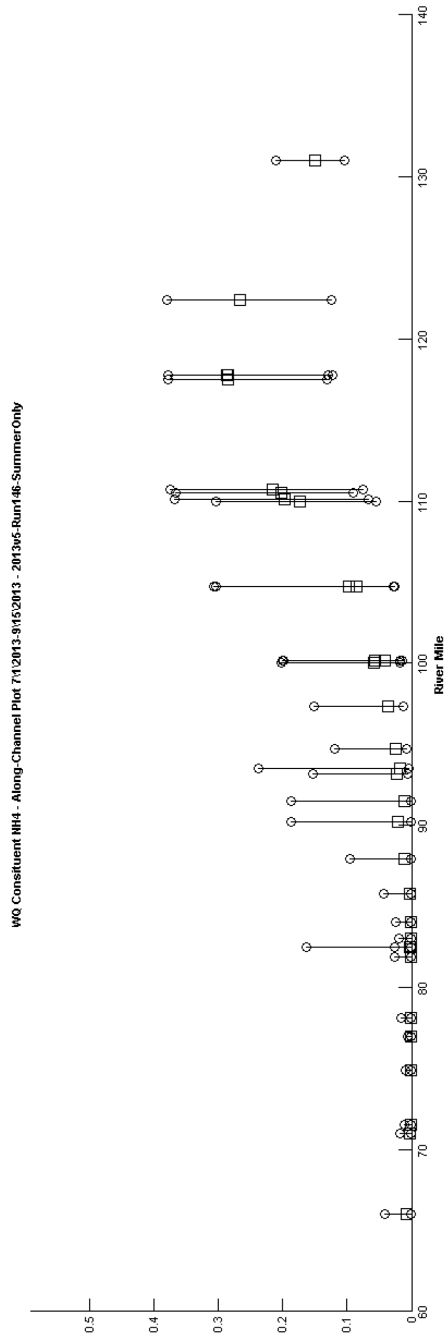

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09472 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR09320 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR09147 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13

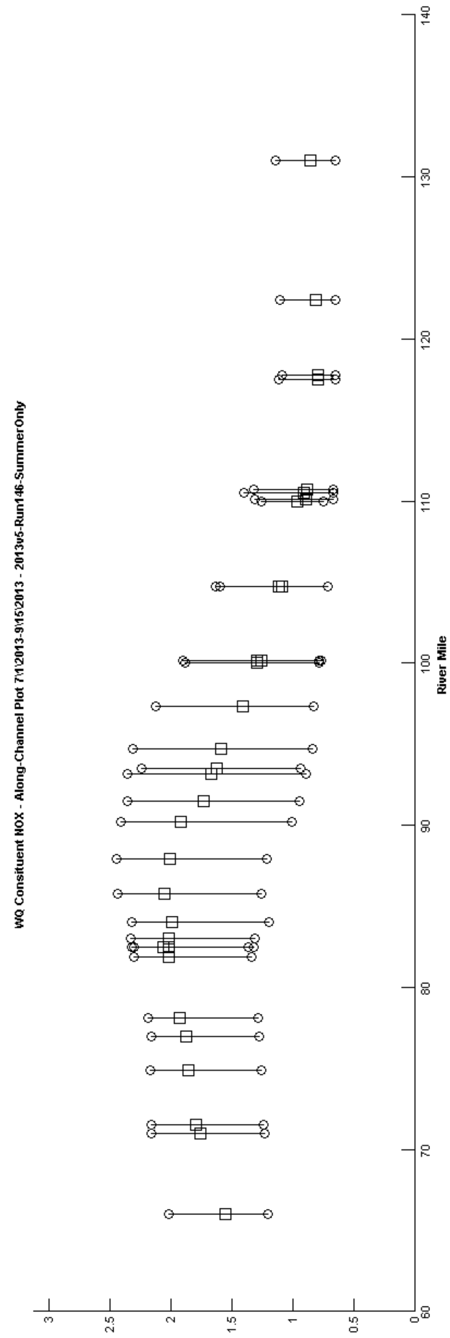

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR09023 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR08790 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR08575 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
0
0.5
1
1.5
2
2.5

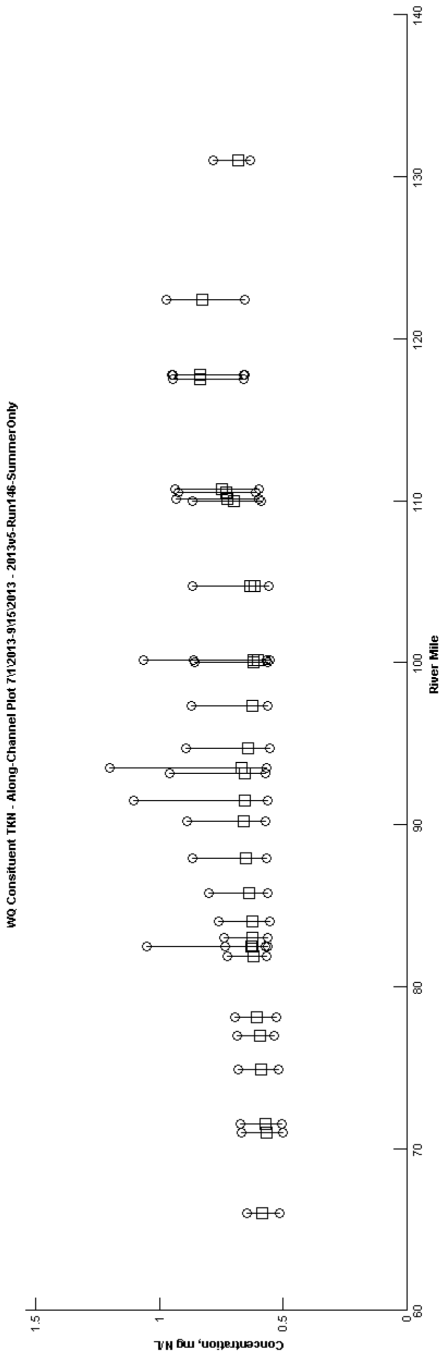

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station DCDR08400 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station PWDR08300 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station UGDR08250 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
0
0.5
1
1.5
2
2.5

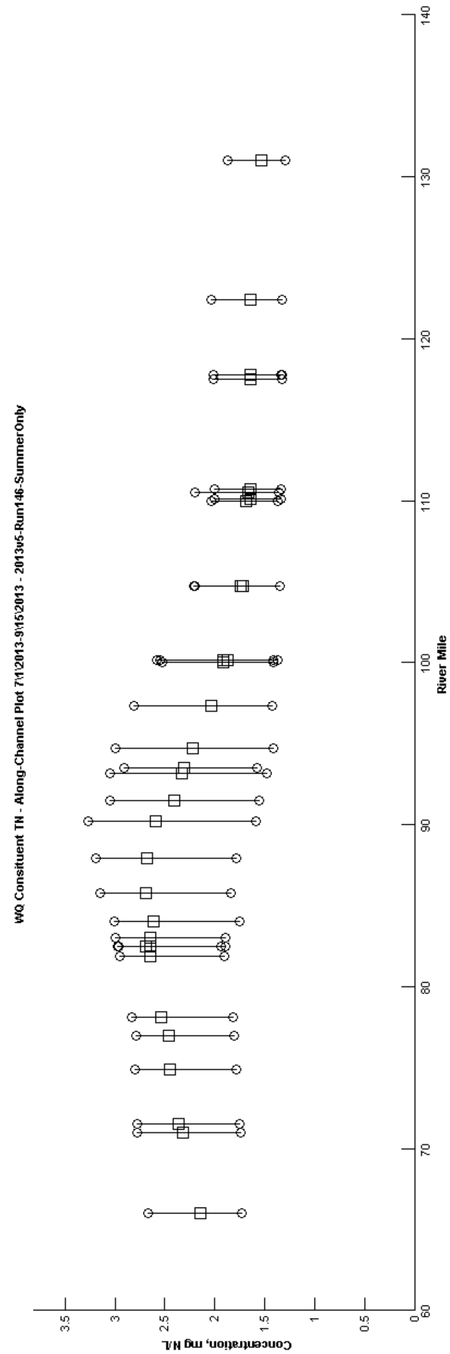

LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR08190 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR07810 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Nitrogen Species at Station DCDR07490 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
0
0.5
1
1.5
2
2.5


LON
DON
NHX
NOX
TKN
Obs. of NH4 or NH4T
Obs. of NO2-3 or IN
Obs. of TKN
PWD Obs. of NH4 or NH4T
PWD Obs. of NO2-3 or IN
PWD Obs. of TKN
Time Average of Modeled Nitrogen Species at Station PWDR07150 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Nitrogen Species at Station DCDR07100 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13
Time Average of Modeled Nitrogen Species at Station DCDR06600 in Simulation 2013v5-Run146-SummerOnly
mg-N/L
Date
07/01/13
08/01/13
09/01/13


WQ Consituent NH4 - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

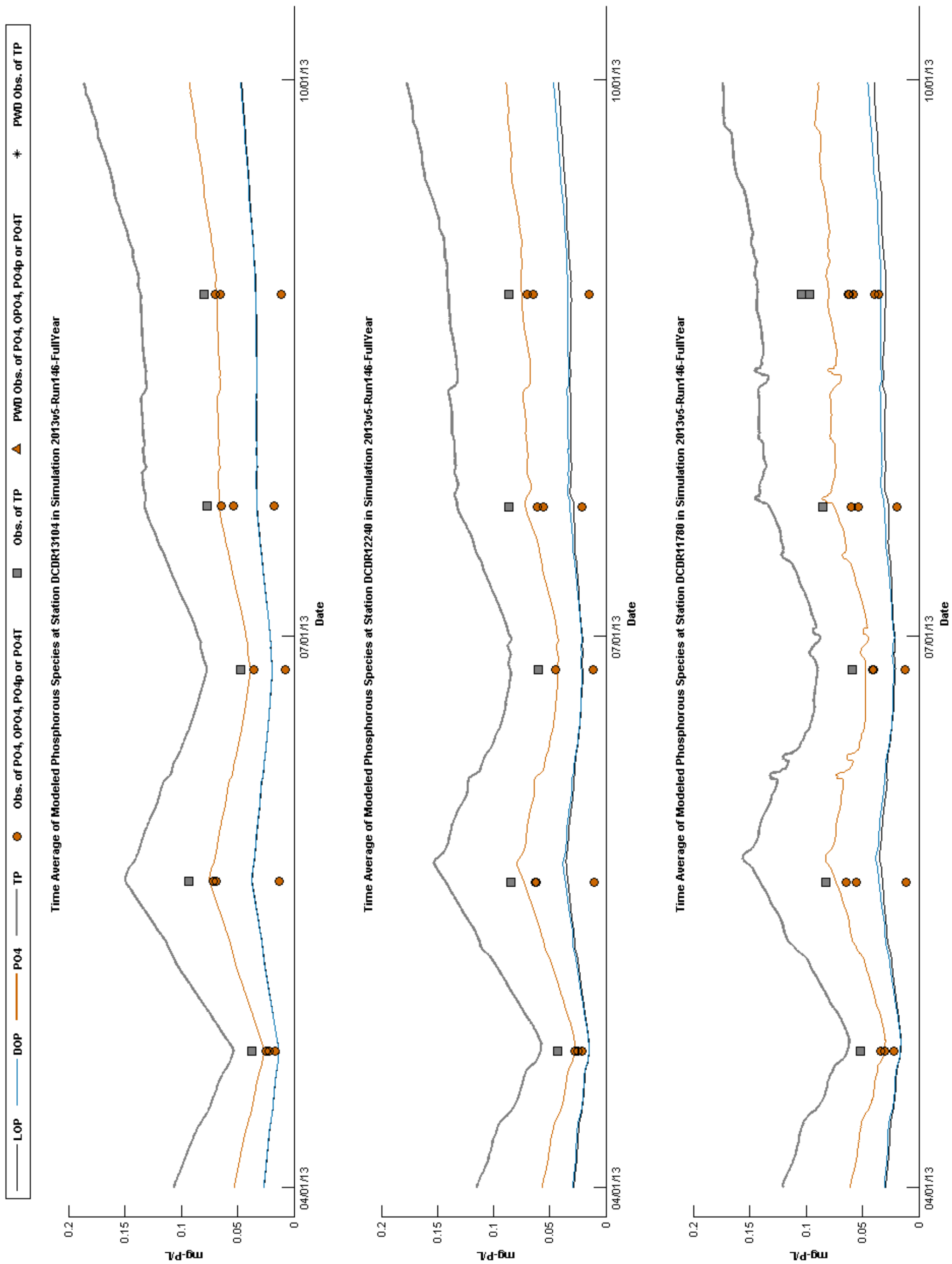

WQ Consituent NOX - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

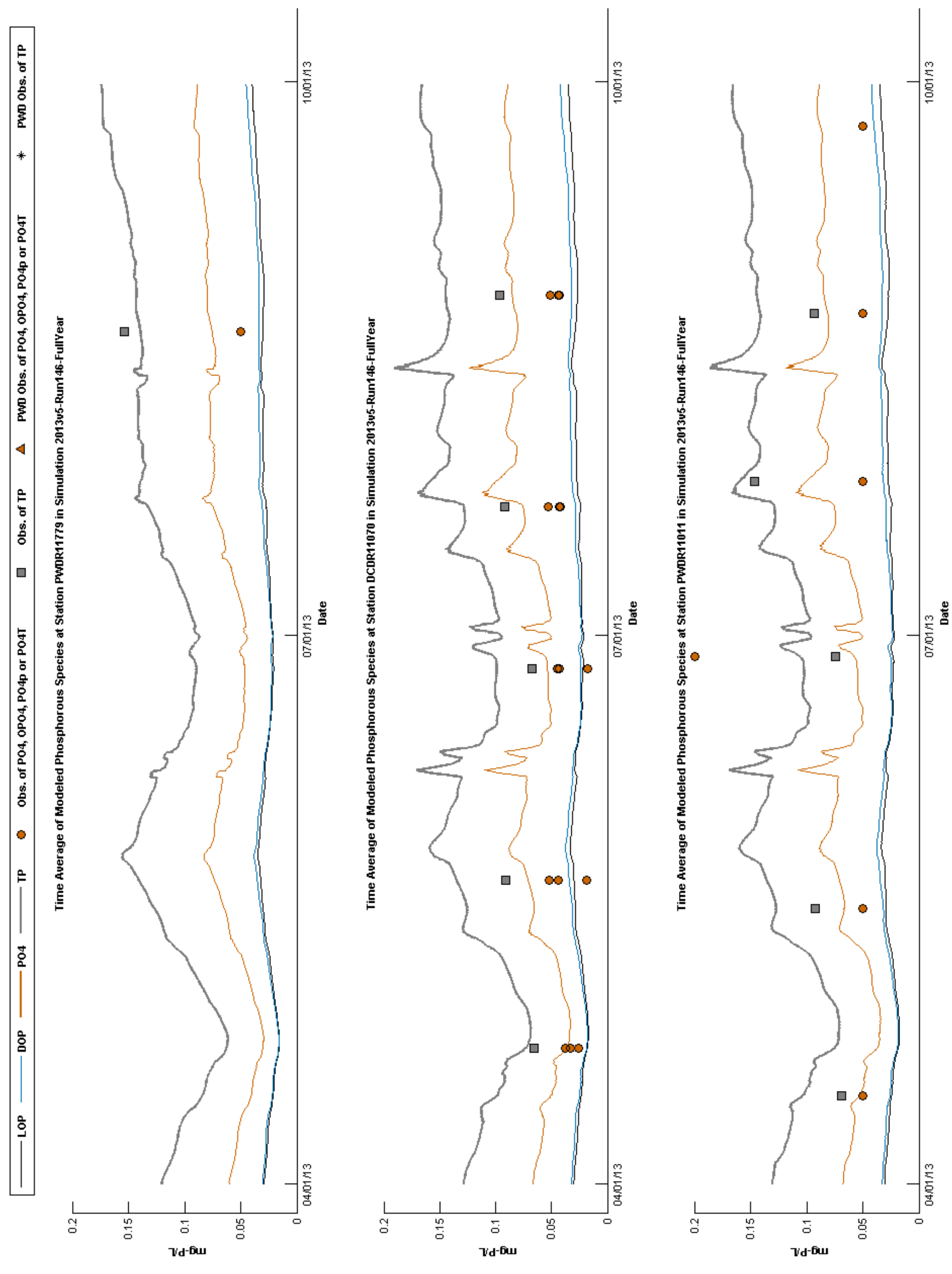

WQ Consituent TKN - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

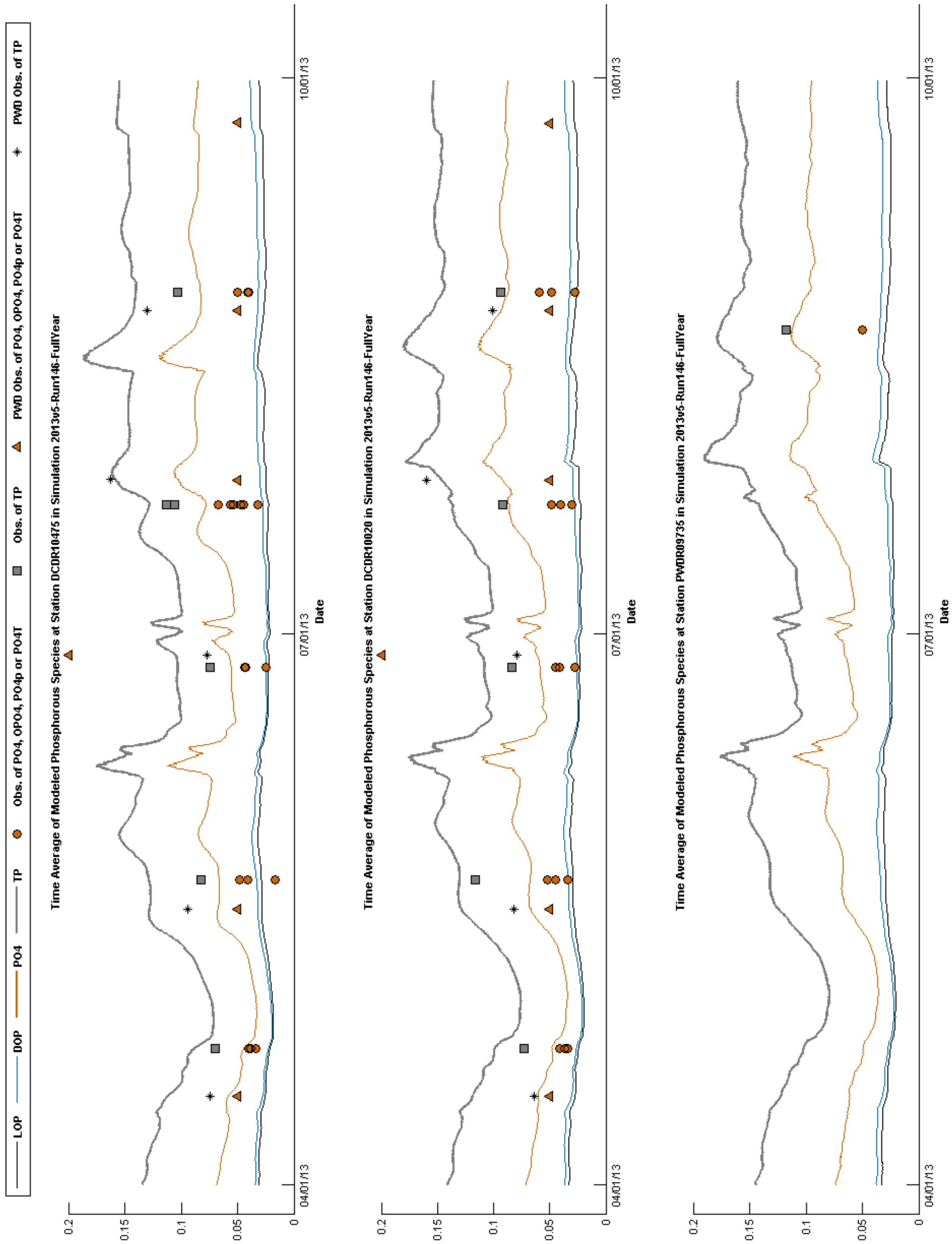

WQ Consituent TN - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg N/L

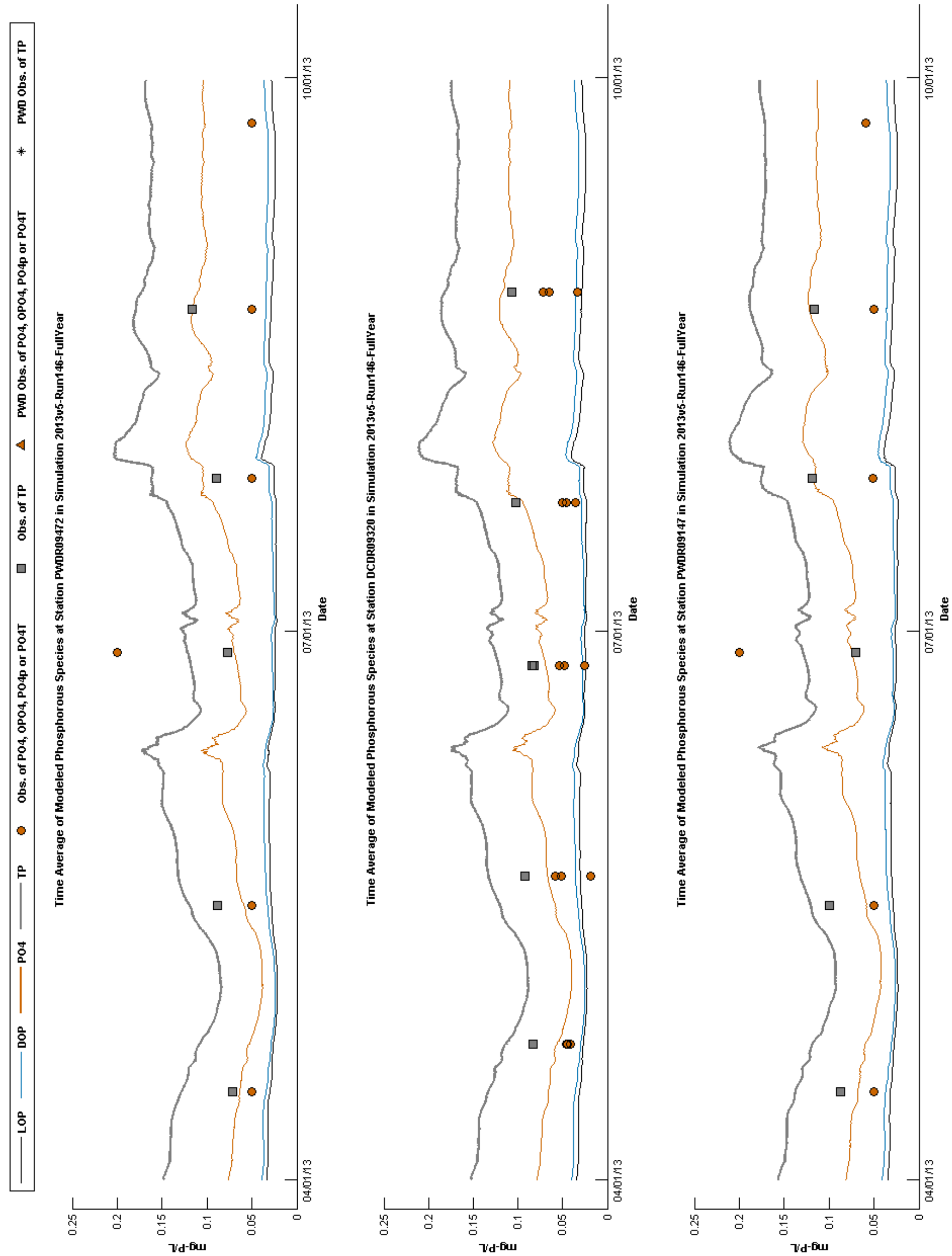
1.6. Phosphorus species

1.6.1. April to October

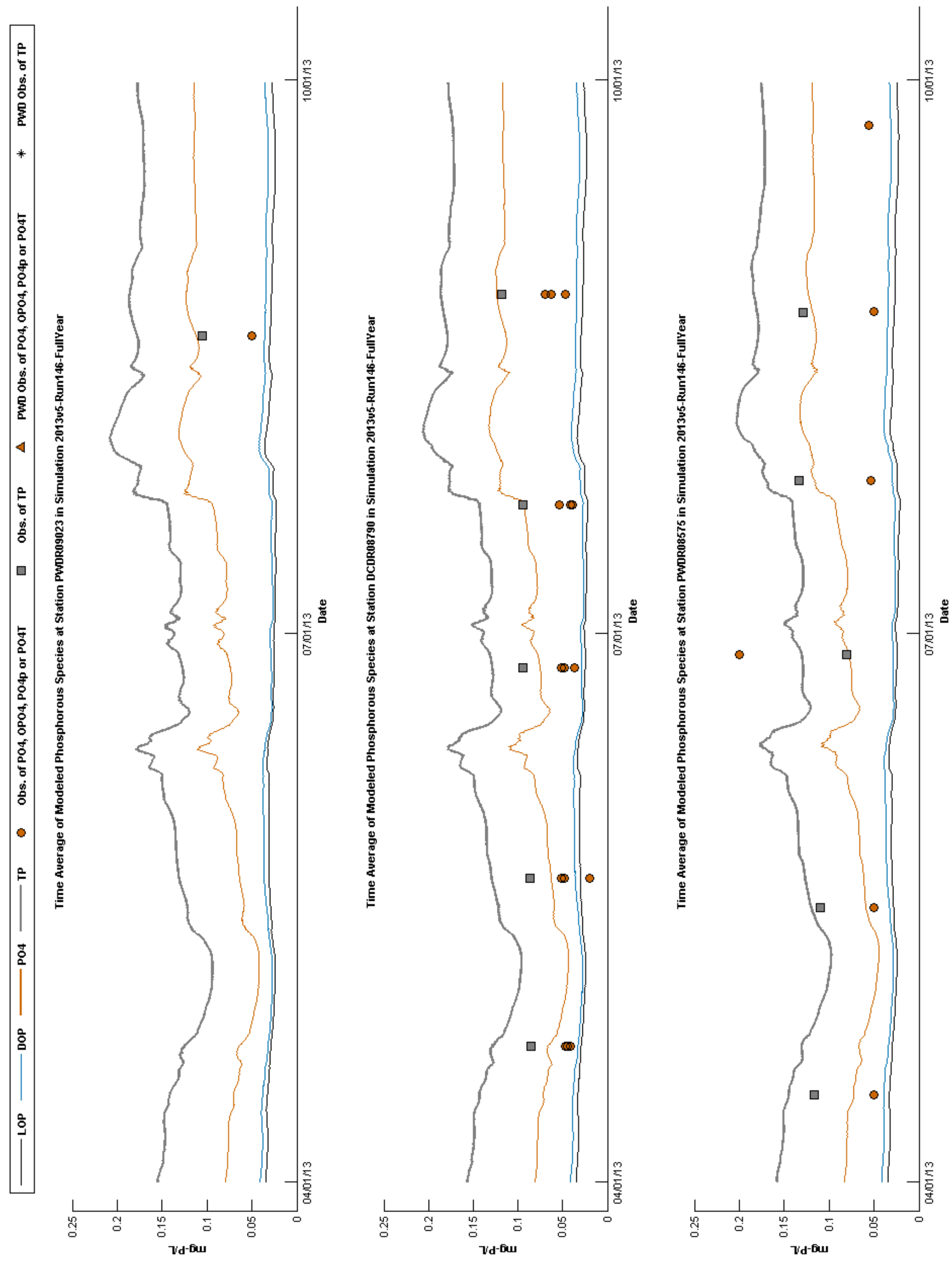


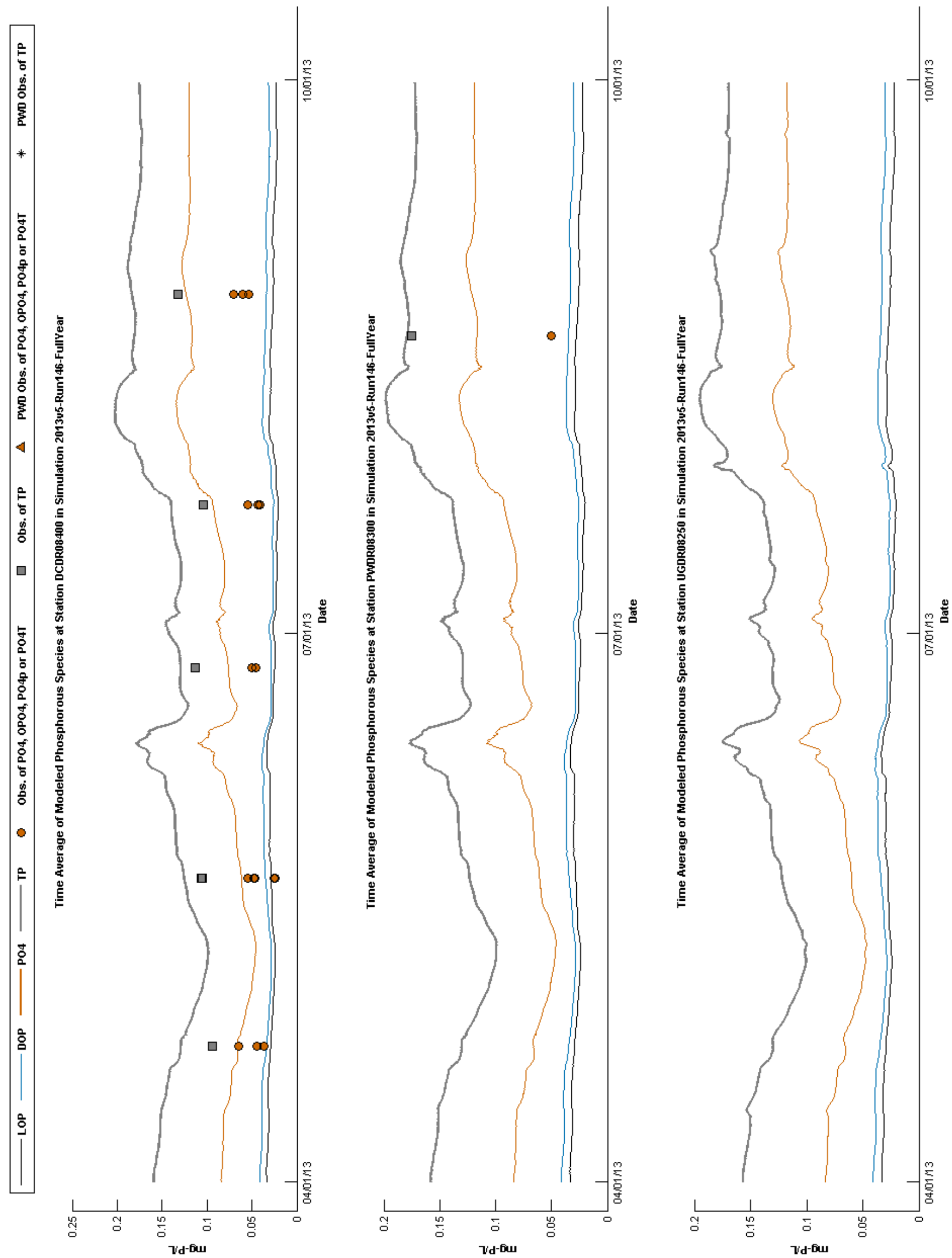

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR11779 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR11070 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR11011 in Simulation 2013v5-Run146-FullYear
mg-P/L
0
0.05
0.1
0.15
0.2
04/01/13
07/01/13
10/01/13
Date

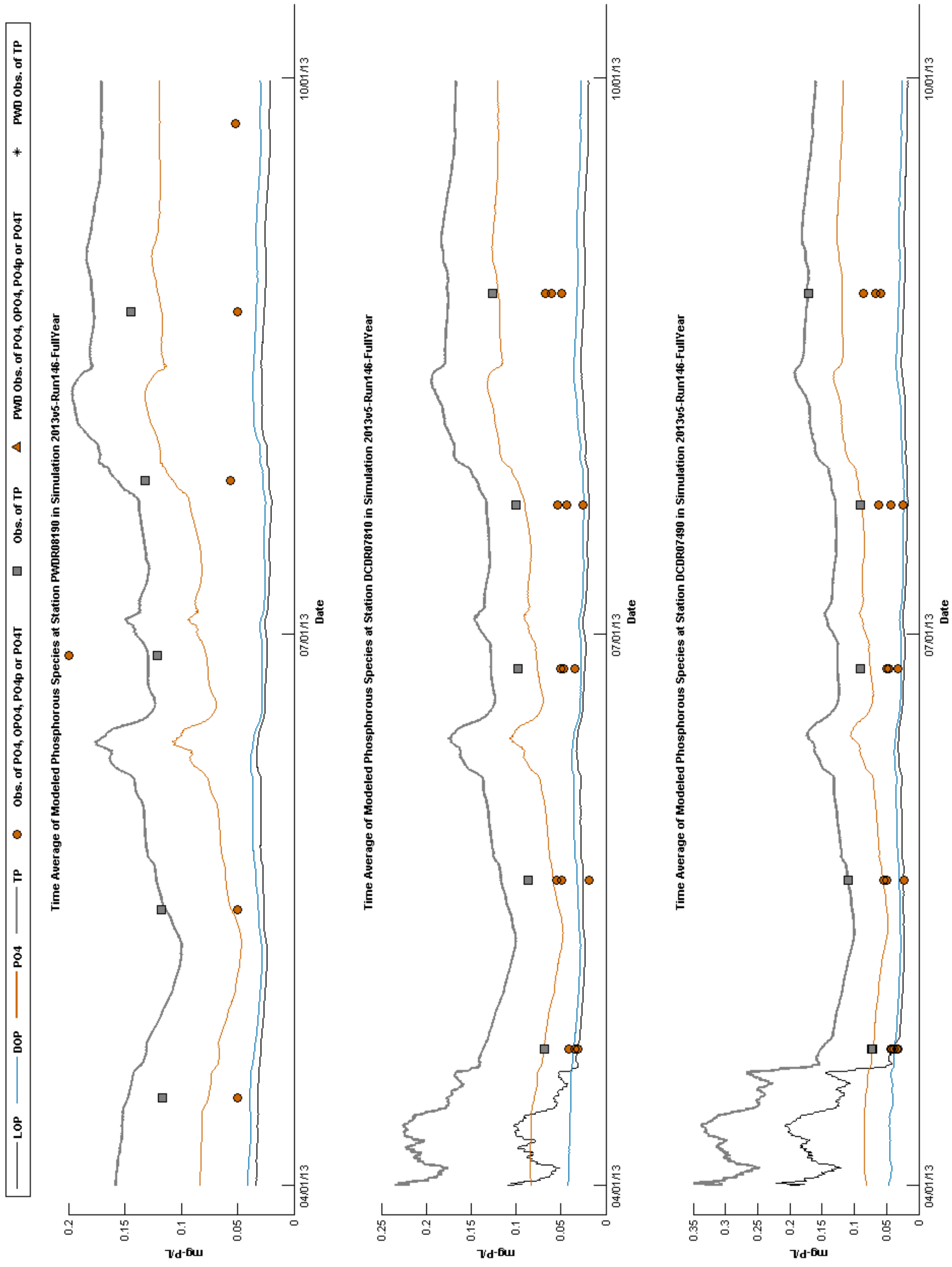

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR10475 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR10020 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR09735 in Simulation 2013v5-Run146-FullYear
mg-P/L
Date
04/01/13
07/01/13
10/01/13

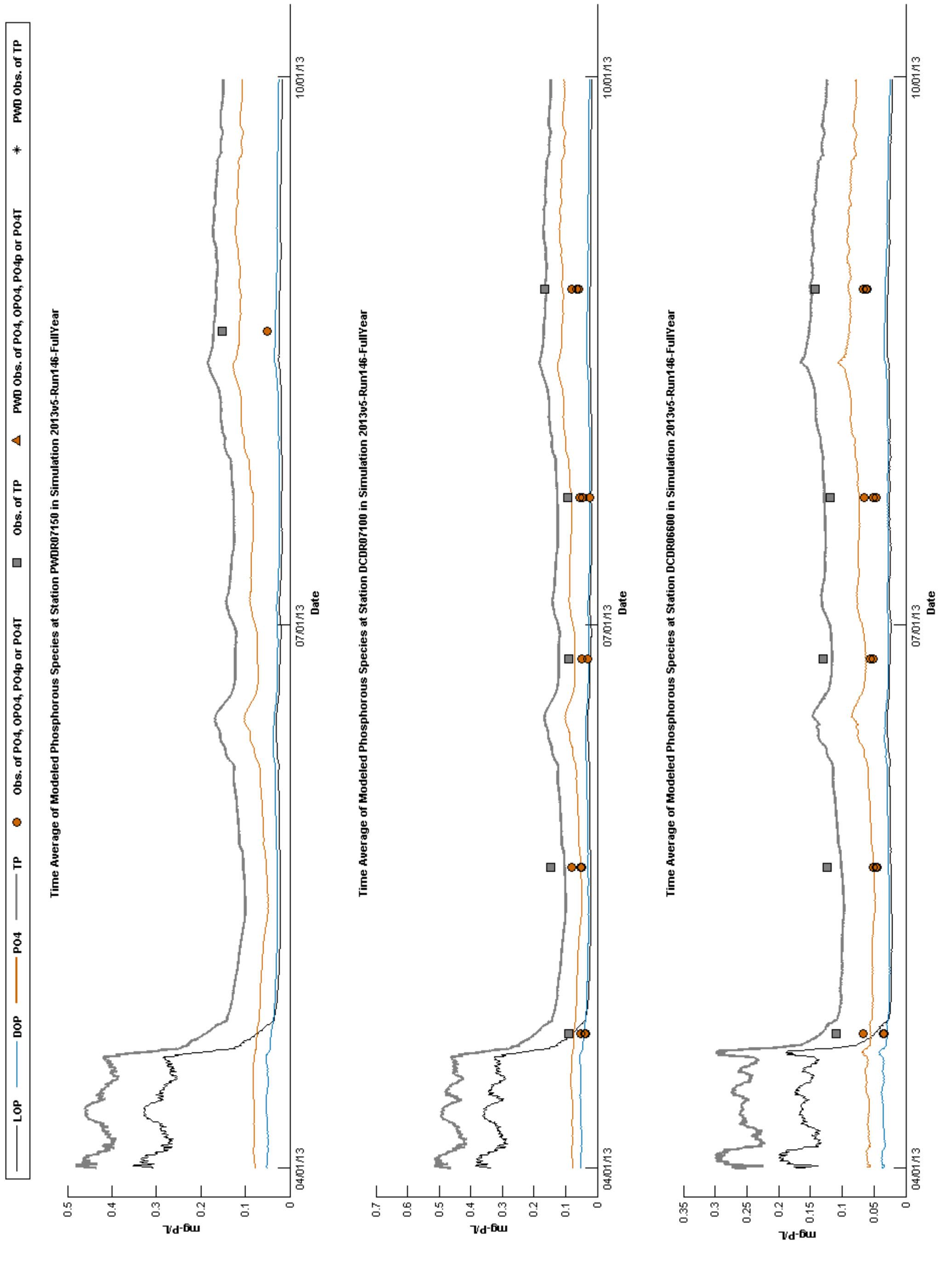


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09472 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR09320 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR09147 in Simulation 2013v5-Run146-FullYear
mg-P/L
0.25
0.2
0.15
0.1
0.05
0
04/01/13
07/01/13
10/01/13
Date

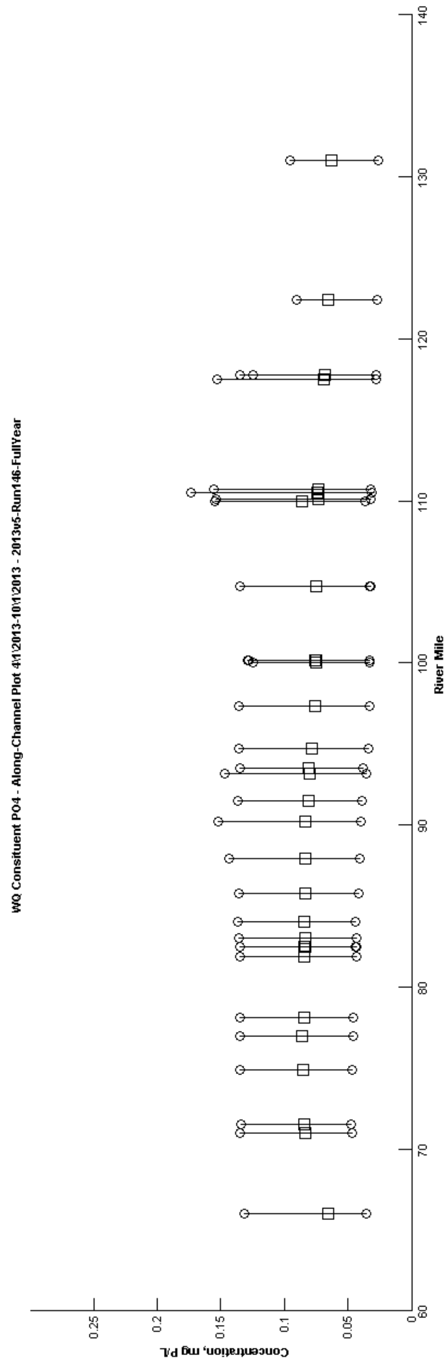

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09023 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR08790 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station PWDR08575 in Simulation 2013v5-Run146-FullYear
mg-P/L
Date
04/01/13
07/01/13
10/01/13

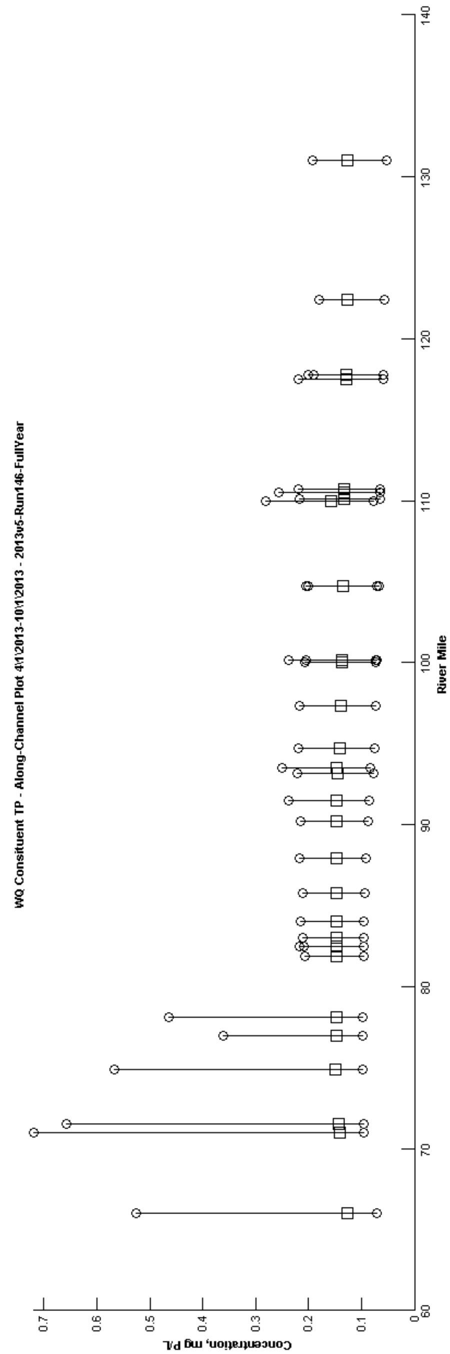

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR08400 in Simulation 2013v5-Run146-FullYear
mg-P/L
0.25
0.2
0.15
0.1
0.05
0
04/01/13
07/01/13
10/01/13
Date
Time Average of Modeled Phosphorous Species at Station PWDR08300 in Simulation 2013v5-Run146-FullYear
mg-P/L
0.2
0.15
0.1
0.05
0
04/01/13
07/01/13
10/01/13
Date
Time Average of Modeled Phosphorous Species at Station UGDR08250 in Simulation 2013v5-Run146-FullYear
mg-P/L
0.2
0.15
0.1
0.05
0
04/01/13
07/01/13
10/01/13
Date


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR08190 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07810 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07490 in Simulation 2013v5-Run146-FullYear
mg-P/L
Date
04/01/13
07/01/13
10/01/13

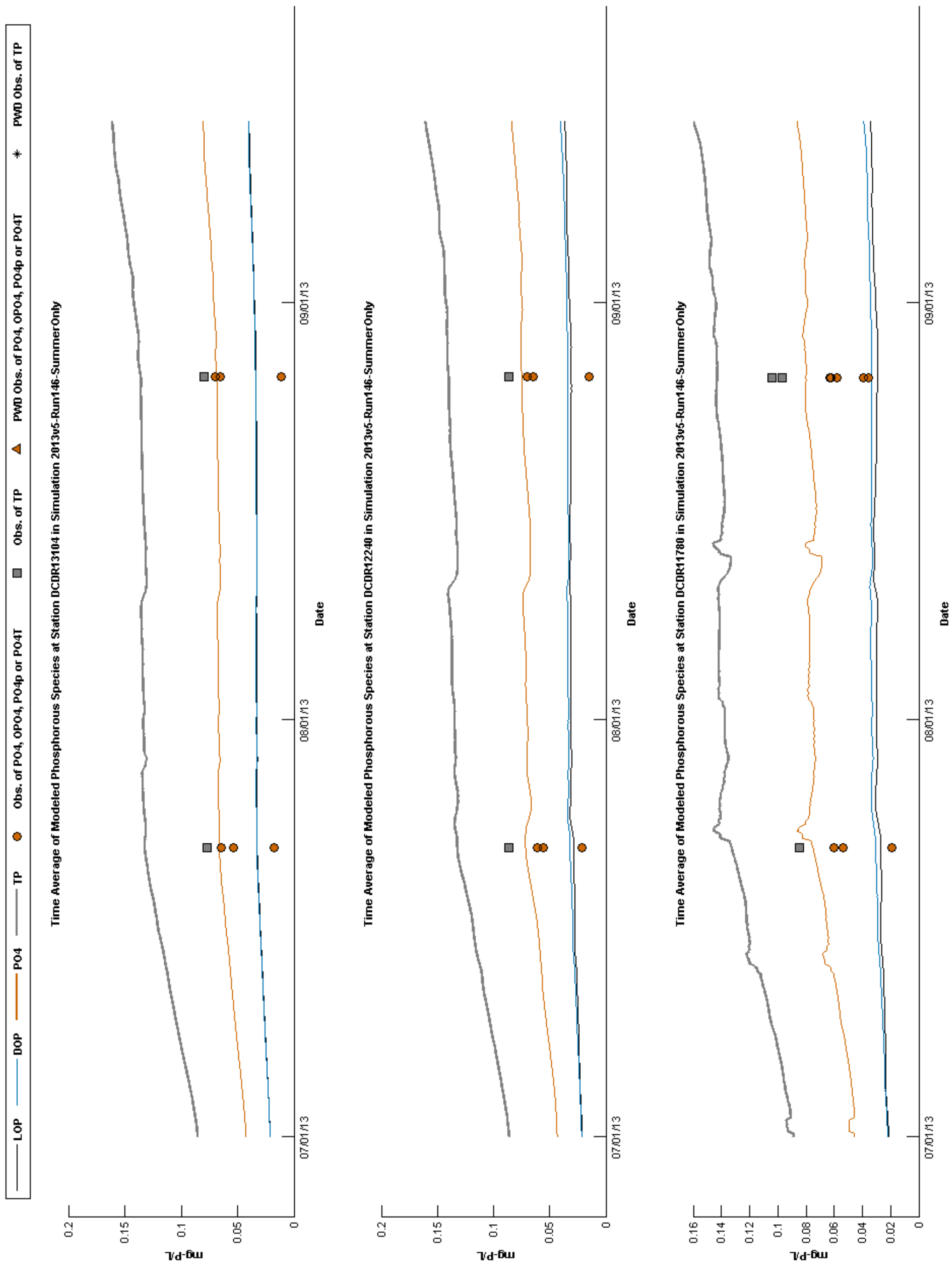


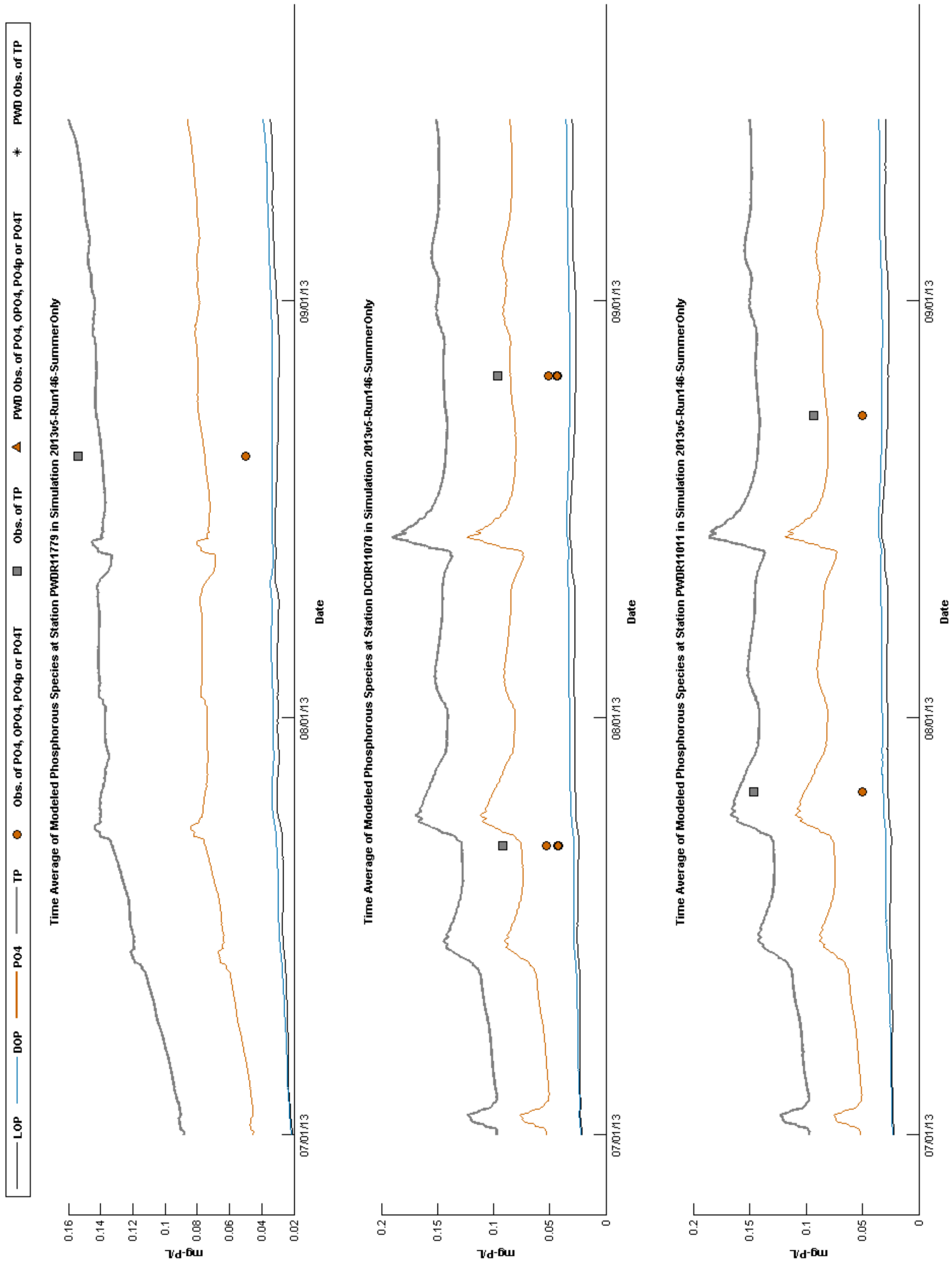
LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR07150 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR07100 in Simulation 2013v5-Run146-FullYear
Time Average of Modeled Phosphorous Species at Station DCDR06600 in Simulation 2013v5-Run146-FullYear
mg-P/L
Date
04/01/13
07/01/13
10/01/13


WQ Consituent PO4 - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg P/L

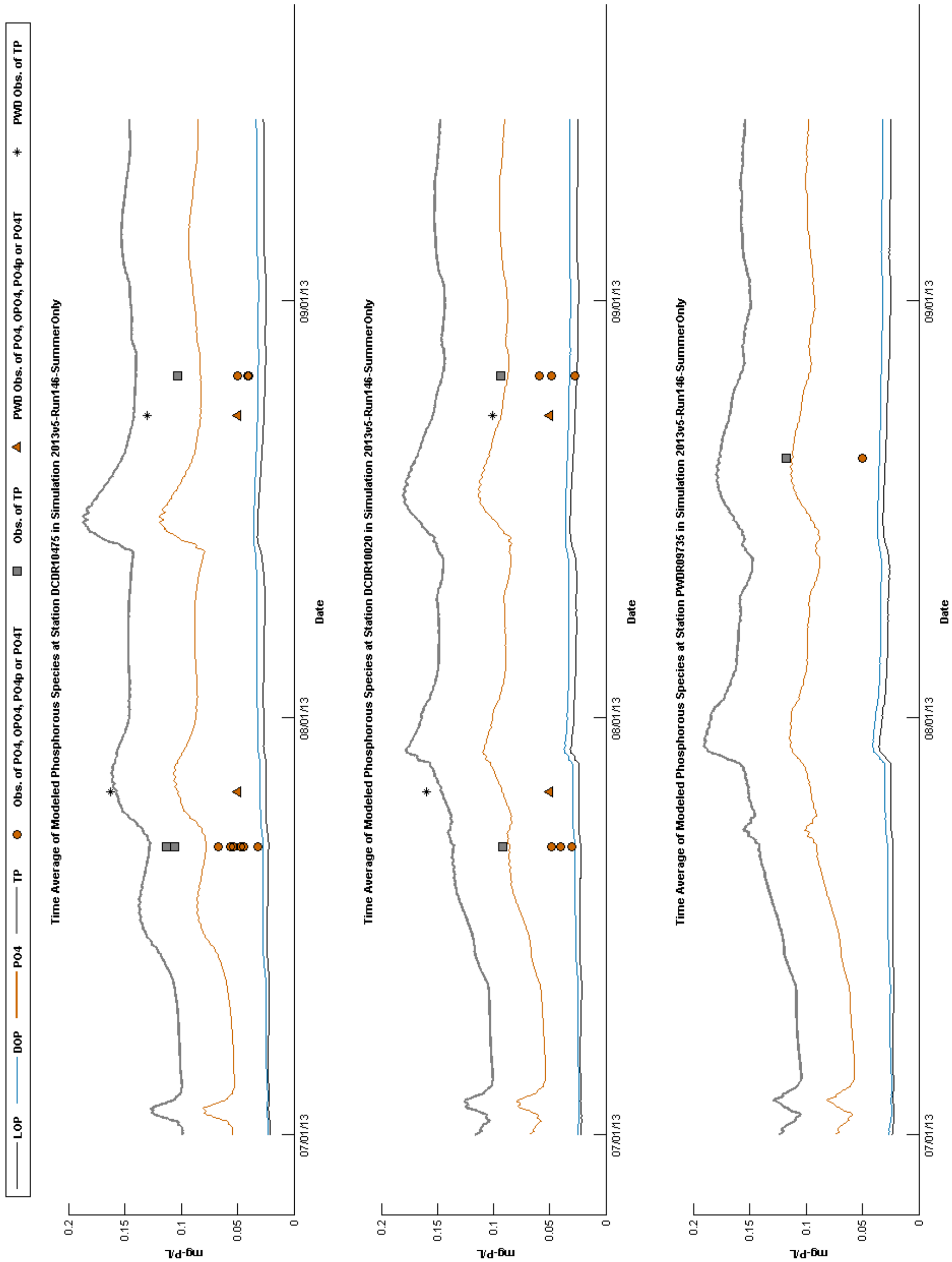

WQ Consituent TP - Along-Channel Plot 4\1\2013-10\1\2013 - 2013v5-Run146-FullYear
River Mile
Concentration, mg P/L

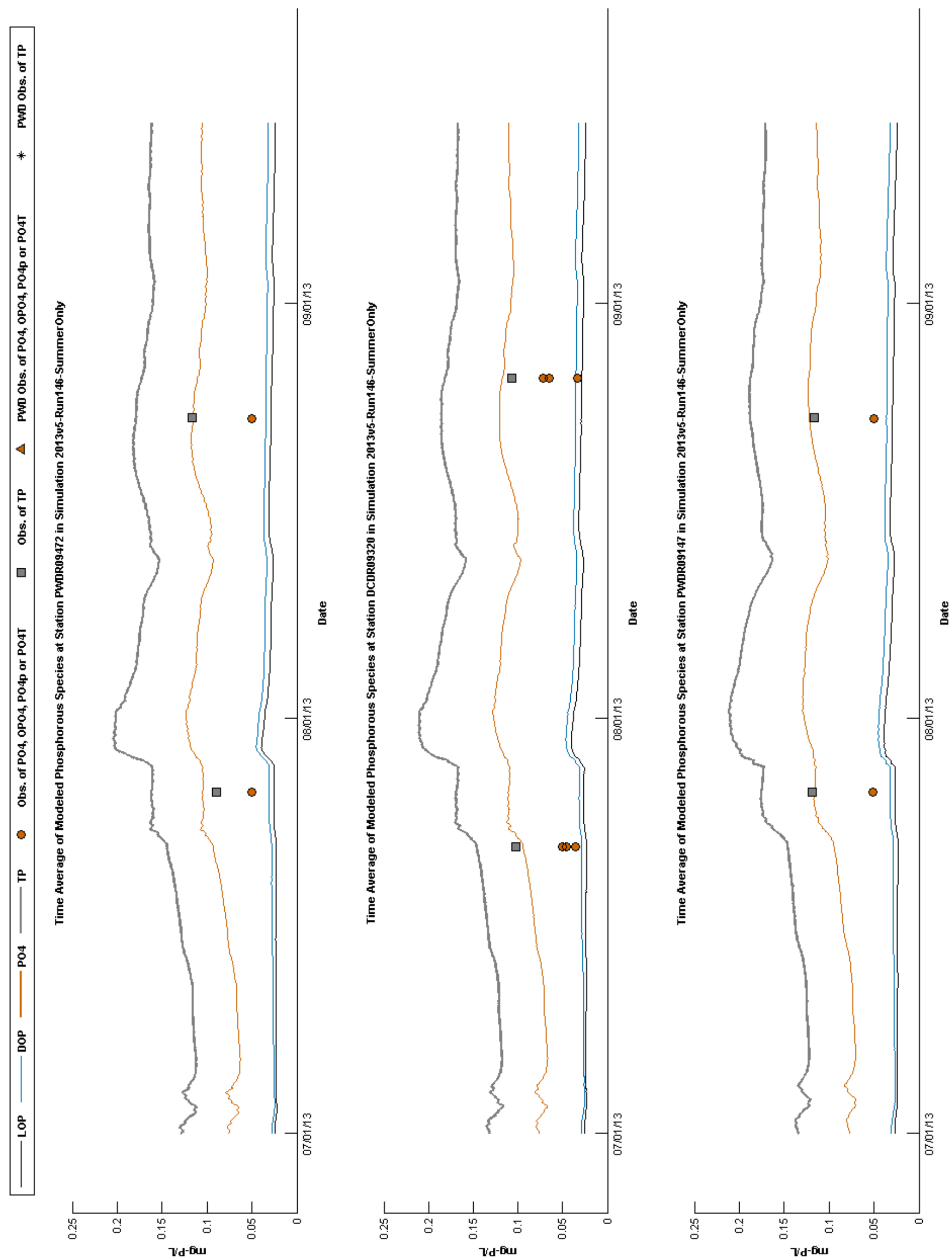
1.6.2. Summer

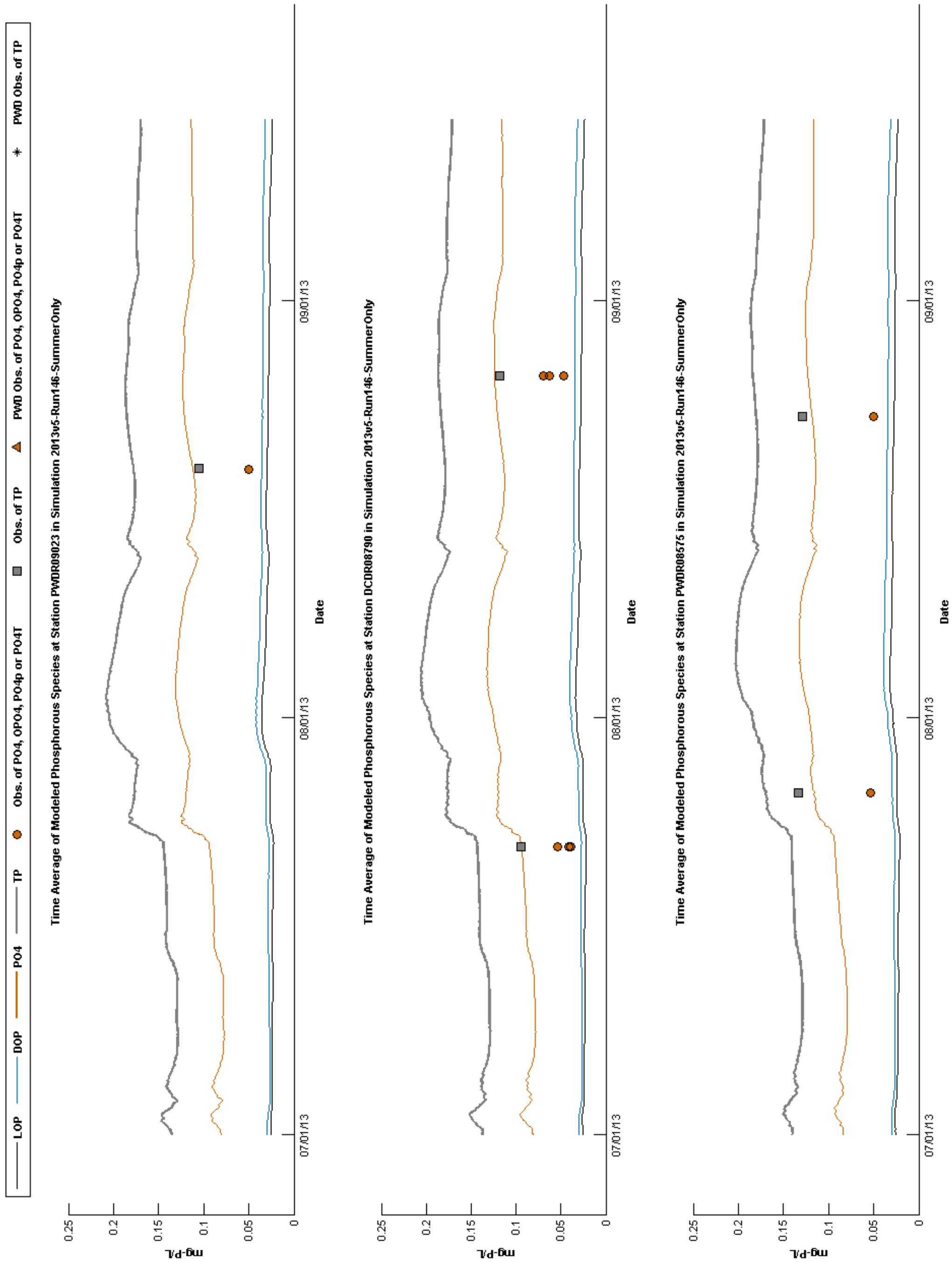

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR13104 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR12240 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR11780 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
Date
07/01/13
08/01/13
09/01/13



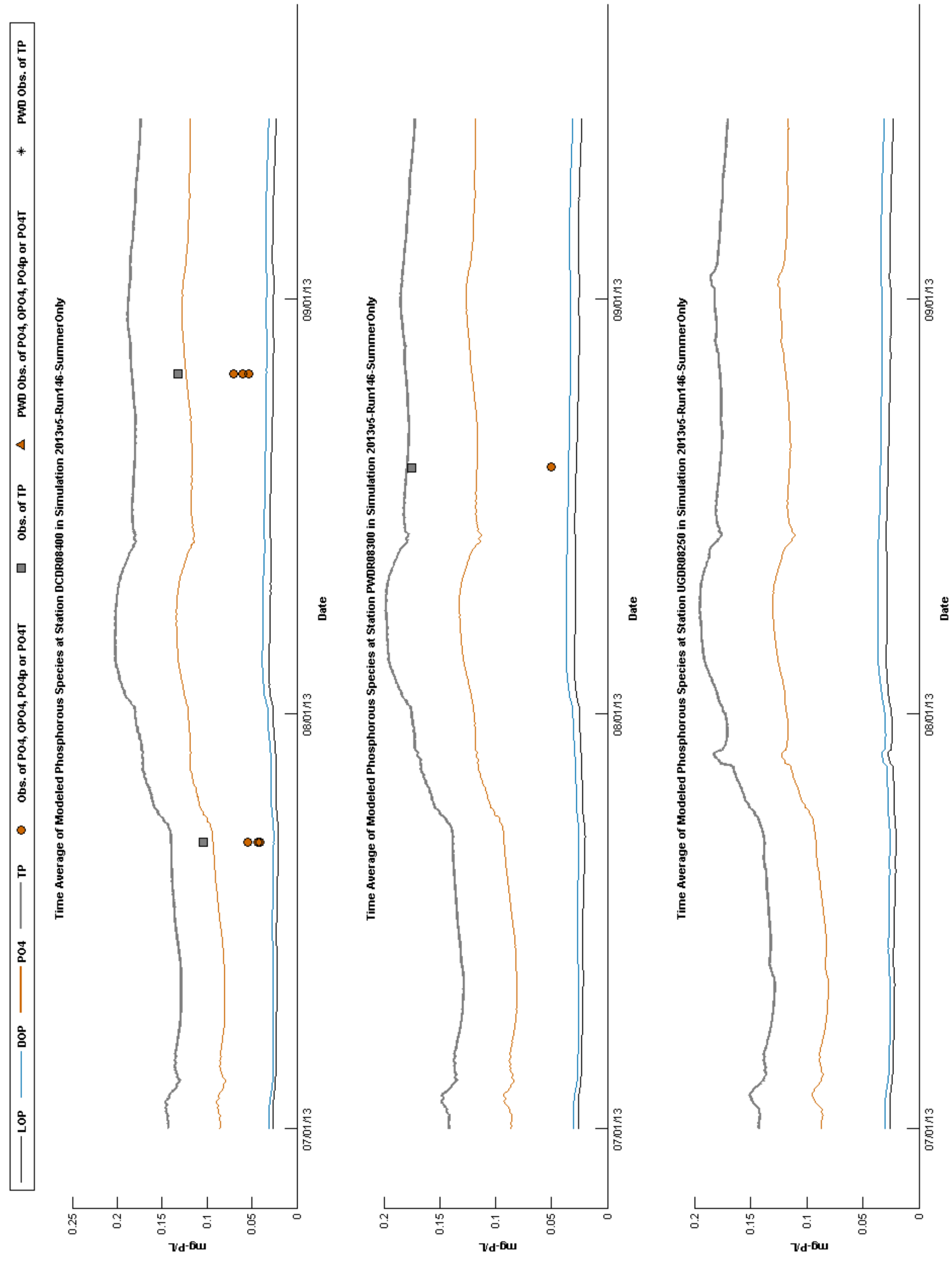
LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR11779 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR11070 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR11011 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
Date
07/01/13
08/01/13
09/01/13

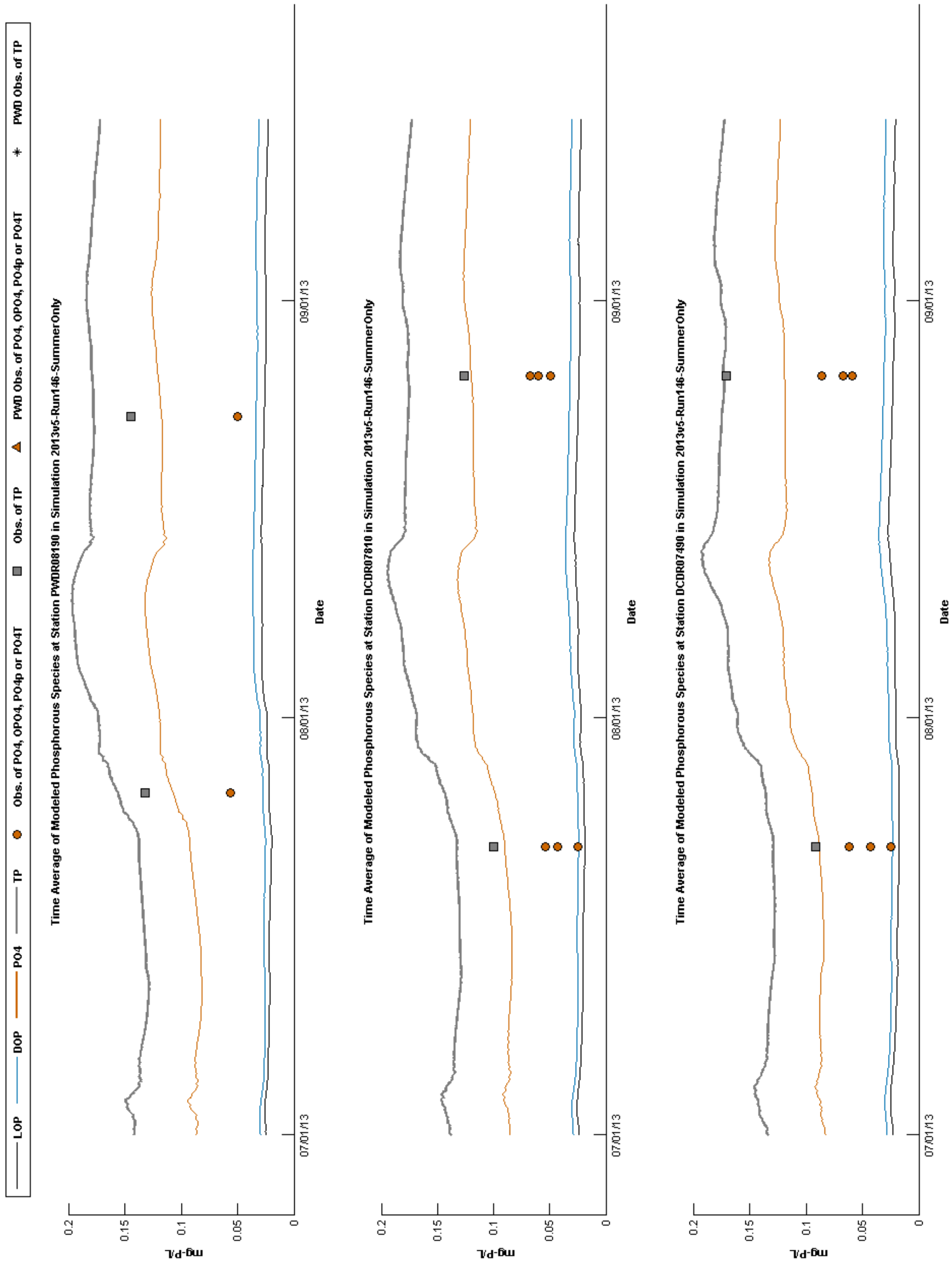

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR10475 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR10020 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR09735 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
0
0.05
0.1
0.15
0.2
07/01/13
08/01/13
09/01/13
Date


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09472 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR09320 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR09147 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
0.25
0.2
0.15
0.1
0.05
0
07/01/13
08/01/13
09/01/13
Date

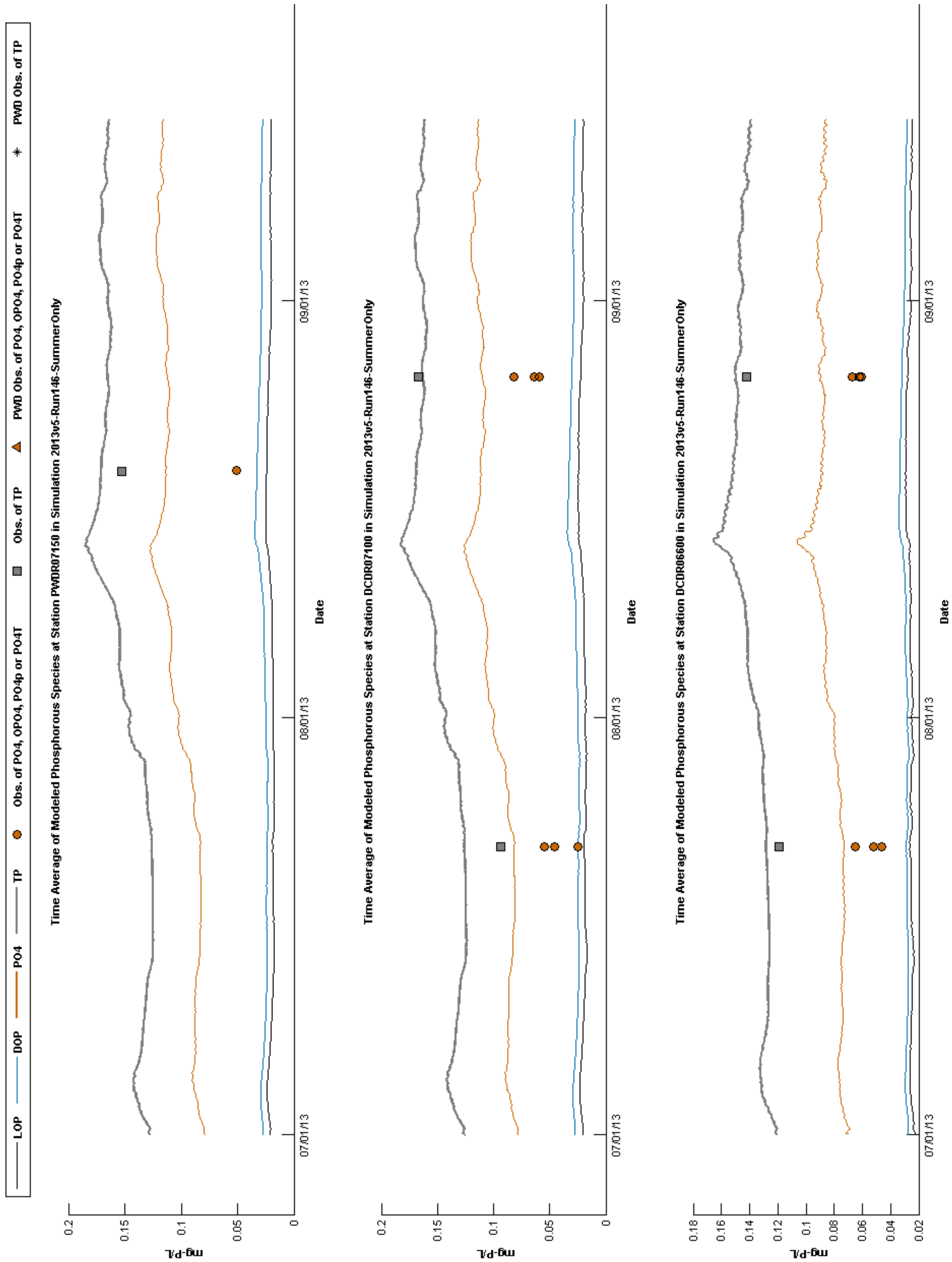


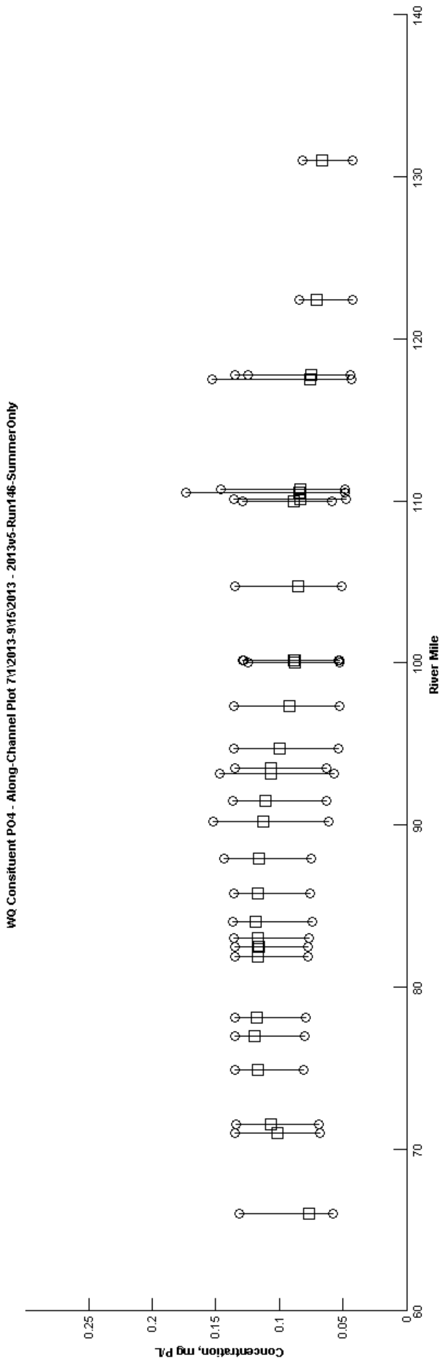
LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR09023 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR08790 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR08575 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
Date
07/01/13
08/01/13
09/01/13

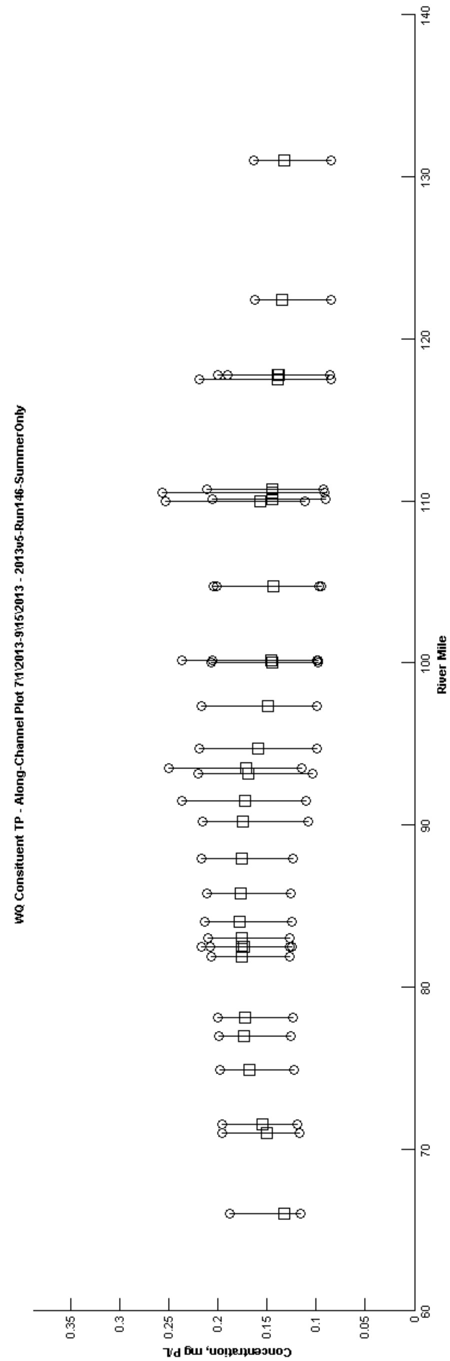

LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station DCDR08400 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station PWDR08300 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station UGDR08250 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
Date
07/01/13
08/01/13
09/01/13



LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR08190 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07810 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07490 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
0
0.05
0.1
0.15
0.2
07/01/13
08/01/13
09/01/13
Date


LOP
DOP
PO4
TP
Obs. of PO4, OPO4, PO4p or PO4T
Obs. of TP
PWD Obs. of PO4, OPO4, PO4p or PO4T
PWD Obs. of TP
Time Average of Modeled Phosphorous Species at Station PWDR07150 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR07100 in Simulation 2013v5-Run146-SummerOnly
Time Average of Modeled Phosphorous Species at Station DCDR06600 in Simulation 2013v5-Run146-SummerOnly
mg-P/L
Date
07/01/13
08/01/13
09/01/13
0
0.05
0.1
0.15
0.2
0.02
0.04
0.06
0.08
0.12
0.14
0.16
0.18

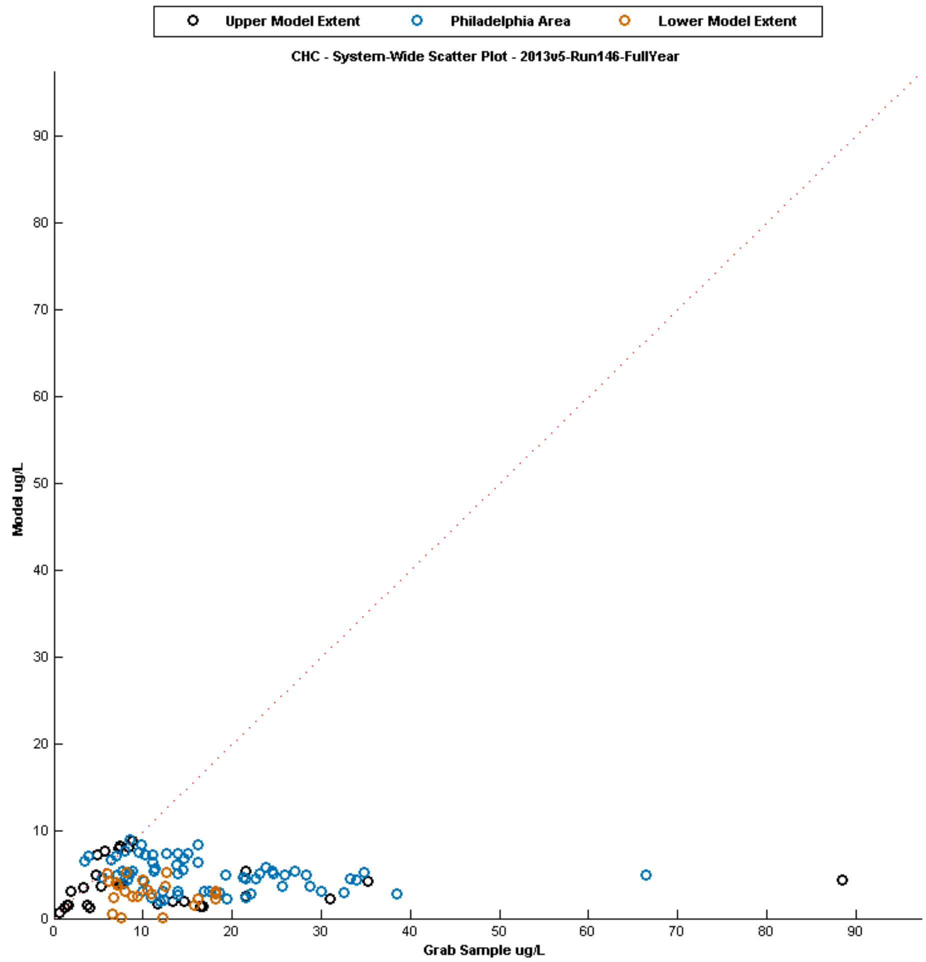

WQ Consituent PO4 - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg P/L


WQ Consituent TP - Along-Channel Plot 7\1\2013-9\15\2013 - 2013v5-Run146-SummerOnly
River Mile
Concentration, mg P/L

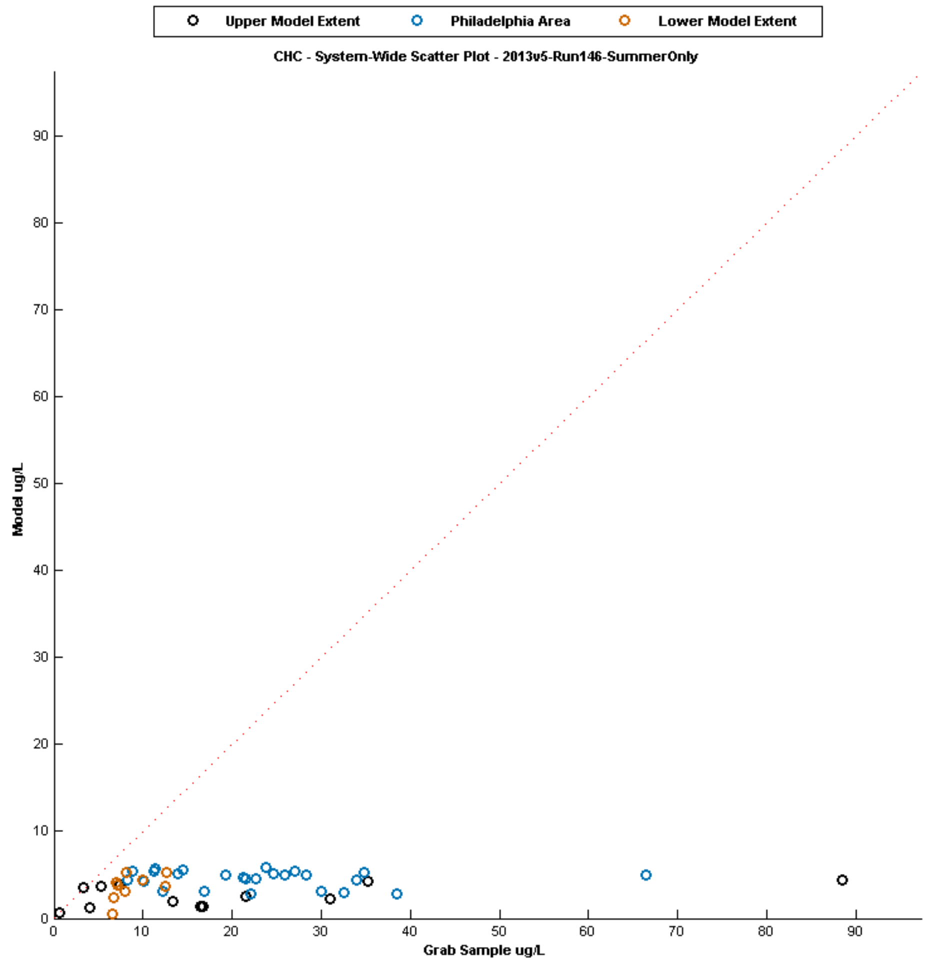
Chapter 2. Scatter Plots

2.1. Biomass - Algae

2.1.1. April to October



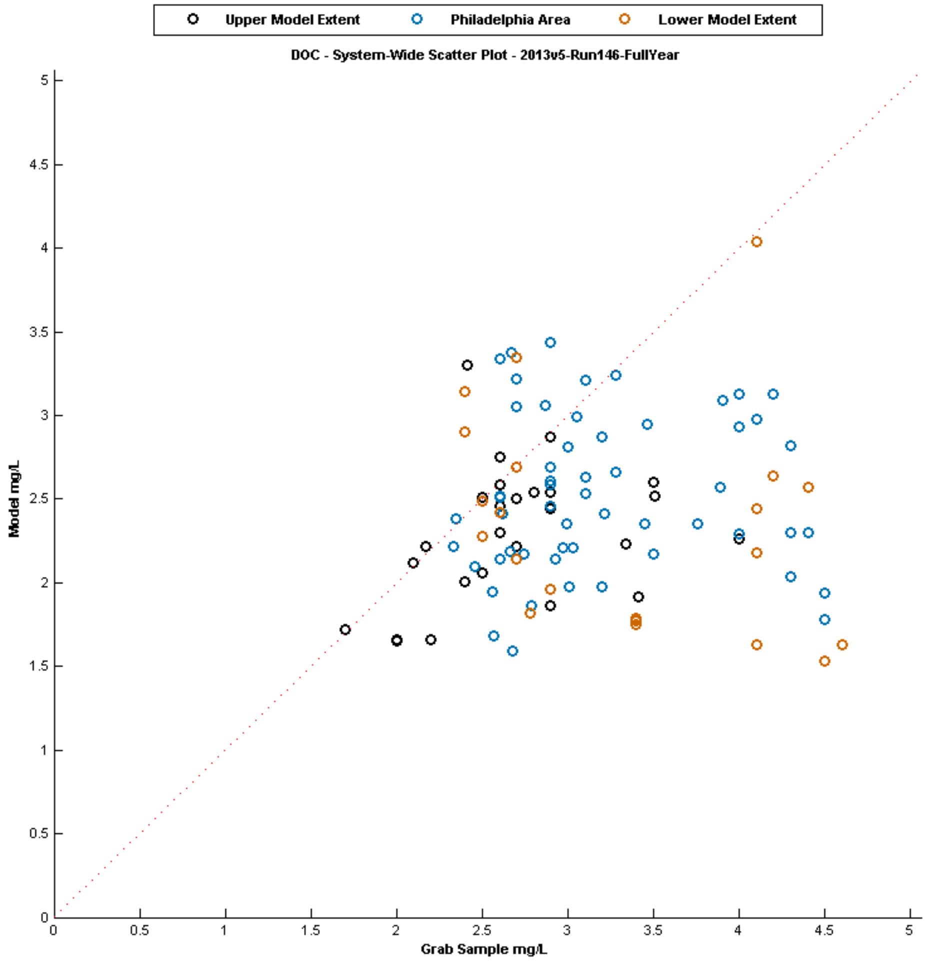
2.1.2. Summer



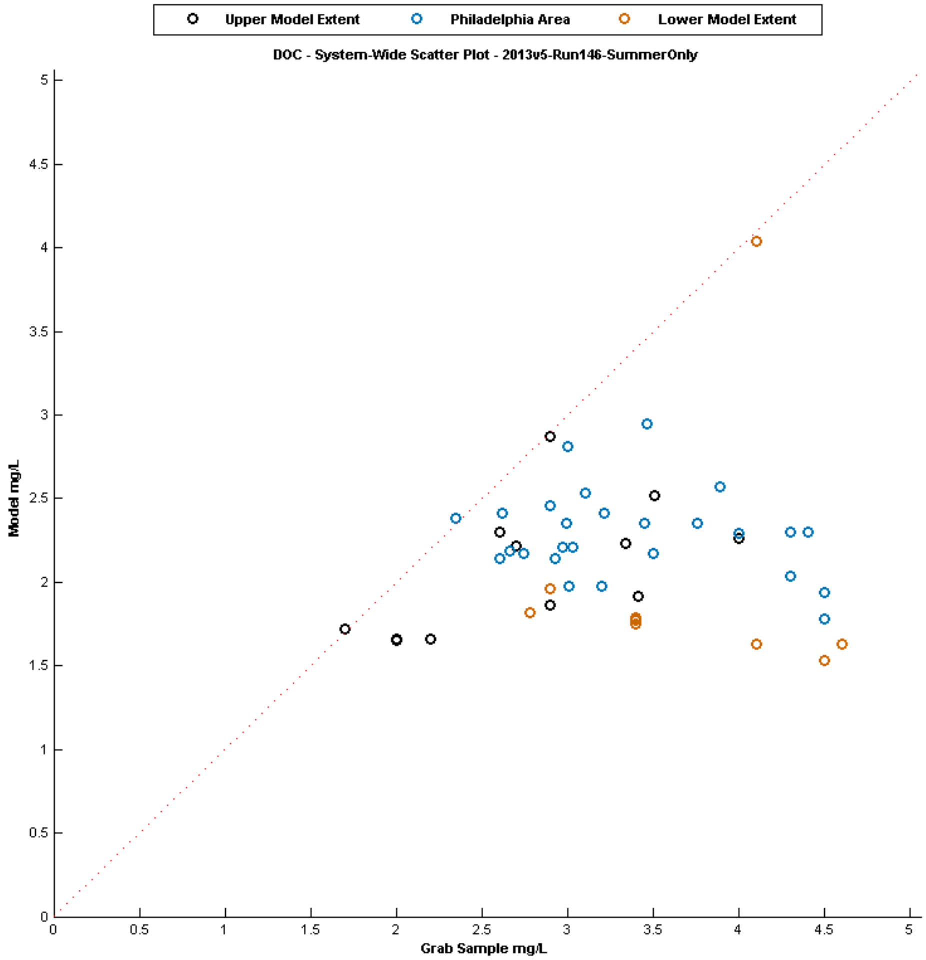
Upper Model Extent
Philadelphia Area
Lower Model Extent
CHC - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model ug/L
Grab Sample ug/L
0
10
20
30
40
50
60
70
80
90

2.2. Dissolved Organic Carbon

2.2.1. April to October

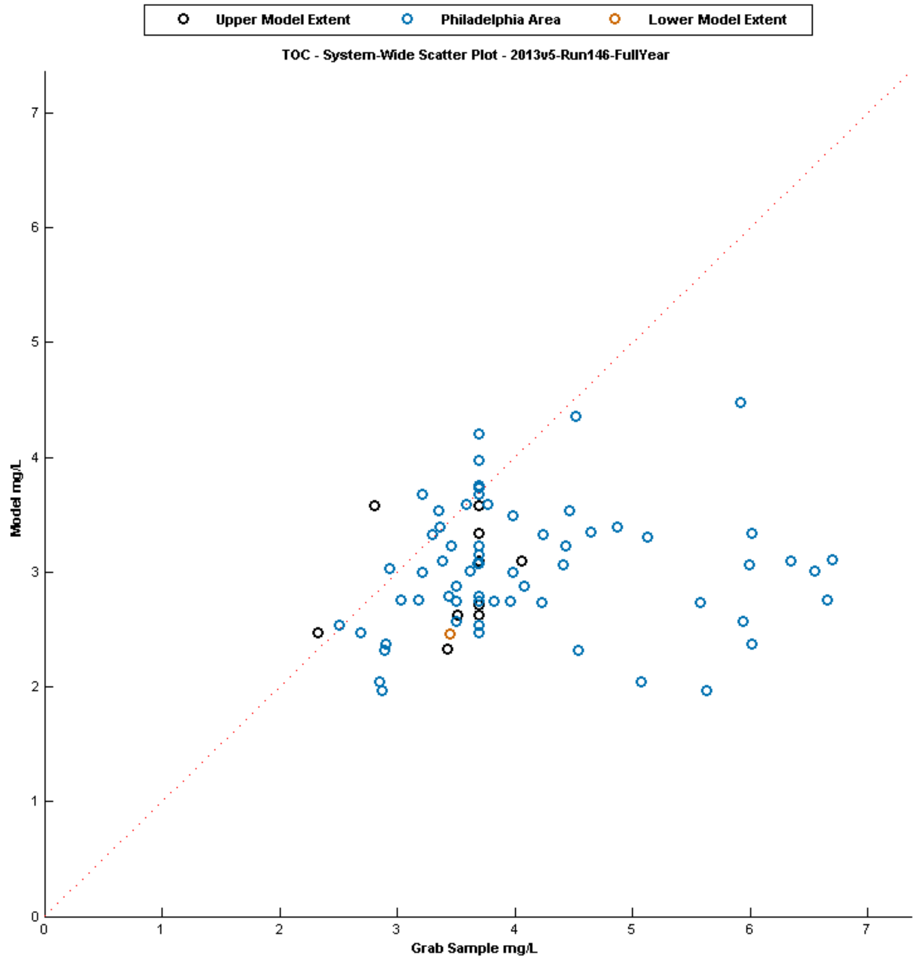


2.2.2. Summer

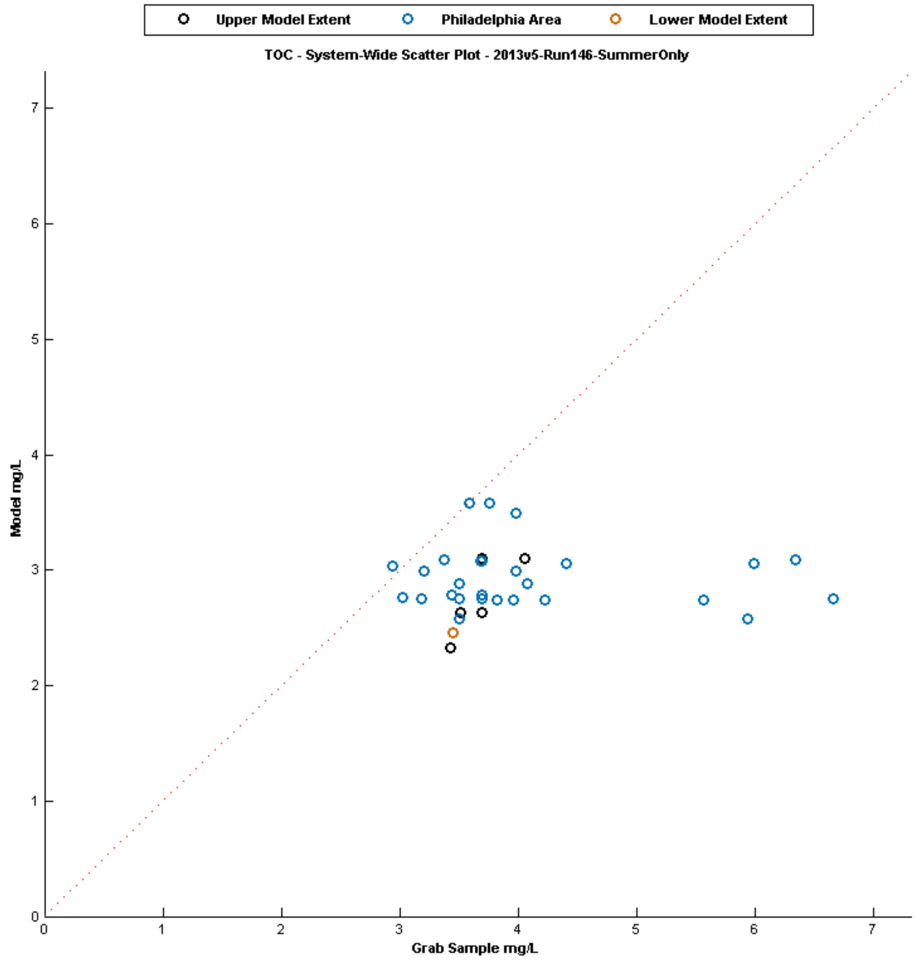

Upper Model Extent
Philadelphia Area
Lower Model Extent
DOC - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg/L
Grab Sample mg/L
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

2.3. Total Organic Carbon

2.3.1. April to October



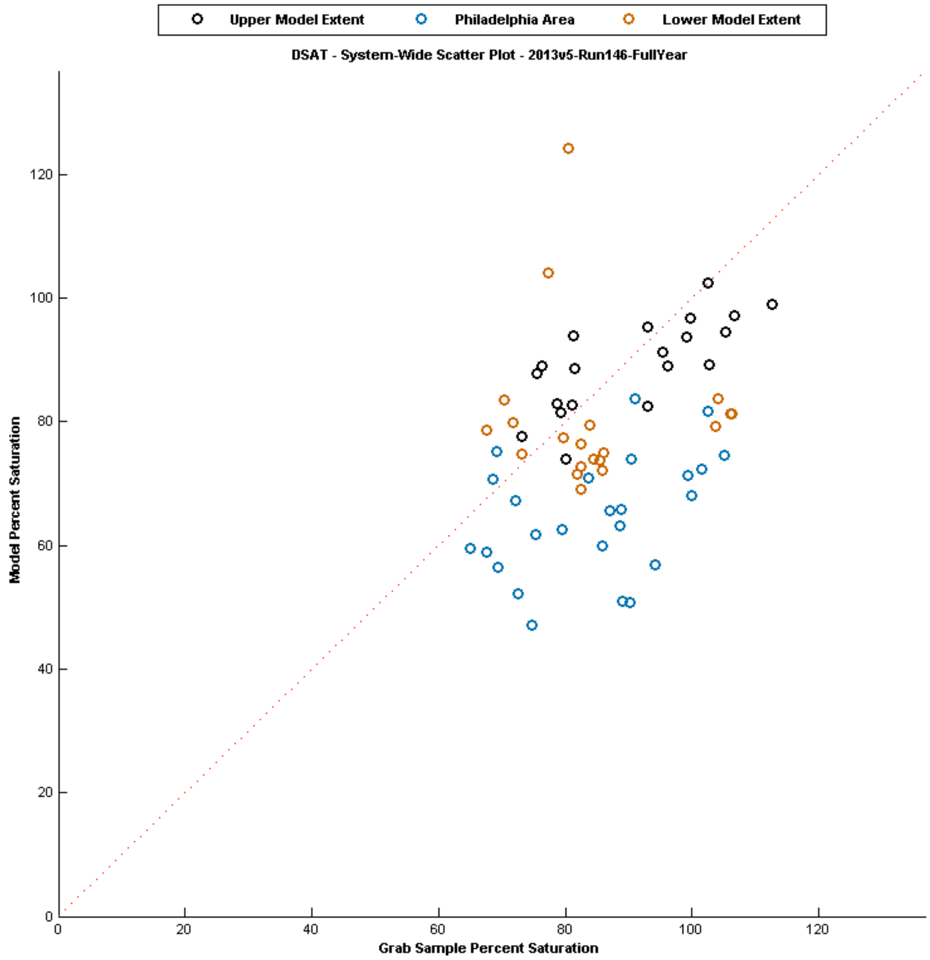
2.3.2. Summer



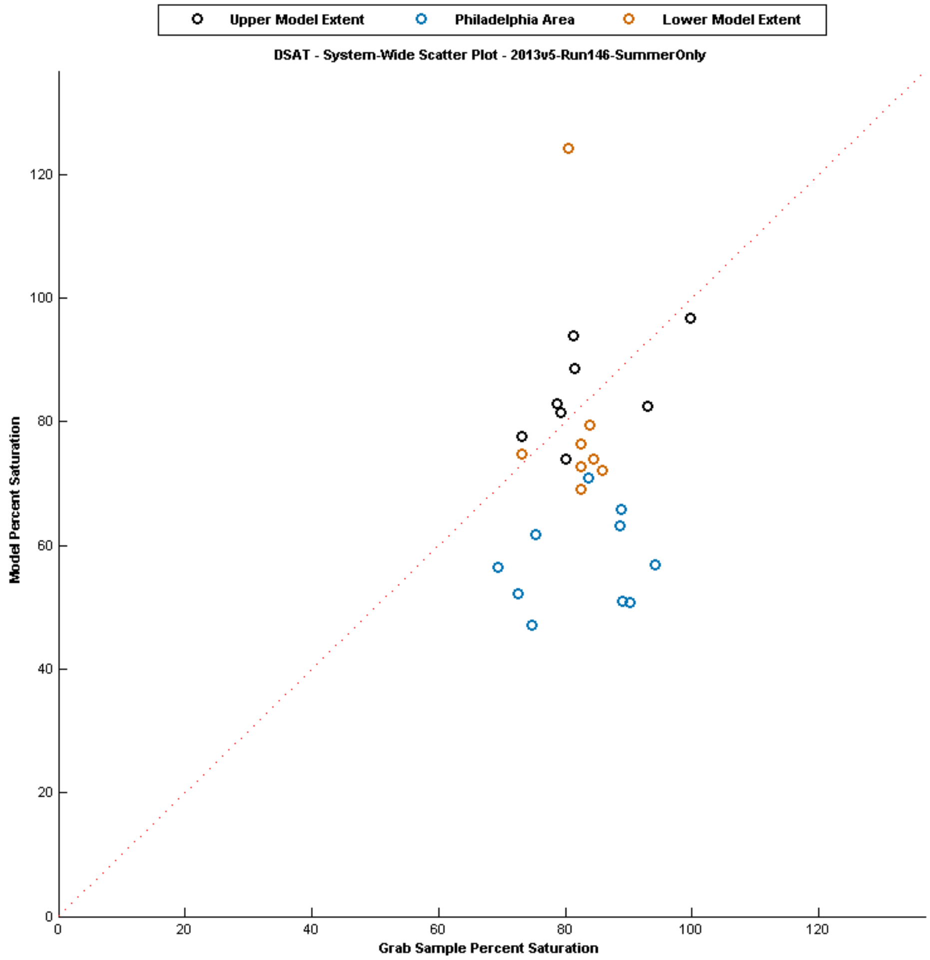
Upper Model Extent
Philadelphia Area
Lower Model Extent
TOC - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg/L
Grab Sample mg/L
0
1
2
3
4
5
6
7

2.4. DO % Saturation

2.4.1. April to October

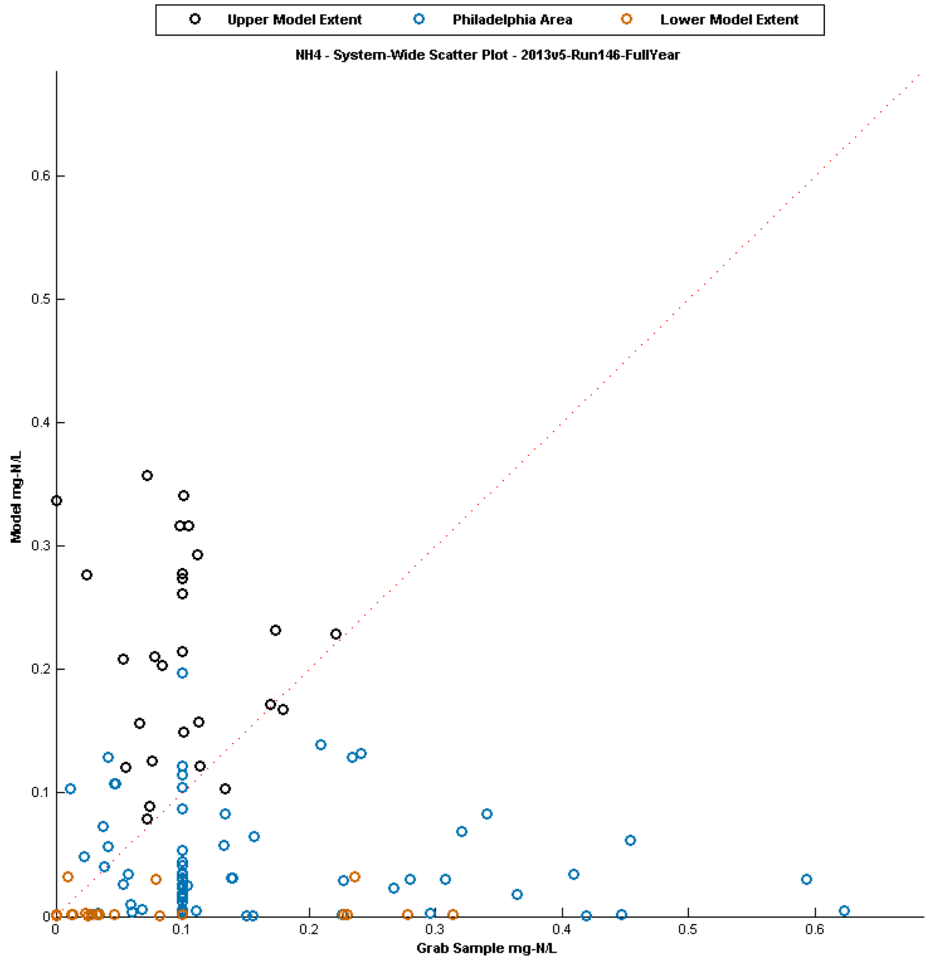


2.4.2. Summer

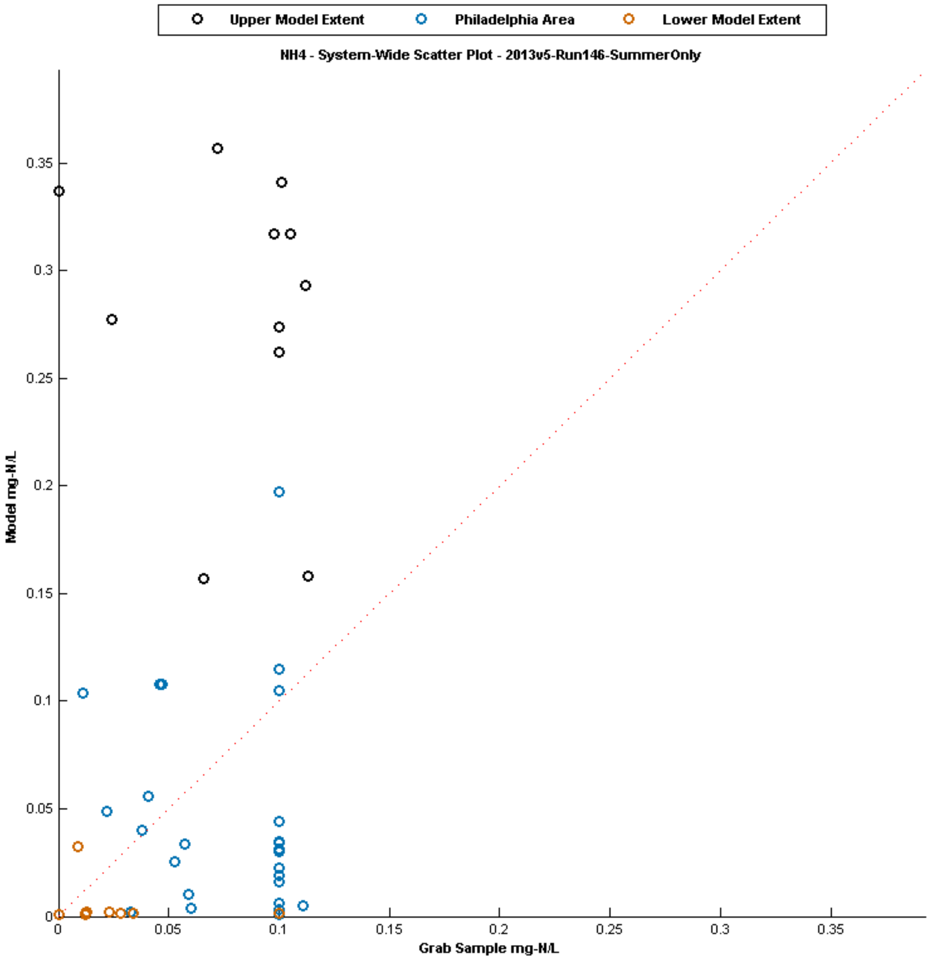

Upper Model Extent
Philadelphia Area
Lower Model Extent
DSAT - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model Percent Saturation
Grab Sample Percent Saturation
0
20
40
60
80
100
120

2.5. Ammonia Nitrogen

2.5.1. April to October

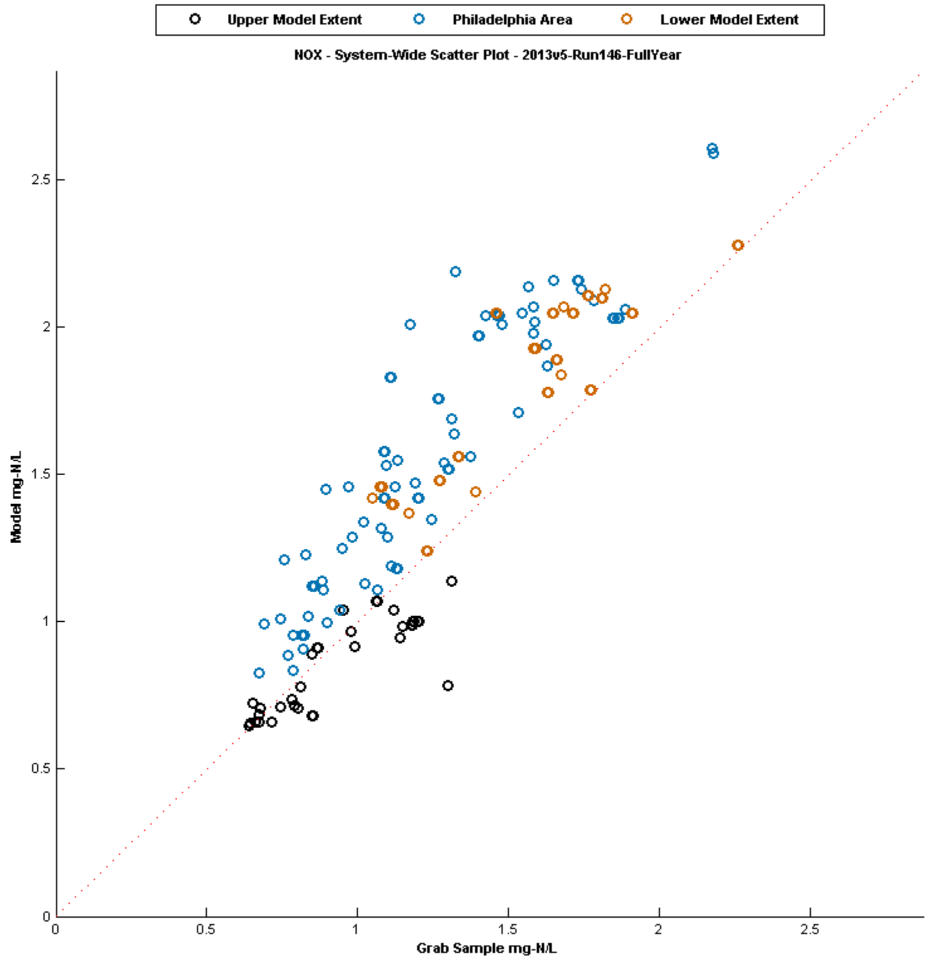


2.5.2. Summer

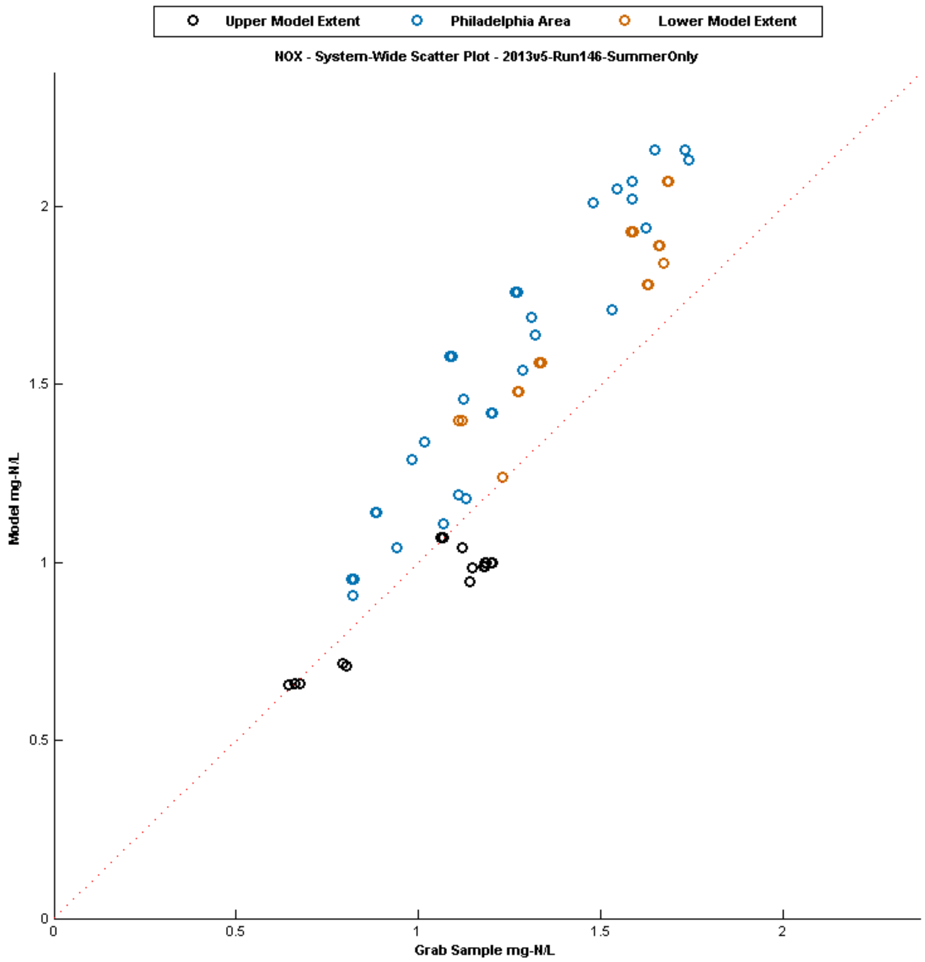

Upper Model Extent
Philadelphia Area
Lower Model Extent
NH4 - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

2.6. Nitrate Nitrogen

2.6.1. April to October



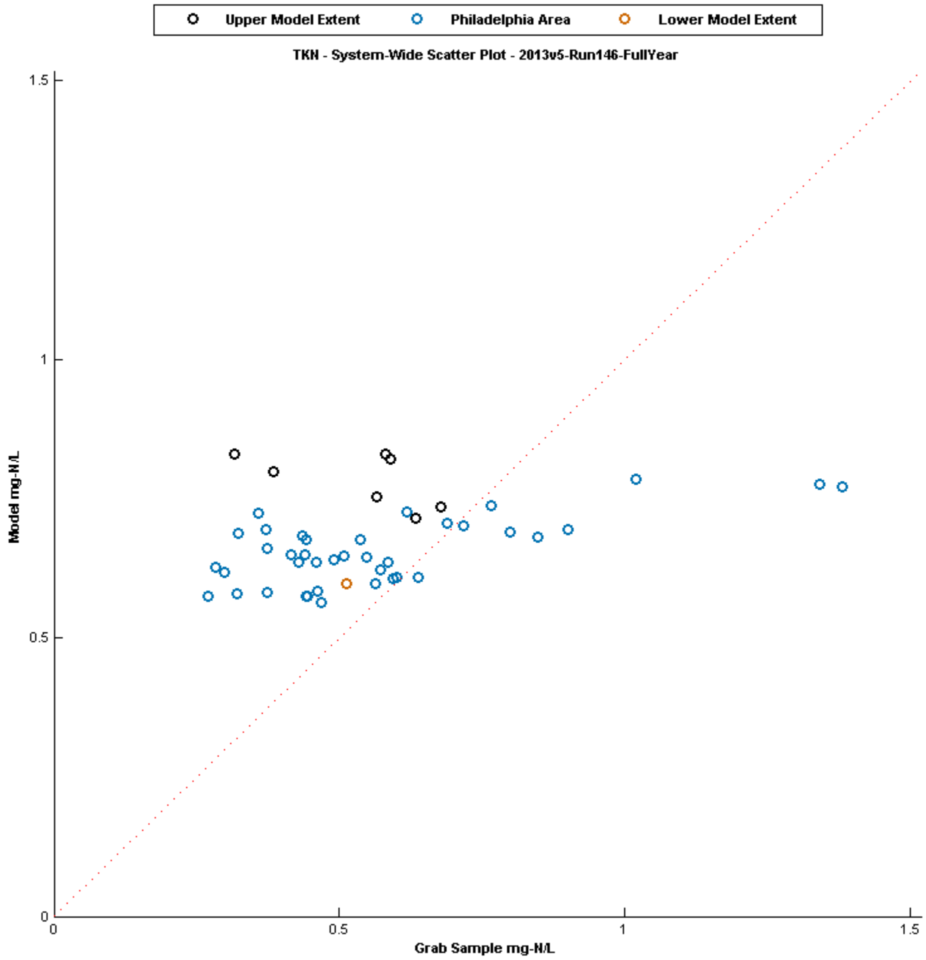
2.6.2. Summer



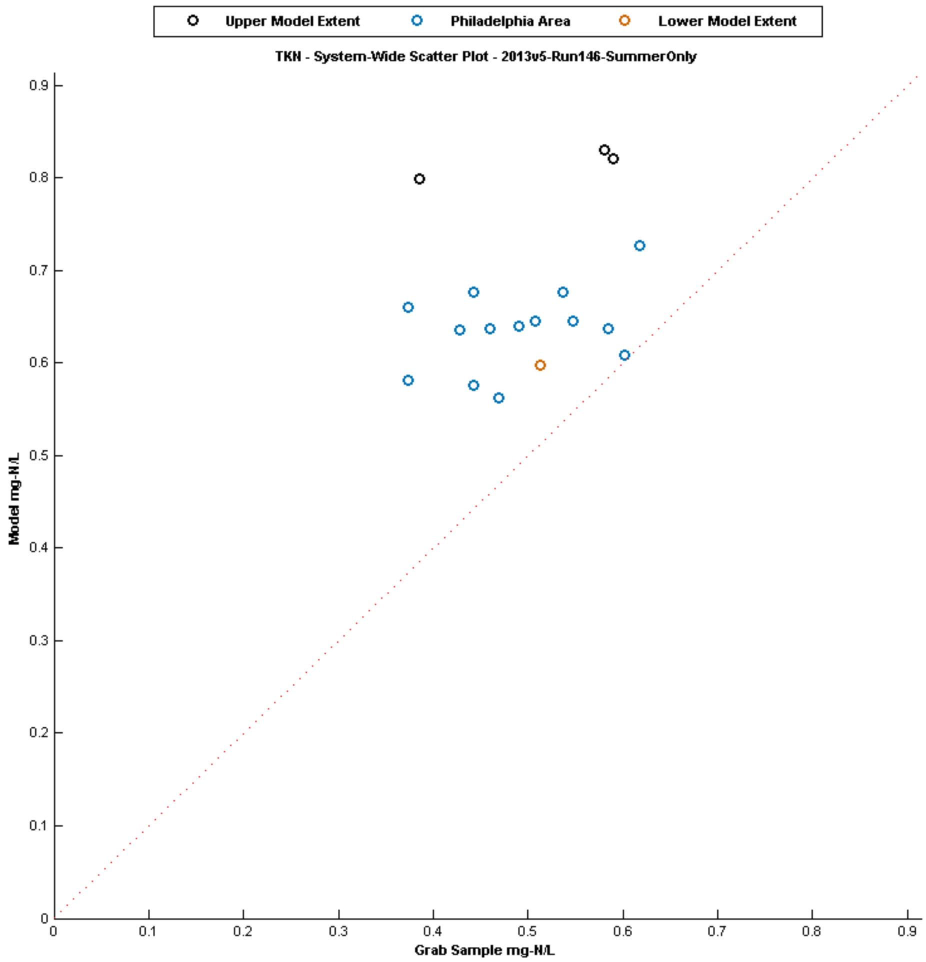
Upper Model Extent
Philadelphia Area
Lower Model Extent
NOX - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.5
1
1.5
2

2.7. Total Kjeldahl Nitrogen

2.7.1. April to October



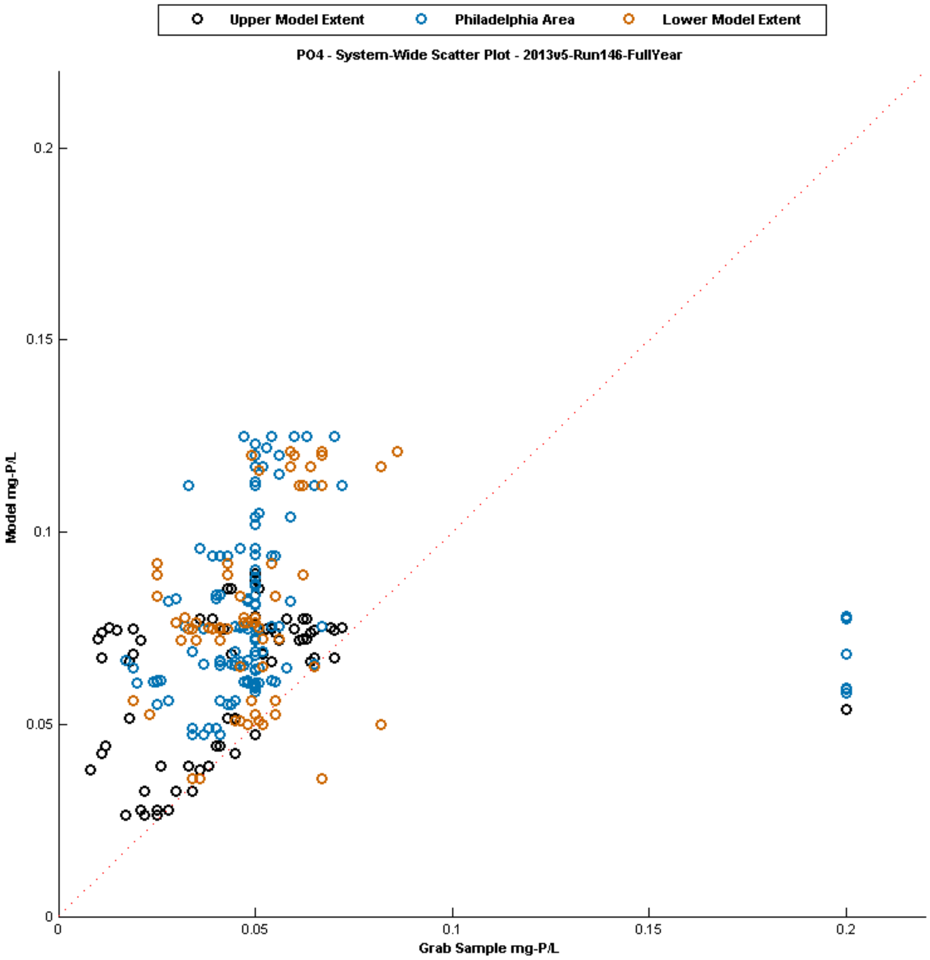
2.7.2. Summer



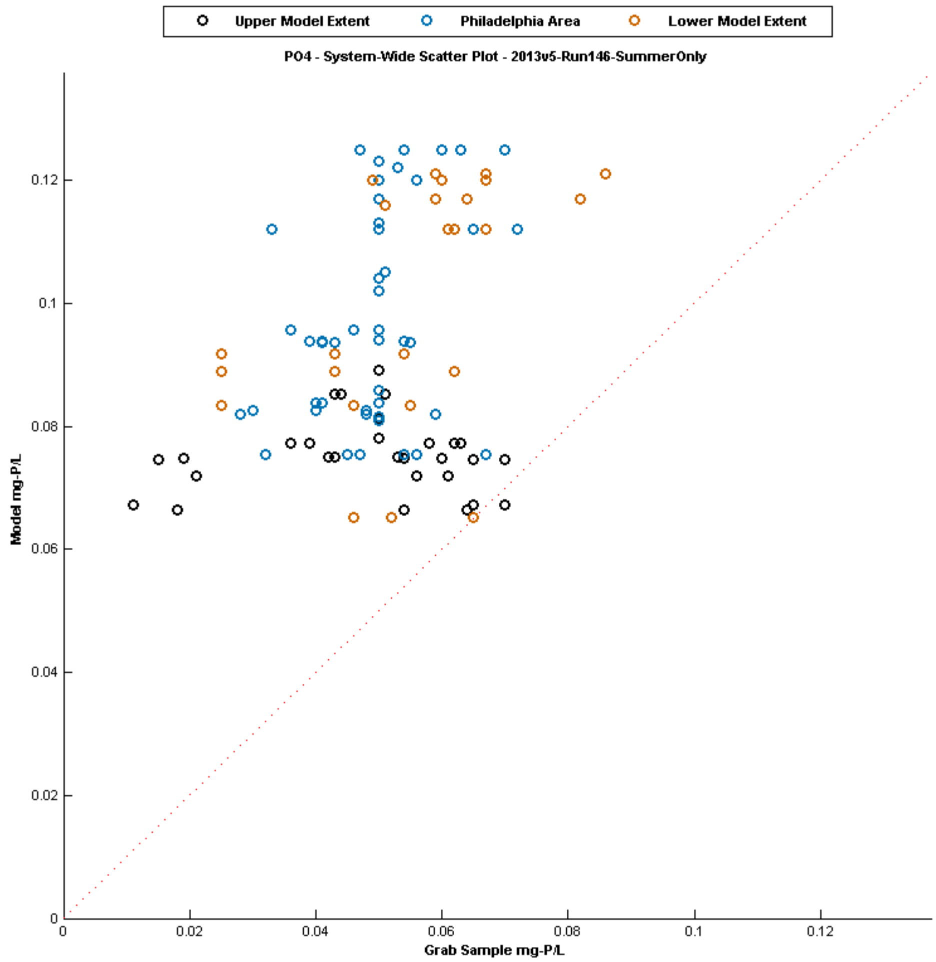
Upper Model Extent
Philadelphia Area
Lower Model Extent
TKN - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg-N/L
Grab Sample mg-N/L
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

2.8. Orthophosphate

2.8.1. April to October

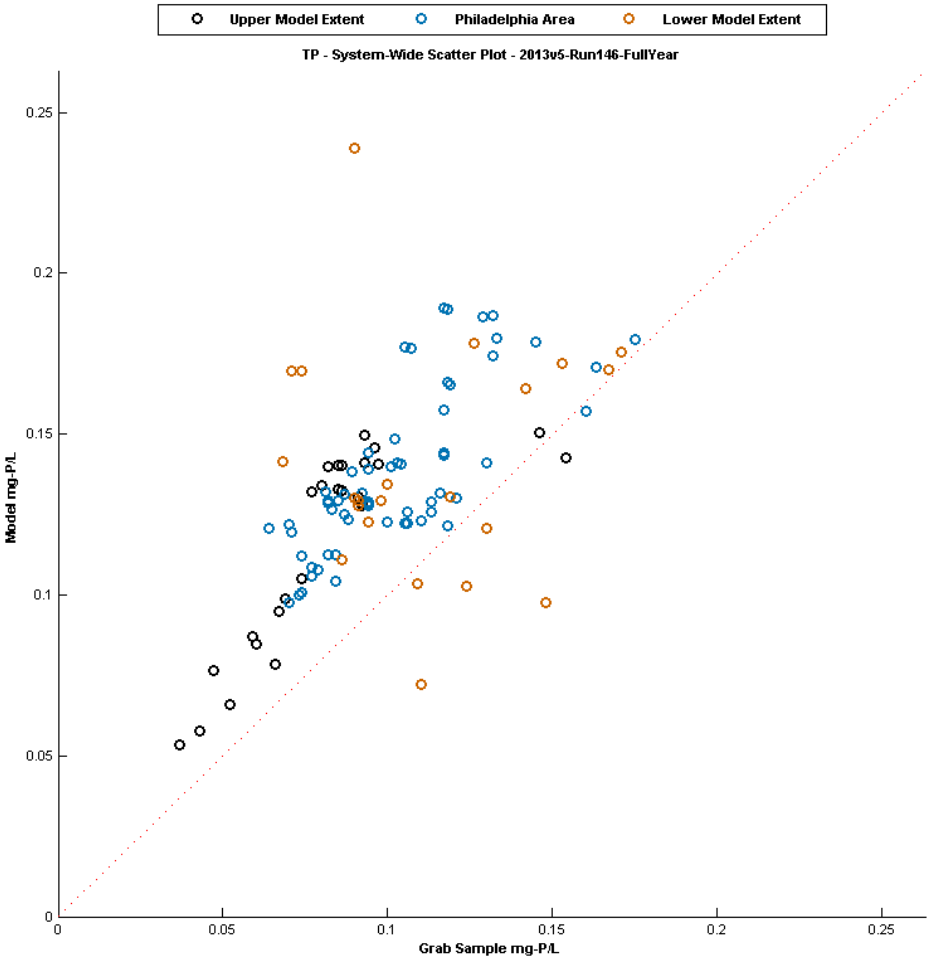


2.8.2. Summer

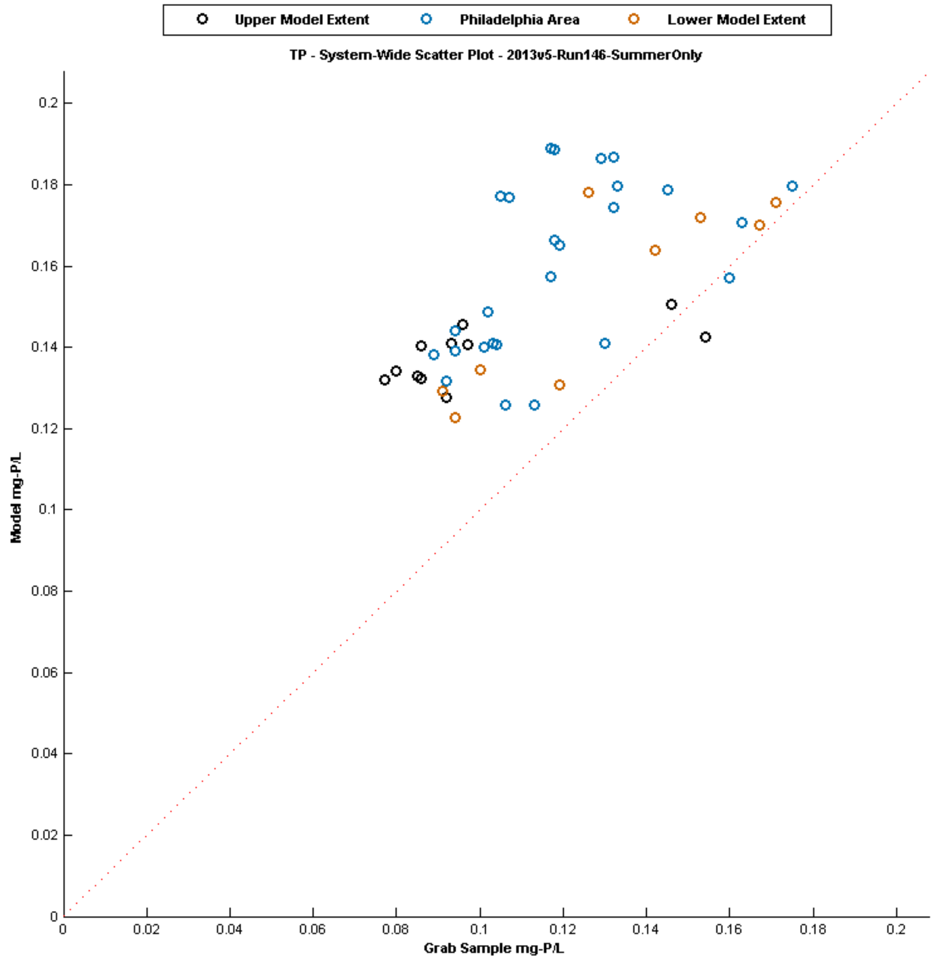

Upper Model Extent
Philadelphia Area
Lower Model Extent
PO4 - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg-P/L
Grab Sample mg-P/L
0
0.02
0.04
0.06
0.08
0.1
0.12

2.9. Total Phosphorous

2.9.1. April to October



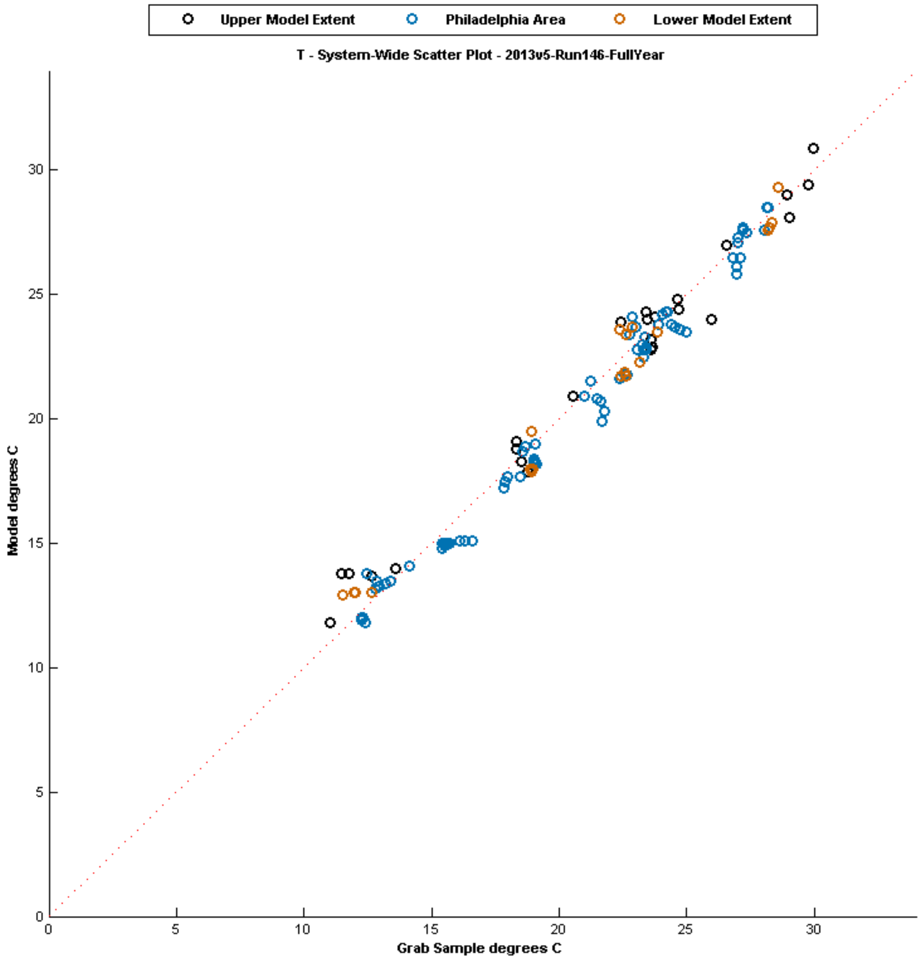
2.9.2. Summer



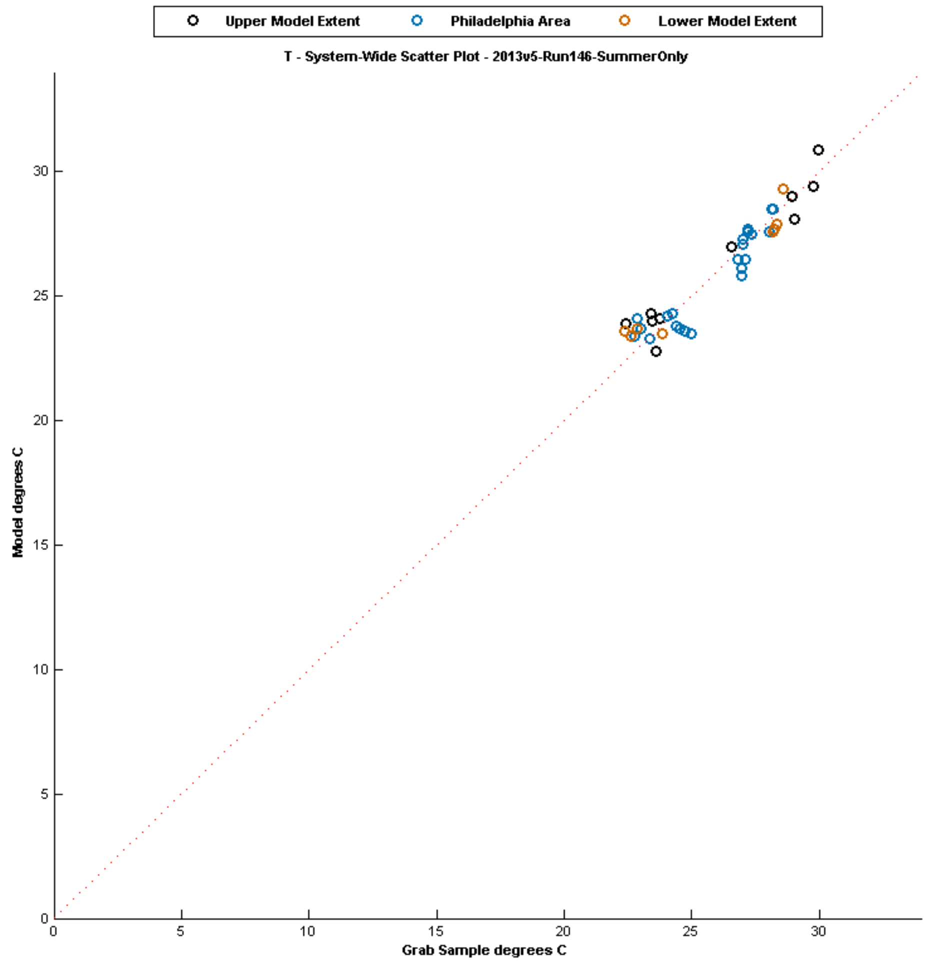
Upper Model Extent
Philadelphia Area
Lower Model Extent
TP - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model mg-P/L
Grab Sample mg-P/L
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

2.10. Temperature

2.10.1. April to October



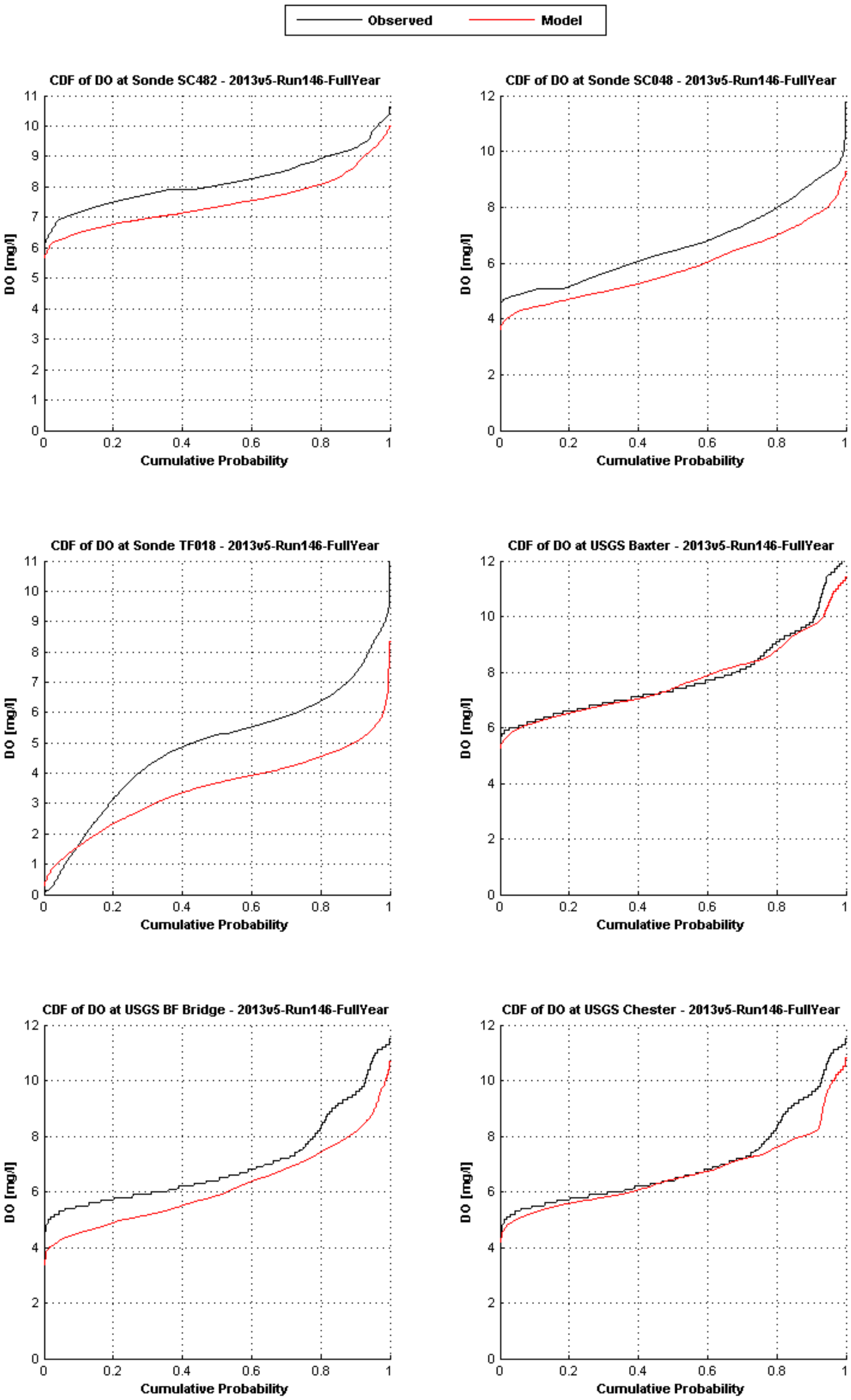
2.10.2. Summer


Upper Model Extent
Philadelphia Area
Lower Model Extent
T - System-Wide Scatter Plot - 2013v5-Run146-SummerOnly
Model degrees C
Grab Sample degrees C
0
5
10
15
20
25
30

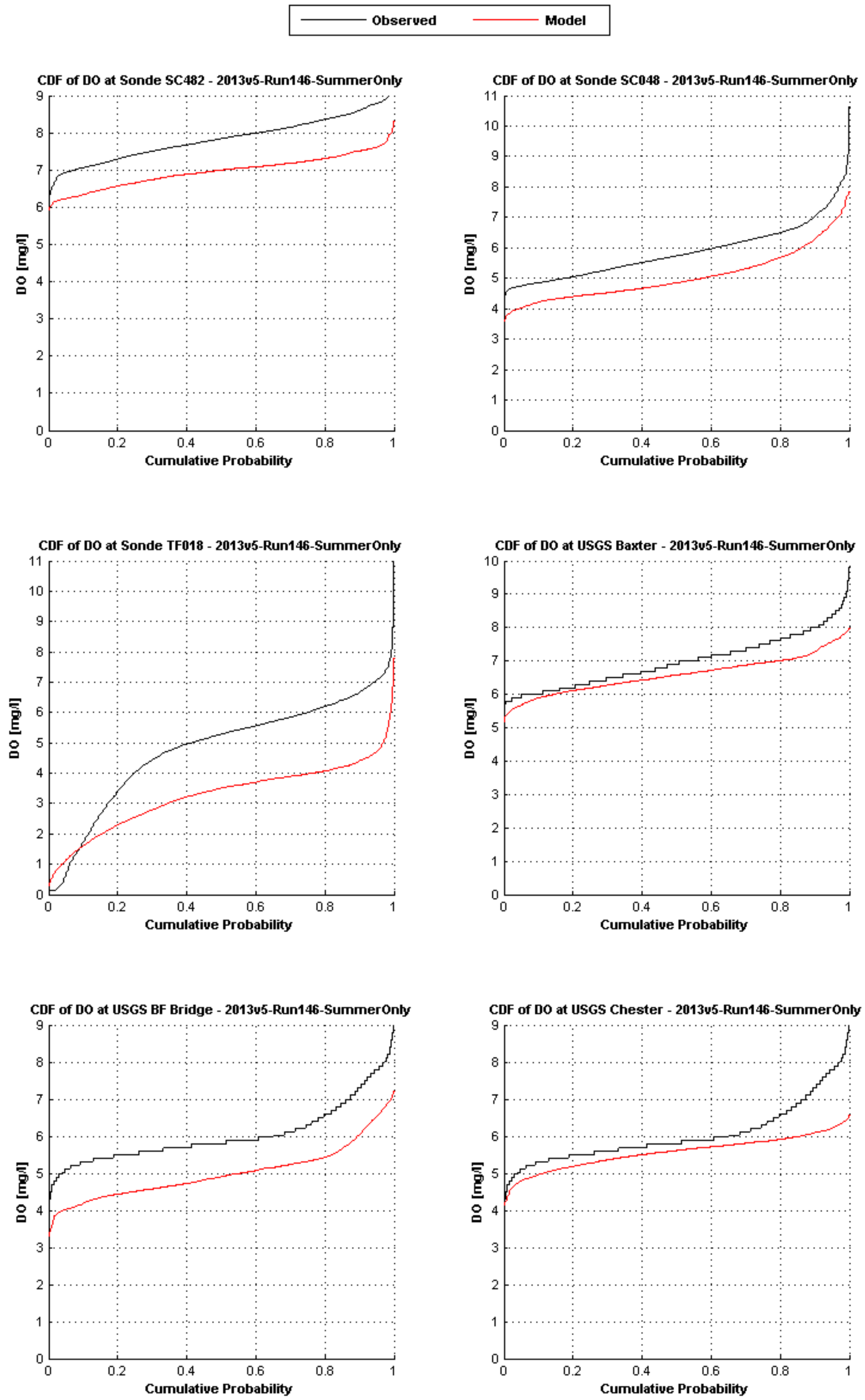
Chapter 3. CDF Plots

3.1. Dissolved Oxygen

3.1.1. April to October



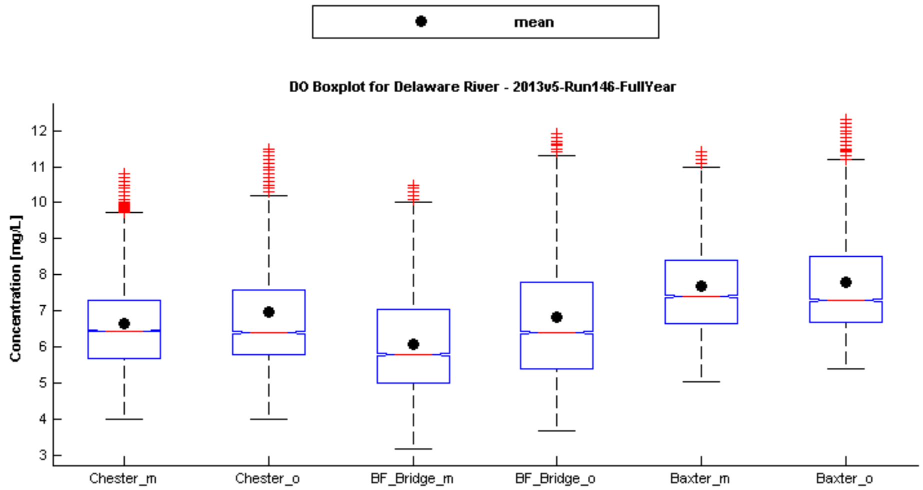
3.1.2. Summer


Observed
Model
CDF of DO at Sonde SC482 - 2013v5-Run146-SummerOnly
CDF of DO at Sonde SC048 - 2013v5-Run146-SummerOnly
CDF of DO at Sonde TF018 - 2013v5-Run146-SummerOnly
CDF of DO at USGS Baxter - 2013v5-Run146-SummerOnly
CDF of DO at USGS BF Bridge - 2013v5-Run146-SummerOnly
CDF of DO at USGS Chester - 2013v5-Run146-SummerOnly
DO [mg/l]
Cumulative Probability

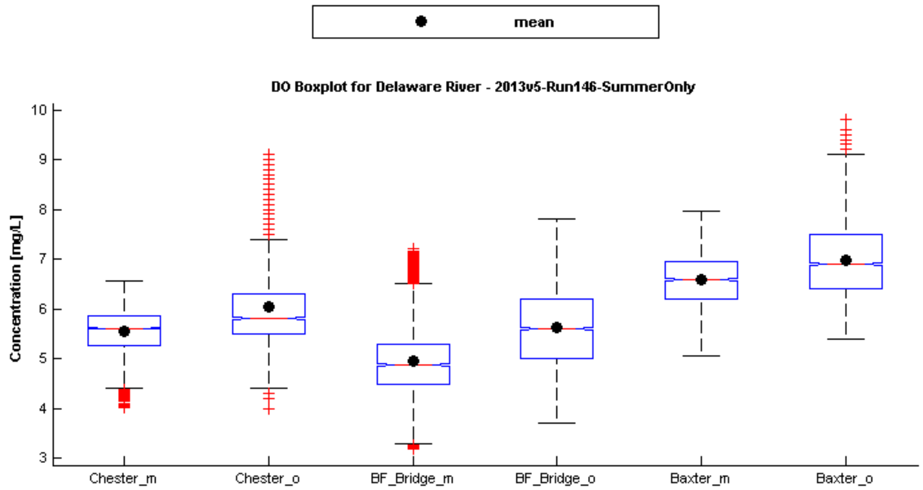
Chapter 4. Box Plots

4.1. Dissolved Oxygen

4.1.1. April to October

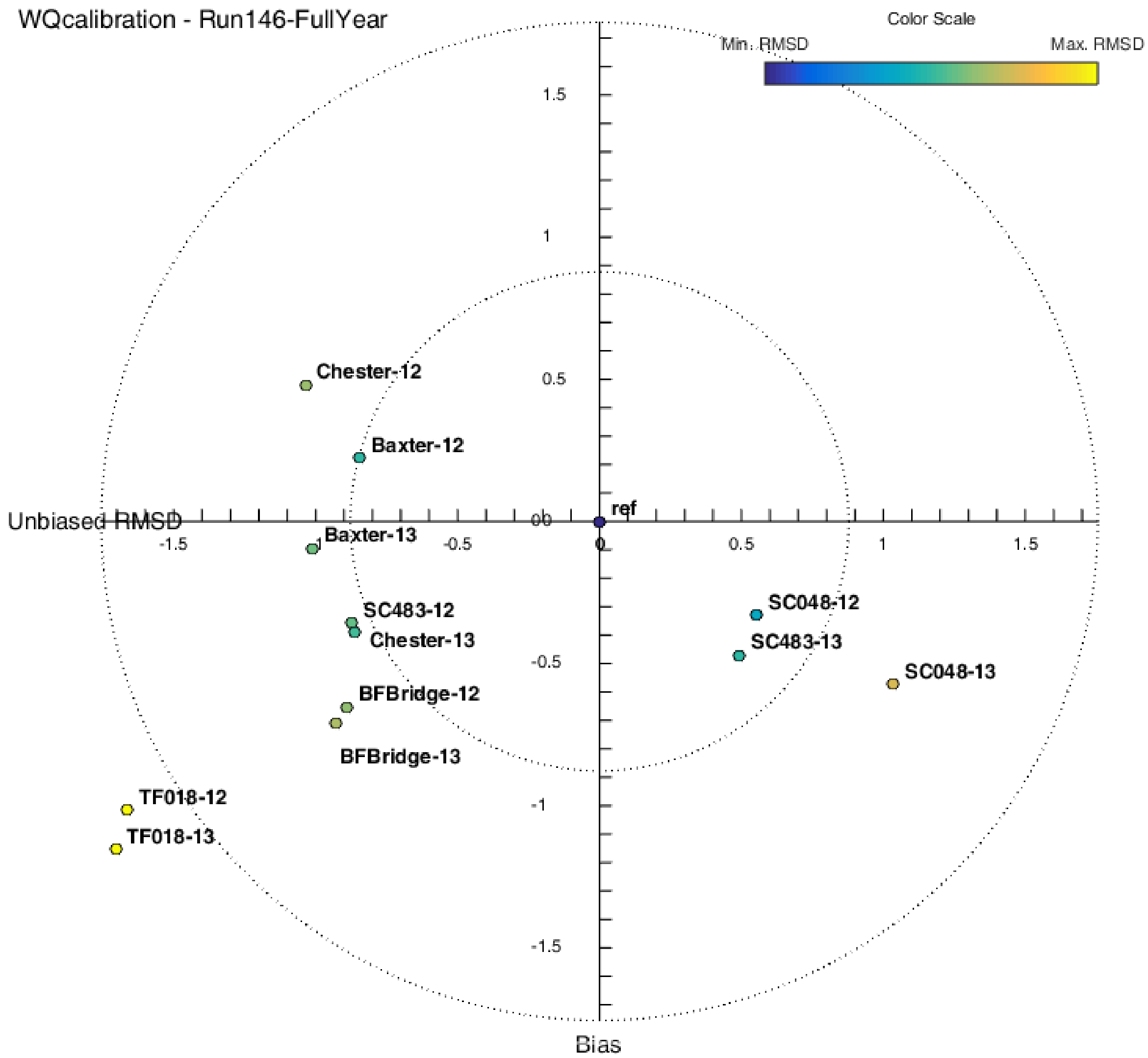


4.1.2. Summer

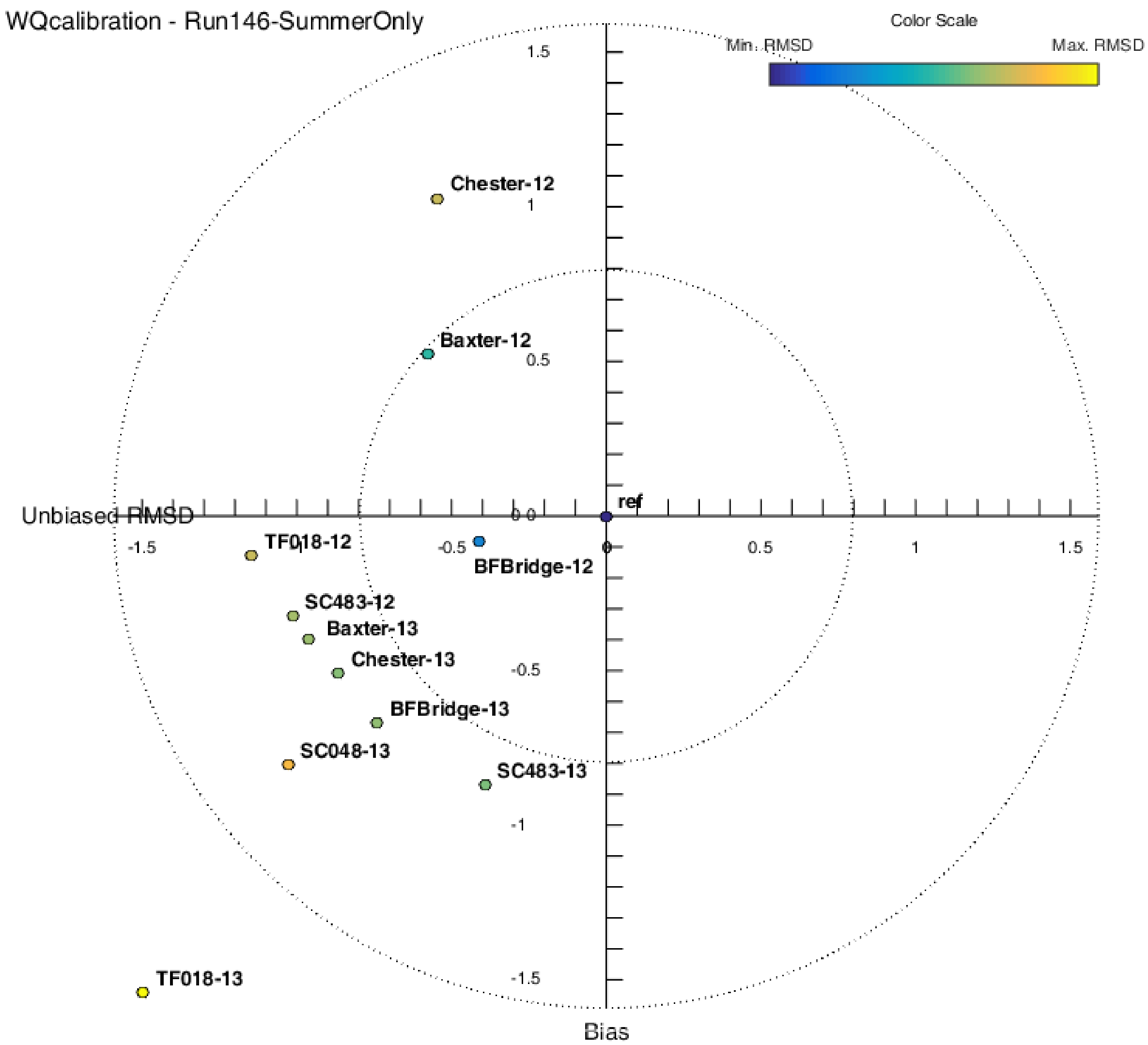

mean
DO Boxplot for Delaware River - 2013v5-Run146-SummerOnly
Concentration [mg/L]
10
9
8
7
6
5
4
3
Chester_m
Chester_o
BF_Bridge_m
BF_Bridge_o
Baxter_m
Baxter_o

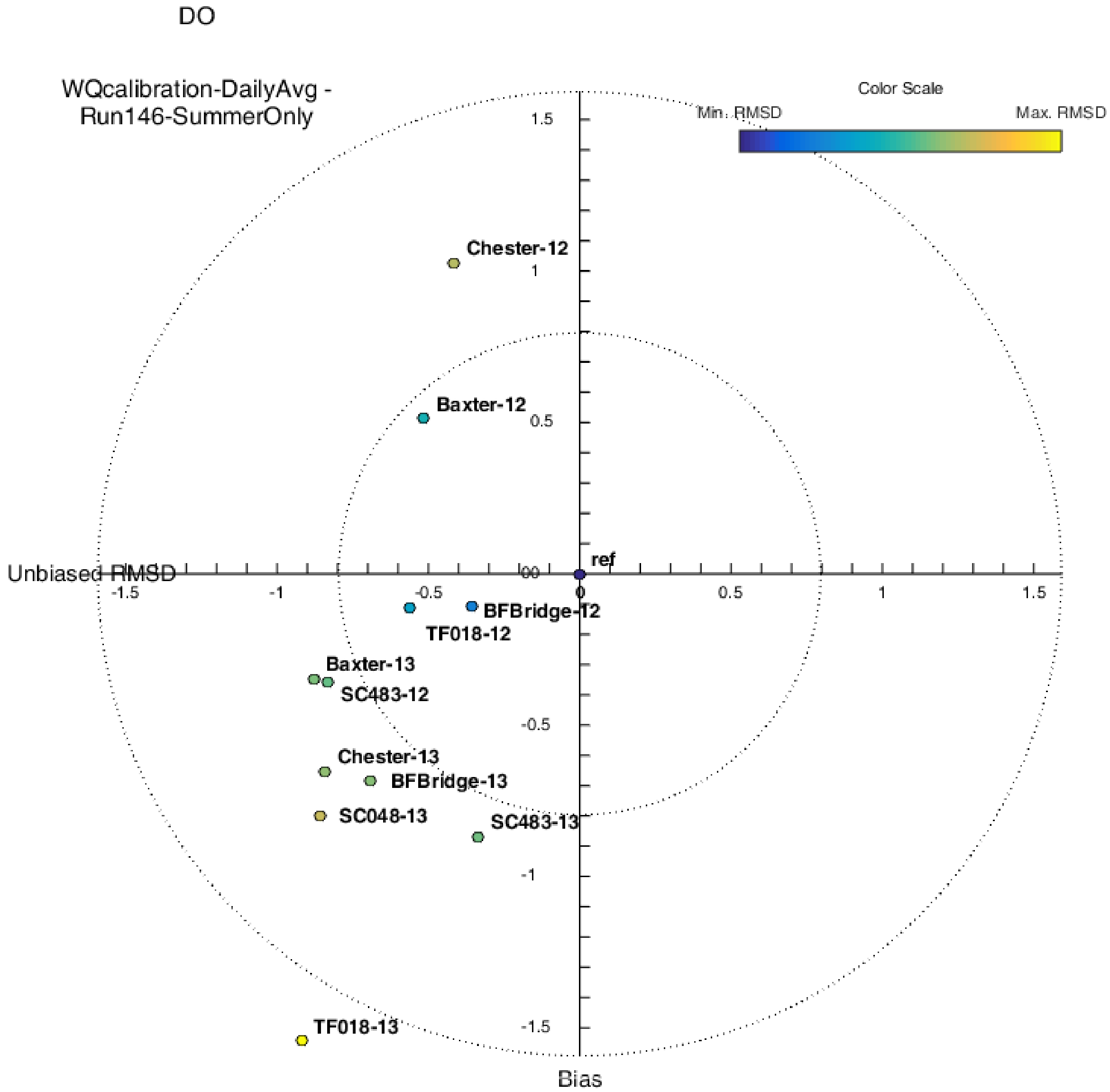
Chapter 5. Target Diagrams

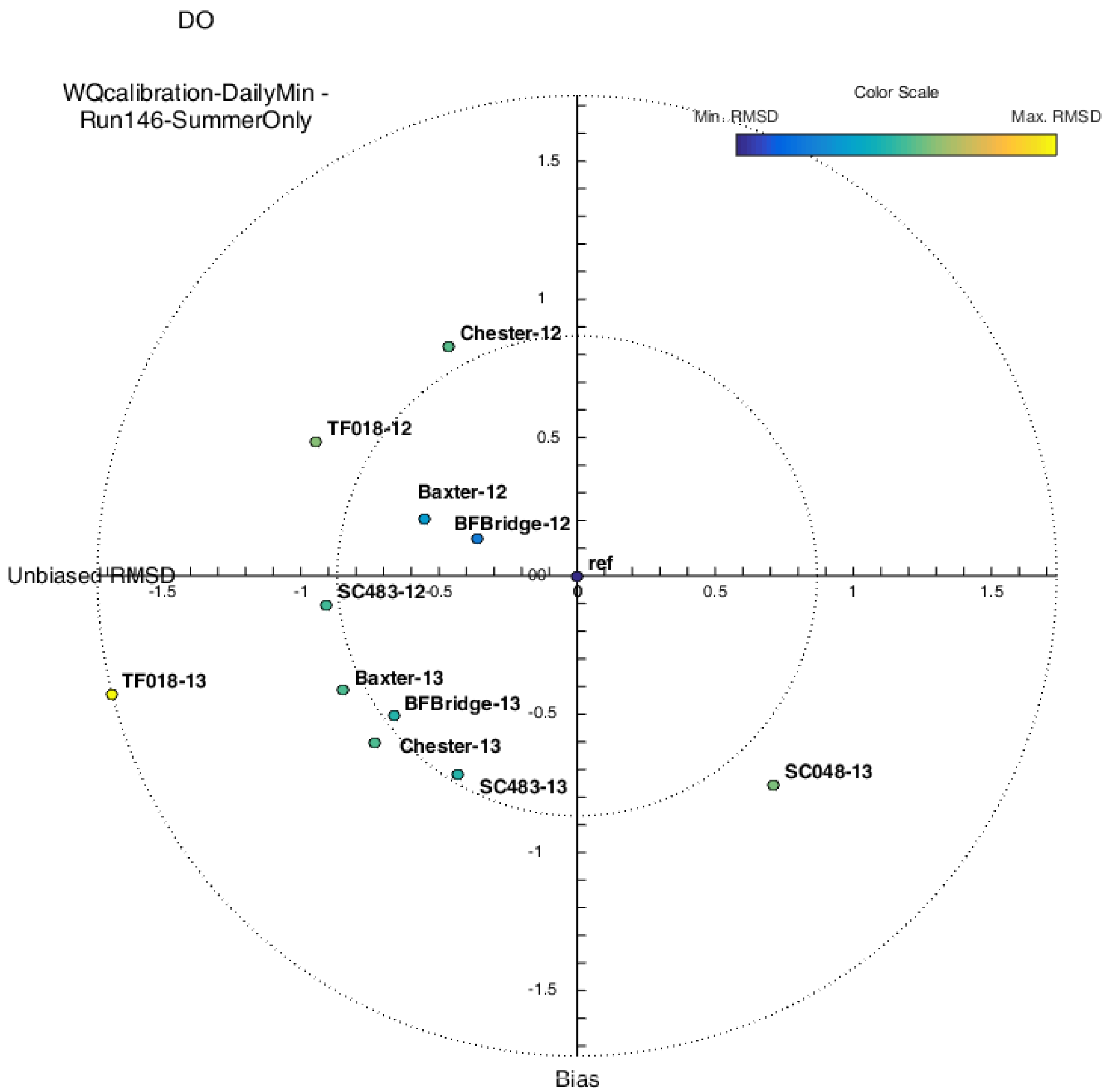
DO



DO


WQcalibration - Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
Unbiased RMSD
Bias
ref
Chester-12
Baxter-12
TF018-12
BFBridge-12
SC483-12
Baxter-13
Chester-13
BFBridge-13
SC048-13
SC483-13
TF018-13
1.5
1
0.5
0
-0.5
-1
-1.5


DO
WQcalibration-DailyAvg -
Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
Chester-12
Baxter-12
ref
BFBridge-12
TF018-12
Baxter-13
SC483-12
Chester-13
BFBridge-13
SC048-13
SC483-13
TF018-13
Unbiased RMSD
Bias
1.5
1
0.5
0
-0.5
-1
-1.5


DO
WQcalibration-DailyMin -
Run146-SummerOnly
Color Scale
Min. RMSD
Max. RMSD
Chester-12
TF018-12
Baxter-12
BFBridge-12
ref
SC483-12
TF018-13
Baxter-13
BFBridge-13
Chester-13
SC483-13
SC048-13
Unbiased RMSD
Bias
1.5
1
0.5
0
-0.5
-1
-1.5