11-1-2010

The Development of a Management Tool to Assess Bacterial Impacts in Rudee Inlet, Virginia Beach

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Recommended Citation

Sisson, M., Shen, J., Reay, W. G., Miles, E. J., Kuo, A. Y., & Wang, H. V. (2010) The Development of a Management Tool to Assess Bacterial Impacts in Rudee Inlet, Virginia Beach. Special Reports in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 423. Virginia Institute of Marine Science, William & Mary. https://doi.org/10.21220/V5KR07

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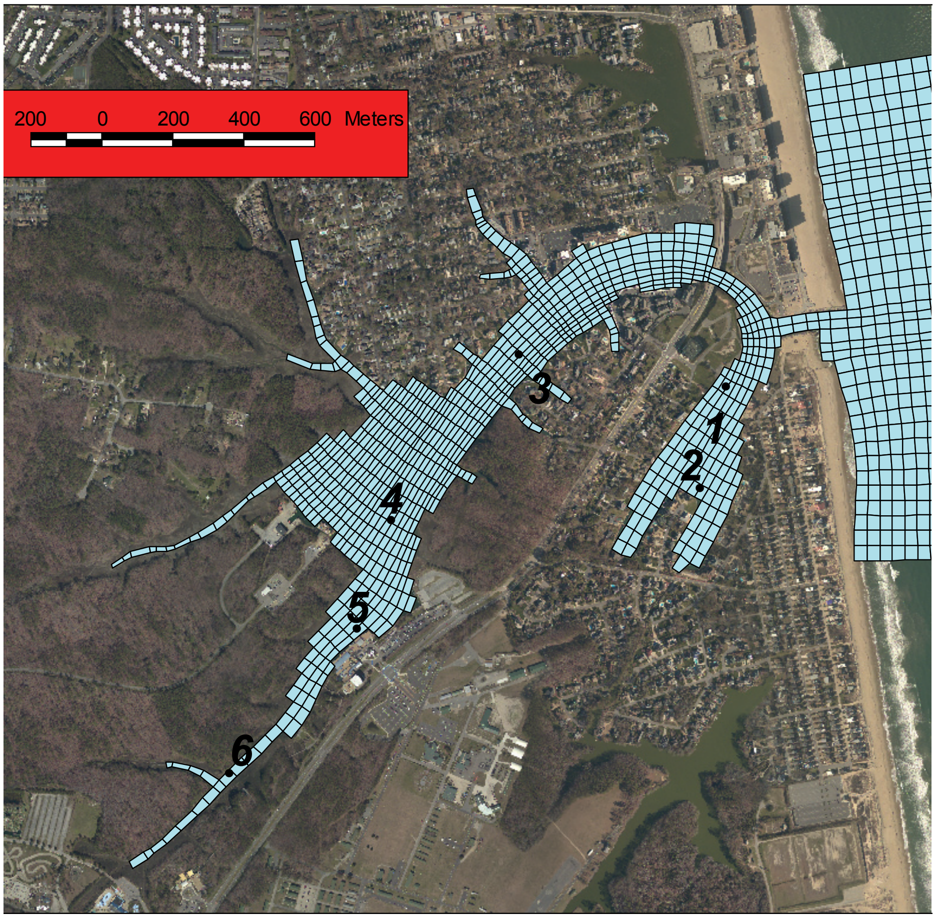
THE DEVELOPMENT OF A MANAGEMENT TOOL TO ASSESS BACTERIAL IMPACTS IN RUDEE INLET, VIRGINIA BEACH



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Final Report to the
U. S. Army Corps of Engineers, Norfolk District
and
The City of Virginia Beach

Special Report No. 423
In Applied Marine Science and Ocean Engineering

Virginia Institute of Marine Science
Department of Physical Sciences
Gloucester Point, Virginia 23062

November 2010

EXECUTIVE SUMMARY

1. The Norfolk District of the US Army Corps of Engineers and the City of Virginia Beach are working together on a cost-shared basis to identify and assess potential water quality problems in the Rudee Inlet system, which includes Lakes Rudee and Wesley and Owl Creek. In 2010, these agencies contracted with the Virginia Institute of Marine Science (VIMS) for field monitoring surveys of the Rudee Inlet system and the development of a high-resolution hydrodynamic model for this system that is capable of assessing the impact of fecal coliform reductions from its watershed.

2. VIMS performed field surveys in summer 2010 spanning the Rudee Inlet system. High-frequency measurements of depth (surface elevation), salinity, water temperature, dissolved oxygen, chlorophyll, and turbidity were made at 6 locations in this region for periods of approximately ten days to two weeks each commencing in June, July, and August of 2010. Grab sample surveys were conducted at over 20 locations spanning this region on July 1, July 12, and August 12, 2010. These grab samples were each analyzed for water temperature, salinity, pH, dissolved oxygen, dissolved oxygen percent saturation, *E. Coli,* and total coliform bacteria (TCB). The parameter of fecal coliform was then calculated from these measurements. Two 30-day, high-frequency tide gauge deployments were conducted at locations of the Rudee Inlet Marina and the Virginia Aquarium on Owl Creek in the spring of 2010. All these data were added to the VIMS Lynnhaven River database.

3. Fecal coliform bacteria (FCB) densities exceeded Commonwealth contact standards (> 200 MPN 100· ml^{-1}) in the upper reaches of Owl Creek on a routine basis while the lower and more open reaches of Lakes Rudee and Wesley typically exhibited FCB densities between shellfish waters and recreational contact standards (> 14 MPN to ≤ 200 MPN·100 ml^{-1}). Findings are consistent with an increased "land effect" due to increases in the ratio of shoreline to water volume in the upper tidal reaches. Elevated FCB densities were also observed after periods of high rainfall. TCB and *E. coli* densities varied between 173-129,965 MPN·100 ml^{-1} and 10-844 MPN·100 ml^{-1}, respectively, in tidal waters of the Rudee Inlet system. A significant linear relationship ($p=0.00$; $r^2=0.48$, $N=81$) was found between log transformed TCB and *E. coli* densities for samples collected during this study period. Elevated counts of TCB and *E. coli* were associated with the upper reaches of selected tidal creeks and non-tidal freshwater sources. Analysis of historical VA-DEQ and DSS data supported the observation of higher coliform bacteria (FCB) in upstream regions and that summer months exhibited elevated average monthly densities as compared to other seasons. Sources of FCB to the Rudee Inlet system include nonpoint source runoff from urbanized and natural lands, direct domestic and wild animal loadings, and direct discharge from vessels. Additional study is required to source track and differentiate FCB loadings and to determine if true health concerns exist.

4. VIMS has completed a successful application of a hydrodynamic numerical model for the Rudee Inlet system. This application utilizes utilizes a watershed model to simulate bacterial processes in the watershed and discharge to the Rudee Inlet system, and a high-resolution 3D hydrodynamic model (HEM-3D hydro) that provides the required transport for a submodel simulating the fecal coliform bacteria levels. The model underwent an extensive calibration for surface elevation and salinity.

5. A fecal coliform model was also developed, as a submodel of HEM-3D hydro, for the Rudee Inlet system and simulations were performed for the fecal coliform load reductions. A long-term calibration was performed comparing model predictions with monthly observations at 6 VA-DEQ stations in the Rudee Inlet system for the period 1996-1999. Additionally, spatial comparisons were made between fecal coliform model predictions and the observations at more than 20 grab sample locations for three surveys (July 1, July 12, and August 12, 2010). The calibrated model was then used to assess fecal coliform loading reductions of 90% and 95%. It was determined that the shellfish harvesting criteria (14 MPN·100 ml^{-1} for 30-day geometric mean and 43 MPN·100 ml^{-1} for the 90^{th} percentile) could be attained with approximately a 95% load reduction.

6. Model applications included additional sensitivity testing for fecal coliform load reduction. A scenario reducing fecal coliform loadings from urban sources by 90% was performed, but little impact was noted in the long-term fecal coliform levels. Assessments of isolated non-point sources of fecal coliform loadings indicated very localized impacts to FCB levels. Model results suggest that loadings from marsh-wetland regions have a higher impact on the system, and in particular, those from small up-reach branches. The study also points to the existence of non runoff-related sources in the summer season, such as boating activities, wildlife in inter-tidal areas, and so forth, which would require more study to identify these sources.

Findings or recommendations contained herein do not constitute Corps of Engineers approval of any project(s) or eliminate the need to follow normal regulatory permitting processes.

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CHAPTER I. INTRODUCTION

Rudee Inlet is located along the southside of the Virginia Beach ocean front and has for several decades provided a major draw to tourism for the City of Virginia Beach, attracting tourists for deepwater fishing charters as well as dolphin- and whale-watching excursions, jet skis, and parachute rides. It is the only inlet available to mariners between Cape Henry and Oregon Inlet, located 90 miles apart. There is a system of important water bodies, just inland of Rudee Inlet, which provides valuable waterfront properties and supports important wetlands (Virginia Senate Document 18, 1999). These water bodies form the Rudee Inlet system, which includes Owl Creek, which drains into Lake Rudee, and Lake Rudee and Lake Wesley, that join at the inlet, as shown in Figure I.1.

However, water quality conditions of the Rudee Inlet system are a concern to the City of Virginia Beach. The Virginia DEQ List of Impaired Waters includes impairments for fecal coliform bacteria (FCB) in Lake Rudee (upper and lower), Lake Wesley, and Owl Creek (upper and lower). FCB concentrations as high as the maximum detection limit of 1200 MPN/100 ml have been measured over most of the system.

There are presently only two (2) No Discharge Zones (NDZs) in the State of Virginia, Smith Mountain Lake and the Lynnhaven River. The City of Virginia Beach was successful in having the Lynnhaven River designated as a NDZ in 2007. City officials are now examining the procedures required to apply for Rudee Inlet to become the State's third NDZ. The Virginia Department of Health (VDH) is requested by House Joint Resolution 448 to study the feasibility of establishing NDZs for boats. NDZs require that boats be equipped with installed or portable toilets, and that they cannot release toilet waste into the surrounding waters. It is illegal to discharge any raw, untreated sewage overboard into any state water bodies, and such discharge can only be done when boaters are three miles offshore or more in the territorial sea (Virginia Department of Health, 2010).

The methodology required in the establishment of an NDZ is that the VDH will examine data related to the effects of pollution from boats on sensitive and productive waters of the Chesapeake Bay and its tributaries. The VDH will also determine the availability of operational marine holding tank pump-out facilities and dump stations in these waters. From this analysis, VDH will evaluate the possible establishment, through petition to the U.S. Environmental Protection Agency (USEPA) under the Clean Water Act (CWA), of NDZs in these waters.

a) b)

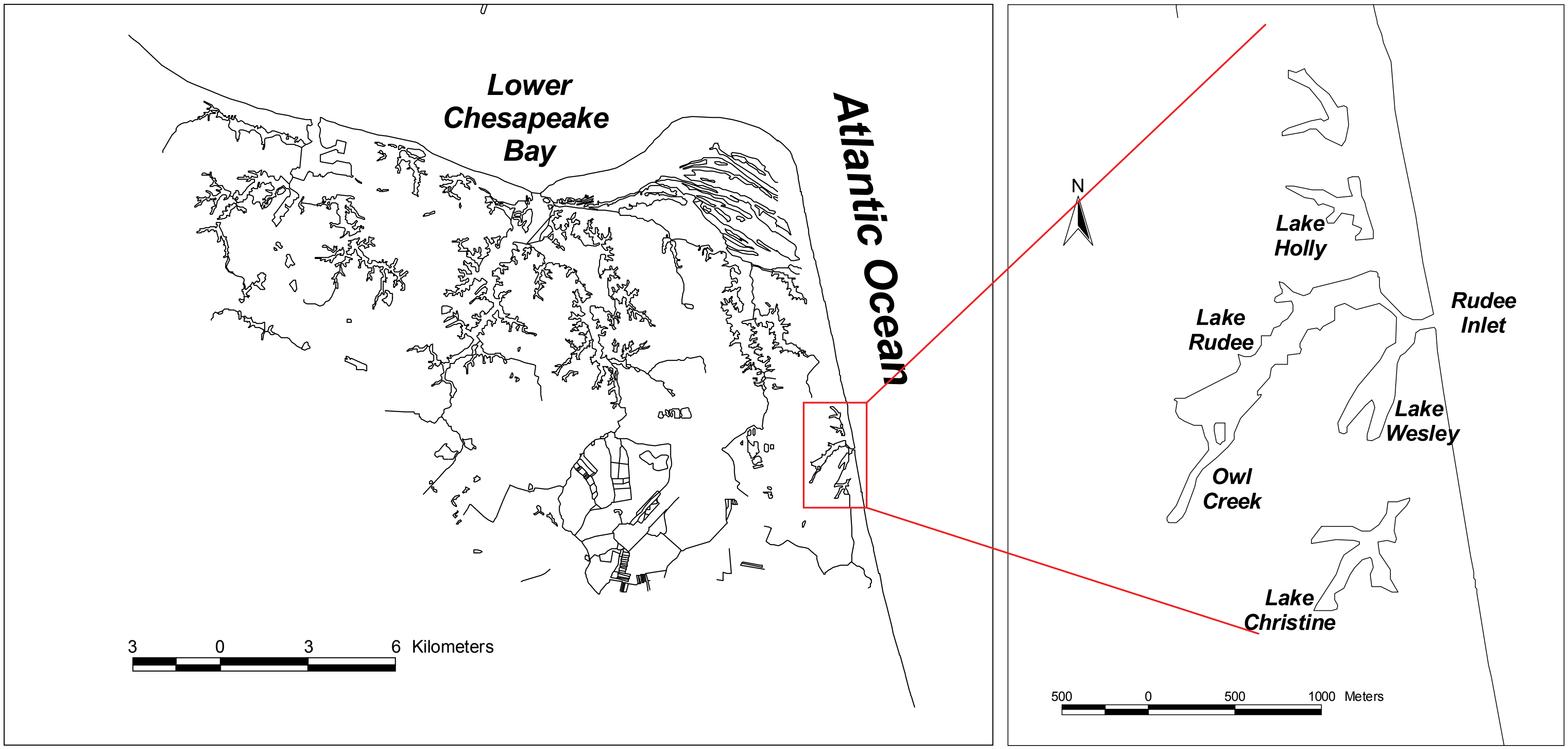


Figure I.1. a) The location of Rudee Inlet along the Virginia Beach oceanfront to the southeast of the Lynnhaven River and b) a "zoomed-in" view showing water bodies of the Rudee Inlet system.

Both the Virginia Department of Environmental Quality (VA-DEQ) and the Virginia Division of Shellfish Sanitation (VA-DSS) maintain monitoring stations in the Rudee Inlet system. For any study of fecal coliform bacteria levels, the presence of these historical data is of key significance because of the need for relatively long-term data sets to assess whether the receiving waters are impaired.

VA-DEQ Measurements:

There are a total of 6 DEQ stations monitored in the water bodies that form their confluence at Rudee Inlet. The locations of these VA-DEQ stations are shown in Figure I.2 and descriptions of these locations are listed in Table I.1. Station 7-LAI000.04 is at the confluence of the two lakes just inside the inlet, Station 7-LAE000.20 is in Lake Wesley, Stations 7-LAI000.18 and 7-LAI000.56 are in Lake Rudee, and Stations 7-OWL000.01 and 7-OWL000.77 are in Owl Creek.

FCB levels were monitored at all 6 stations over the 7-year period 1996-2003. FC levels at the stations in Lake Wesley and confluence region are shown in Figure I.3 and those for the Lake Rudee and Owl Creek stations are shown in Figure I.4. As expected, higher FC levels were seen at the upstream stations in Owl Creek. It is noted that VA-DEQ has a maximum detection limit of 1200 MPN/100 ml.

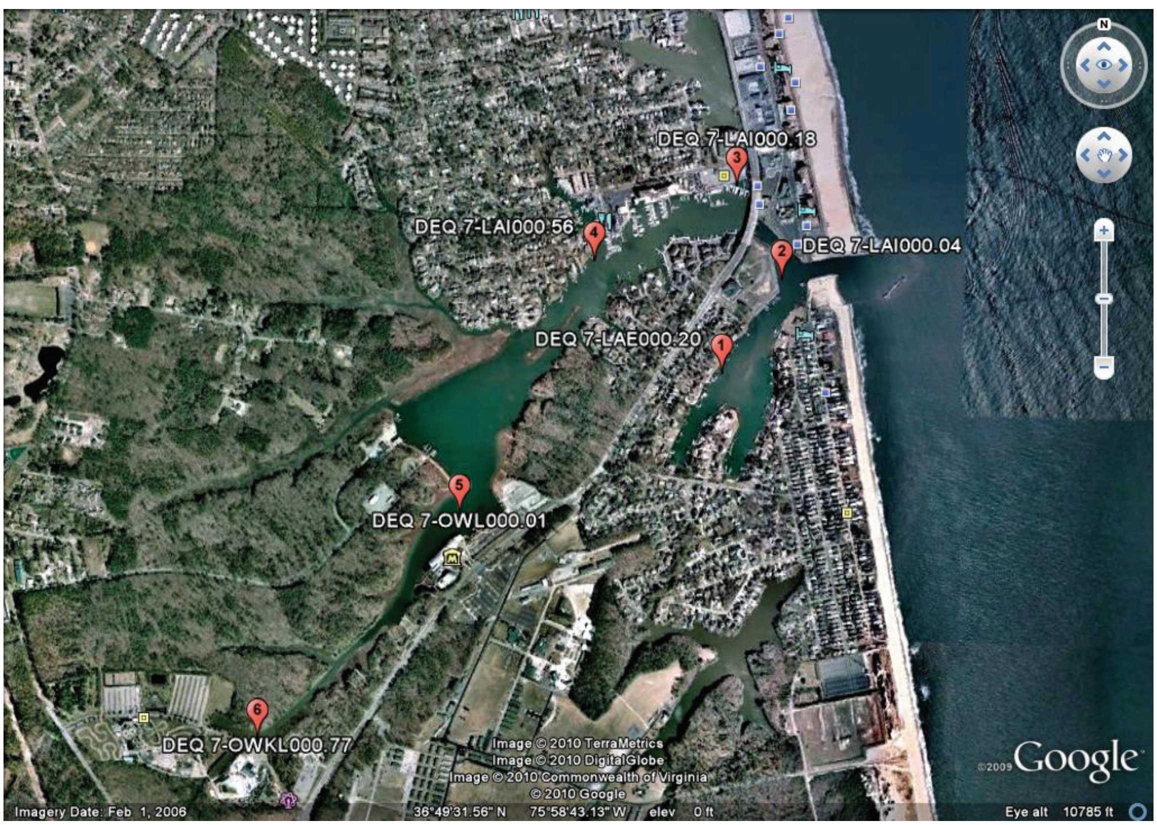
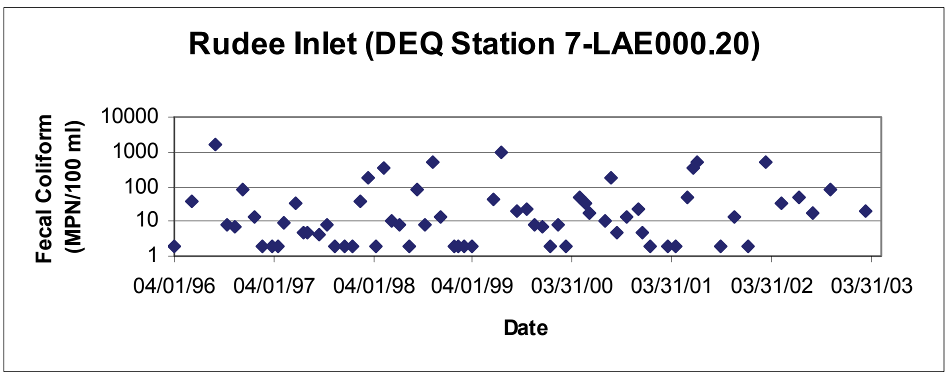


Figure I.2. Locations of VA-DEQ monitoring stations within the Rudee Inlet system.

Table I.1: VA-DEQ stations in the Rudee Inlet system, Virginia Beach.

DEQ Station	Location	DEQ Location Description
7-LAE000.20	36 deg 49 min 36 sec – north lat 75 deg 58 min 24 sec – west long	Midlake (Lake Wesley) 100 m from point
7-LAI000.04	36 deg 49 min 46 sec – north lat 75 deg 58 min 16 sec – west long	Midchannel at confluences
7-LAI000.18	36 deg 49 min 56 sec – north lat 75 deg 58 min 22 sec – west long	Lake Rudee, near Lake Holley culvert
7-LAI000.56	36 deg 49 min 48 sec – north lat 75 deg 58 min 41 sec – west long	Midchannel, 600 m upstream off Goldsboro Avenue
7-OWL000.01	36 deg 49 min 21 sec – north lat 75 deg 58 min 59 sec – west long	Off Va Marine Science museum parking lot
7-OWL000.77	36 deg 48 min 57 sec – north lat 75 deg 59 min 26 sec – west long	0.6 miles upstream at headwater



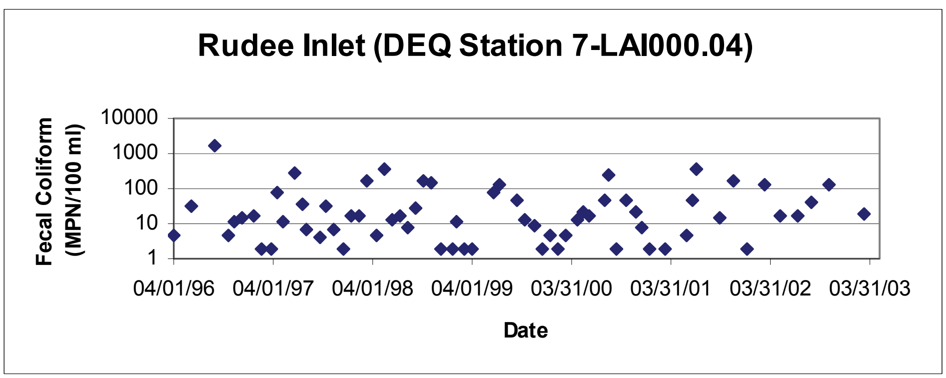


Figure I.3. Fecal coliform bacteria observations at VA-DEQ Stations in Lake Wesley and confluence region during the 7-year period 1996-2003.

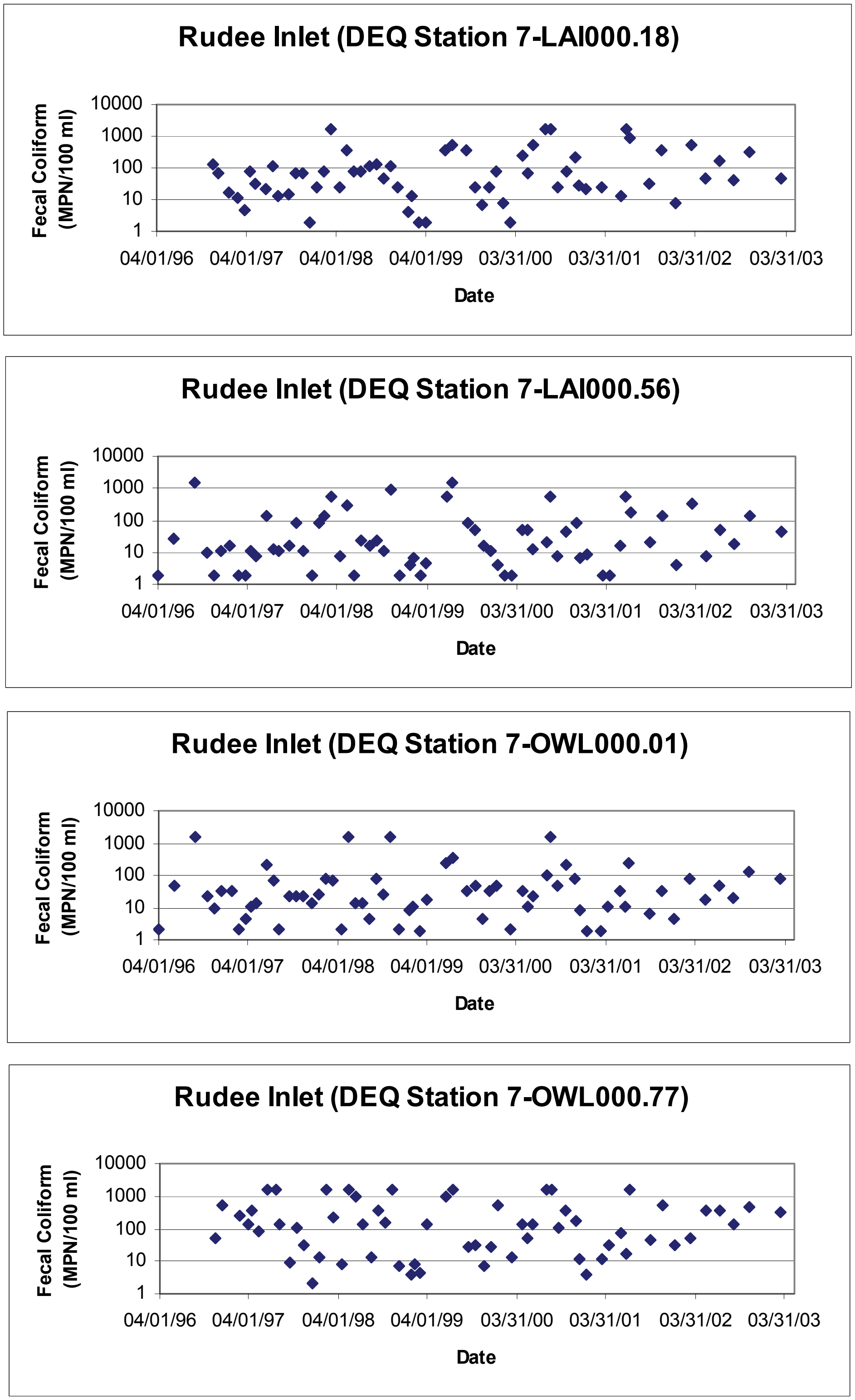


Figure I.4. Fecal coliform bacteria observations from Lake Rudee VA-DEQ Stations (top 2 panels) and from upstream Owl Creek Stations (bottom 2 panels) during the 7-year period 1996-2003.

In order to get an overview assessment of the fecal coliform conditions in the Rudee Inlet system, two analyses of the VA-DEQ data were conducted. The first analysis was to determine the geometric mean and 90th percentile values of observations over successive 3-year periods at all 6 VA-DEQ stations in the system, as shown below in Table I.2.

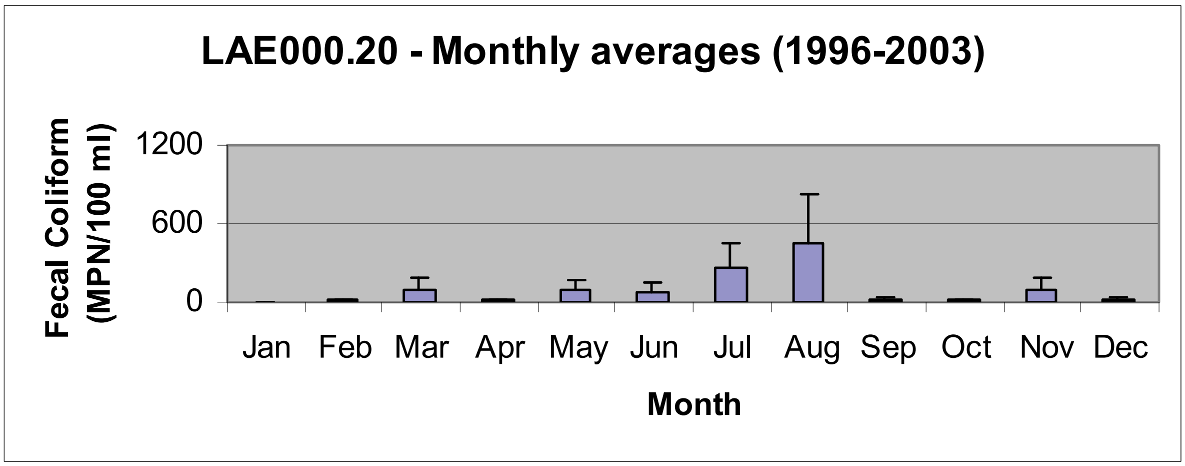
Table I.2: Geometric mean and 90th percentile values at VA-DEQ stations in the Rudee Inlet system.

VA-DEQ Station	3-year period	Number of Samples	Geometric mean	90th Percentile
LAE000.20	04/1996-03/1999	34	9.7	104.0
	04/1997-03/2000	34	9.7	93.0
	04/1998-03/2001	33	11.7	110.8
	04/1999-03/2002	28	16.5	190.3
	04/2000-03/2003	24	20.2	198.0
LAI000.04	04/1996-03/1999	34	15.1	142.0
	04/1997-03/2000	34	14.8	118.5
	04/1998-03/2001	33	12.9	101.8
	04/1999-03/2002	27	16.6	136.4
	04/2000-03/2003	23	21.6	158.8
LAI000.18	04/1996-03/1999	30	33.1	248.7
	04/1997-03/2000	34	36.7	325.2
	04/1998-03/2001	33	52.6	544.4
	04/1999-03/2002	27	88.3	1033.2
	04/2000-03/2003	23	119.4	988.5
LAI000.56	04/1996-03/1999	34	15.7	170.9
	04/1997-03/2000	34	20.5	239.1
	04/1998-03/2001	33	19.0	218.0
	04/1999-03/2002	28	29.3	351.4
	04/2000-03/2003	24	30.8	244.9
OWL000.01	04/1996-03/1999	34	21.3	222.8
	04/1997-03/2000	33	24.6	236.5
	04/1998-03/2001	32	26.2	344.4
	04/1999-03/2002	27	29.3	261.2
	04/2000-03/2003	24	30.3	230.8
OWL000.77	04/1996-03/1999	29	90.5	1307.9
	04/1997-03/2000	33	81.2	1274.7
	04/1998-03/2001	32	77.1	1099.7
	04/1999-03/2002	27	87.7	904.0
	04/2000-03/2003	24	117.0	955.9

From this analysis, it can be seen that those stations located most upstream, particularly those in Owl Creek, had the highest values, presumably from poorer flushing or a higher ratio of watershed acreage to receiving water volume.

The second analysis was to determine if a seasonal trend existed over any part of the Rudee Inlet system. This was done by determining the monthly averages of FCB over the 7-year period from 1996-2003, as shown in Figures I.5 to I.6.

This analysis suggested that, in general, peak levels of fecal coliform occurred in the summer months (particularly in August) throughout the Rudee Inlet system. However, the most upstream station, OWL000.77, had significant averages for FCB in other months as well.



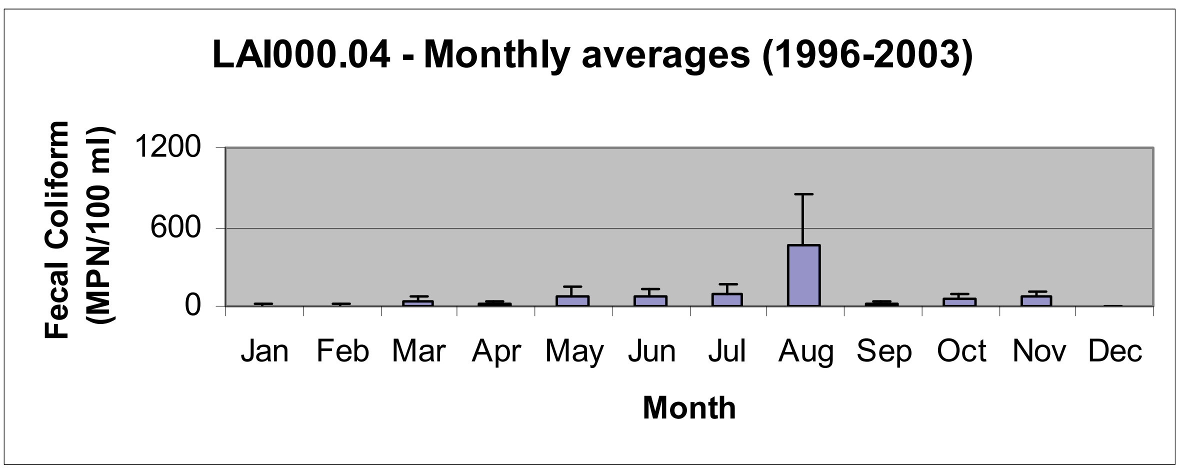


Figure I.5. Monthly averages of fecal coliform bacteria observations at VA-DEQ stations in Lake Wesley and confluence region from 1996-2003. Note: averages are shown in blue and the vertical extension bar represents one-half the standard deviation.

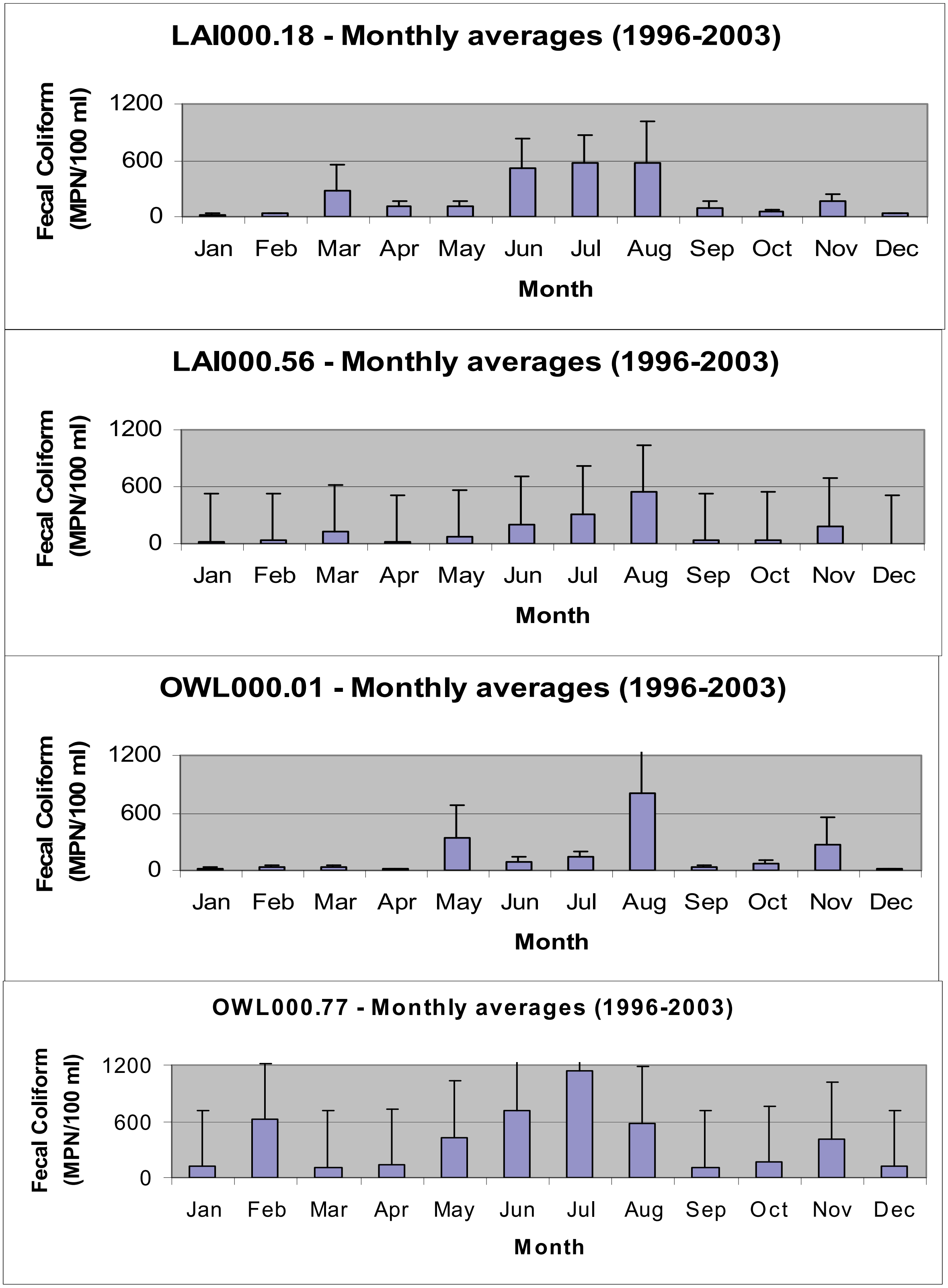


Figure I.6. Monthly averages of fecal coliform bacteria observations at Lake Rudee VA-DEQ Stations (top 2 panels) and from upstream Owl Creek Stations (bottom 2 panels) for 1996-2003. Note: averages are shown in blue and the vertical extension bar represents one-half the standard deviation.

VA-DSS Measurements:

Currently, there are two stations monitored by VA-DSS in the Rudee Inlet system. Station 73-1 has been monitored monthly for the past 25 years. Station 73-2 was added towards latter 2009. The locations of these stations are shown in Figure I.7, and a 25-year record of observations at Station 73-1 is shown in Figure I.8.

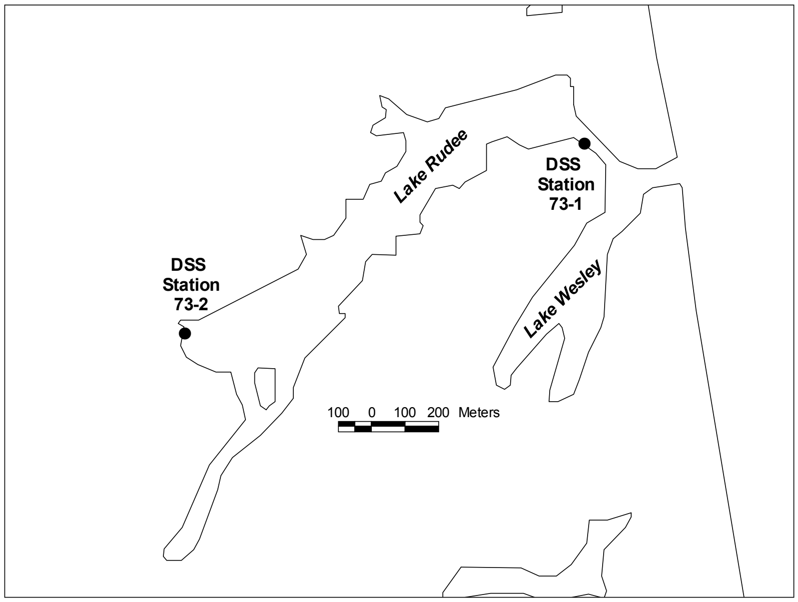


Figure I.7. Locations of VA-DSS monitoring stations within the Rudee Inlet system.

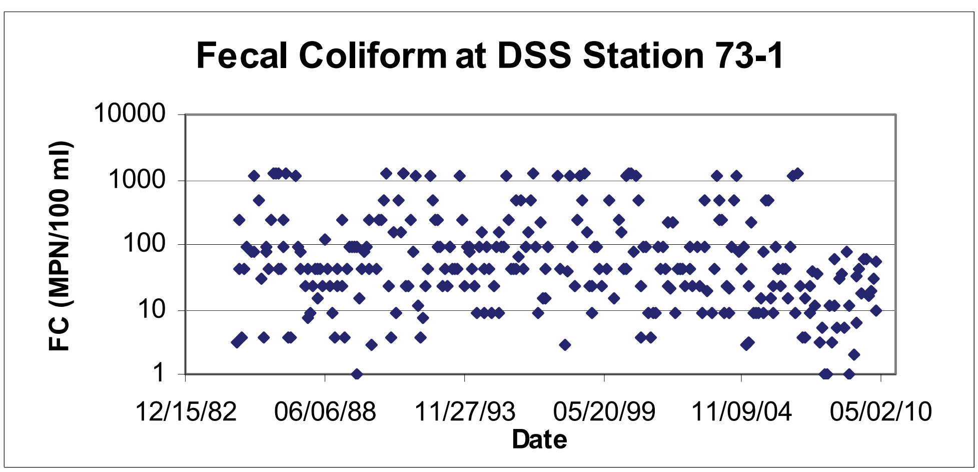


Figure I.8. Fecal coliform bacteria observations at Rudee Inlet VA-DSS Station 73-1.

A seasonal analysis of the 25-year record from DSS Station 73-1 showed that the highest average FCB concentrations were measured in the summer months of June to August, in the plot of monthly average shown in Figure I.9 below.

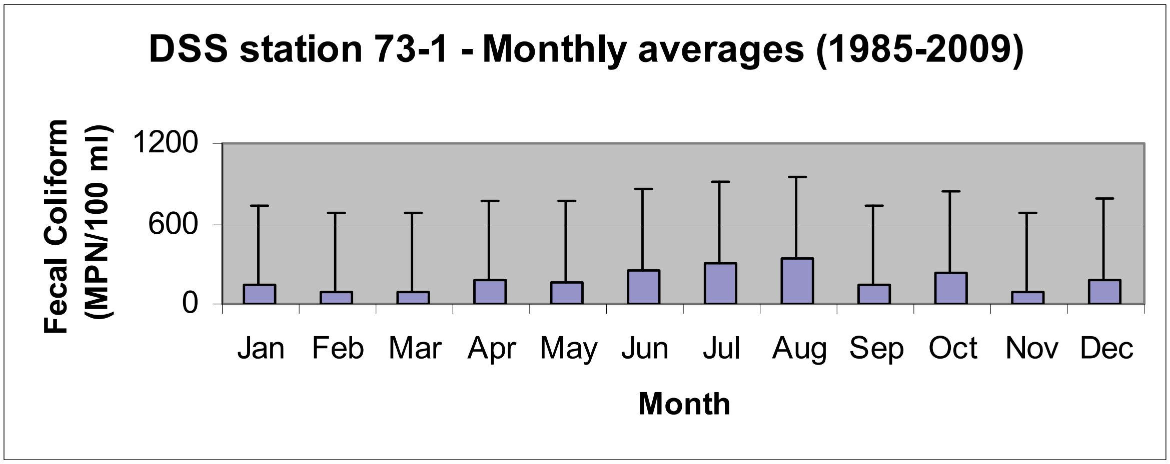


Figure I.9. Monthly averages of fecal coliform bacteria observations at VA-DSS station 73-1 near Rudee Inlet from 1985-2009. Note: averages are shown in blue and the vertical extension bar represents one-half the standard deviation.

In the earlier discussion about available VA-DEQ FCB data in the Rudee Inlet system, our analysis focused on the 7-year period 1996-2003. It should be noted that additional monitoring of Rudee was conducted from 2003-2007 (Everton, 2010).

The analyses presented in this chapter helped to outline our objectives in this study. The data show clearly the higher FCB levels in the mid-summer, high temperature periods. VIMS selected these periods to perform intensive grab sample surveys to better characterize the spatial distribution of FCB in the Rudee Inlet system with the intent to help identify sources of FCB in this region.

CHAPTER II. FIELD OBSERVATIONS

II-1 Introduction

Field studies were conducted in the tidal Rudee Inlet system in 2010. The collected data provide information on the current summertime water quality conditions of this waterbody, offer insight as to important controlling processes, and to be used for calibration and verification of both hydrodynamic and FCB models. Additional samples were also collected in adjacent lake systems and included Lake Holly to the north and Lake Christine to the south.

Studies encompassed the following efforts: (1) a bathymetry study, (2) collection of on-site meteorological data, (3) high frequency observations of water level and water quality at fixed stations (ConMon stations), (4) vertical water quality profiles, and (5) three water quality grab sample surveys. Sampling time periods for the studies and supporting activities are provided in Figure II.1. ConMon and weather station locations are provided in Figure II.2.   Grab sample survey stations are provided in Figure II.3. Vertical profiles were collected at the ConMon station locations during periods of sonde retrieval and deployment.

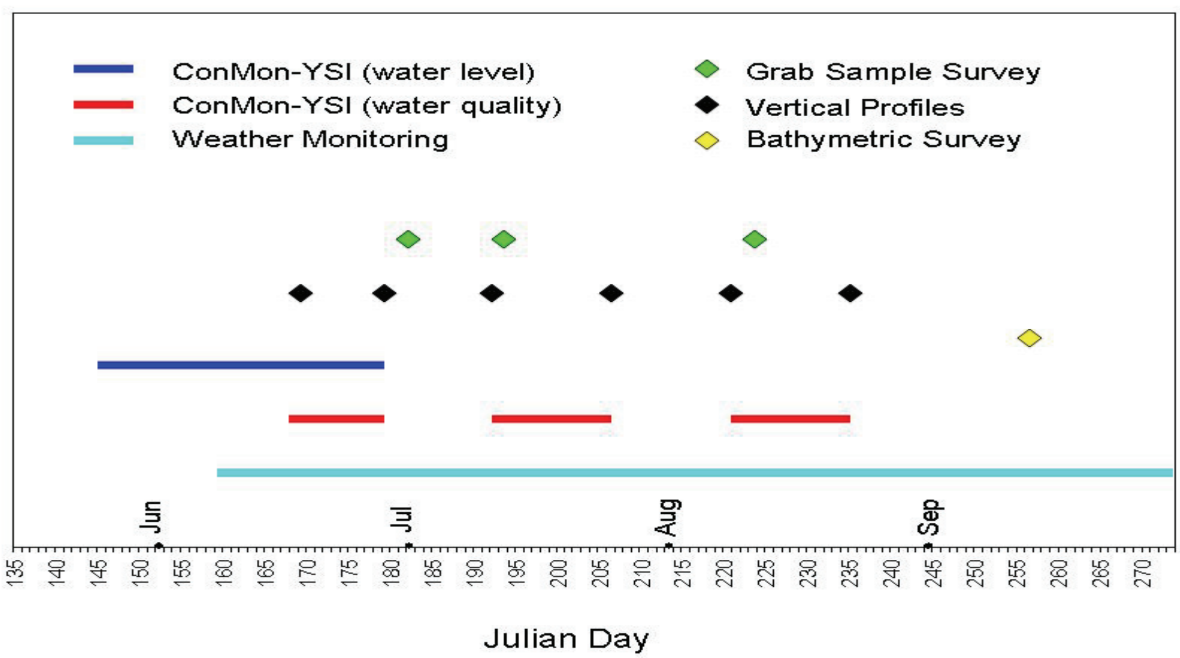


Figure II.1. Timeline for field data collection efforts in the Rudee Inlet system during 2010.

Within the Rudee Inlet system, VA-DEQ maintains multiple long-term water quality monitoring stations for physical, chemical, nutrient and microbial parameters. VA-DEQ monitoring station identification codes are DEQ 7-LAI000.04, DEQ 7-LAE000.20, DEQ 7-LAI000.18 and DEQ 7-LAI000.56, DEQ 7-OWL000.01, and DEQ 7-OWL000.77 (Figure II.4). Additionally, the Virginia Aquarium and Marine Science Center (VA Aquarium) maintains a single long-term monitoring station in Owl Creek near its water intake source.

Figure II.2. Sampling station locations for high-frequency, ConMon water level and water quality measurements conducted in 2010. Note: Stations 2 and 5 included both near surface and near bottom sondes.

Figure II.3. Sampling station locations for water quality grab sampling surveys conducted in 2010.

II-2 Bathymetry Study

A bathymetric survey of the Rudee Inlet system was conducted on September 14, 2010. Depth and position data was collected using a Garmin GPSMAP 540s equipped with a dual frequency transducer and GPS antenna set in a continuous sampling mode. The GPS system used Wide Area Augmentation System technology to achieve an error margin of ≤ 3 m. In order to account for water level variations due to tidal processes over the data collection period, two vented YSI 600LS data sondes were deployed at a fixed depth during the study. Depth was verified manually at the sonde locations throughout the study. In order to assure adequate coverage, cruise tracks were overlain by a model-generated bathymetry map and efforts were taken to sample multiple times in each grid cell. In a number of the shallow reaches, cruise tracks were somewhat dependent on channel and shoreline morphology (Figure II.5). Using field collected position and tide-corrected depth data, a bathymetric map was created using the Dr. Depth sea bottom mapping software package (Figure II.6).

Figure II.4. VaDEQ water quality sampling station locations.

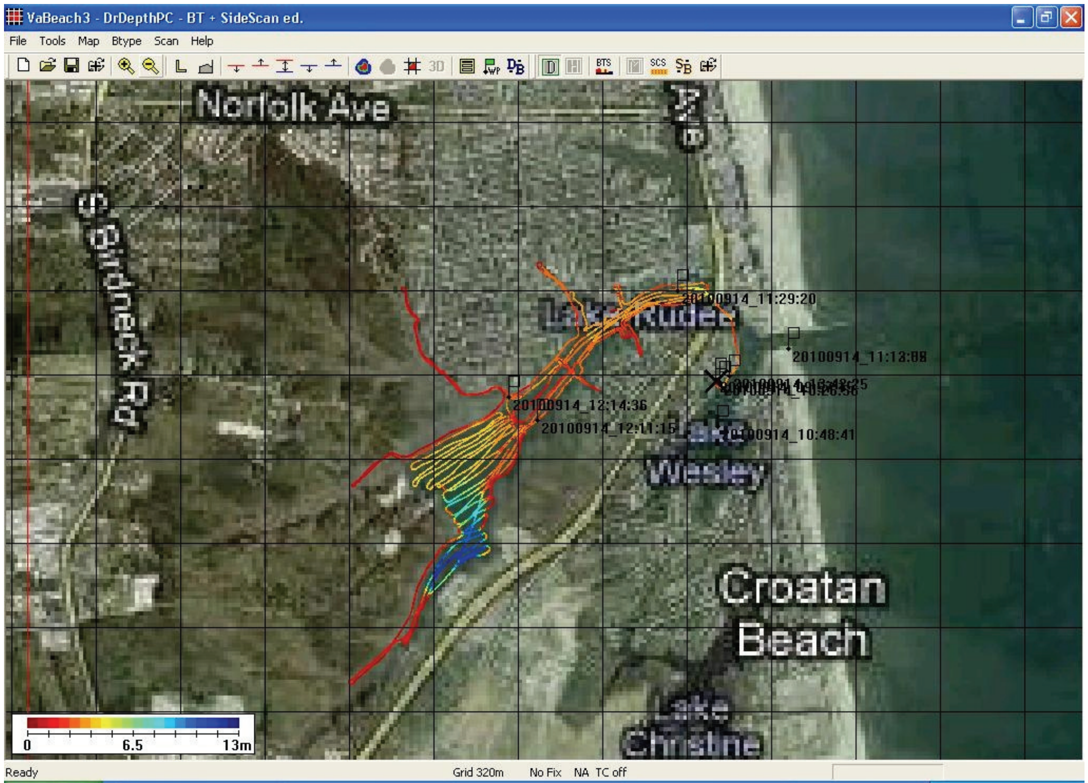


Figure II.5. Bathymetric survey cruise tracks in the Rudee Inlet system. Sample date: 9/14/2010.

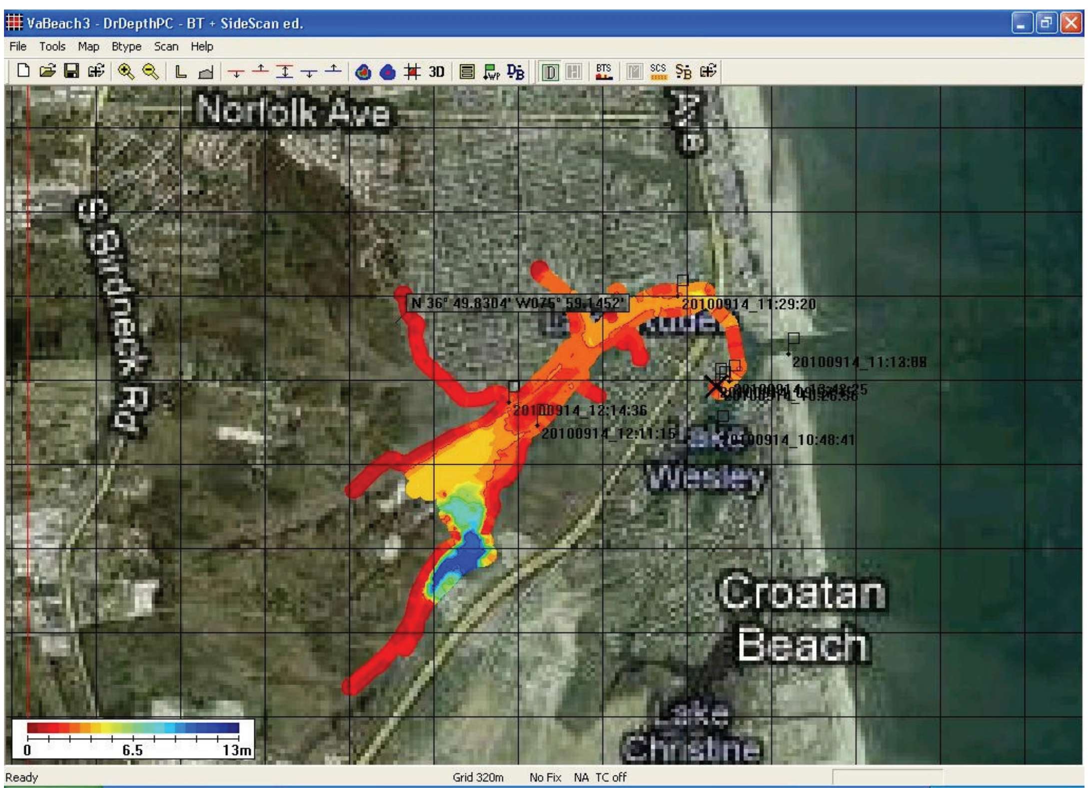


Figure II.6. Interpolated bathymetric map (relative to MSL) of the Rudee Inlet system. Sample date: 9/14/2010.

II-3 High Frequency Meteorological Observations

This study established a continuous monitoring weather station (Campbell Scientific Instruments UT-10) at the Virginia Aquarium pier in order to provide on-site meteorological information (Figure II.2). Meteorological data was collected from June 10 (15:30) to September 30, 2010. Collected information included: (1) temperature and relative humidity (Vaisala HM45C sensor), (2) wind speed and direction (R.M. Young Model 03001-5 Wind Sentry), (3) precipitation (Texas Electronics TR-525 rain gauge), (4) photosynthetic active radiation (PAR LiCor LI190SB sensor), and (5) atmospheric pressure (Vaisala PTB101B sensor). Collected data included 15-minute, 1-hour and 24-hour formats; parameters were sampled every 5 seconds to produce hourly and daily averages. Daily air temperature (average and maximum), wind speed (average and maximum), Total PAR and rainfall time series plots are shown in Figure II.7.

II-4 High Frequency Observations at Fixed (ConMon) Stations

This study established synoptic, continuous monitoring (ConMon) stations in the Rudee Inlet system to provide information on water level and water quality. Two ConMon water level stations, one near the marina at the mouth of Rudee Inlet (water level Station 1) and the other upstream at the Virginia Aquarium along Owl Creek (Figure II.2), were established in order to determine tide characteristics over a single, 30^{+} day period (May 26 – June 28, 2010). Six ConMon water quality stations were established within tidal portions of the Rudee Inlet system along a main channel transect to capture physical, chemical and biological parameter variations observed within the system (Figure II.2). Due the relative deep water column depths in portions of the Rudee Inlet system, two stations included additional YSIs to measure both near bottom and surface waters. ConMon water quality stations were deployed on three separate occasions beginning in June and ending in August 2010. Deployment periods lasted between 10-13 days depending on the level of sensor biofouling (see Table II.1 for greater detail).

ConMon water level station sondes were deployed off pier locations using a mooring anchor that fixed YSI 600LS data sondes in a horizontal position 0.1m off the bottom substrate. The YSI 600LS data sondes were outfitted with vented pressure sensors and a YSI 6560 Temperature/Specific Conductance sensor and sampled at 15-minute intervals. Water level sondes were cleaned mid-way through the deployment period in order to minimize any fouling issues.

ConMon water quality stations were equipped with YSI 6600 V2 data sondes with the Clean Sweep Extended Deployment System and sampled at 15-minute intervals. Measured parameters included water depth (unvented pressure sensor), specific conductance (YSI 6560 sensor), percent dissolved oxygen saturation (%DO_{sat}; YSI 6150 ROX and 6562 Rapid Pulse sensor), pH (YSI 6561 sensor), turbidity (YSI 6136 sensor) and chlorophyll fluorescence (YSI 6025 sensor); salinity and dissolved oxygen

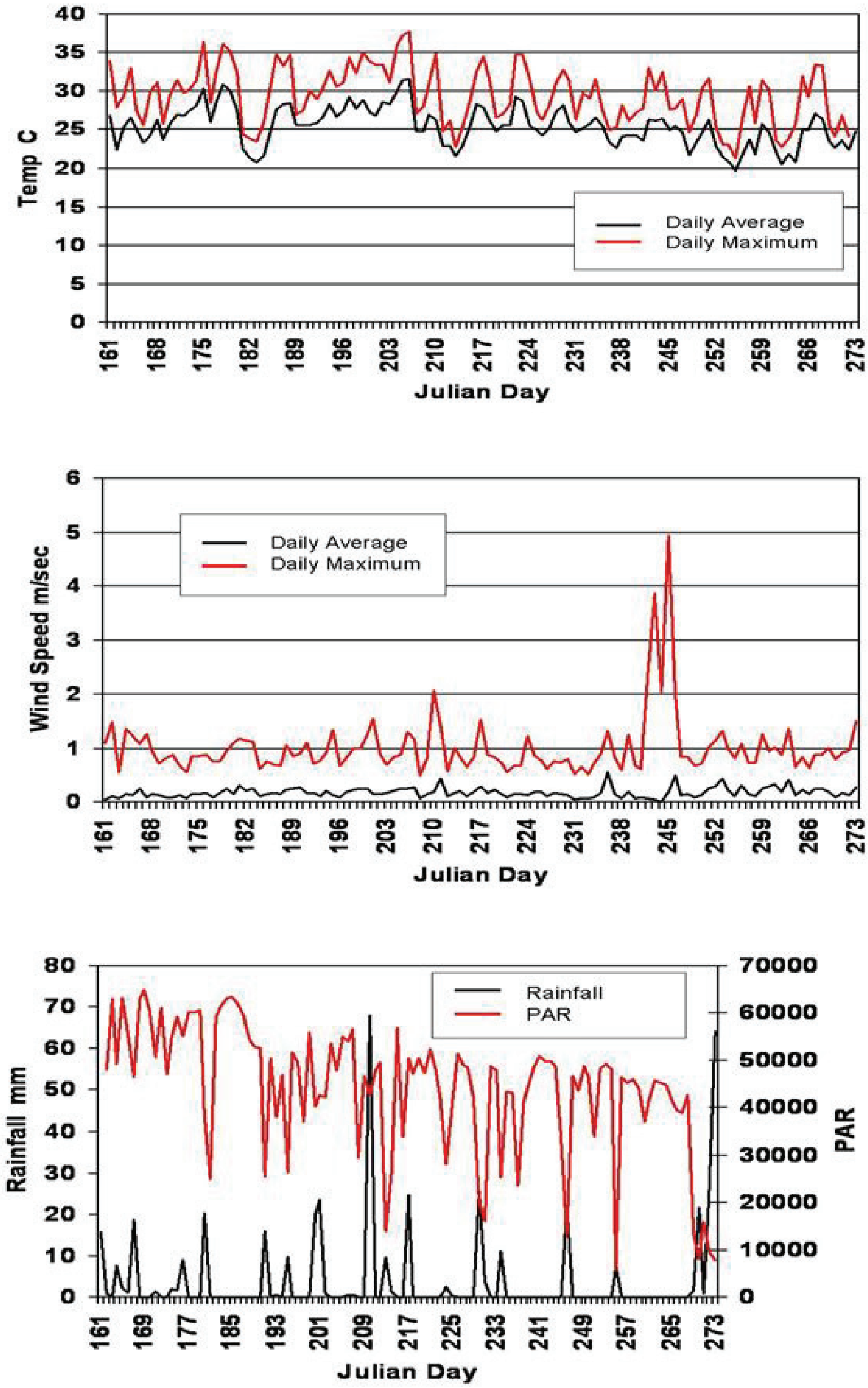


Figure II.7. Meteorological data derived from on-site established meteorologic station at the VA Aquarium (36.82211N, 75.98237W). Note: Data is based on Eastern Standard Time (EST).

Table II.1. ConMon water quality station deployment time periods (June-August 2010).

Location	Deployment No.	Start date (time-EST)	End date (time-EST)	No. of Obs.
Station 1	1	06/17/10 (1415)	06/28/10 (1300)	1052
Station 2 – surface	1	06/17/10 (1315)	06/28/10 (1315)	1057
Station 2 – bottom	1	06/17/10 (1315)	06/28/10 (1315)	1057
Station 3	1	06/17/10 (1230)	07/13/09 (1200)	1055
Station 4	1	06/17/10 (1100)	07/13/09 (1145)	1060
Station 5 – surface	1	06/17/10 (1145)	07/13/09 (1115)	1055
Station 5 – bottom	1	06/17/10 (1145)	07/13/09 (1115)	1055
Station 6	1	06/17/10 (1015)	07/13/09 (1045)	1059
Station 1	2	07/12/10 (1130)	07/26/10 (1015)	1340
Station 2 – surface	2	07/12/10 (1145)	07/26/10 (1030)	1340
Station 2 – bottom	2	07/12/10 (1145)	07/26/10 (1030)	1340
Station 3	2	07/12/10 (1145)	07/26/10 (1030)	1340
Station 4	2	07/12/10 (0945)	07/26/10 (1130)	1352
Station 5 – surface	2	07/12/10 (0915)	07/26/10 (1145)	1355
Station 5 – bottom	2	07/12/10 (0915)	07/26/10 (1145)	1355
Station 6	2	07/12/10 (0845)	07/26/10 (0930)	1348
Station 1	3	08/10/10 (1130)	08/23/10 (1130)	1249
Station 2 – surface	3	08/10/10 (1200)	08/23/10 (1200)	1249
Station 2 – bottom	3	08/10/10 (1200)	08/23/10 (1200)	1249
Station 3	3	08/10/10 (1230)	08/23/10 (1115)	1244
Station 4	3	08/10/10 (1100)	08/23/10 (1045)	1248
Station 5 – surface	3	08/10/10 (1045)	08/23/10 (1015)	1247
Station 5 – bottom	3	08/10/10 (1045)	08/23/10 (1015)	1247
Station 6	3	08/10/10 (1015)	08/23/10 (0945)	1247

Table II.2. Mean water column depth and distance of sensors below average water level at ConMon water quality stations (June-August 2010).

	ConMon Station ID							
	1	2 Surf	2 Deep	3	4	5 Surf	5 Deep	6
Distance of sensors below surface (m)	1.8	1.8	4.2	1.7	3.6	2.5	8.1	0.9
Water depth (m)	3.1	6.2	6.2	2.1	5.5	10.0	10.0	1.3

concentrations (DO_{conc}) were calculated parameters. Specific conductance sensors were located approximately 15 cm below the pressure sensor, whereas all other sensors were approximately 20 cm below the pressure sensor. All pre- and post-deployment calibrations and maintenance were completed in accordance with the YSI, Inc. operating manual methods (YSI 6-series Environmental Monitoring Systems Manual; YSI, Inc. Yellow Springs, OH).

All ConMon water quality stations were marked with a surface buoy and GPS located at the time of deployment and retrieval. A mooring anchor secured the instrument at various depths above the bottom substrate and a float immediately above the instrument kept the unit in a taut vertical position. Table II.2 provides approximate sampling depths of the ConMon water quality data sondes. Depths of instrument deployment were selected to sample approximately the upper and lower third of the deep (>6m) water stations (ConMon stations 2 and 5), approximately mid-depth of the medium (>3m and <6m) depth stations (ConMon stations 1 and 4), and to assure vertical positioning at the shallow water stations (ConMon stations 3 and 6).

II-4-1 30^+ Day Water Levels

Water level time series from the 30^+ day deployment (05/26 – 06/28/2010) are shown in Figure II.8 with extracted major tidal constituents presented in Table II.3. Tidal constituent information was generated through harmonic regression analysis using a least squares method. Results indicate that the tide exhibits standing wave characteristics as it propagates between the entrance to Rudee Inlet and Owl Creek. Tidal range was on the order of 1.0 meters and phase differences for most constituents were within several minutes (exceptions: S_2, K_1, and O_1).

II-4-2 Water Depth

Water depth time series plots for each ConMon water quality station are shown in Figures II.9, II.10, and II.11 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Water depths were calculated based on instrument height off the bottom and water column pressure above the sensor. All depth values were corrected for atmospheric pressure variations during the period of deployment. It should be noted that water level patterns at ConMon Station 6 did not remain taut during selected periods of low tide and that the sonde at Station 4 during deployment period 2 was moved (believed to be from vessel activity) to shallower water approximately 3 days after deployment. From inspection of data not impacted by non-taut mooring lines, the system exhibited standing wave characteristic and a tidal range of approximately 1.0 meters; results are consistent with the 30^+-day water level study. These water depth data, as well as water level data from the 30^+-day study were used to support high-frequency model predictions of surface elevations presented in Chapter IV, Section IV-3 of this report.

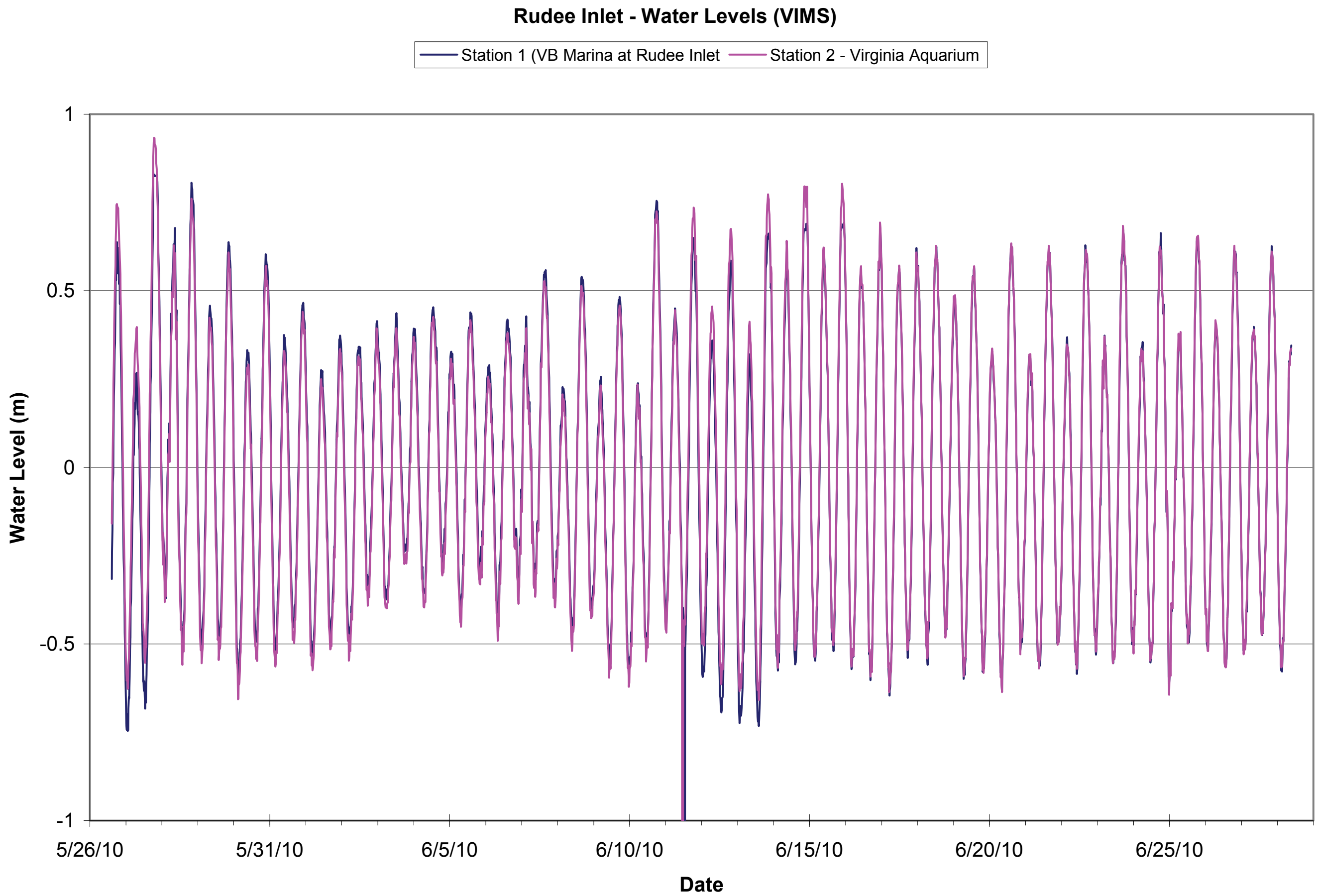


Figure II.8. Virginia Beach Marina at Rudee Inlet (Station 1, downstream) and the Virginia Aquarium (Station 2, upstream) 30^+ day water levels (relative to respective mean tide levels).

Table II.3. Amplitudes and phases of major tidal constituents extracted from 30^+ day records of water level at RI (marina site) and OC (Virginia Aquarium site). Period of record: 5/26/2010-6/28/2010.

	Station (Location)			
Constituent	**Station 1 (VB Marina, Rudee Inlet, downstream)**		**Station 2 (Virginia Aquarium, Owl Creek, upstream)**	
	Amplitude (cm)	**Phase (minutes)**	**Amplitude (cm)**	**Phase (minutes)**
M_2	48.4	165.0	48.3	169.2
S_2	5.4	-299.6	5.5	-336.1
N_2	10.8	273.1	10.8	276.4
K_1	10.2	-150.6	10.5	-239.5
M_4	0.7	97.2	0.5	95.9
O_1	6.3	580.2	6.3	518.5
M_6	0.8	-70.5	0.8	-82.5

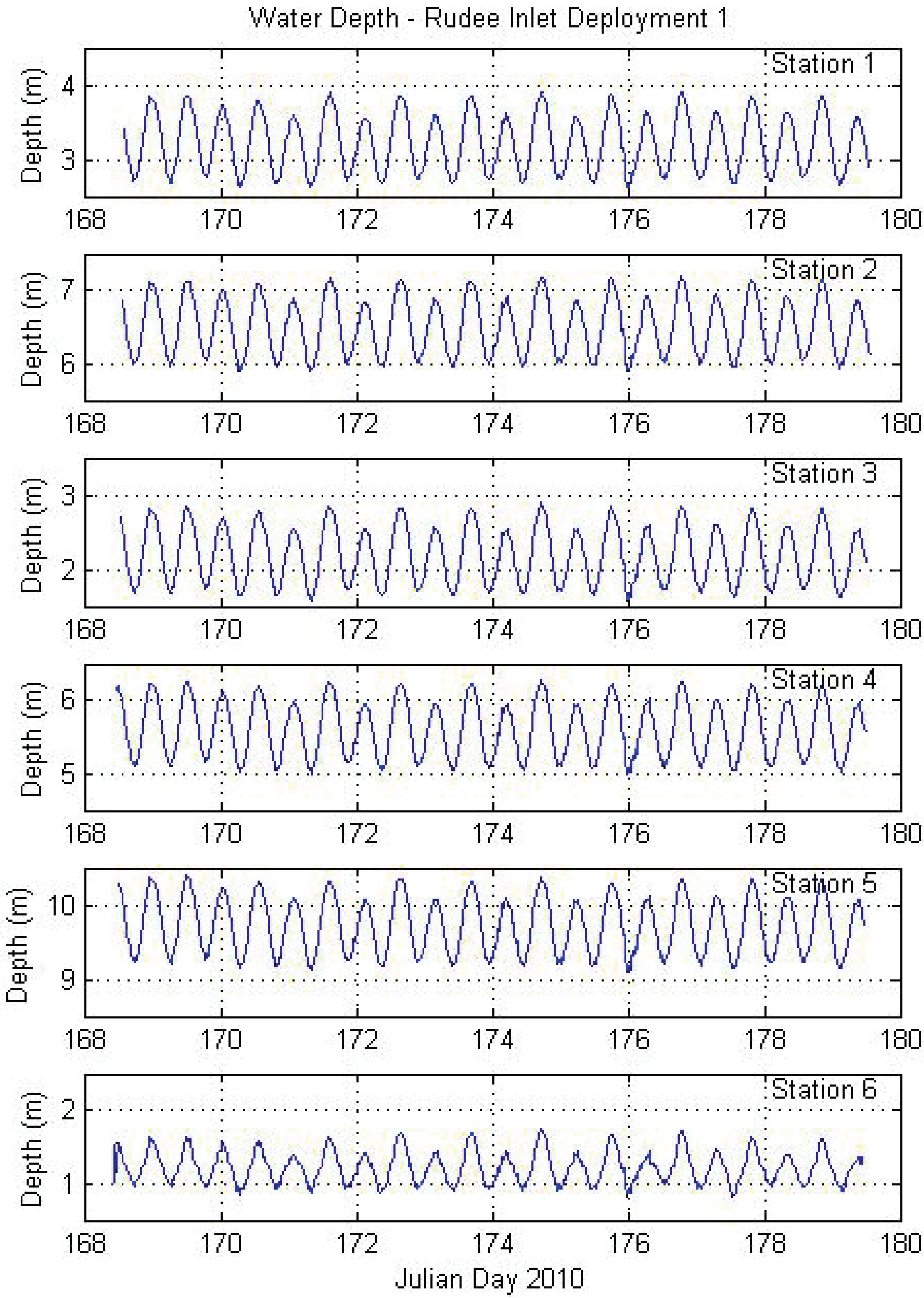


Figure II.9. ConMon water quality station water depth – Rudee Inlet system Deployment 1 (June 17 – 28, 2010).

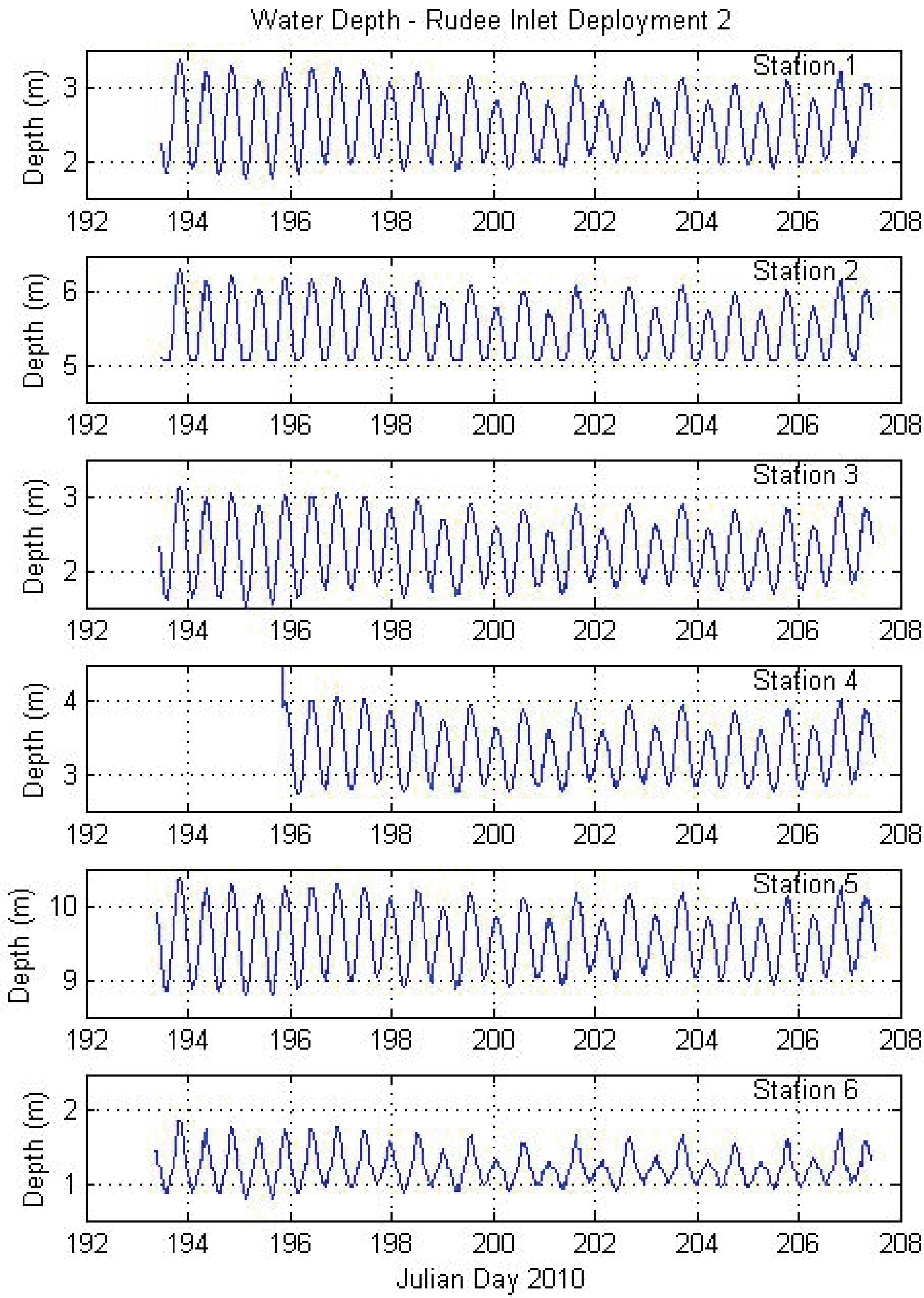


Figure II.10. ConMon water quality station water depth – Rudee Inlet system Deployment 2 (July 12 – 26, 2010).

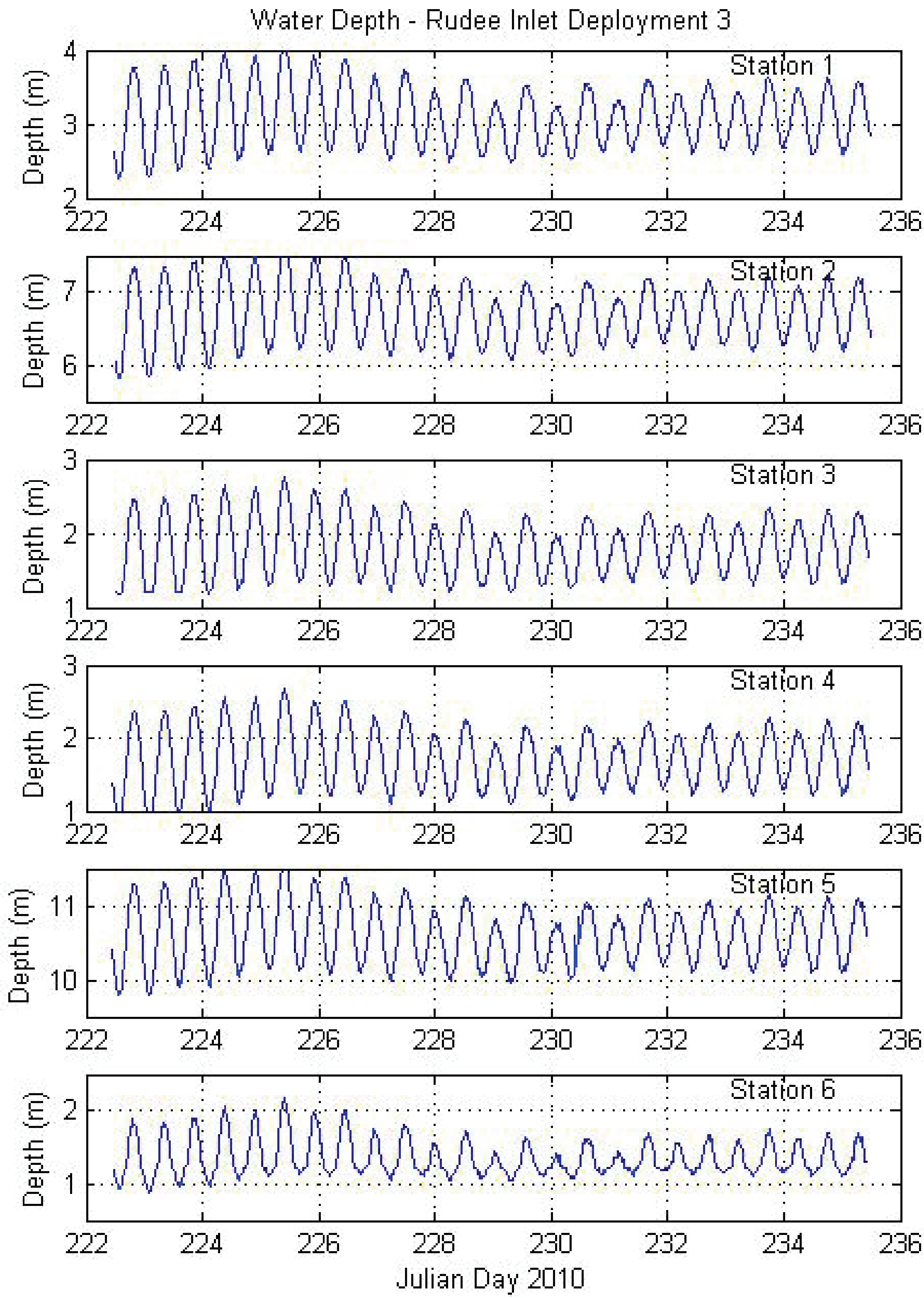


Figure II.11. ConMon water quality station water depth – Rudee Inlet system Deployment 3 (August 10 – 23, 2010).

II-4-3 Water Temperature

Water temperature time series plots for each ConMon water quality station are shown in Figures II.12, II.13, and II.14 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010, and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.4. During periods of instrument deployment, near surface water temperatures ranged between 18.5 and 33.4 ^{o}C. Mean surface water temperatures over a deployment period were relatively similar between stations; average temperature ranges for deployments 1 through 3 were on the order of 22-29, 24-27 and 24-27 ^{o}C, respectively. On average, near bottom water temperatures at ConMon water quality stations 2 and 5 were 4-6 ^{o}C and 6-12 ^{o}C cooler, respectively, than near surface waters over the three deployment periods. Diel temperature variations, up to 5°C, were more pronounced at the shallow water stations (ConMon water quality stations 3 and 6). On some occasions (see deployment 1, JD 178 for example), the introduction of denser water (higher salinity, lower temperature) following storm activity resulted in lowered temperatures in the main body of the Rudee Inlet system.

II-4-4 Salinity

Salinity time series plots for each ConMon water quality station are shown in Figures II.15, II.16, and II.17 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.5. Sampled portions of Rudee Inlet sytem were representative of upper polyhaline (18-30 psu) salinity regime conditions. Minimal differences in mean salinity was observed between stations over the deployment periods; deployment mean salinity values varied between 24.7 to 28.4 psu over the three deployment stations and across the six ConMon stations. The greatest variation in salinity was observed at ConMon water quality station 6 (range over entire study: 5.8-27.9 psu) located in the upper reaches of Owl Creek where runoff impacts would be most noticeable. This station was also the only station to show a somewhat consistent (2 of the 3 deployment periods) semi-diurnal pattern with salinity. Storm activity influenced near surface water salinities in two ways. While significant rainfall and associated runoff events served to reduce salinities, the intrusion of denser (higher salinity, lower temperature) water was also observed on a number of occasions (see deployment 1, JD 178 and deployment 3, JD 235 for examples). Where measured (ConMon water quality stations 2 and 5), salinity bottom waters typically averaged 30 psu and showed minimal variation throughout the deployment period.

II-4-5 Dissolved Oxygen

Dissolved oxygen concentration (DO_{conc}) time series plots for each ConMon water quality station are shown in Figures II.18, II.19, and II.20 for deployment periods 6/17-

6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.6. Figures II.21, II.22, and II.23 show times series of dissolved oxygen as a percent saturation ($DO_{\%sat}$) accounting for *in situ* salinity and temperature with summary statistics provided in Table II.7. Near surface water dissolved oxygen patterns within the Rudee Inlet system were dynamic with concentrations ranging from near anoxic to supersaturated conditions; minimum and maximum DO_{conc} observed during the study were 0.2 and 19.2 $mg{\cdot}L^{-1}$ with corresponding $\%DO_{sat}$ of 1% and 288.3%. ConMon water quality station 6, the shallowest station located in the upper reaches of Owl Creek, exhibited the strongest semi-diurnal and diurnal signals. Semi-diurnal (12.4 hr) influences are principally driven by tidal advection whereas water temperature variation and biological activities dominate diurnal (24 hr) signals. Hypoxic and anoxic conditions were observed within the Rudee Inlet system. Percent of time that ConMon water quality stations exhibited hypoxic (hypoxia criteria: $DO_{\%sat} > 0$ to $< 30\%$ and $DO_{conc} \leq 2.0$ $mg{\cdot}L^{-1}$) and anoxic conditions during summer deployment periods are provided in Table II.8. Bottom waters measured at selected stations (ConMon water quality stations 2 and 5) exhibited severe DO_{conc} conditions throughout most of the deployment periods; exception occurred at ConMon station 2 during the first deployment period. Low DO_{conc} conditions, limited to hypoxia, were also noted in the ConMon water quality stations 4, 5 and 6 located in the upper regions of the Rudee Inlet system.

II-4-6 Chlorophyll

Chlorophyll concentration (chl_{fl}; based on fluorescence) time series plots for each ConMon water quality station are shown in Figures II.24, II.25, and II.26 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.9.

II-4-7 Turbidity

Turbidity level time series plots for each ConMon water quality station are shown in Figures II.27, II.28, and II.29 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.10. Turbidity levels were generally low (mean deployment average < 10 NTUs) in the more open, moderate to deep water stations (ConMon water quality stations 1,2, 4 and 5). Mean deployment NTU values and variability increased (mean deployment average > 10 NTUs) at the more shallow water stations (ConMon water quality stations 3 and 6).

II-4-8 pH

pH level time series plots for each ConMon water quality station are shown in Figures II.30, II.31, and II.32 for deployment periods 6/17-6/28/2010, 7/12-7/26/2010 and 8/10-8/23/2010, respectively. Summary statistics for individual stations by deployment period are provided in Table II.11.

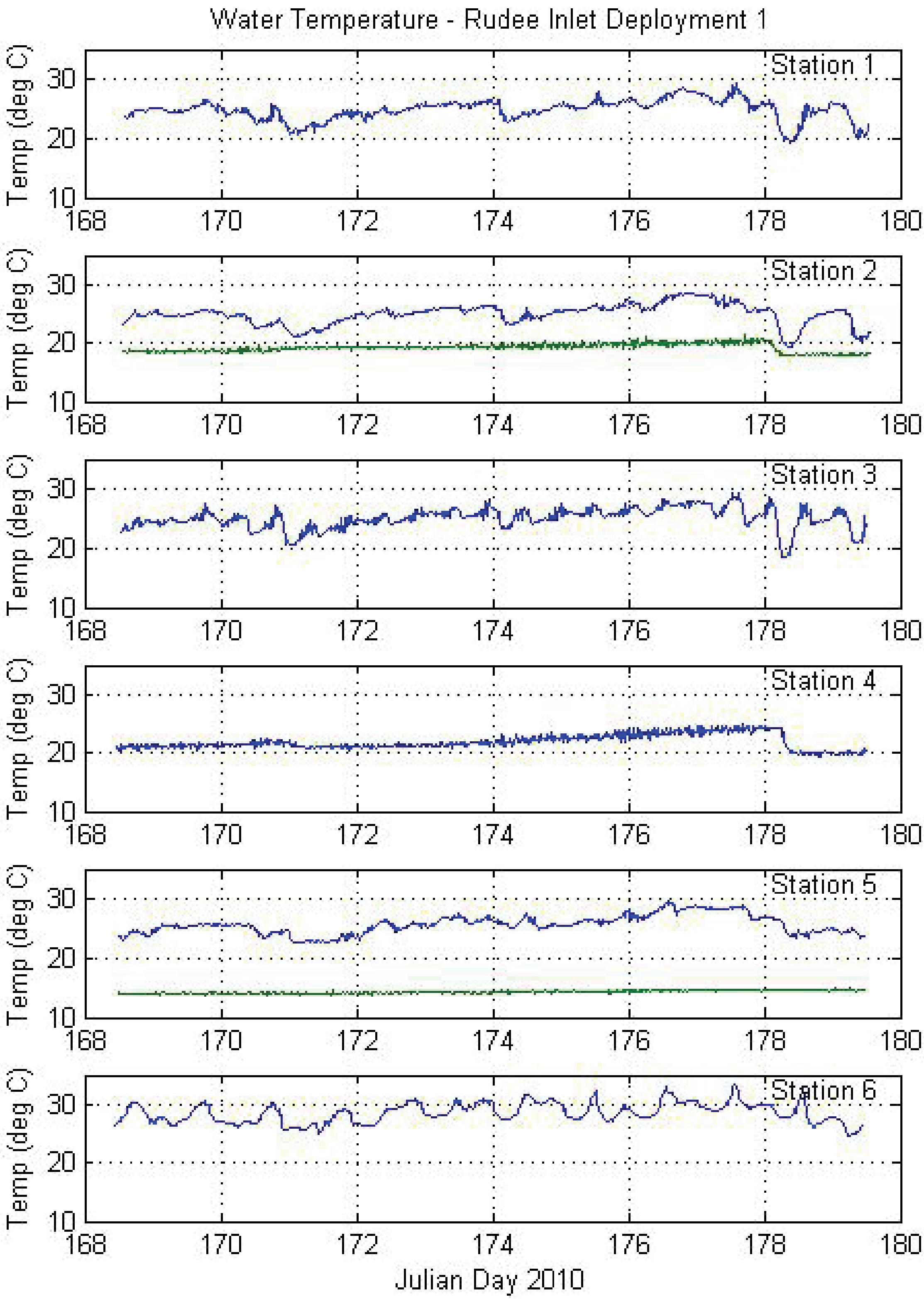


Figure II.12. ConMon water quality station temperature – Rudee Inlet system Deployment 1 (June 17 - 28, 2010). Green lines represent near bottom waters.

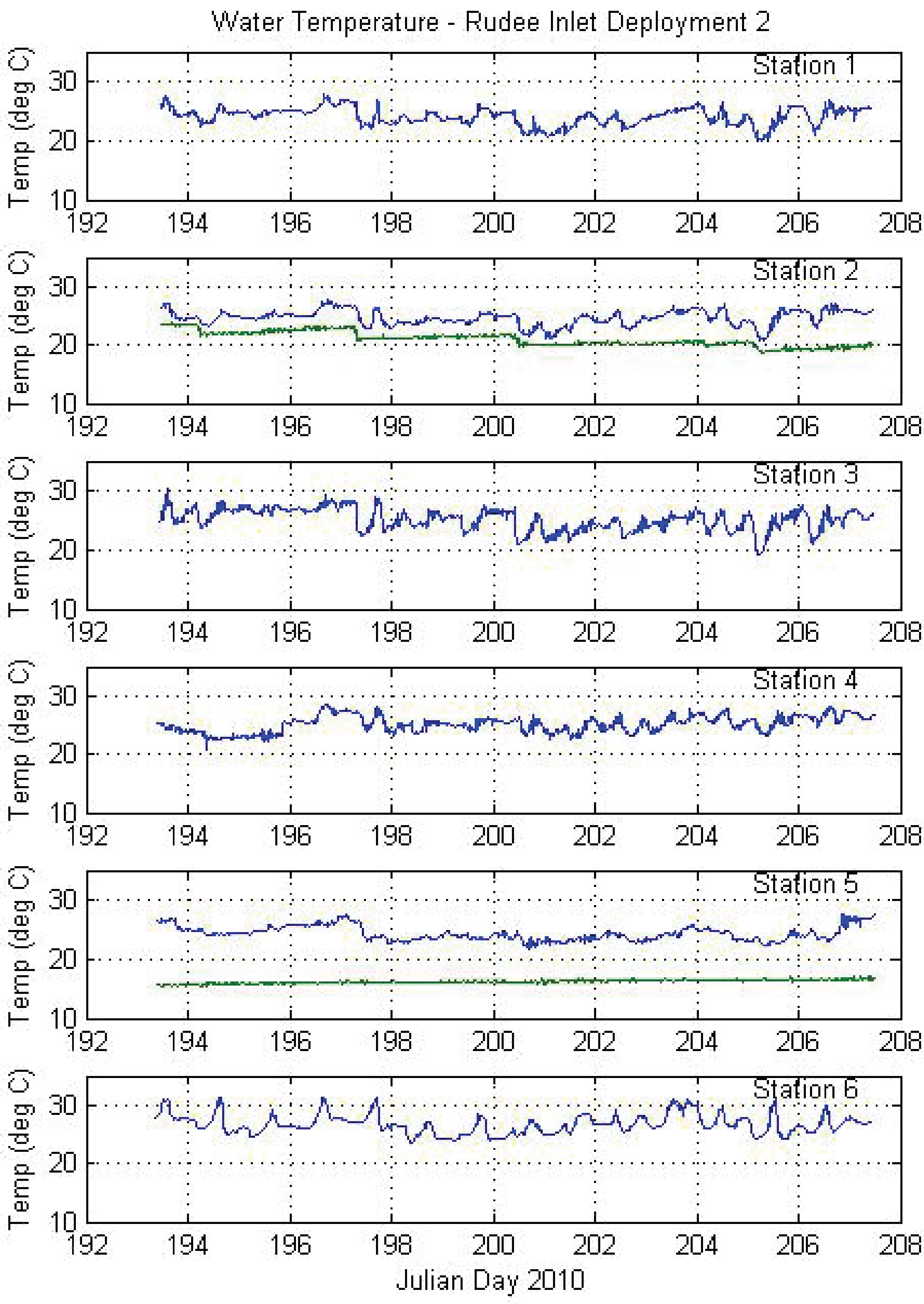


Figure II.13. ConMon water quality station temperature – Rudee Inlet system Deployment 2 (July 12 -26, 2010). Green lines represent near bottom waters.

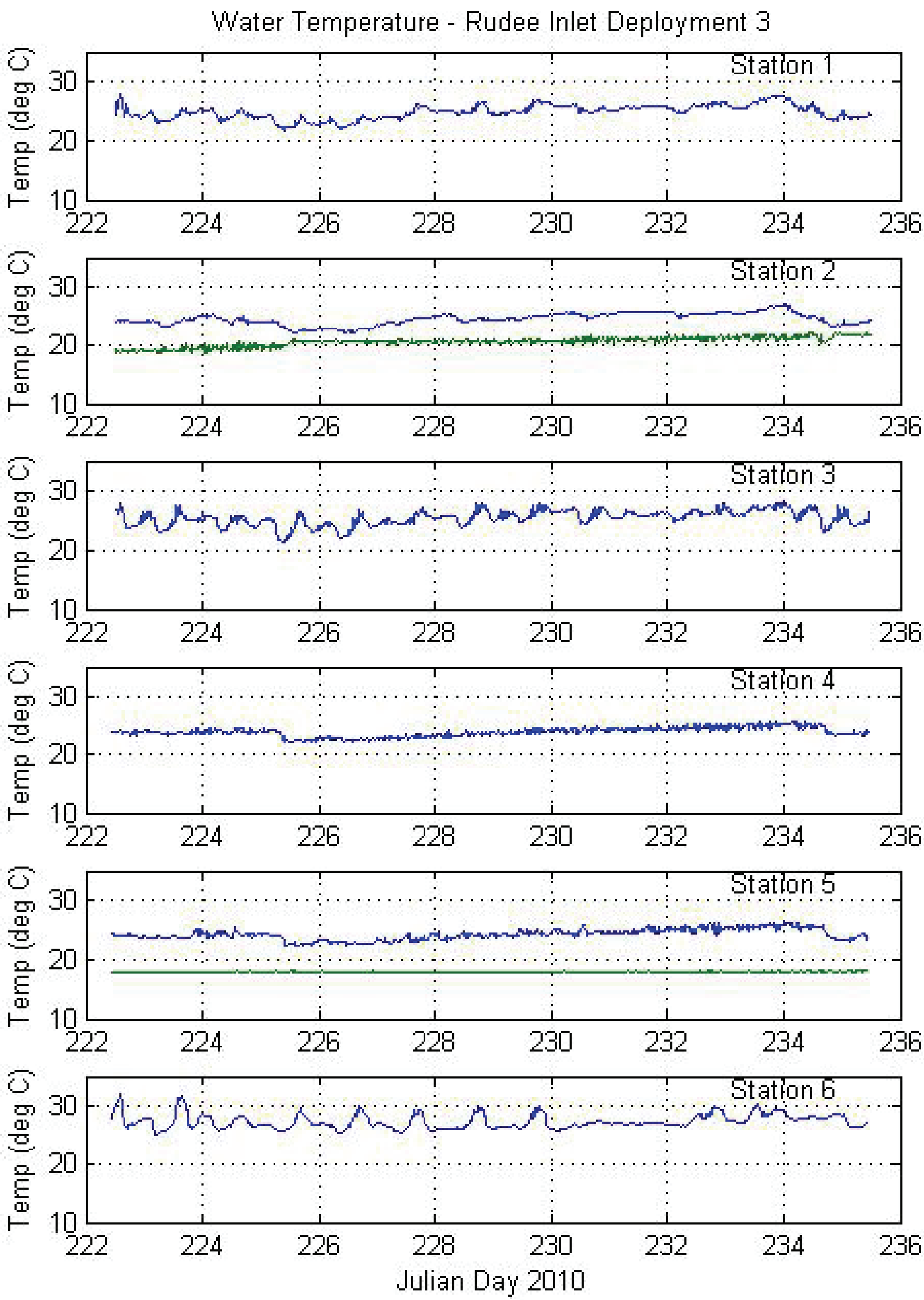


Figure II.14. ConMon water quality station temperature – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.4. Summary statistics for water temperature within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/29/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 24.8 Min: 19.2 Max: 29.2 Std Dev: 1.7 N: 1052	Avg: 24.1 Min: 19.9 Max: 28.0 Std Dev: 1.5 N: 1340	Avg: 24.9 Min: 21.8 Max: 27.8 Std Dev: 1.2 N: 1249
2 - surface	Avg: 24.9 Min: 19.3 Max: 28.5 Std Dev: 1.8 N: 1057	Avg: 24.7 Min: 20.6 Max: 27.7 Std Dev: 1.3 N: 1340	Avg: 24.5 Min: 22.1 Max: 27.0 Std Dev: 1.0 N: 1249
2 – bottom	Avg: 19.2 Min: 17.9 Max: 21.3 Std Dev: 0.7 N: 1057	Avg: 21.0 Min: 18.6 Max: 24.1 Std Dev: 1.2 N: 1340	Avg: 20.6 Min: 18.6 Max: 22.2 Std Dev: 0.8 N: 1249
3	Avg: 25.1 Min: 18.5 Max: 29.3 Std Dev: 1.8 N: 1055	Avg: 25.1 Min: 19.0 Max: 30.5 Std Dev: 1.8 N: 1346	Avg: 25.4 Min: 21.3 Max: 28.0 Std Dev: 1.3 N: 1244
4	Avg: 21.9 Min: 19.2 Max: 24.9 Std Dev: 1.3 N: 1060	Avg: 25.2 Min: 20.6 Max: 28.6 Std Dev: 1.4 N: 1352	Avg: 23.9 Min: 22.0 Max: 25.8 Std Dev: 0.8 N: 1248
5 – surface	Avg: 25.7 Min: 22.5 Max: 29.8 Std Dev: 1.6 N: 1055	Avg: 24.3 Min: 21.7 Max: 27.6 Std Dev: 1.2 N: 1355	Avg: 24.3 Min: 22.2 Max: 26.2 Std Dev: 0.9 N: 1247
5 – bottom	Avg: 14.3 Min: 13.6 Max: 14.9 Std Dev: 0.3 N: 1055	Avg: 16.2 Min: 15.3 Max: 17.1 Std Dev: 0.3 N: 1354	Avg: 17.9 Min: 17.7 Max: 18.1 Std Dev: 0.1 N: 1247
6	Avg: 28.5 Min: 24.7 Max: 33.4 Std Dev: 1.7 N: 1059	Avg: 26.7 Min: 23.6 Max: 31.5 Std Dev: 1.7 N: 1348	Avg: 27.3 Min: 24.8 Max: 31.9 Std Dev: 1.2 N: 1247

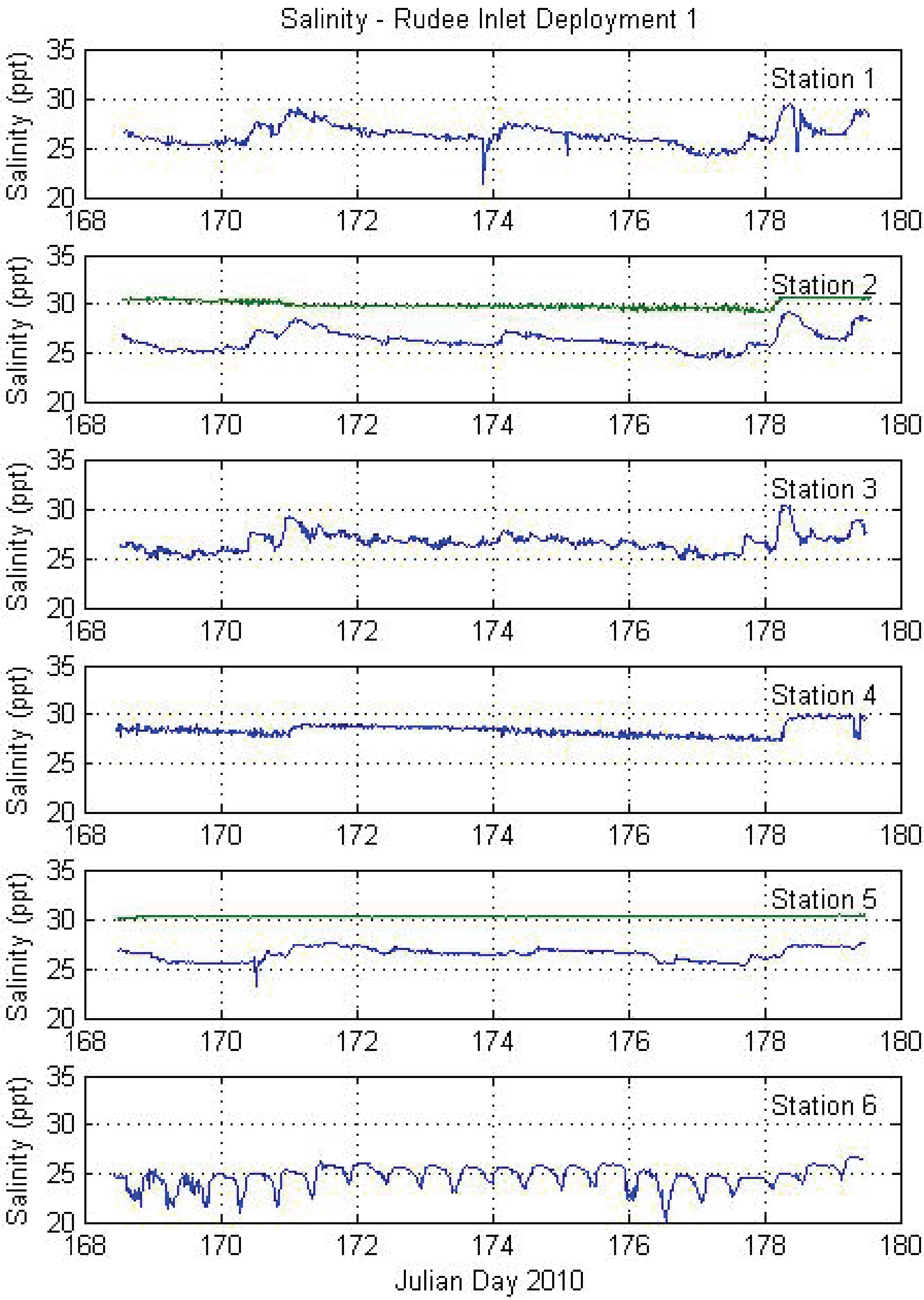


Figure II.15. ConMon water quality station salinity – Rudee Inlet system Deployment 1 (June 17 - 28, 2010). Green lines represent near bottom waters.

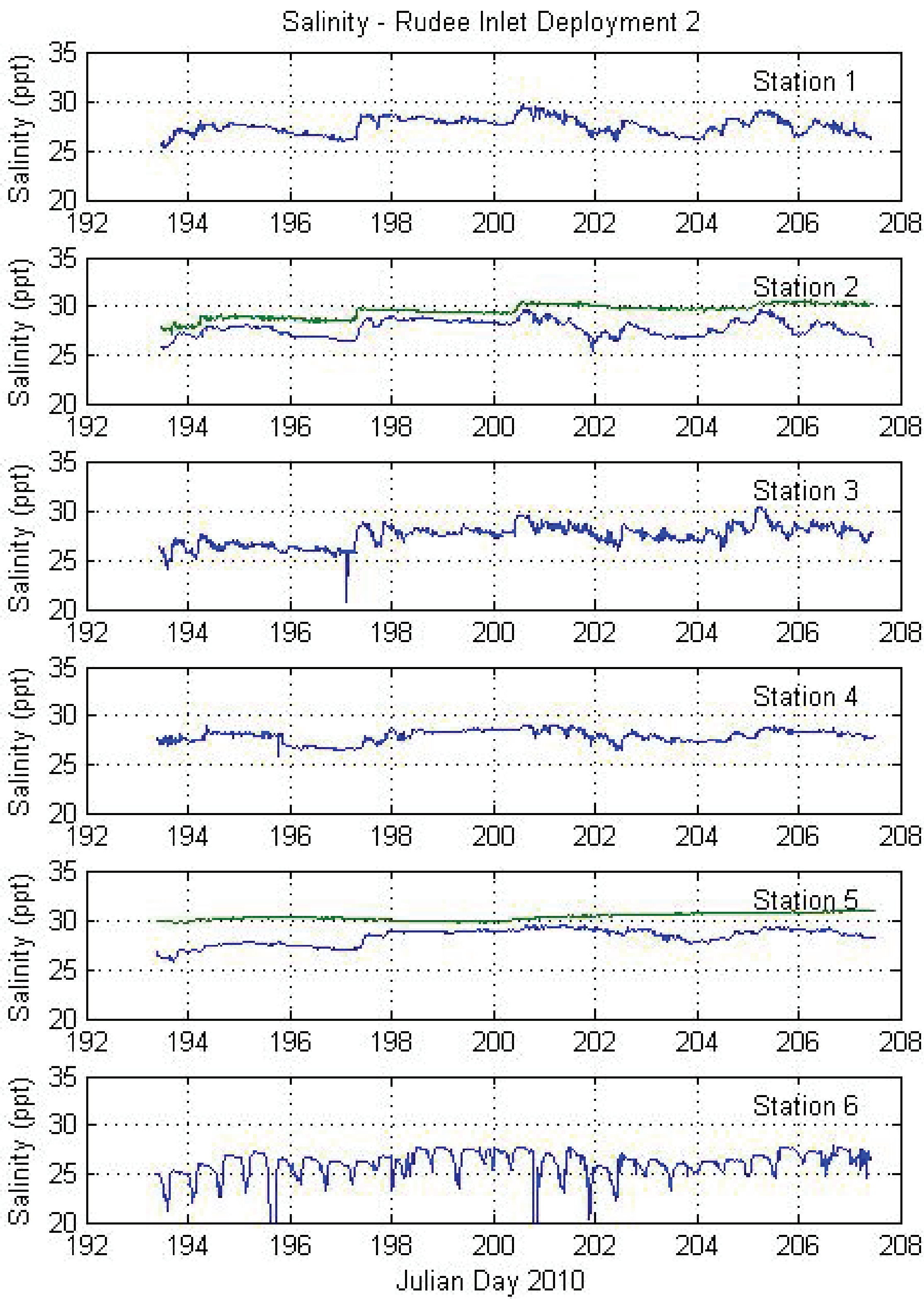


Figure II.16. ConMon water quality station salinity – Rudee Inlet system Deployment 2 (July 12 - 26, 2010). Green lines represent near bottom waters.

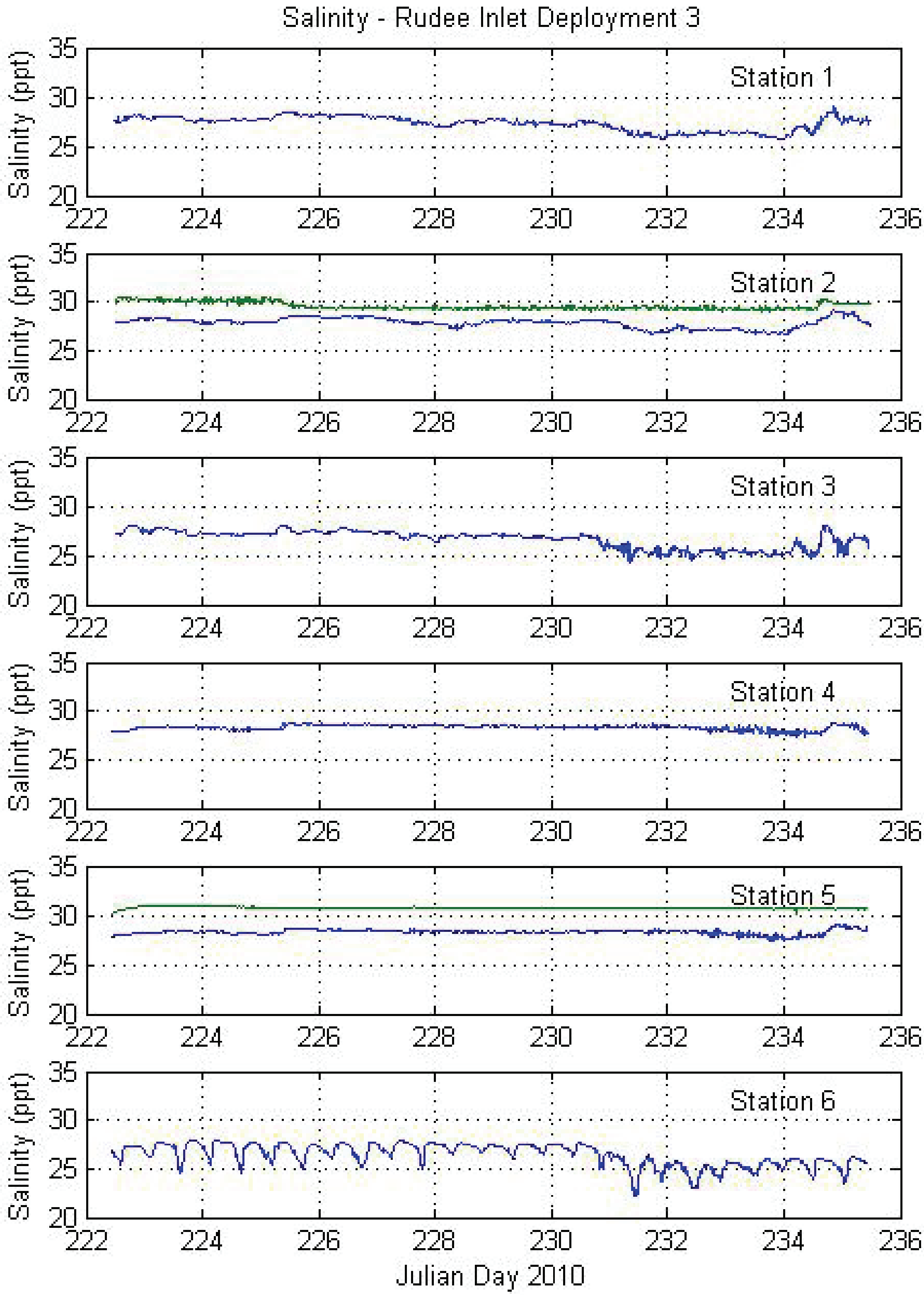


Figure II.17. ConMon water quality station salinity – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.5. Summary statistics for salinity within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 26.34 Min: 21.26 Max: 29.46 Std Dev: 1.06 N: 1052	Avg: 27.48 Min: 25.22 Max: 29.60 Std Dev: 0.84 N: 1340	Avg: 27.31 Min: 25.65 Max: 28.96 Std Dev: 0.73 N: 1249
2 – surface	Avg: 26.29 Min: 24.39 Max: 29.29 Std Dev: 0.98 N: 1057	Avg: 27.76 Min: 2 5.48 Max: 29.58 Std Dev: 0.83 N: 1340	Avg: 27.85 Min: 26.59 Max: 29.18 Std Dev: 0.54 N: 1249
2 – bottom	Avg: 29.96 Min: 28.90 Max: 30.69 Std Dev: 0.40 N: 1057	Avg: 29.52 Min: 27.15 Max: 30.57 Std Dev: 0.69 N: 1340	Avg: 29.59 Min: 29.02 Max: 30.58 Std Dev: 0.37 N: 1249
3	Avg: 26.63 Min: 24.85 Max: 30.35 Std Dev: 0.95 N: 1055	Avg: 27.46 Min: 20.64 Max: 30.31 Std Dev: 1.05 N: 1346	Avg: 26.63 Min: 24.26 Max: 28.08 Std Dev: 0.89 N: 1244
4	Avg: 28.39 Min: 27.27 Max: 29.94 Std Dev: 0.60 N: 1060	Avg: 27.91 Min: 25.86 Max: 29.10 Std Dev: 0.64 N: 1352	Avg: 28.32 Min: 27.33 Max: 28.79 Std Dev: 0.26 N: 1248
5 – surface	Avg: 26.48 Min: 23.23 Max: 27.72 Std Dev: 0.63 N: 1055	Avg: 28.32 Min: 25.80 Max: 29.51 Std Dev: 0.82 N: 1355	Avg: 28.31 Min: 27.32 Max: 29.04 Std Dev: 0.24 N: 1247
5 – bottom	Avg: 30.30 Min: 29.98 Max: 30.49 Std Dev: 0.06 N: 1055	Avg: 30.32 Min: 29.75 Max: 31.05 Std Dev: 0.34 N: 1354	Avg: 30.74 Min: 30.04 Max: 31.05 Std Dev: 0.11 N: 1246
6	Avg: 24.70 Min: 20.08 Max: 26.67 Std Dev: 1.08 N: 1059	Avg: 25.99 Min: 5.83 Max: 27.84 Std Dev: 1.76 N: 1348	Avg: 26.43 Min: 22.12 Max: 27.88 Std Dev: 1.14 N: 1247

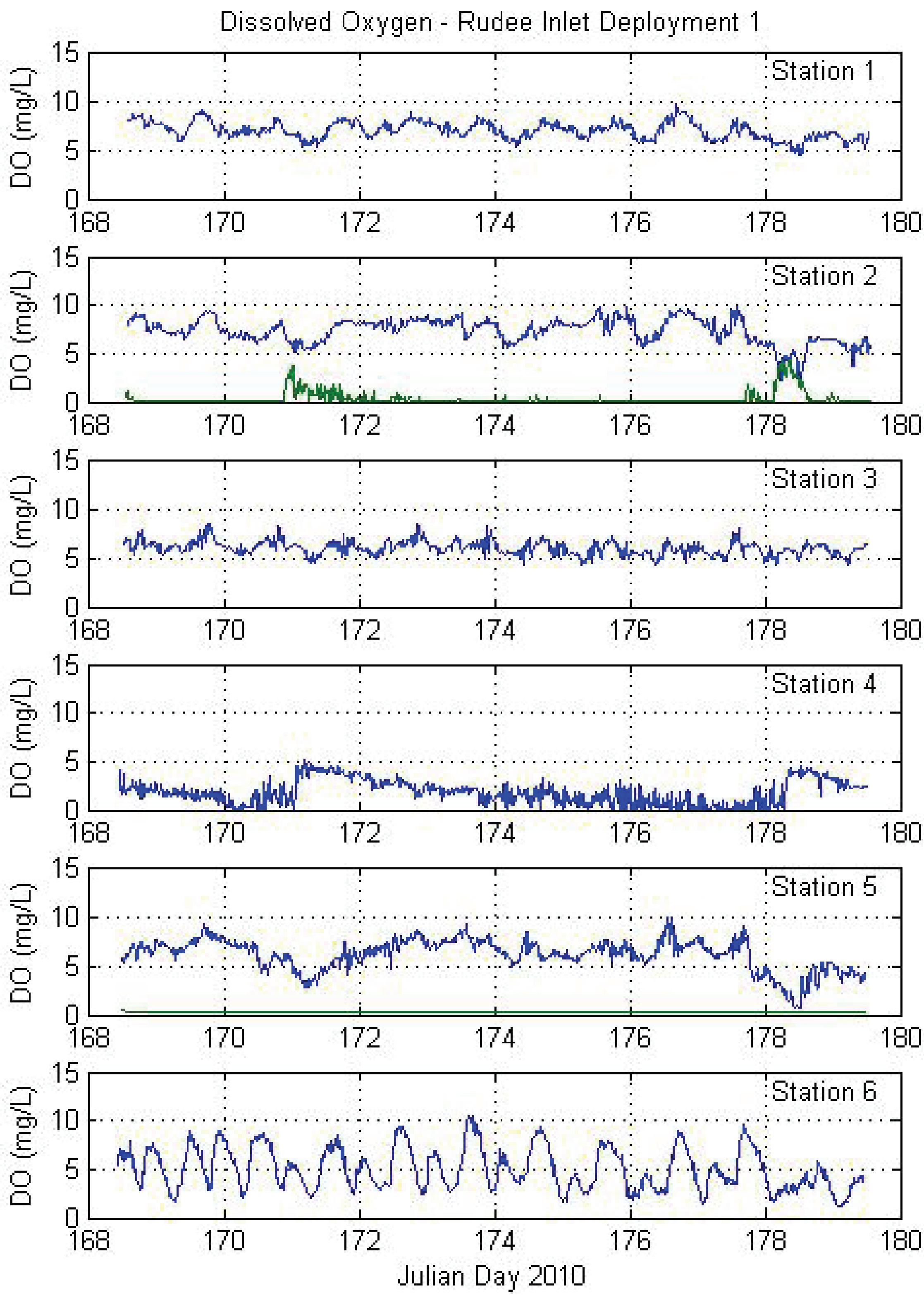


Figure II.18. ConMon water quality station dissolved oxygen concentration – Rudee Inlet system Deployment 1 (June 17 - 28, 2010). Green lines represent near bottom waters.

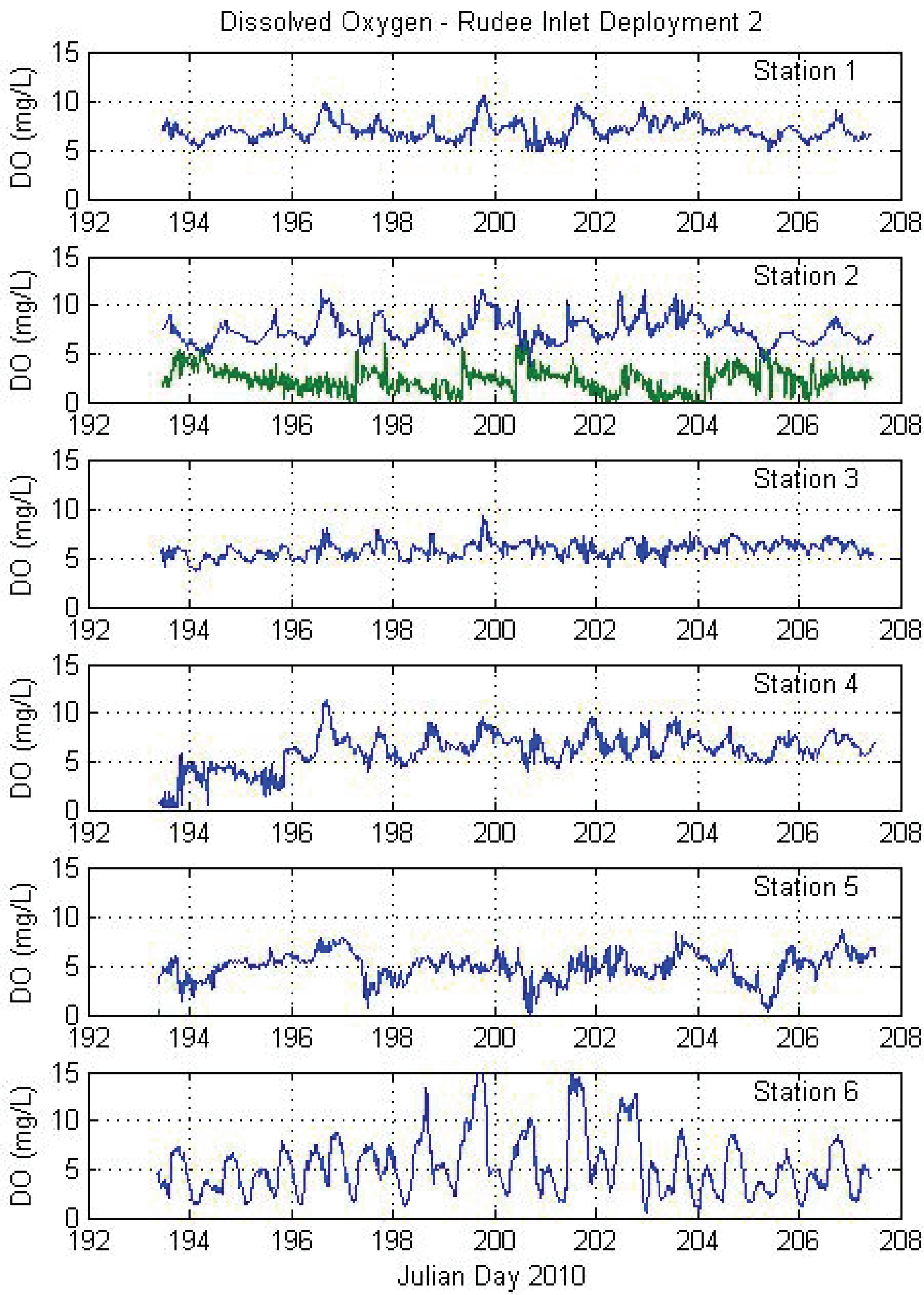


Figure II.19. ConMon water quality station dissolved oxygen concentration – Rudee Inlet system Deployment 2 (July 12 - 26, 2010). Green lines represent near bottom waters.

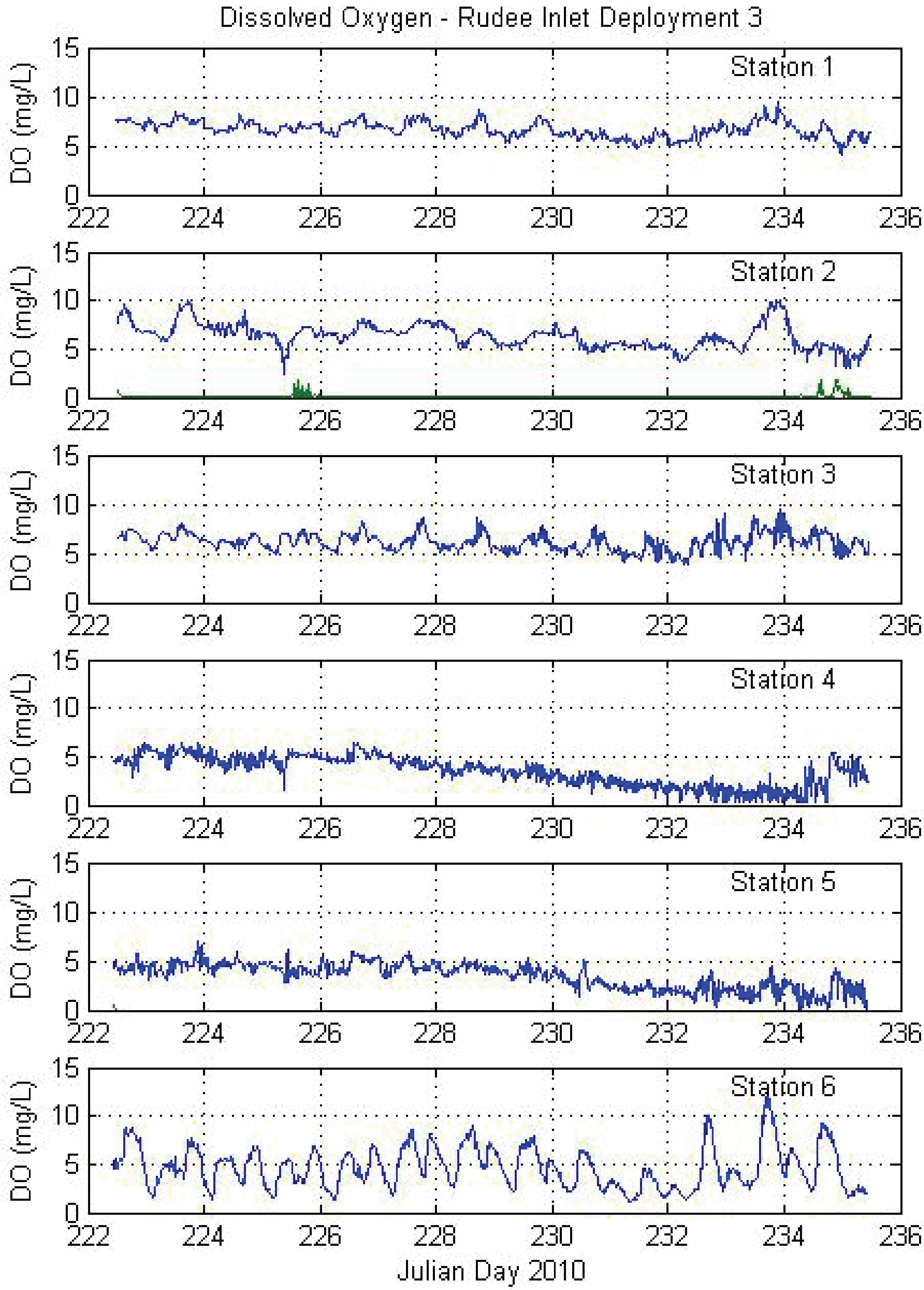


Figure II.20. ConMon water quality station dissolved oxygen concentration – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.6. Summary statistics for DO_{conc} ($mg \cdot L^{-1}$) within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 7.0 Min: 4.5 Max: 9.8 Std Dev: 0.9 N: 1052	Avg: 7.0 Min: 4.8 Max: 10.6 Std Dev: 0.9 N: 1340	Avg: 6.7 Min: 4.1 Max: 9.6 Std Dev: 0.8 N: 1249
2 - surface	Avg: 7.3 Min: 2.1 Max: 9.9 Std Dev: 1.3 N: 1057	Avg: 7.4 Min: 3.2 Max: 11.5 Std Dev: 1.3 N: 1340	Avg: 6.4 Min: 2.4 Max: 10.1 Std Dev: 1.3 N: 1249
2 – bottom	Avg: 0.3 Min: 0.1 Max: 4.3 Std Dev: 0.7 N: 1057	Avg: 2.3 Min: 0.1 Max: 6.4 Std Dev: 1.2 N: 1340	Avg: 0.1 Min: 0.1 Max: 1.9 Std Dev: 0.2 N: 1248
3	Avg: 6.0 Min: 4.2 Max: 8.5 Std Dev: 0.7 N: 1055	Avg: 5.9 Min: 3.7 Max: 9.2 Std Dev: 0.8 N: 1346	Avg: 6.2 Min: 3.8 Max: 9.5 Std Dev: 0.9 N: 1244
4	Avg: 1.8 Min: 0.1 Max: 5.1 Std Dev: 1.2 N: 1060	Avg: 6.1 Min: 0.3 Max: 11.2 Std Dev: 1.8 N: 1352	Avg: 3.5 Min: 0.3 Max: 6.5 Std Dev: 1.5 N: 1248
5 - surface	Avg: 6.1 Min: 0.7 Max: 10.0 Std Dev: 1.6 N: 1055	Avg: 4.9 Min: 0.2 Max: 8.6 Std Dev: 1.4 N: 1355	Avg: 3.5 Min: 0.2 Max: 6.9 Std Dev: 1.3 N: 1247
5 – bottom	Avg: 0.3 Min: 0.3 Max: 0.6 Std Dev: 0.0 N: 1054	Avg: 0.0 Min: 0.0 Max: 0.0 Std Dev: 0.0 N: 1352	Avg: 0.0 Min: 0.0 Max: 0.0 Std Dev: 0.0 N: 1244
6	Avg: 5.1 Min: 0.9 Max: 10.5 Std Dev: 2.1 N: 1059	Avg: 5.3 Min: 0.6 Max: 19.2 Std Dev: 3.1 N: 1348	Avg: 4.7 Min: 1.2 Max: 12.0 Std Dev: 2.1 N: 1247

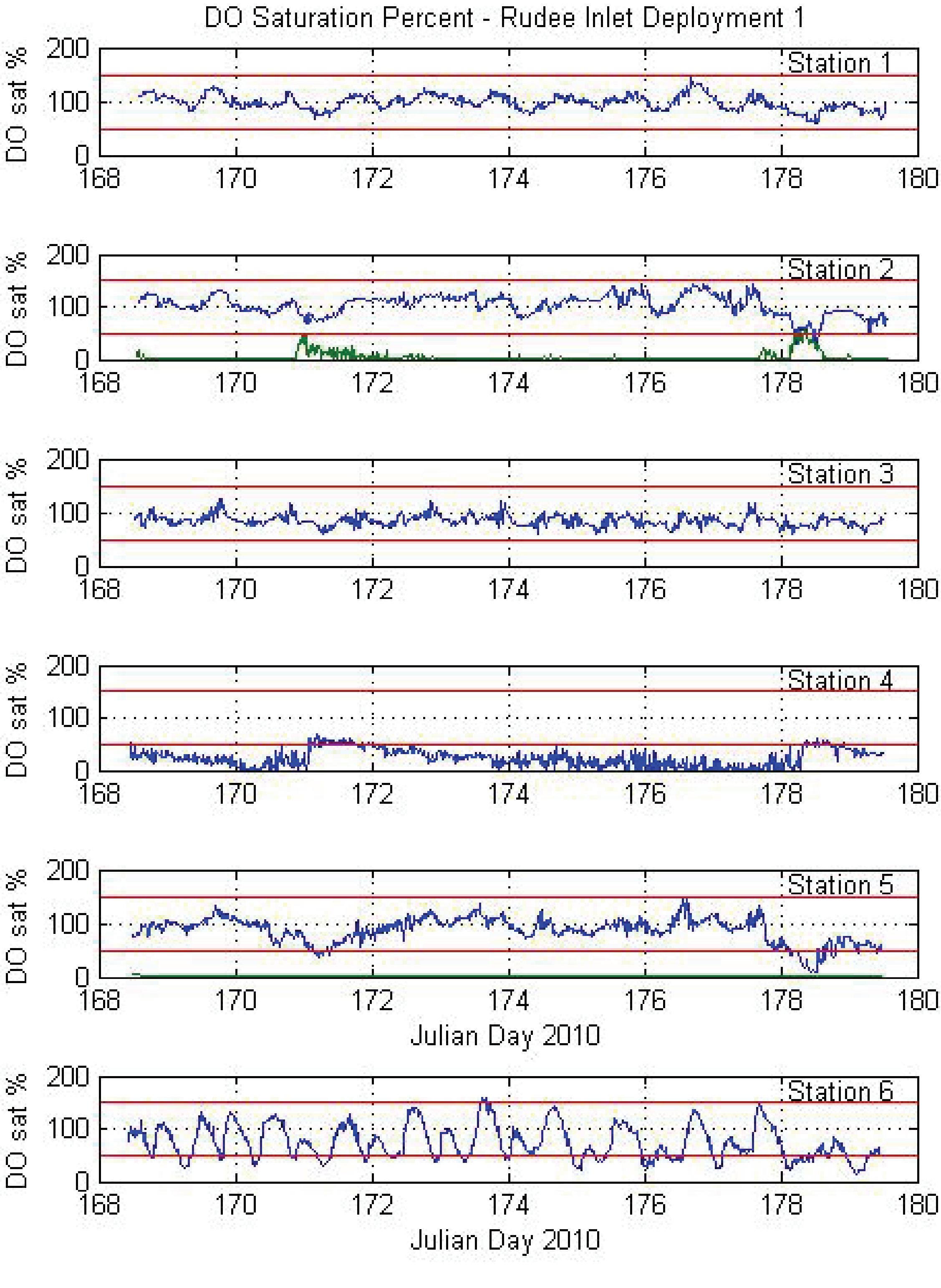


Figure II.21. ConMon water quality station percent saturation of dissolved oxygen – Rudee Inlet system Deployment 1 (June 17 - 28, 2010). Green lines represent near bottom waters.

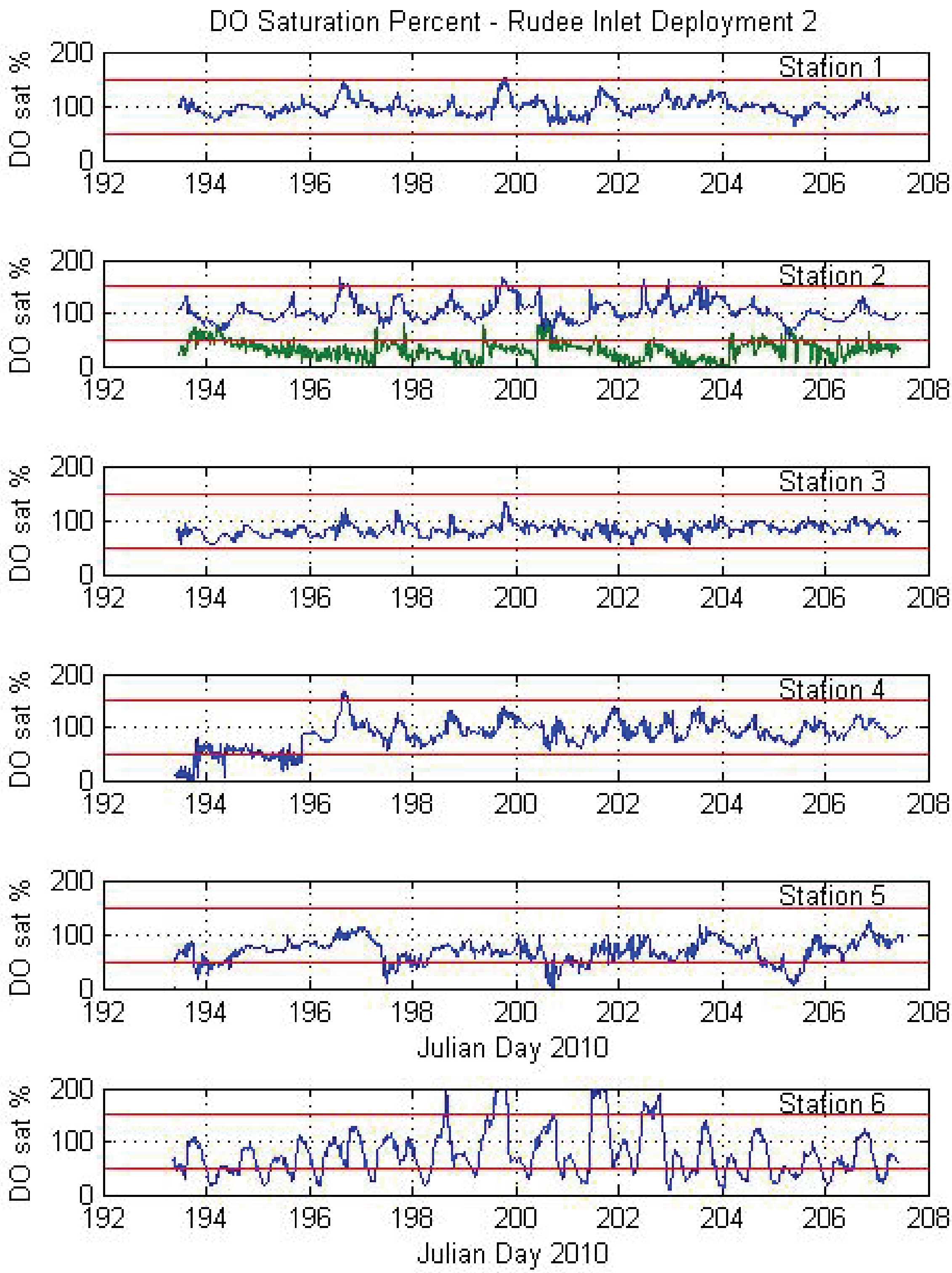


Figure II.22. ConMon water quality station percent saturation of dissolved oxygen – Rudee Inlet system Deployment 2 (July 12 – 26, 2010). Green lines represent near bottom waters.

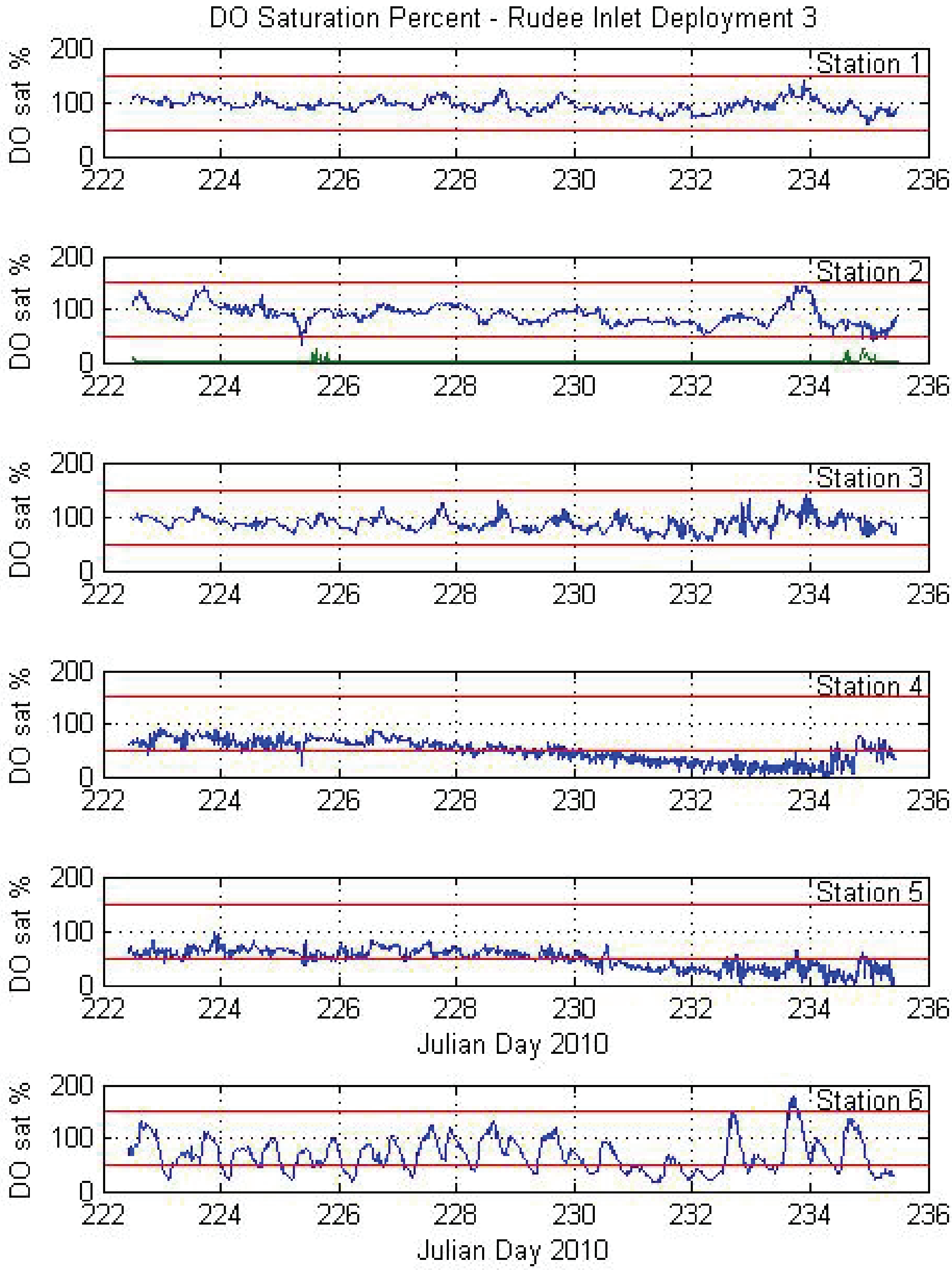


Figure II.23. ConMon water quality station percent saturation of dissolved oxygen – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.7. Summary statistics for $DO_{\%sat}$ within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 97.8 Min: 59.4 Max: 143.2 Std Dev: 3.3 N: 1052	Avg: 97.5 Min: 63.3 Max: 152.7 Std Dev: 14.0 N: 1340	Avg: 94.2 Min: 57.8 Max: 139.3 Std Dev: 11.6 N: 1249
2 - surface	Avg: 103.3 Min: 28.9 Max: 144.5 Std Dev: 19.4 N: 1057	Avg: 103.9 Min: 43.4 Max: 167.8 Std Dev: 19.1 N: 1340	Avg: 89.6 Min: 32.7 Max: 144.7 Std Dev: 18.0 N: 1249
2 - bottom	Avg: 4.3 Min: 0.6 Max: 55.1 Std Dev: 8.7 N: 1057	Avg: 31.1 Min: 1.4 Max: 84.2 Std Dev: 16.4 N: 1340	Avg: 1.6 Min: 1.0 Max: 25.2 Std Dev: 2.3 N: 1248
3	Avg: 84.3 Min: 59.4 Max: 123.5 Std Dev: 10.2 N: 1055	Avg: 83.2 Min: 54.3 Max: 134.1 Std Dev: 10.7 N: 1346	Avg: 87.8 Min: 53.9 Max: 139.0 Std Dev: 13.2 N: 1244
4	Avg: 23.9 Min: 1.0 Max: 67.9 Std Dev: 16.1 N: 1060	Avg: 86.6 Min: 3.8 Max: 167.4 Std Dev: 26.7 N: 1352	Avg: 49.2 Min: 3.7 Max: 90.7 Std Dev: 21.0 N: 1248
5 - surface	Avg: 87.2 Min: 9.2 Max: 149.9 Std Dev: 23.3 N: 1055	Avg: 69.2 Min: 2.4 Max: 126.2 Std Dev: 21.0 N: 1355	Avg: 48.3 Min: 2.2 Max: 98.3 Std Dev: 18.2 N: 1247
5 - bottom	Avg: 3.4 Min: 3.2 Max: 6.8 Std Dev: 0.2 N: 1054	Avg: 0.0 Min: 0.0 Max: 0.3 Std Dev: 0.0 N: 1352	Avg: 0.0 Min: 0.0 Max: 0.0 Std Dev: 0.0 N: 1244
6	Avg: 75.1 Min: 13.5 Max: 158.4 Std Dev: 32.2 N: 1059	Avg: 77.3 Min: 8.2 Max: 288.3 Std Dev: 44.5 N: 1348	Avg: 68.7 Min: 16.9 Max: 177.8 Std Dev: 31.2 N: 1247

Table II.8. Percent of time that ConMon water quality stations exhibited anoxic and hypoxic conditions (hypoxia criteria: $DO_{\%sat} > 0$ to $< 30\%$ and $DO_{conc} \leq 2.0$ $mg \cdot L^{-1}$) during summer deployment periods 1. Note: deployment period 1: (6/17-6/28/2010), deployment period 2 (7/12-7/26/2010) and deployment period 3 (8/10-8/23/2010).

ConMon Station	Deployment Period	% Time DO Met Anoxia Criteria	% Time DO Met Hypoxia Criteria	
			DO_{sat}	DO_{conc}
1	1	0.0	0.0	0.0
1	2	0.0	0.0	0.0
1	3	0.0	0.0	0.0
2	1	0.0	<0.1	<0.1
2	2	0.0	0.0	0.0
2	3	0.0	0.0	<0.1
2 deep	1	0.0	96.3	97.5
2 deep	2	0.0	45.7	66.6
2 deep	3	0.0	100.0	100.0
3	1	0.0	0.0	0.0
3	2	0.0	0.0	0.0
3	3	0.0	0.0	0.0
4	1	0.0	67.7	79.9
4	2	0.0	3.2	4.9
4	3	0.0	22.3	34.3
5	1	0.0	2.0	3.6
5	2	0.0	4.4	7.5
5	3	0.0	19.2	33.0
5 deep	1	0.0	100.0	100.0
5 deep	2	99.9	<0.1	<0.1
5 deep	3	100.0	0.0	0.0
6	1	0.0	5.4	15.1
6	2	0.0	11.3	20.5
6	3	0.0	8.9	22.2

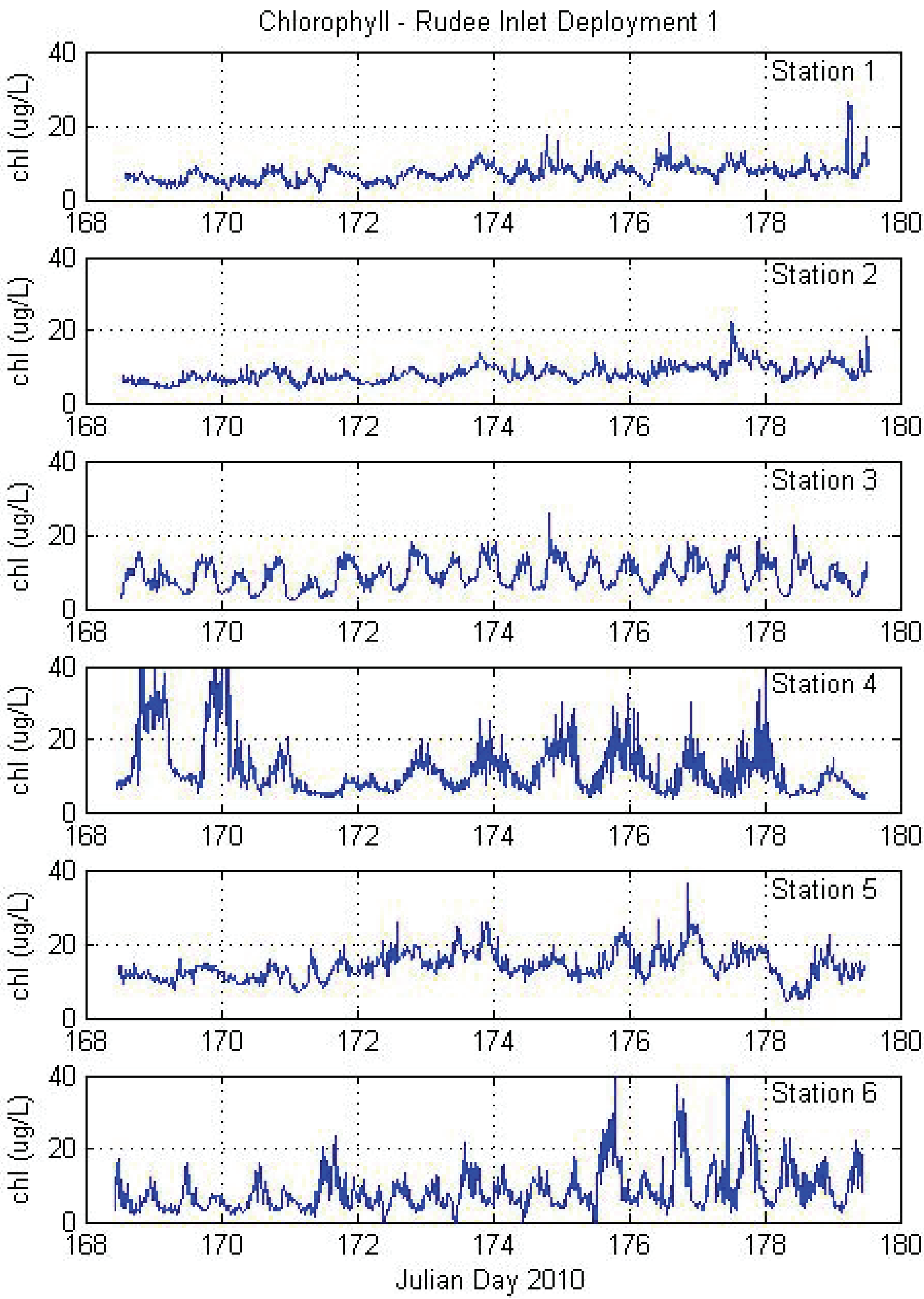


Figure II.24. ConMon water quality station chlorophyll (fluorescence) – Rudee Inlet system Deployment 1 (June 17 - 28, 2010).

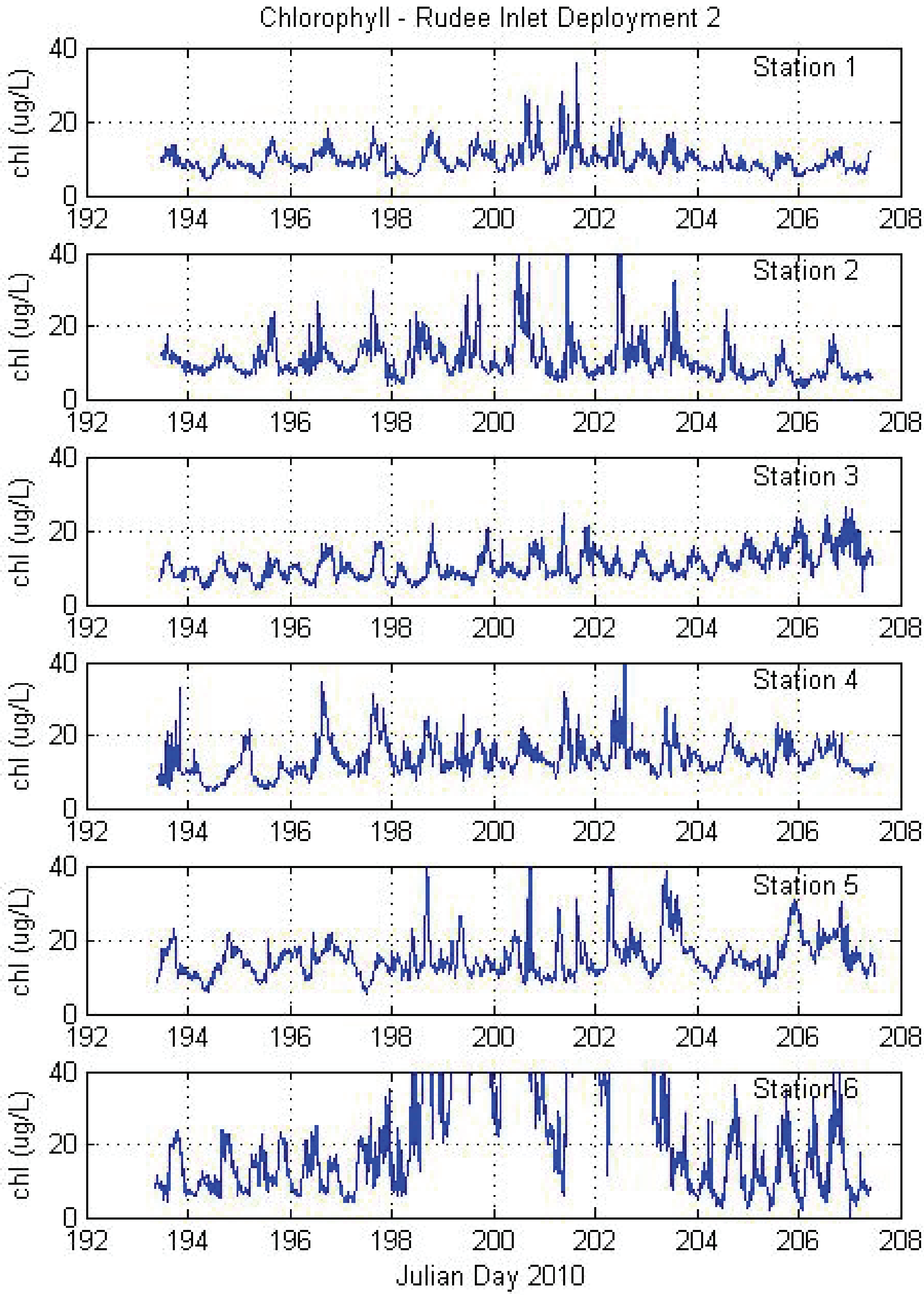


Figure II.25. ConMon water quality station chlorophyll (fluorescence) – Rudee Inlet system Deployment 2 (July 12 - 26, 2010).

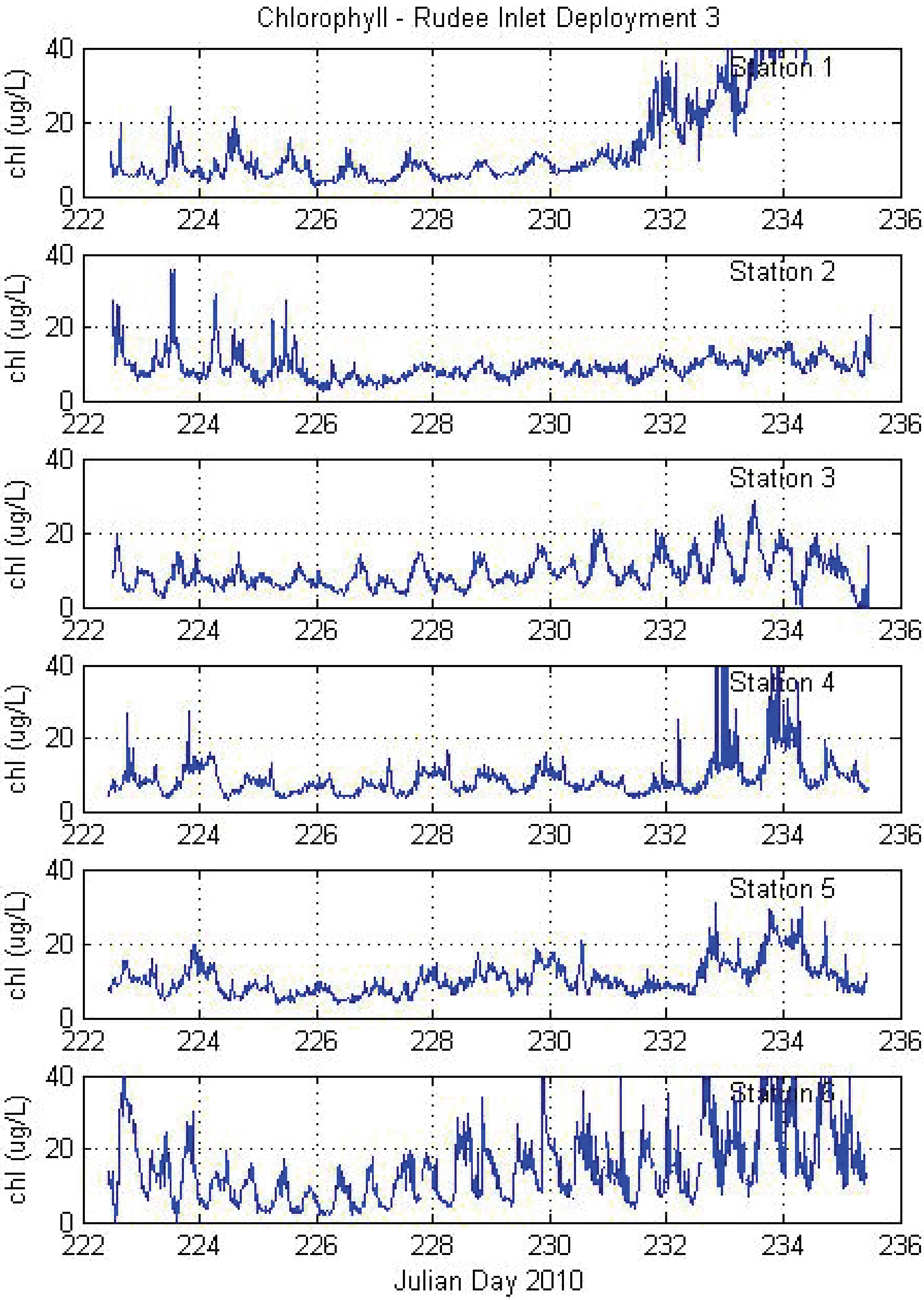


Figure II.26. ConMon water quality station chlorophyll (fluorescence) – Rudee Inlet system Deployment 3 (August 10 - 23, 2010).

Table II.9. Summary statistics for chl_{fl} ($\mu g \cdot L^{-1}$) within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 7.2 Min: 2.1 Max: 26.5 Std Dev: 2.5 N: 1049	Avg: 9.6 Min: 4.2 Max: 36.1 Std Dev: 3.1 N: 1340	Avg: 20.3 Min: 2.7 Max: 250.7 Std Dev: 28.9 N: 1249
2 - surface	Avg: 8.3 Min: 3.9 Max: 22.3 Std Dev: 2.3 N: 1057	Avg: 11.0 Min: 3.0 Max: 109.5 Std Dev: 7.0 N: 1340	Avg: 9.4 Min: 2.7 Max: 35.8 Std Dev: 3.7 N: 1244
2 – bottom	Avg: 16.0 Min: 1.4 Max: 89.9 Std Dev: 11.6 N: 1049	Avg: 17.3 Min: 4.6 Max: 274.6 Std Dev: 20.9 N: 1320	Avg: 25.9 Min: 3.8 Max: 135.7 Std Dev: 17.9 N: 1247
3	Avg: 9.2 Min: 2.3 Max: 25.8 Std Dev: 3.7 N: 1055	Avg: 10.9 Min: 3.6 Max: 26.5 Std Dev: 3.8 N: 1346	Avg: 9.2 Min: 0.0 Max: 28.6 Std Dev: 4.3 N: 1244
4	Avg: 11.8 Min: 3.7 Max: 59.2 Std Dev: 7.7 N: 1054	Avg: 13.7 Min: 4.9 Max: 45.6 Std Dev: 4.7 N: 1350	Avg: 9.0 Min: 3.3 Max: 107.5 Std Dev: 6.0 N: 1243
5 – surface	Avg: 14.1 Min: 4.5 Max: 36.5 Std Dev: 3.9 N: 1055	Avg: 15.2 Min: 5.2 Max: 59.3 Std Dev: 5.5 N: 1355	Avg: 10.5 Min: 3.4 Max: 31.1 Std Dev: 4.5 N: 1244
5 – bottom	Avg: 4.4 Min: 1.0 Max: 12.3 Std Dev: 2.3 N: 1055	Avg: 26.0 Min: 12.5 Max: 46.6 Std Dev: 4.7 N: 1354	Avg: 14.2 Min: 4.9 Max: 33.4 Std Dev: 4.5 N: 1247
6	Avg: 8.6 Min: 0.0 Max: 52.8 Std Dev: 6.0 N: 1059	Avg: 37.8 Min: 0.1 Max: 396.1 Std Dev: 53.3 N: 1343	Avg: 14.7 Min: 0.0 Max: 61.0 Std Dev: 10.0 N: 1201

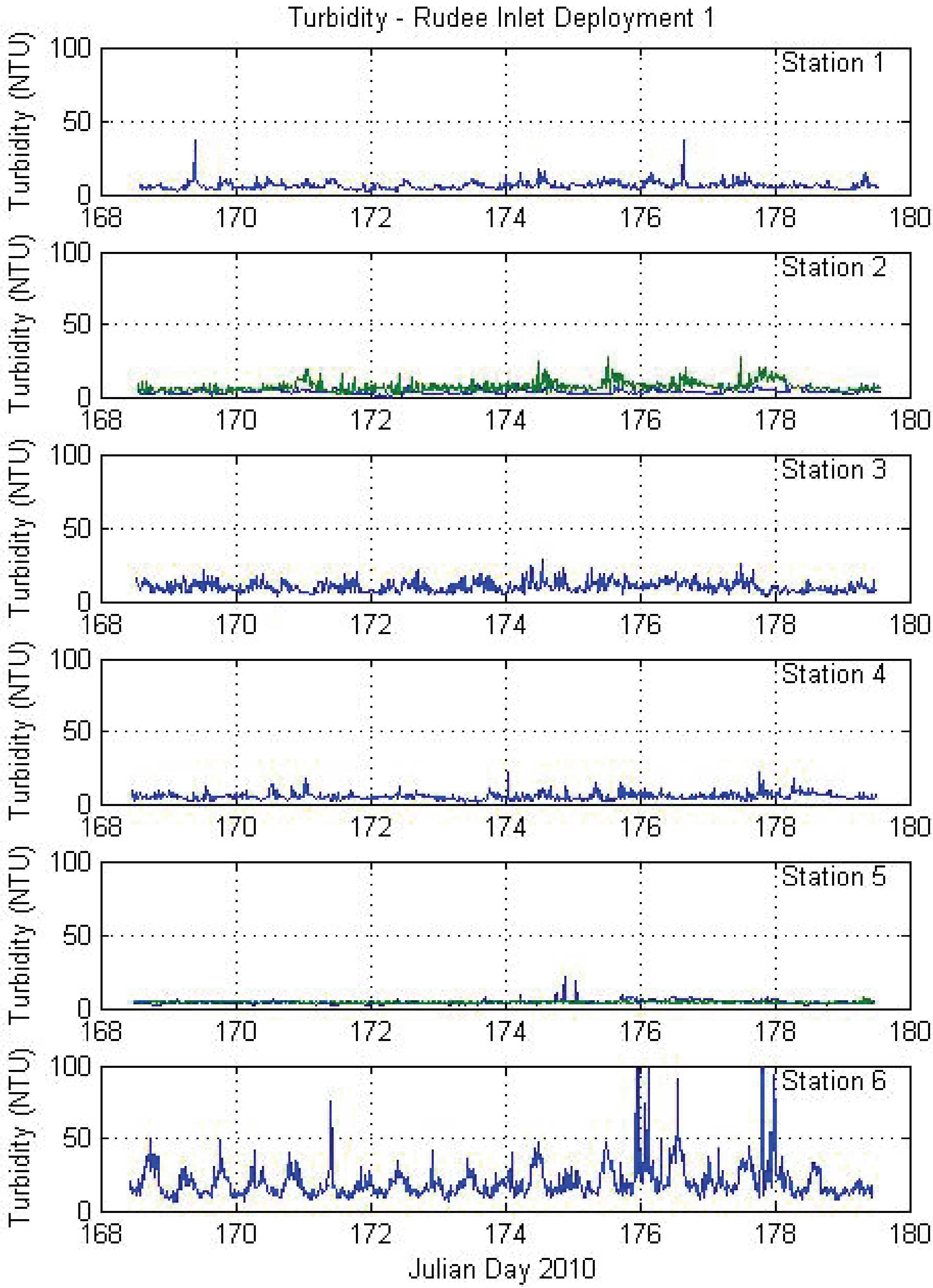


Figure II.27. ConMon water quality station turbidity – Rudee Inlet system Deployment 1 (June 17 - 28, 2010). Green lines represent near bottom waters.

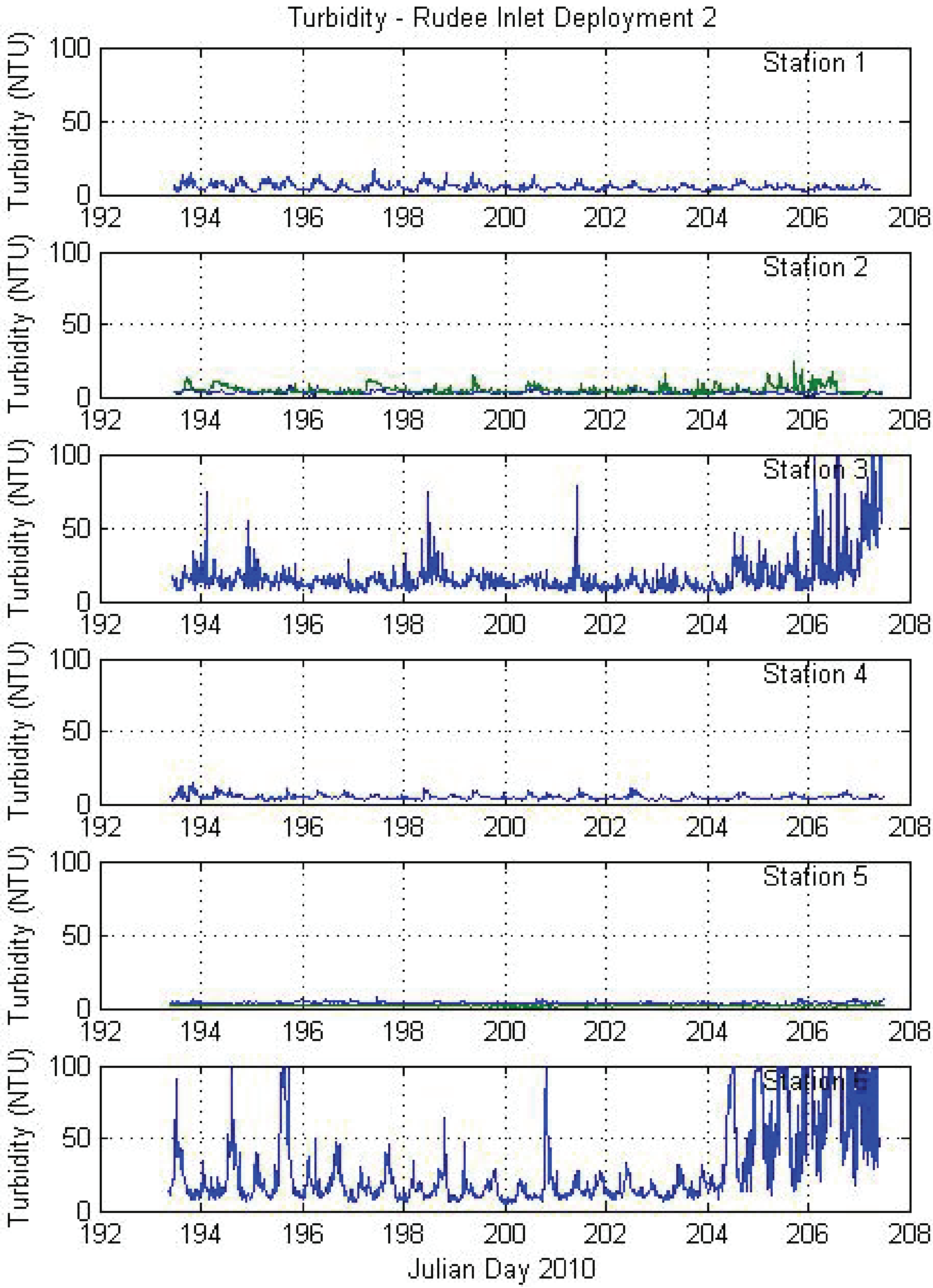


Figure II.28. ConMon water quality station turbidity – Rudee Inlet system Deployment 2 (July 12 - 26, 2010). Green lines represent near bottom waters.

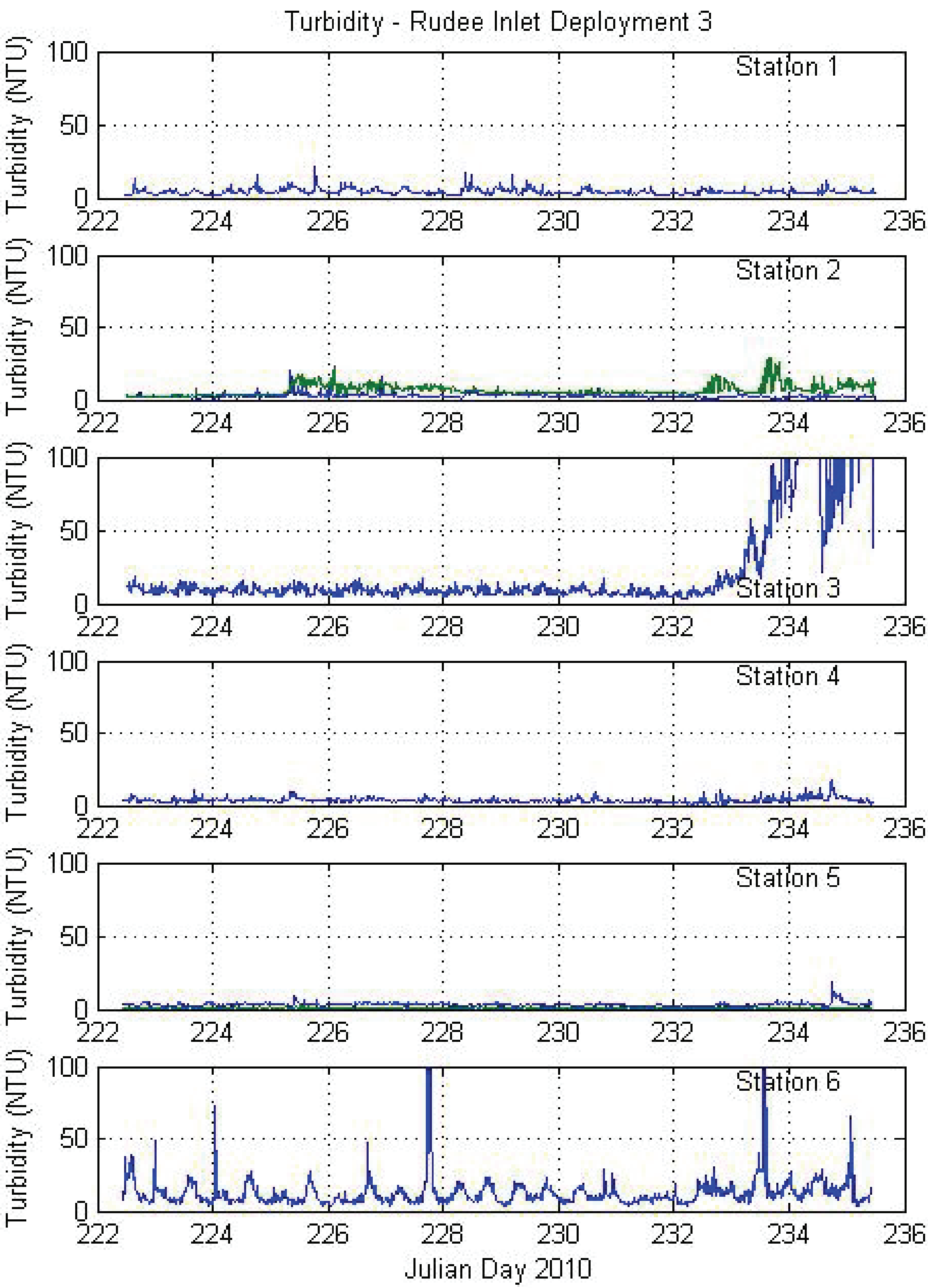


Figure II.29. ConMon water quality station turbidity – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.10. Summary statistics for turbidity (NTU) within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 6.0 Min: 2.4 Max: 37.3 Std Dev: 2.6 N: 1052	Avg: 5.2 Min: 1.8 Max: 17.0 Std Dev: 2.3 N: 1340	Avg: 4.3 Min: 1.6 Max: 22.0 Std Dev: 1.9 N: 1249
2 - surface	Avg: 3.7 Min: 0.9 Max: 12.6 Std Dev: 1.5 N: 1057	Avg: 3.0 Min: 1.2 Max: 8.2 Std Dev: 1.1 N: 1340	Avg: 2.7 Min: 0.9 Max: 20.4 Std Dev: 1.4 N: 1249
2 - bottom	Avg: 7.1 Min: 1.4 Max: 27.8 Std Dev: 3.4 N: 1057	Avg: 4.9 Min: 1.3 Max: 24.4 Std Dev: 2.5 N: 1340	Avg: 6.6 Min: 1.6 Max: 28.6 Std Dev: 3.8 N: 1248
3	Avg: 10.0 Min: 3.9 Max: 28.3 Std Dev: 3.5 N: 1052	Avg: 16.7 Min: 5.4 Max: 147.0 Std Dev: 13.8 N: 1341	Avg: 26.3 Min: 2.8 Max: 505.5 Std Dev: 49.4 N: 1244
4	Avg: 5.2 Min: 1.2 Max: 21.9 Std Dev: 2.4 N: 1060	Avg: 4.7 Min: 2.0 Max: 14.4 Std Dev: 1.7 N: 1352	Avg: 3.6 Min: 0.9 Max: 18.1 Std Dev: 1.7 N: 1248
5 - surface	Avg: 4.2 Min: 1.9 Max: 20.9 Std Dev: 1.4 N: 1055	Avg: 3.6 Min: 1.5 Max: 7.4 Std Dev: 0.7 N: 1354	Avg: 3.1 Min: 1.2 Max: 18.9 Std Dev: 1.2 N: 1247
5 - bottom	Avg: 4.2 Min: 3.4 Max: 8.3 Std Dev: 0.3 N: 1055	Avg: 1.7 Min: 1.0 Max: 5.1 Std Dev: 0.3 N: 1354	Avg: 0.9 Min: 0.4 Max: 3.9 Std Dev: 0.3 N: 1247
6	Avg: 20.1 Min: 6.5 Max: 260.6 Std Dev: 13.9 N: 1056	Avg: 29.6 Min: 5.2 Max: 223.2 Std Dev: 31.7 N: 1348	Avg: 12.5 Min: 3.6 Max: 231.9 Std Dev: 10.9 N: 1247

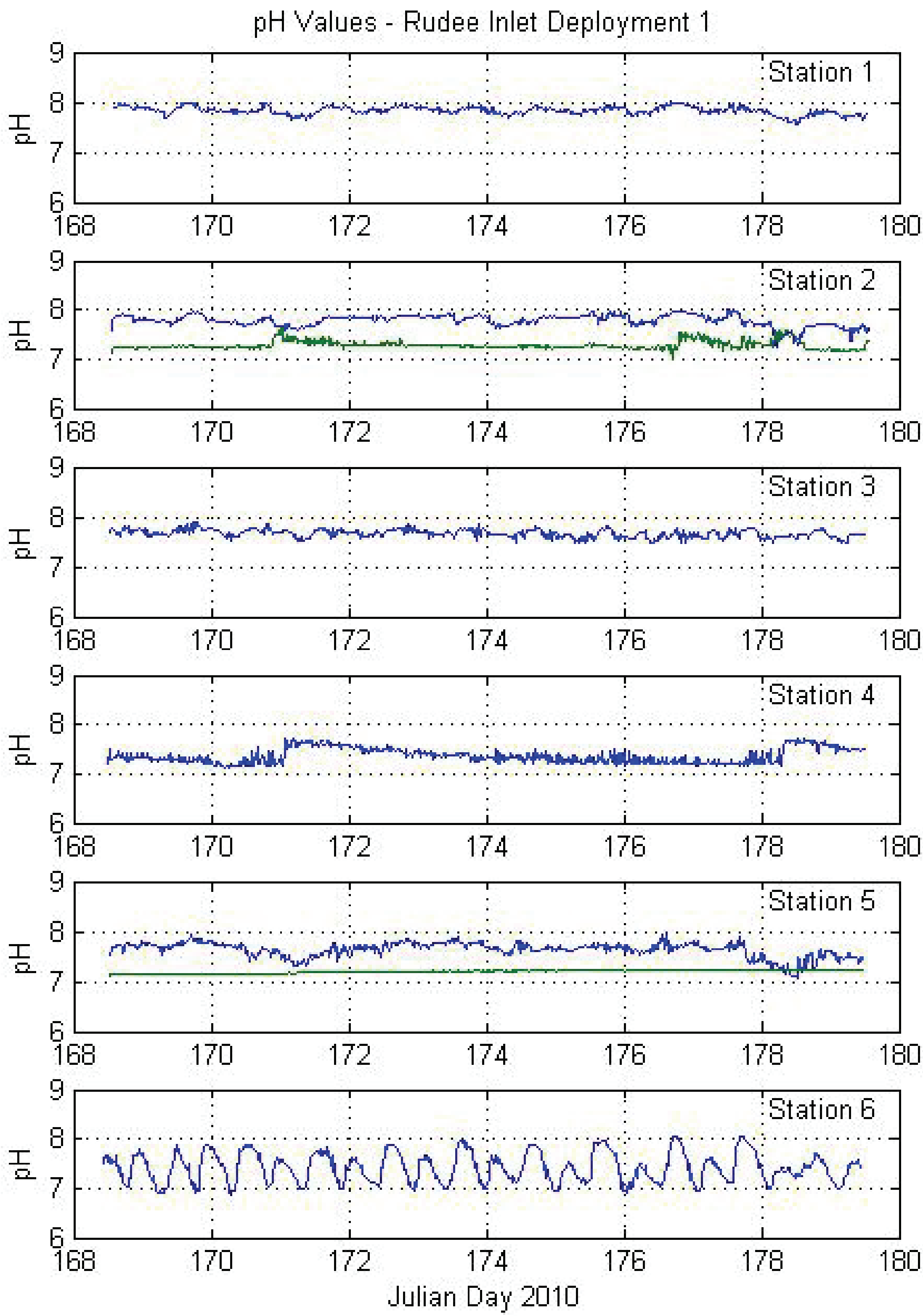


Figure II.30. ConMon water quality station pH – Rudee Inlet system Deployment 2 (June 17-28, 2010). Green lines represent near bottom waters.

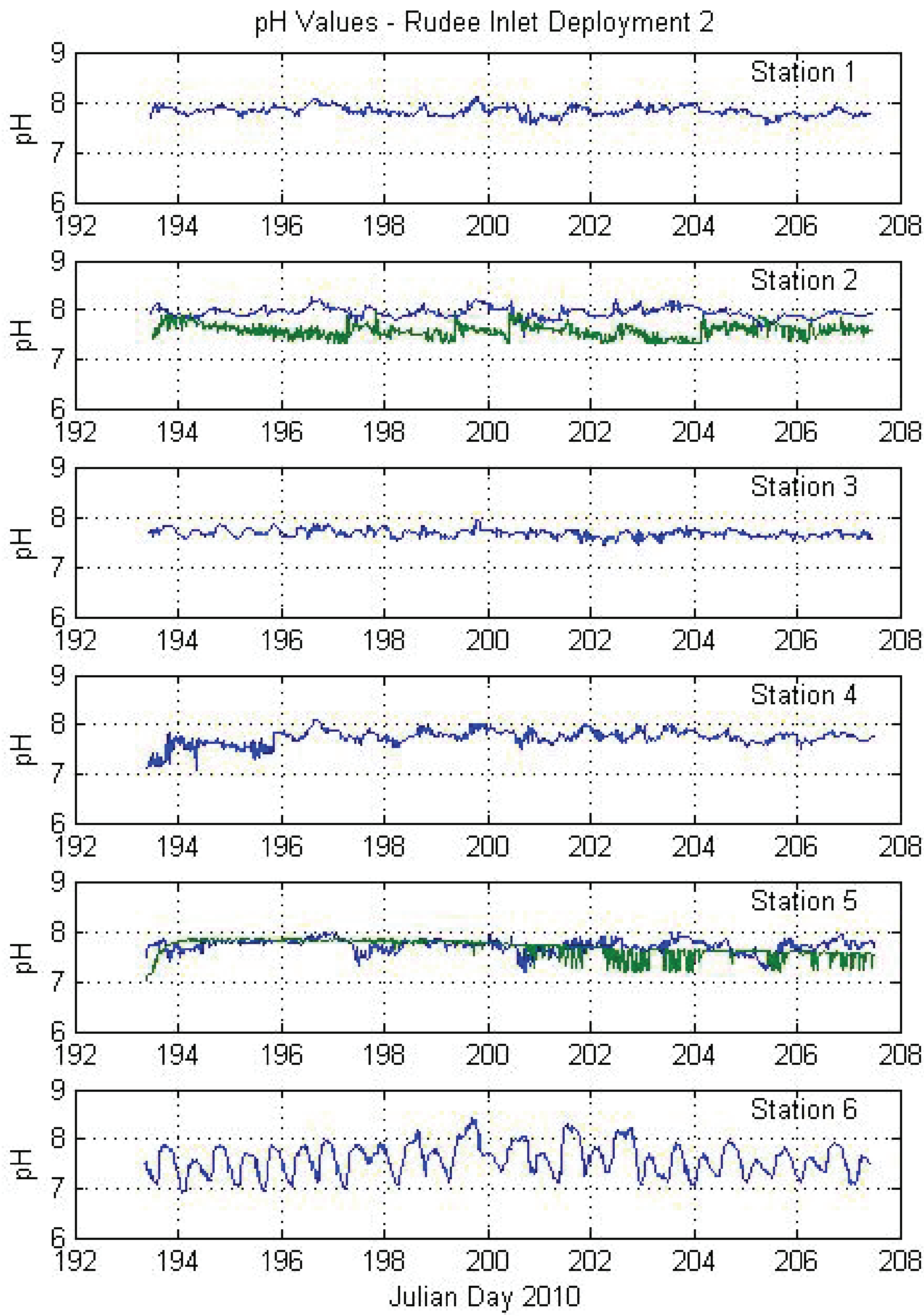


Figure II.31. ConMon water quality station pH – Rudee Inlet system Deployment 2 (July 12-26, 2010). Green lines represent near bottom waters.

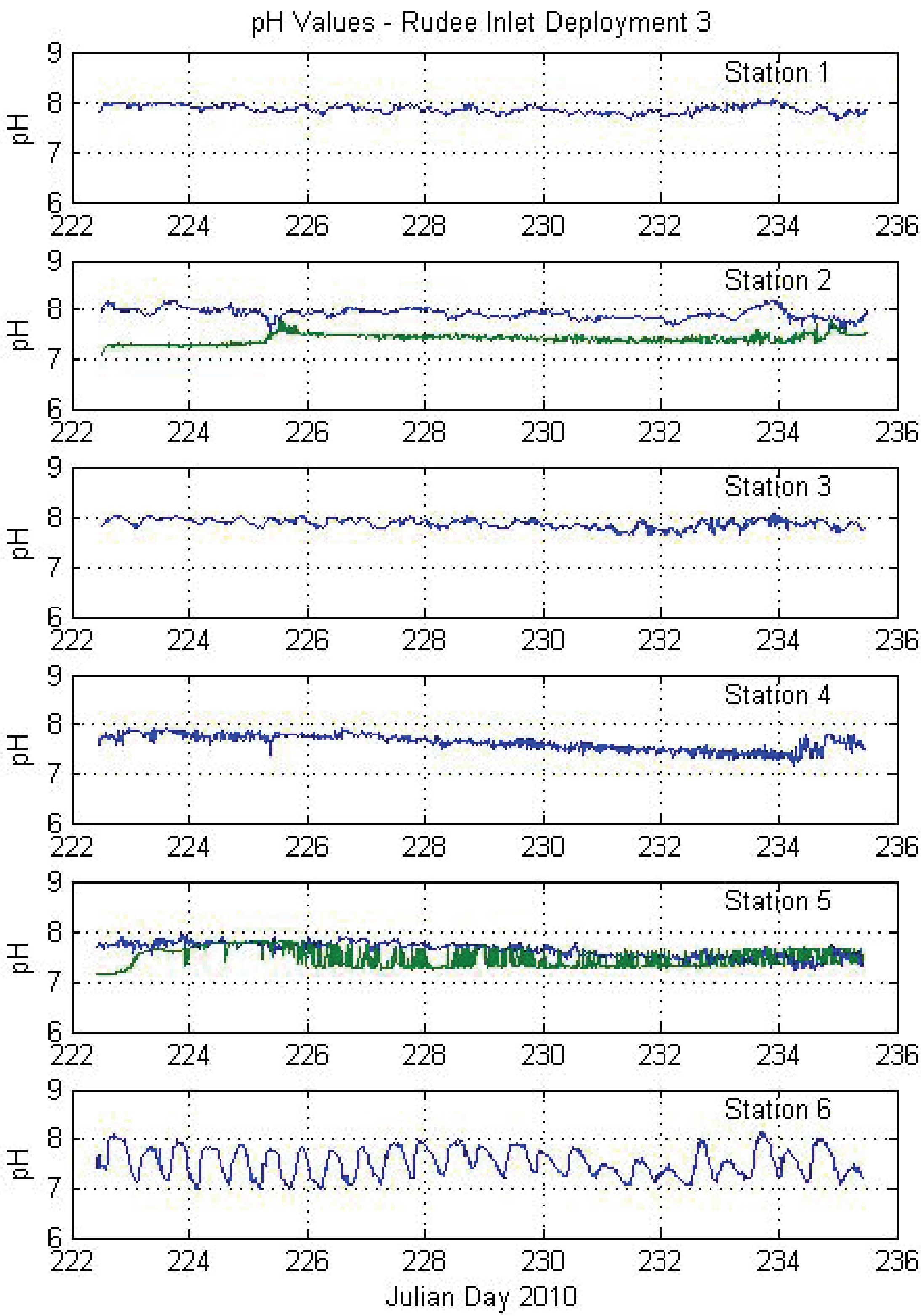


Figure II.32. ConMon water quality station pH – Rudee Inlet system Deployment 3 (August 10 - 23, 2010). Green lines represent near bottom waters.

Table II.11. Summary statistics for pH within the Rudee Inlet system by ConMon water quality station and deployment period.

ConMon Station	Sampling Period 6/17-6/28/2010	Sampling Period 7/12-7/26/2010	Sampling Period 8/10-8/23/2010
1	Avg: 7.8 Min: 7.6 Max: 8.0 Std Dev: 0.1 N: 1052	Avg: 7.8 Min: 7.6 Max: 8.1 Std Dev: 0.1 N: 1340	Avg: 7.9 Min: 7.6 Max: 8.1 Std Dev: 0.1 N: 1248
2 – surface	Avg: 7.8 Min: 7.3 Max: 8.0 Std Dev: 0.1 N: 1057	Avg: 7.9 Min: 7.5 Max: 8.3 Std Dev: 0.1 N: 1340	Avg: 7.9 Min: 7.5 Max: 8.2 Std Dev: 0.1 N: 1249
2 – bottom	Avg: 7.3 Min: 7.0 Max: 7.6 Std Dev: 0.1 N: 1056	Avg: 7.6 Min: 7.3 Max: 8.0 Std Dev: 0.1 N: 1339	Avg: 7.4 Min: 7.1 Max: 7.9 Std Dev: 0.1 N: 1248
3	Avg: 7.7 Min: 7.5 Max: 7.9 Std Dev: 0.1 N: 1055	Avg: 7.7 Min: 7.4 Max: 7.9 Std Dev: 0.1 N: 1346	Avg: 7.9 Min: 7.6 Max: 8.1 Std Dev: 0.1 N: 1244
4	Avg: 7.4 Min: 7.1 Max: 7.7 Std Dev: 0.2 N: 1059	Avg: 7.7 Min: 7.1 Max: 8.1 Std Dev: 0.2 N: 1352	Avg: 7.6 Min: 7.2 Max: 7.9 Std Dev: 0.2 N: 1247
5 – surface	Avg: 7.6 Min: 7.1 Max: 8.0 Std Dev: 0.2 N: 1054	Avg: 7.7 Min: 7.2 Max: 8.0 Std Dev: 0.1 N: 1355	Avg: 7.6 Min: 7.2 Max: 8.0 Std Dev: 0.2 N: 1246
5 – bottom	Avg: 7.2 Min: 7.1 Max: 7.2 Std Dev: 0.0 N: 1054	Avg: 7.7 Min: 7.0 Max: 7.9 Std Dev: 0.2 N: 1354	Avg: 7.5 Min: 7.1 Max: 7.8 Std Dev: 0.2 N: 1246
6	Avg: 7.4 Min: 6.9 Max: 8.1 Std Dev: 0.3 N: 1059	Avg: 7.6 Min: 6.9 Max: 8.4 Std Dev: 0.3 N: 1348	Avg: 7.5 Min: 7.0 Max: 8.2 Std Dev: 0.3 N: 1247

II-5 Water Quality Grab Sample Surveys

In addition to the ConMon water quality stations, three water quality grab sampling surveys were conducted throughout the Rudee Inlet system in the summer of 2010. Each survey consisted of approximately 20 sampling stations with locations depicted in Figure II.3 and listed in Table II.12. Because sampling stations had to be accessed by a variety of means (i.e., vessel, vehicle and foot), a near synoptic sampling of the Rudee Inlet system was not possible. Survey sampling began in mid-late-morning (9:00-10:00 EST) and was typically completed within 4 hours.

Table II.12. Locations of grab samples taken in the Rudee Inlet system with additional stations located in Lake Holly and Lake Christine.

Station	Location	Latitude	Longitude	July 1	July 12	August 12
RU-1	Lake Rudee	36.82955	75.97072	x	x	x
RU-2		36.83116	75.97281	x	x	x
RU-3		36.82901	75.97842	x	x	x
RU-4		36.82697	75.98080	x	x	x
RU-5 (surf)		36.82493	75.98270	x	x	x
RU-5 (2 m)		36.82493	75.98270	x	x	x
RU-5 (4 m)		36.82493	75.98270	x	x	x
HL-1	Lake Holly	36.83389	75.97257	x	x	x
HL-2		36.83532	75.97339	x	x	x
HL-3		36.83622	75.97778	x	x	x
FS-1	Feeder Stream	36.82476	75.98753	x	x	x
LW-1	Lake Wesley	36.82812	75.9716	x	x	x
LW-2 (surf)		36.82626	75.9725	x	x	
LW-2 (2.5 m)		36.82626	75.9725	x	x	x
LW-2 (5 m)		36.82626	75.9725	x	x	x
LW-3		36.82327	75.97345	x	x	x
OC-1 (surf)	Owl Creek	36.8222	75.98323	x	x	x
OC-1		36.8222	75.98323	x	x	x
OC-1		36.8222	75.98323	x	x	x
OC-2		36.81811	75.98745	x	x	x
OC-3		36.81827	75.98721	x	x	x
UN1-1	Tribs NW of Lake Rudee	36.82846	75.98355	x	x	x
UN1-2		36.82887	75.98553	x	x	x
UN1-3		36.83136	75.98533	x	x	x
UN2-1		36.83112	75.97829	x	x	x
UN2-2		36.83228	75.97963	x	x	x
LC-1	Lake Christine	36.82064	75.97031			x
LC-2		36.81924	75.97578			x

The grab samples were taken at a depth of 0.25 m below the surface and during day-time hours. At selected deeper water stations (RU-5, LW-2, and OC-1), multiple samples were collected with a Van Dorn style horizontal water sampler to represent surface, mid-depth and bottom waters. For each grab sample, the following parameters were measured: water temperature, specific conductance, pH, percent saturation of dissolved oxygen ($DO_{\%sat}$), total coliform ($MPN \cdot 100\ ml^{-1}$), and *Escherichia coli* (*E. coli*; $MPN \cdot 100\ ml^{-1}$). Calculated parameters at each station included DO_{conc} (based on DO_{sat}; $mg \cdot L^{-1}$) and salinity (based on specific conductance). At each grab sampling point, vertical profiles of water temperature, salinity, pH, $DO_{\%sat}$ were field measured with a YSI 600 XL instrument.

Bacteriological samples were collected in sterile 100 ml bottles, stored at 4 °C until analysis which occurred within eight hours of collection. Total coliform (TCB) and *E. coli* bacteria were enumerated using the U.S. EPA-approved Colilert-18® (SM 9223) system with the 2000 Quanti-Tray®. The lower and upper method detection limit for TCB and *E. coli* was dependent upon sample dilution rate. It should be noted that when the study was initiated in June 2010, the Colilert-18® method had not received U.S. EPA-approval for FCB enumeration. In the summer of 2010, U.S. EPA decided to recommend Colilert-18® for inclusion in 40 CFR 136.3 for the measurement of FCB in wastewater (note: Primary differences in Colilert-18® methodology for TCB (35 °C) and FCB (44.5 °C) is incubation temperature). Equation II.1 was used to provide an estimate of FCB densities based on measured *E. coli* densities, using a relationship derived by VA-DEQ (2003).

$$FCB = 2^{\left(\frac{\log 2 E.coli + 0.0172}{0.91905}\right)} \qquad \text{Eq. II.1}$$

Where:

FCB = Fecal coliform bacteria density (MPN/100 ml)
E. coli = *E. coli* density (MPN/100 ml)

II-5-1 Temperature, Salinity, pH and Dissolved Oxygen

Grab sample data for temperature, salinity, pH and dissolved oxygen are provided in Table II.13 for July 1, 2010, Table II.14 for July 12, 2010 and Table II.15 for August 12, 2010 sampling. Spatial plots of temperature are provided in Figures II.33-II.35 for the respective sampling dates. Tidal surface water temperatures varied between 22.5-27.0 °C during the July 1 survey, 25.4-27.9 °C during the July 12 survey and 25.6-27.6 °C during the August 12, 2010 survey. At selected stations where vertical information was collected, bottom temperatures were 6.2-9.2 °C cooler than surface waters at station LW-2 (water depth range: 5-6 m), 4.5-8.2 °C cooler at station RU-5 (water depth range: 4-6 m) and 7.2-12.5 °C cooler at station OC-1 (water depth range: 10 m). Daytime temperatures with non-tidal water inputs (stations: HL-1 through 3, LW-3 and LC-1 and 2) were generally 1-2 °C warmer than the warmest temperatures observed in tidal waters.

Spatial plots of salinity are provided in Figures II.36 for the July 1 sampling, Figure II.37 for the July 12 sampling and Figure II.38 for the August 12, 2010 sampling. Salinity within tidal surface waters varied from 22.0-27.6 psu, 4.8-25.4 psu and 25.1-27.2 psu on July 1, July 12 and August 12, 2010, respectively. The lowest salinity values were consistently observed in the upper tidal regions of Owl Creek (station OC-3). For reference, surface salinity values in offshore waters immediately adjacent to Rudee Inlet were 27.9 psu on July 1, 25.8 psu on July 12 and 27.0 psu on August 12, 2010. At selected stations where vertical information was collected, bottom salinity values were elevated over surface waters by 2-5 psu at LW-2, 2-4 psu at RU-5 and 2-4 psu at OC-1 and generally exceed offshore surface waters by 2-4 psu. Freshwater/low salinity input signals were observed at stations (LW-3 and HL-1, 2 and 3) that do not have a direct connection to the tidal Rudee Inlet system. Station LW-3, receiving drainage from the freshwater Lake Christine (0.05 psu), exhibited a freshwater signal (psu<0.4 psu) on all three sampling dates. Holly Lake, which discharges into Rudee Inlet via a spillway, exhibited salinities on the order 0.8 - 4.2 ppt.

Spatial plots of pH are provided in Figures II.39-II.41 for July 1, July 12 and August 12, 2010, respectively. Surface tidal water exhibited a relatively narrow range of pH values, they were 7.4-8.0 on July 1, 7.4-8.0 on July 12, and 7.1-8.0 on August 12, 2010. pH values were consistently lower (range: 7.1-7.6) in the upper reaches of sampled tidal creeks (stations OC-3 and UN1-3). Bottom water pH at selected deeper water stations (LW-2, RU-5 and OC-1) were generally depressed as compared to surface waters and reflect enhanced benthic respiration rates and limited water exchange across established density gradients.

Spatial plots of dissolved oxygen concentrations are provided in Figures II.42-II.44 for the July 1, July 12 and August 12, 2010 samplings, respectively. Spatial plots of percent saturation of dissolved oxygen are presented in Figure II.45 for July 1, Figure II.46 for July 12 and Figure II.47 for August 12, 2010. Day-time concentrations of dissolved oxygen varied from 3.3-8.3 $mg \cdot L^{-1}$ on July 1 and 2.6-7.6 $mg \cdot L^{-1}$ on July 12, 2010 within tidal portions of the Rudee Inlet system. Due to equipment failure, less than one-half of the stations were sampled on August 12, 2010 and therefore discussion is limited to the first two samplings. Near (>85%) or greater than saturated dissolved oxygen conditions were noted in the main body of the tidal region of the Rudee Inlet system on both sampling dates. Decreased dissolved oxygen levels (< 80% saturations) were observed in the upper reaches of the tidal creeks (stations FS-1, OC-3 and UN1-1 to 3) and presumed to be under a greater influence of benthic oxygen consuming processes. Of note was the elevated oxygen levels associated with the main body of Lake Holly (stations HL-1 and HL-2). Elevated levels ($DO_{\%sat}$ range: 135-168) may be indicative of eutrophic conditions.

II-5-2 Total Coliforms and *E. coli*

The existence of pathogens in coastal waters is of health concern and currently the Rudee Inlet system is impaired due to elevated coliform bacteria densities. Coliform bacteria belong to the family Enterobacteriaceae and include the genera *Enterobacter*, *Klebsiella*, *Citrobacter* and *Escherichia*. Of these genera, *Enterobacter*, *Klebsiella*, and *Escherichia* are associated with human and animal feces, in addition, some are derived from other environmental (e.g., soil, wood and other plant material) sources. In order to further identify potential fecal sources, methods can be adopted to further classify the TCB group into fecal coliform bacteria (FCB) or more specific *E. coli* subsets.

Measured *E. coli* bacteria, calculated FCB and measured TCB densities for the three grab sample periods are provided in Tables II.13 to II.15. Spatial plots of *E. coli* are presented in Figures II.48 – II.50, Figures II.51-II.53 for calculated FCB and Figures II.54-II.56 for TCB. The relationship between TCB and *E. coli* densities for all samples collected within the Rudee Inlet region (including adjacent offshore waters, tidal waters within Rudee Inlet system, Lakes Holly and Christine) is presented in Figure II.57. *E. coli* samples from tidal waters of the Rudee Inlet system varied from 10-422 MPN·100 ml^{-1} on July1, 10-844 MPN·100 ml^{-1} on July 12 and 41-821 MPN·100 ml^{-1} on August 12, 2010. Values within the upper reaches of selected creeks (stations OC-3 and UN1-3) were generally elevated as compared to more open waters. TCB densities from these same tidal waters varied from 173-15,531 MPN·100 ml^{-1}, 426-24,196 MPN·100 ml^{-1} and 521-129,965 MPN·100 ml^{-1} for the July 1, July 12 and August 12, 2010 samplings, respectively. As with *E. coli*, TCB counts were elevated within the upper reaches of selected creeks (stations OC-2, OC-3, UN1-1, UN1-2 and UN1-3). At selected stations where vertical information was collected, *E. coli* and TCB densities exhibited a mixed pattern with depth for the July 1 sampling and a decreasing trend with depth for the July 12 and August 12, 2010 samplings. Elevated *E. coli* (range: 644-3641 MPN·100 ml^{-1}) and TCB (>24,196-241,960 MPN·100 ml^{-1}) densities were observed at a non-tidal freshwater source (station LW-3) that drains into Lake Wesley. While data is limited to one sampling at the presumed source of this stream, Lake Christine, *E. coli* densities were low (50 MPN·100 ml^{-1}) whereas TCB counts were elevated (>30,000 MPN·100 ml^{-1}).

Table II.13. Grab sample data collected in the Rudee Inlet system on July 1, 2010.

Station	Time (EST)	WT (^oC)	Sal (ppt)	pH	DO (mg/L)	DO %sat	E. coli MPN/ 100 ml	FC ** MPN/ 100 ml	Total Coliform MPN/ 100ml
RU-1	11:13	23.15	27.29	8.46	7.19	98.1	95	143	173
RU-2	11:09	22.52	27.61	8.39	6.42	87.0	62	90	480
RU-3	11:04	24.24	26.56	8.30	6.27	87.1	106	162	934
RU-4	10:59	24.84	26.26	8.39	6.95	97.6	10	12.4	1130
RU-5 (surf)	10:50	25.05	26.16	8.39	7.39	103.9	31	42	1019
RU-5 (2 m)	10:53	23.24	26.85	8.32	4.90	67.3	30	41	1274
RU-5 (4 m)	10:54	20.63	28.40	8.39	4.61	60.8	51	73	798
HL-1	13:08	28.62	4.21	9.27	12.72	168.1	86	129	24196
HL-2	13:11	28.35	4.20	8.16	11.84	155.8	160	253	24196
HL-3	13:29	28.74	1.31	7.97	7.29	94.7	451	783	24196
FS-1	10:41	25.56	25.77	8.43	8.34	117.9	52	75	1421
LW-1	11:22	24.03	27.09	8.39	7.08	97.3	116	179	199
LW-2 (surf)	11:28	24.49	26.09	8.41	7.34	102.0	30	41	231
LW-2 (3 m)	11:31	20.49	28.50	8.50	6.17	80.9	130	202	315
LW-2 (6 m)	11:34	17.92	30.36	8.09	0.36	4.6	<10	12.4	187
LW-3	12:55	27.83	0.09	8.10	6.80	86.8	644	1153	24196
OC-1 (surf)	10:18	25.01	25.50	8.52	9.04	126.4	74	110	2603
OC-1 (5 m)	10:21	19.75	29.13	8.11	0.56	7.5	52	75	908
OC-1 (10 m)	10:31	15.30	29.36	8.31	0.45	5.3	73	108	288
OC-2	10:09	25.25	25.01	8.35	8.06	112.9	52	75	3448
OC-3	12:39	26.29	21.99	7.62	3.28	45.4	341	577	15531
UN1-1	11:57	25.97	26.43	8.17	5.95	85.1	121	187	3130
UN1-2	12:02	27.04	26.07	8.01	5.25	76.0	75	111	2282
UN1-3	12:08	27.01	24.25	7.79	4.51	65.5	422	728	11199
UN2-1	11:45	24.50	26.64	8.22	6.08	85.5	20	26	727
UN2-1	11:49	26.09	26.18	8.15	6.01	85.5	96	145	2755

*: no sample collected; WT: water temperature, Sal: salinity, DO: dissolved oxygen concentration, $DO_{\%sat}$: percent saturation of dissolved oxygen, FC: fecal coliform, E. coli: *Escherichia coli*

** note: FC derived from *E. Coli*

Table II.14. Grab sample data collected in the Rudee Inlet system on July 12, 2010.

Station	Time (EST)	WT (^oC)	Sal (ppt)	pH	DO (mg/L)	DO %sat	E. coli MPN/ 100 ml	FC ** MPN/ 100 ml	Total Coliform MPN/ 100ml
RU-1	11:20	25.38	25.42	7.91	6.24	87.9	41	58	1076
RU-2	10:59	27.03	25.04	7.83	6.52	94.2	20	26	2142
RU-3	10:38	27.24	24.97	7.76	6.41	92.9	62	90	1918
RU-4	10:11	27.26	24.97	7.71	6.51	94.4	72	106	3654
RU-5 (surf)	9:51	27.43	24.97	7.68	6.49	94.4	74	110	2909
RU-5 (2.5 m)	9:53	24.6	26.2	7.74	3.57	49.8	52	75	1314
RU-5 (5 m)	9:56	19.16	28.89	7.23	0.21	2.7	62	90	496
HL-1	13:17	29.12	3.89	8.75	10.07	134.6	100	152	41058
HL-2	13:22	28.99	3.84	9.06	11.25	149.2	306	513	27551
HL-3	13:36	29.89	1.94	8.36	5.98	79.6	626	1118	141361
FS-1	10:04	27.86	24.83	7.4	3.48	61.2	204	330	24196
LW-1	11:25	27.22	24.7	7.97	7.36	106.4	10	12.4	426
LW-2 (surf)	11:47	27.3	24.85	8	7.63	110.7	41	58	471
LW-2 (2.5 m)	11:51	23.36	26.13	7.87	5.83	79.6	20	26	211
LW-2 (5 m)	11:55	18.05	29.96	7.03	0.17	2.2	20	26	121
LW-3	13:05	28.31	0.36	8.04	3.50	45.2	1223	2317	24196
OC-1 (surf)	9:18	27.11	24.92	7.62	5.84	84.5	131	204	2909
OC-1 (5 m)	9:16	19.96	28.98	7.71	1.40	18.0	10	12.4	410
OC-1 (10 m)	9:22	14.61	29.22	7.31	0.50	5.9	10	12.4	41
OC-2	8:45	27.3	24.9	7.87	4.82	70.2	437	756	19863
OC-3	12:45	26.77	4.82	7.8	7.14	90.5	794	1448	24196
UN1-1	10:32	27.46	24.84	7.45	3.63	52.8	844	1548	14497
UN1-2	10:17	27.88	24.82	7.48	3.34	49.2	335	566	10824
UN1-3	10:24	27.07	24.05	7.37	2.64	38.0	411	707	14136
UN2-1	10:50	26.85	25.02	7.82	6.61	95.4	109	167	1565
UN2-2	10:52	27.22	24.71	7.77	5.07	80.7	97	147	2613

*: no sample collected; WT: water temperature, Sal: salinity, DO: dissolved oxygen concentration, $DO_{\%sat}$: percent saturation of dissolved oxygen, FC: fecal coliform, E. coli: *Escherichia coli*

** note: FC derived from *E. Coli*

Table II.15. Grab sample data collected in the Rudee Inlet system on August 12, 2010.

Station	TIME (EST)	WT (^oC)	Sal (ppt)	pH	DO (mg/L)	DO %sat	E. coli MPN/ 100 ml	FC ** MPN/ 100 ml	Total Coliform MPN/ 100 ml
RU-1	11:53	26.69	27.01	7.96	*	*	62	90	645
RU-2	11:37	25.85	27.14	7.98	*	*	52	75	763
RU-3	11:22	26.31	27.17	7.94	*	*	105	160	784
RU-4	11:18	26.73	27.23	7.92	*	*	139	218	984
RU-5 (surf)	10:24	25.67	27.11	8.01	6.32	90.3	130	202	1296
RU-5 (2.5 m)	10:27	24.07	27.34	7.86	4.88	68.1	63	92	705
RU-5 (5 m)	10:30	19.49	28.86	7.21	0.31	4.0	52	75	670
HL-1	14:15	30.18	0.86	8.46	*	*	100	152	4711
HL-2	14:11	30.59	0.8	8.59	*	*	100	152	100
HL-3	13:56	28.31	0.77	7.44	*	*	1068	2000	18501
FS-1	10:37	26.58	27.22	7.85	5.72	83	100	152	521
LW-1	11:40	26.76	27.11	8.02	*	*	72	106	4284
LW-2 (surf)	11:43	26.62	27.01	8.04	*	*	85	127	1430
LW-2 (2.5 m)	11:46	23.4	27.31	7.89	*	*	84	126	1336
LW-2 (5 m)	11:49	20.4	28.91	7.31	*	*	31	43	865
LW-3	13:43	28.97	0.17	7.06	*	*	3641	7595	24196
OC-1 (surf)	10:10	26.06	27.22	7.98	6.13	88.4	119	184	1968
OC-1 (5 m)	10:15	20.57	28.47	7.25	0.31	4.0	84	126	1254
OC-1 (10 m)	10:17	18.87	29.34	7.2	0.00	0.0	10	12.4	279
OC-2	10:00	26.51	27.15	7.83	5.67	82.6	181	290	6488
OC-3	12:47	27.58	25.06	7.14	*	*	821	1502	129965
UN1-1	10:48	25.56	27.08	7.82	5.31	76.4	168	267	1414
UN1-2	10:52	26.01	27.08	7.75	4.88	71.4	197	318	1989
UN1-3	11:00	26.35	26.96		*	*	296	495	12033
UN2-1	11:25	26.62	27.14	7.9	*	*	41	58	723
UN2-2	11:28	27.29	27.15	7.81	*	*	106	162	7701
LC-1	13:10	30.88	0.05	7.82	*	*	50	72	120979
LC-2	13:31	30.64	0.05	7.46	*	*	50	72	34334

*: no sample collected; WT: water temperature, Sal: salinity, DO: dissolved oxygen concentration, $DO_{\%sat}$: percent saturation of dissolved oxygen, FC: fecal coliform, E. coli: Escherichia coli

** note: FC derived from *E. Coli*

Note: The dissolved oxygen meter became inoperable after approximately 10 stations on the August 12, 2010 grab sample survey.

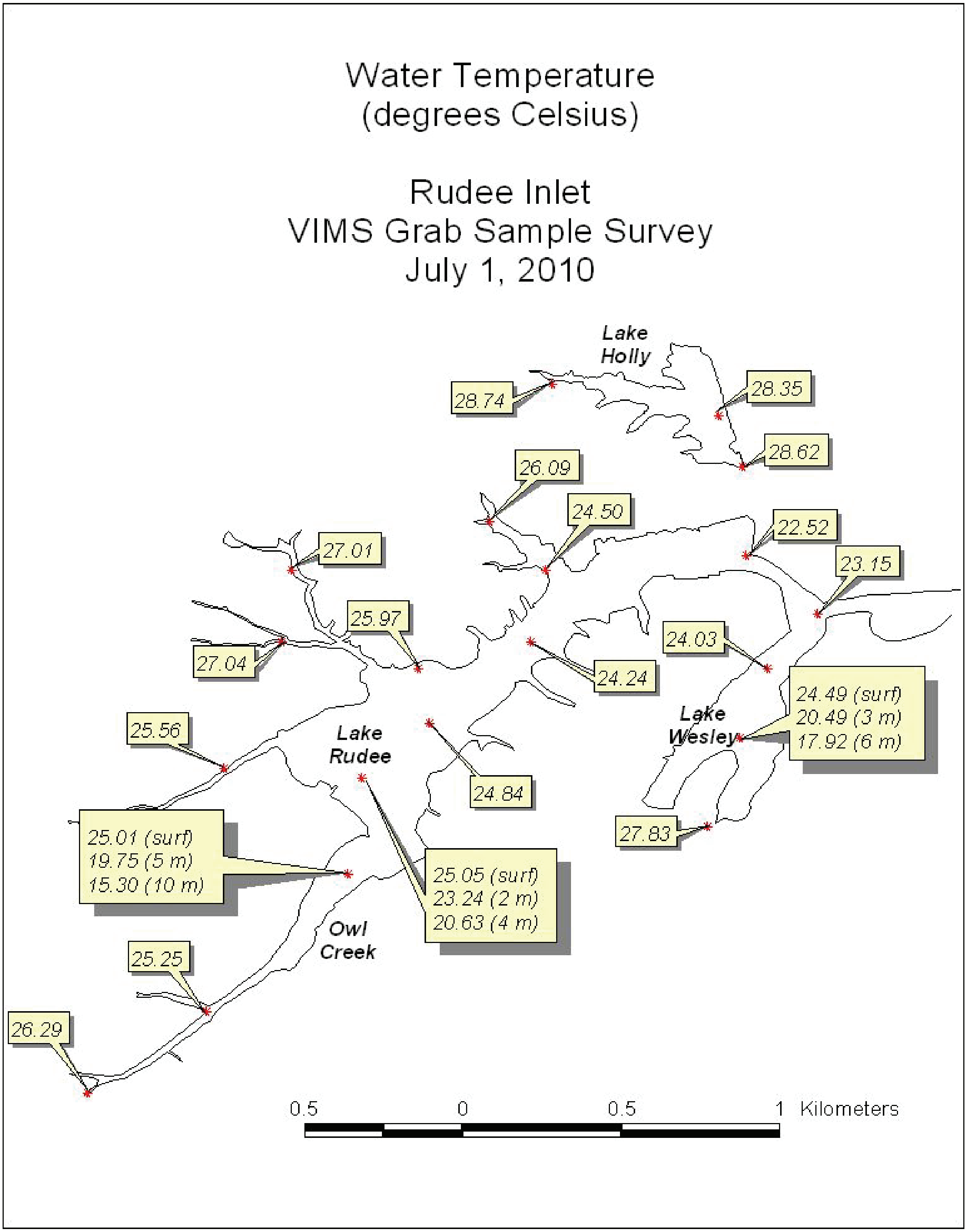


Figure II.33. Spatial plot of water temperature from Rudee Inlet system grab samples, July 1, 2010.

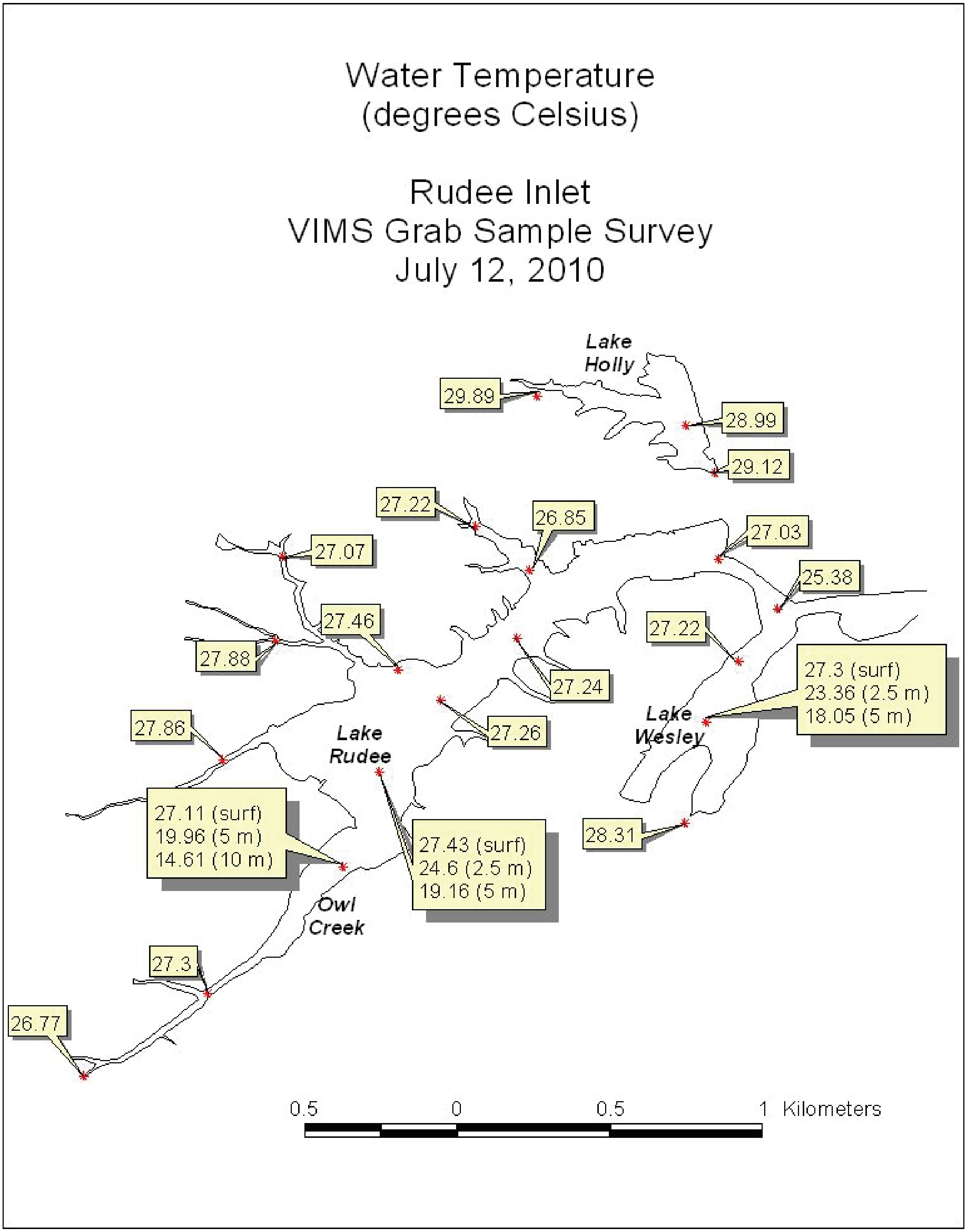


Figure II.34. Spatial plot of water temperature from Rudee Inlet system grab samples, July 12, 2010.

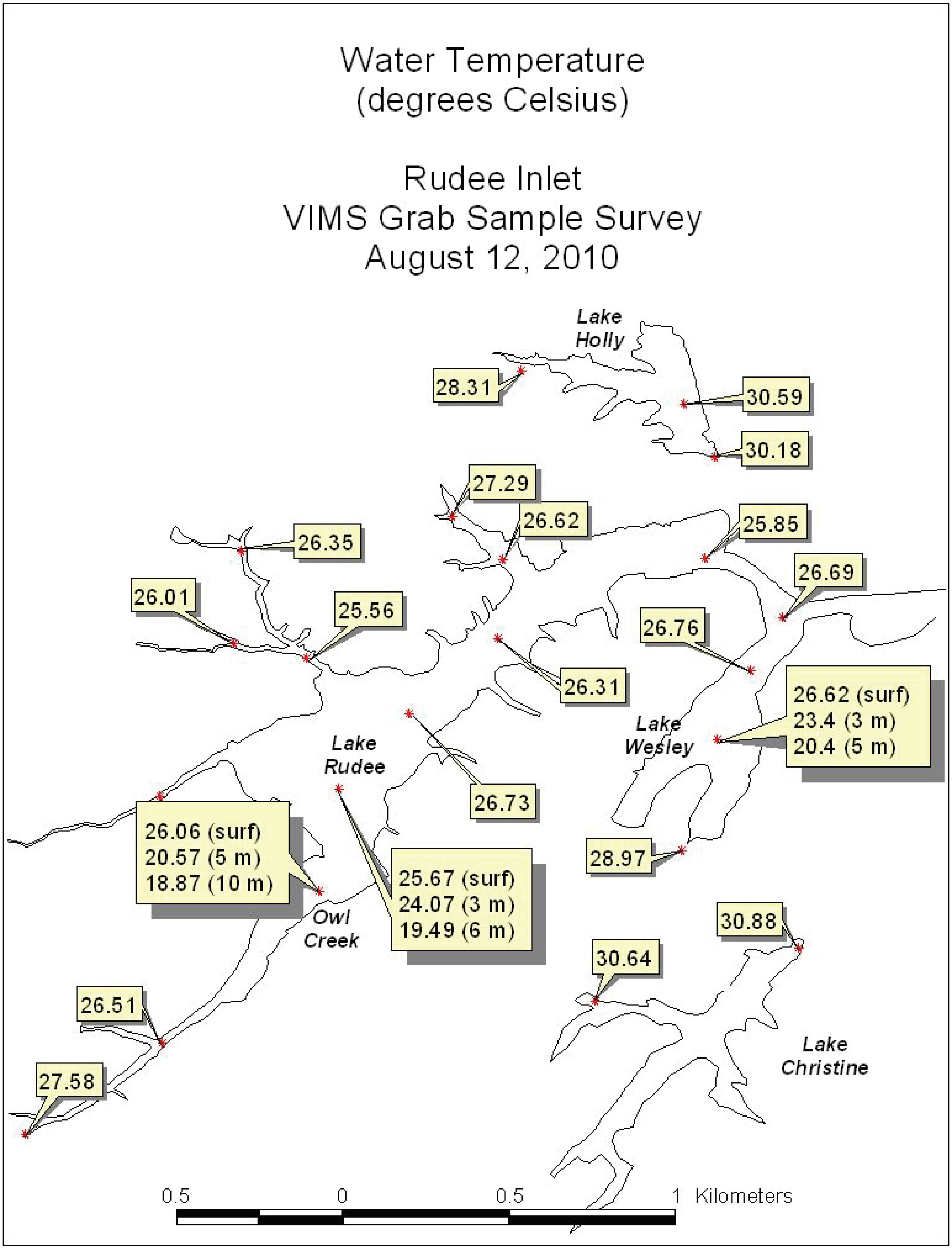


Figure II.35. Spatial plot of water temperature from Rudee Inlet system grab samples, August 12, 2010.

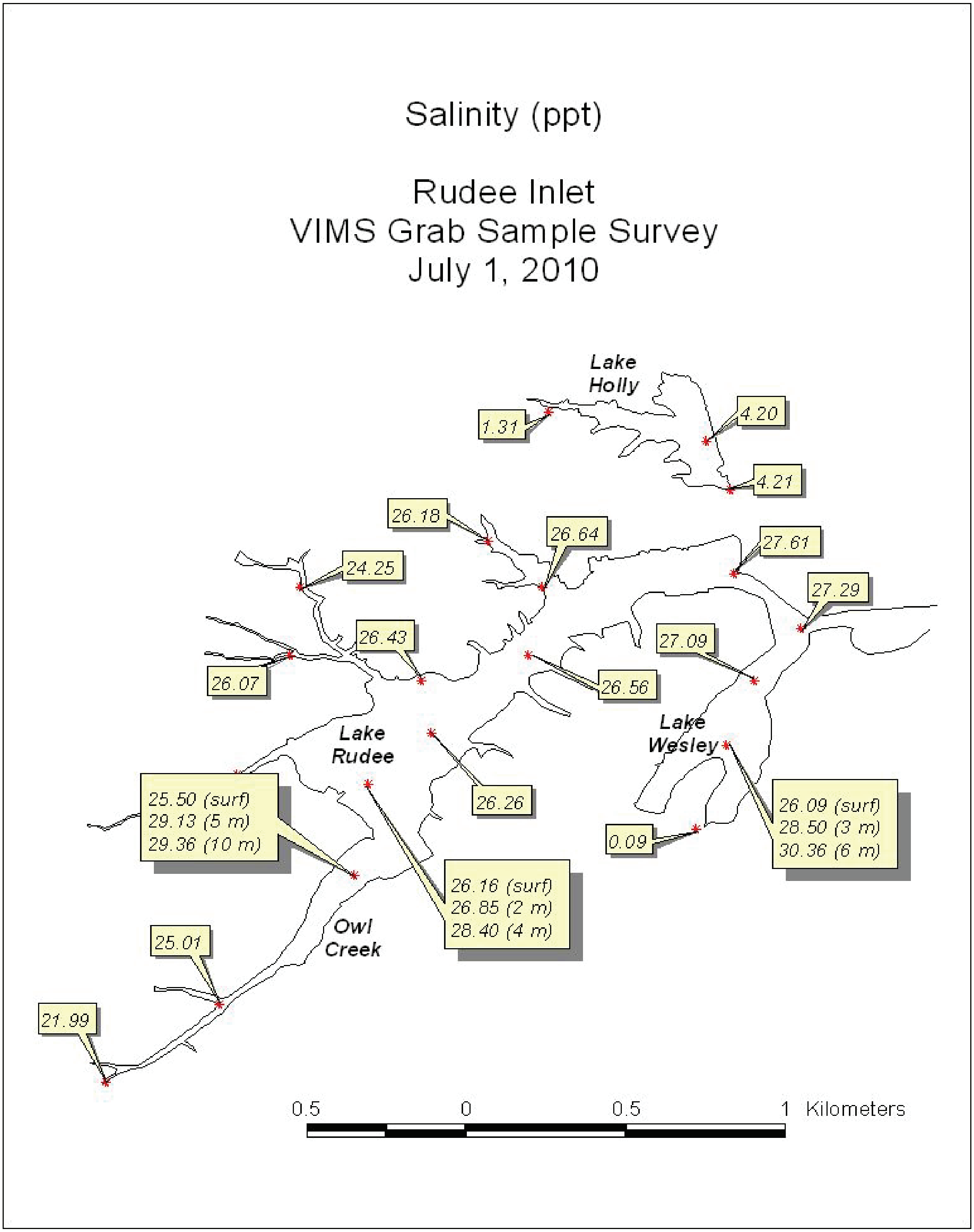


Figure II.36. Spatial plot of salinity from Rudee Inlet system grab samples, July 1, 2010.

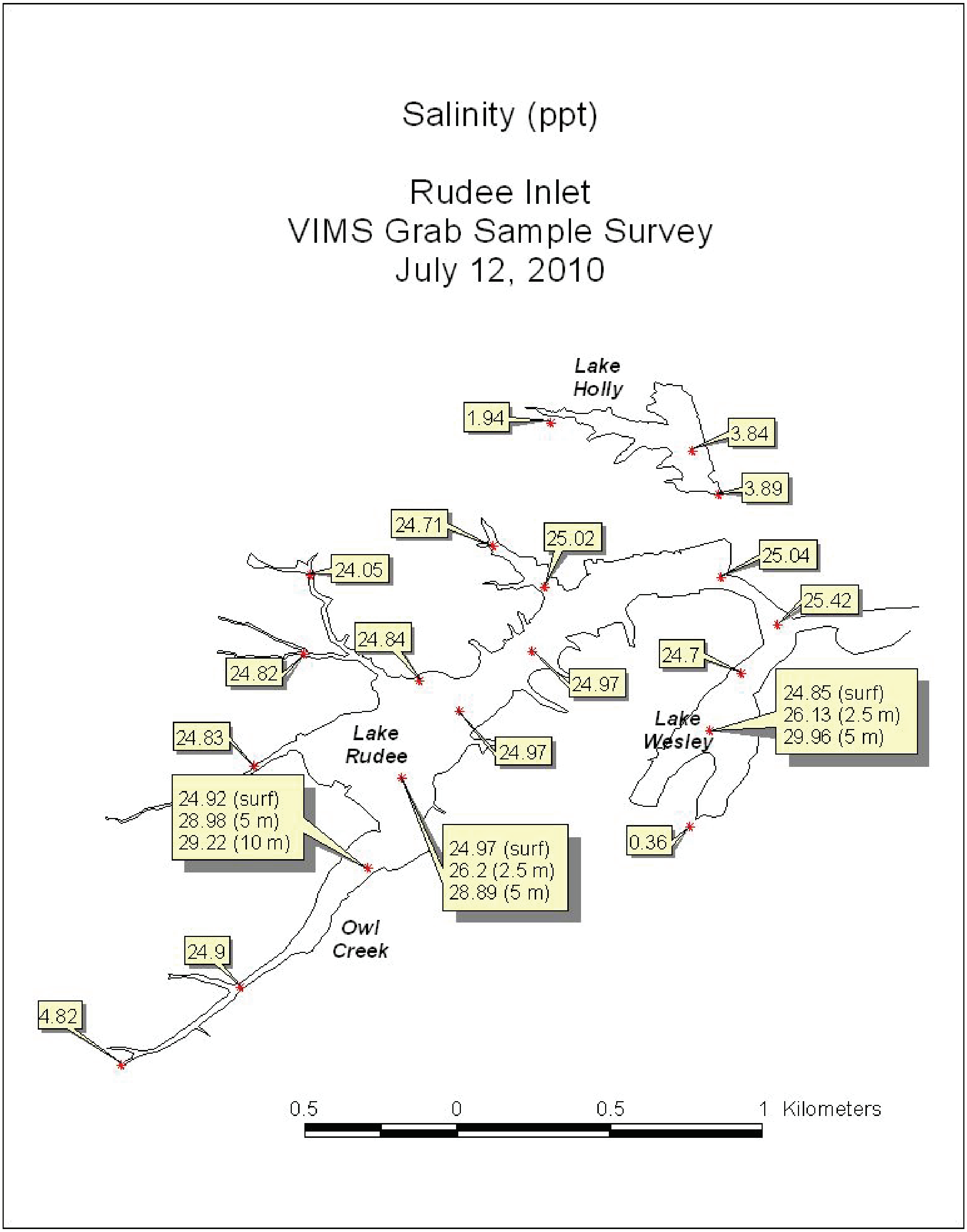


Figure II.37. Spatial plot of salinity from Rudee Inlet system grab samples, July 12, 2010.

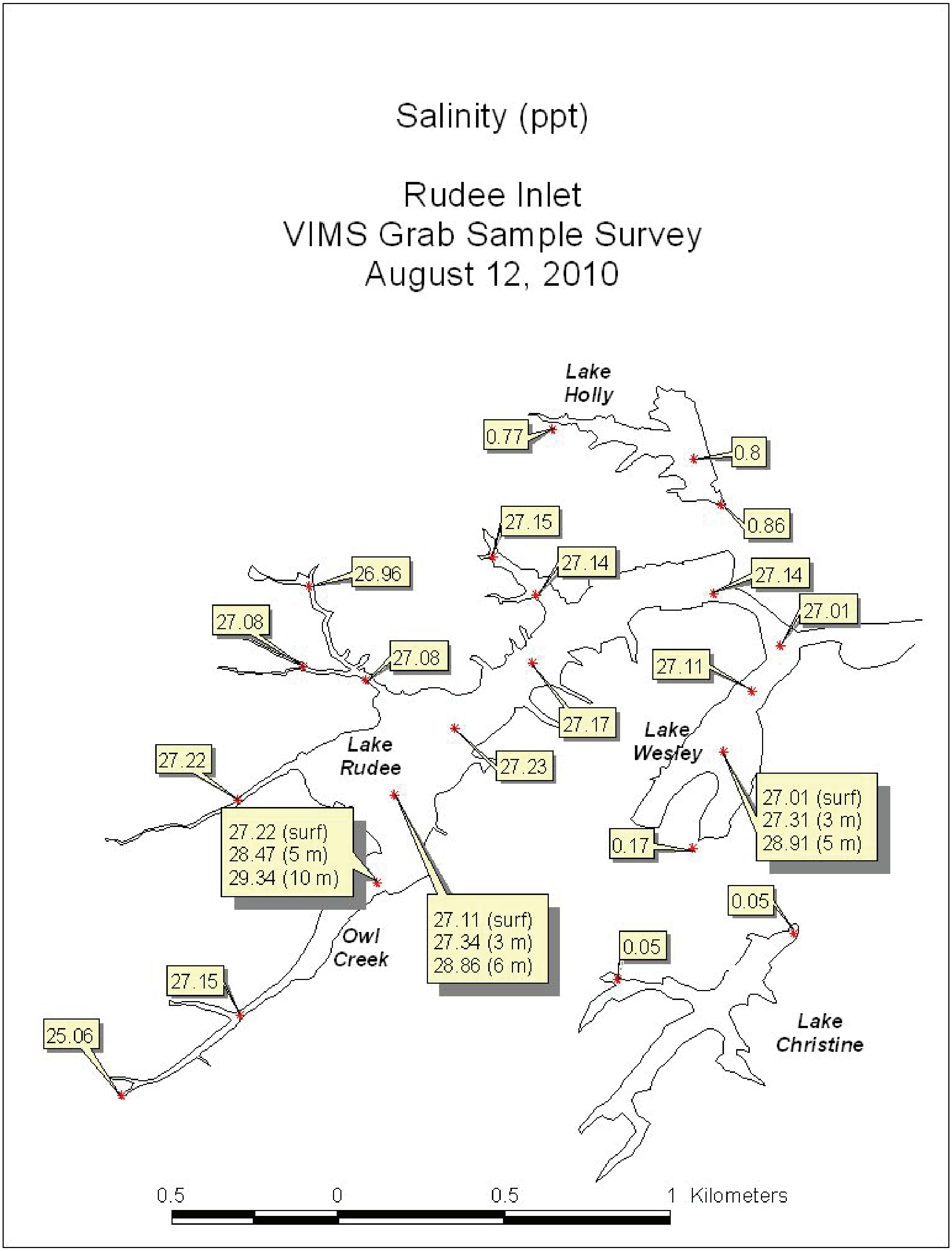


Figure II.38. Spatial plot of salinity from Rudee Inlet system grab samples, August 12, 2010.

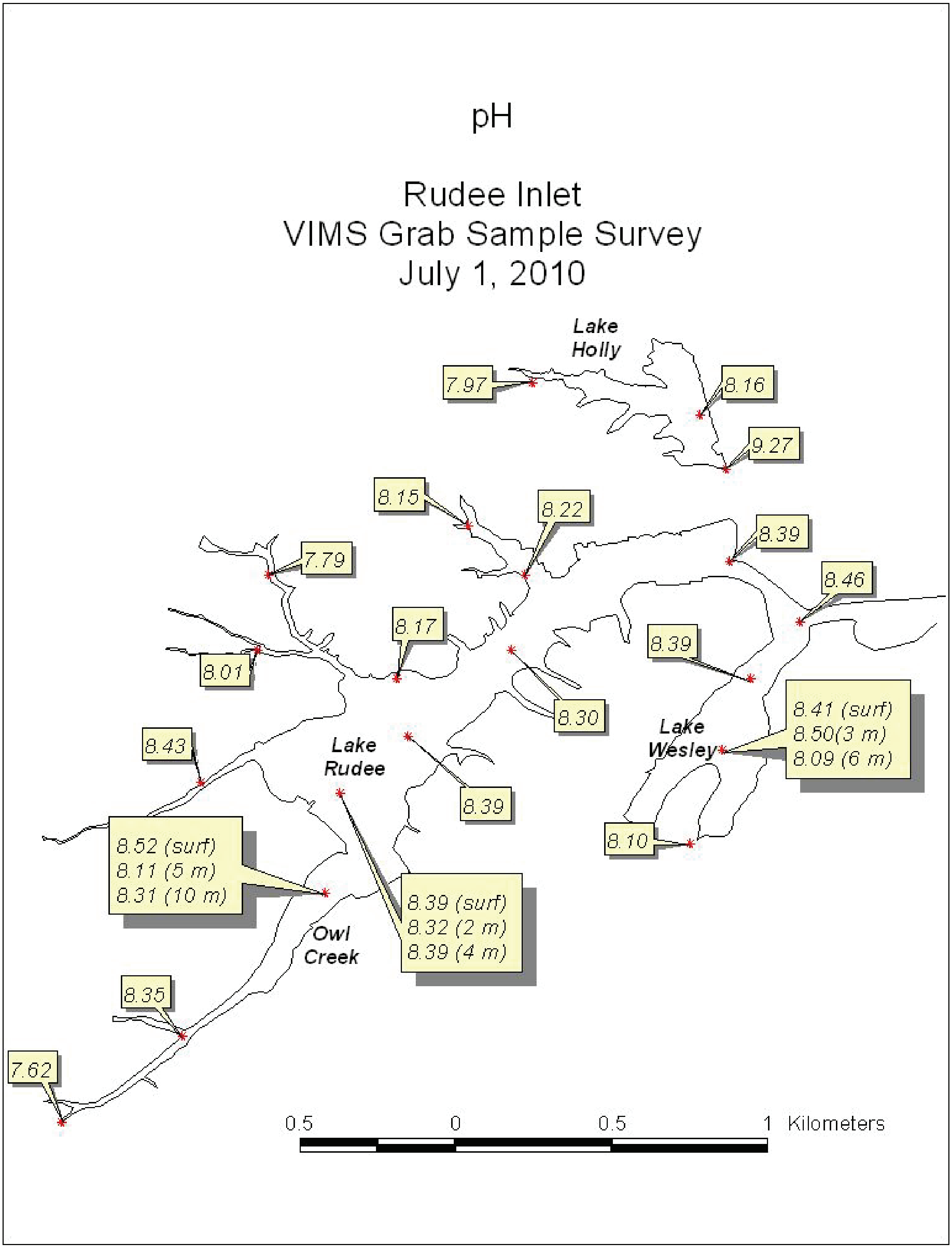


Figure II.39. Spatial plot of pH from Rudee Inlet system grab samples, July 1, 2010.

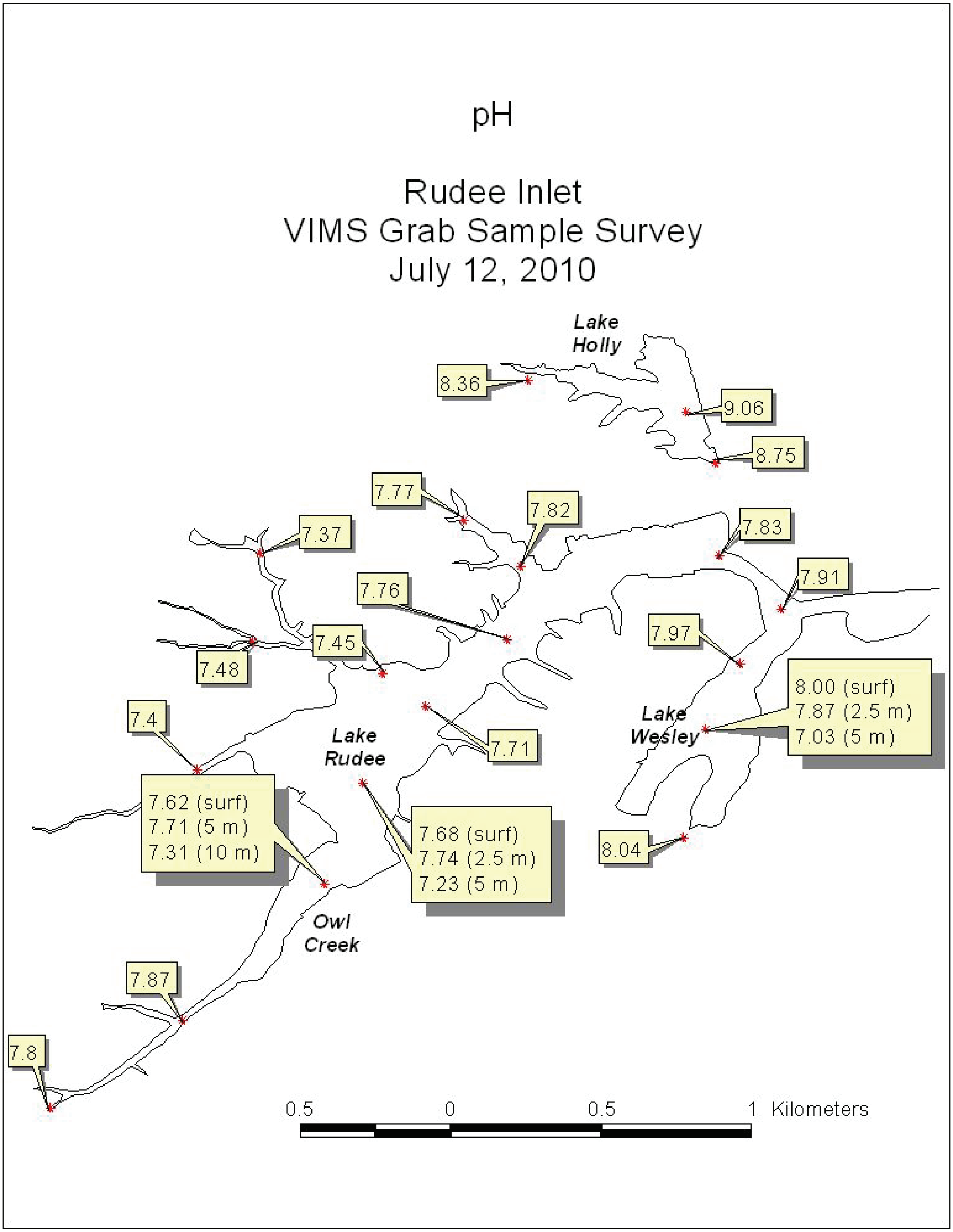


Figure II.40. Spatial plot of pH from Rudee Inlet system grab samples, July 12, 2010.

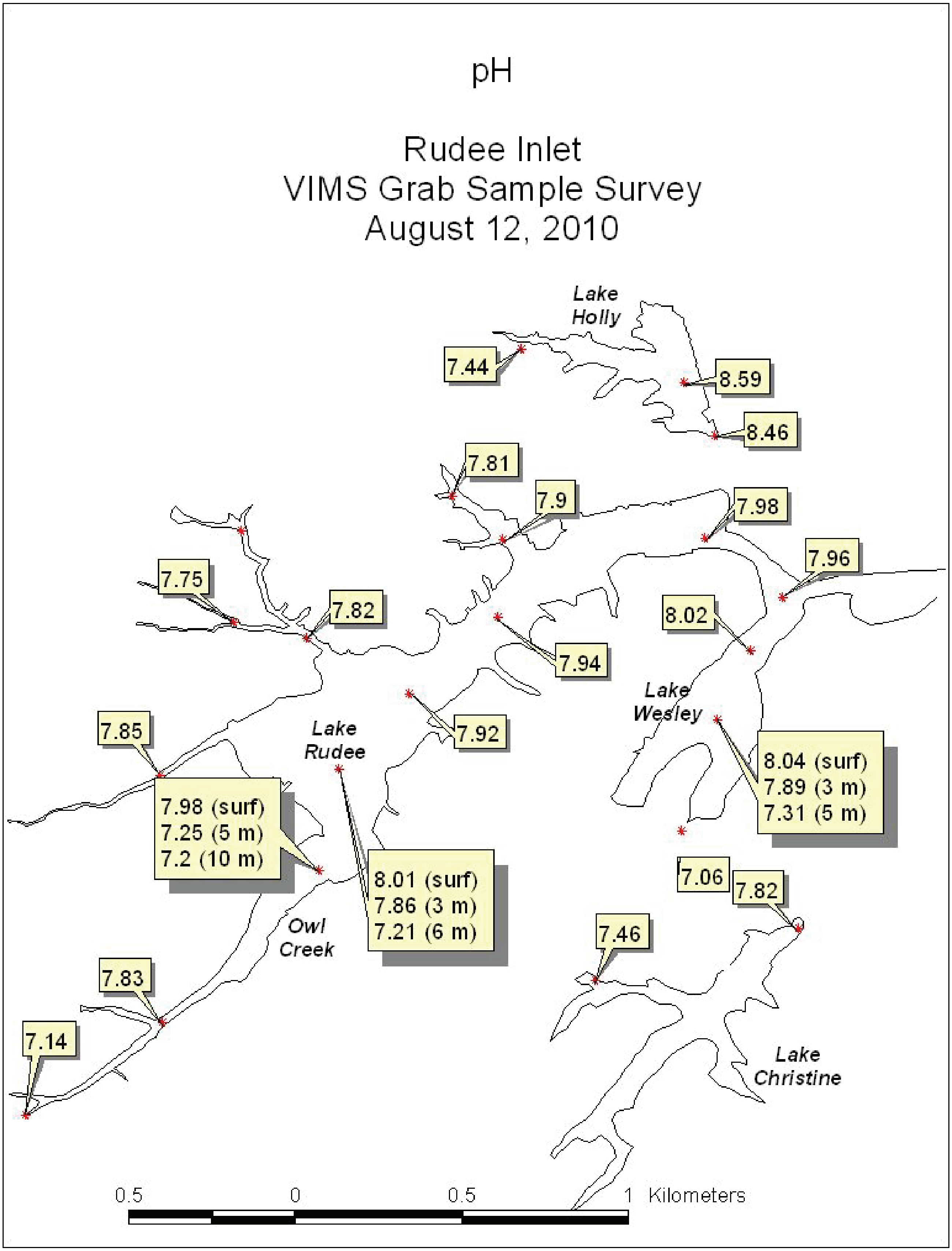


Figure II.41. Spatial plot of pH from Rudee Inlet system samples, August 12, 2010.

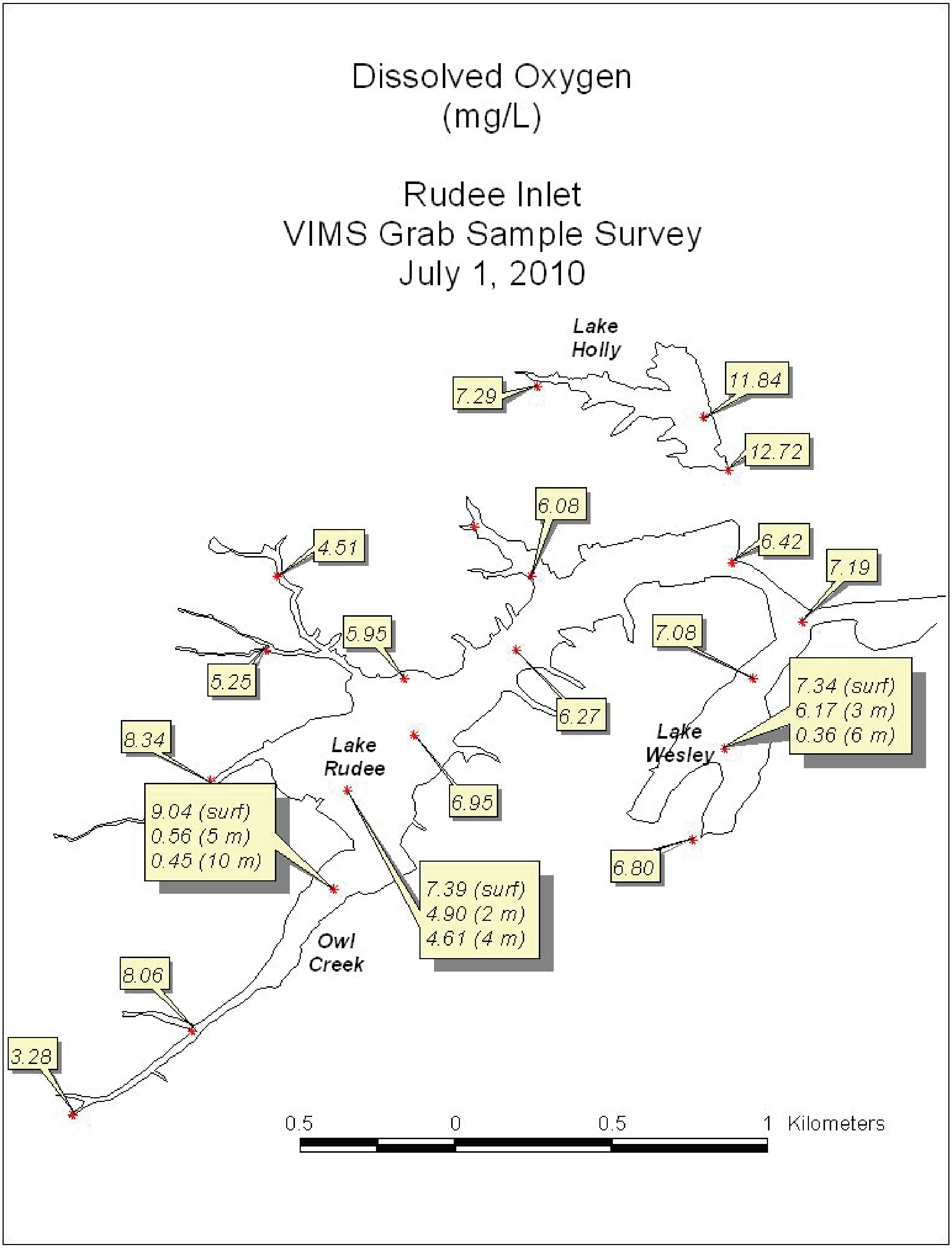


Figure II.42. Spatial plot of dissolved oxygen concentration from Rudee Inlet system grab samples, July 1, 2010.

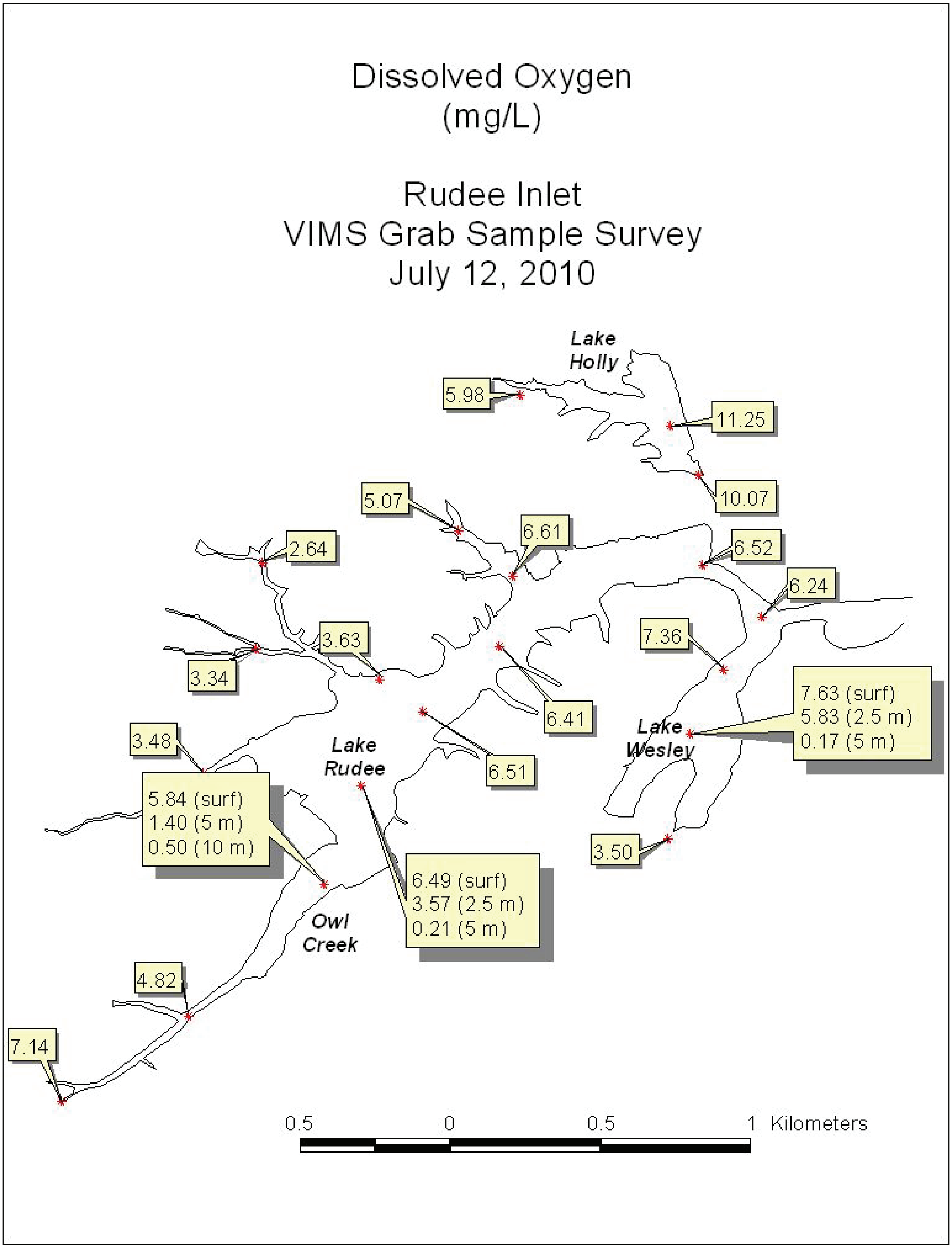


Figure II.43. Spatial plot of dissolved oxygen concentration from Rudee Inlet system grab samples, July 12, 2010.

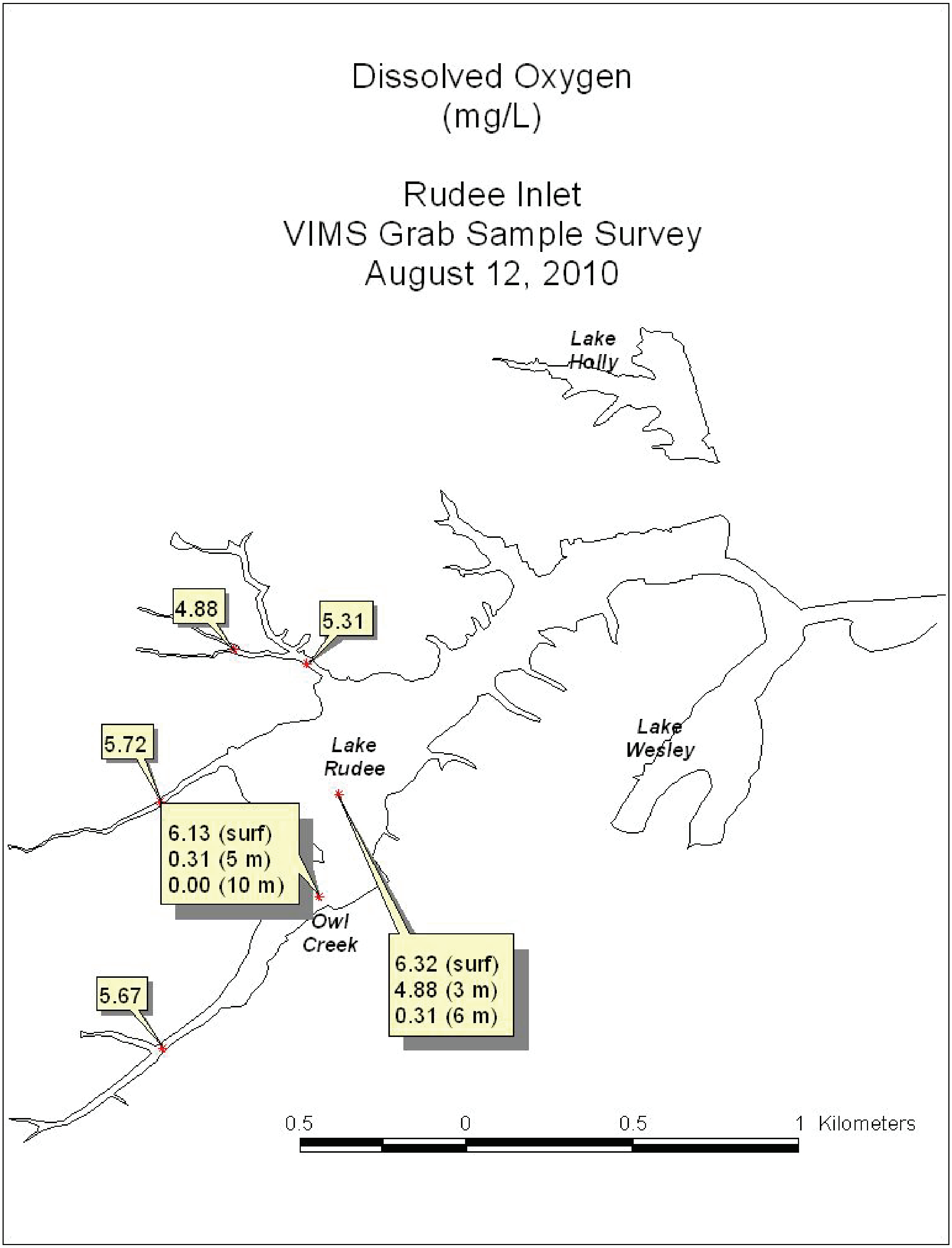


Figure II.44. Spatial plot of dissolved oxygen concentration from Rudee Inlet system grab samples, August 12, 2010.

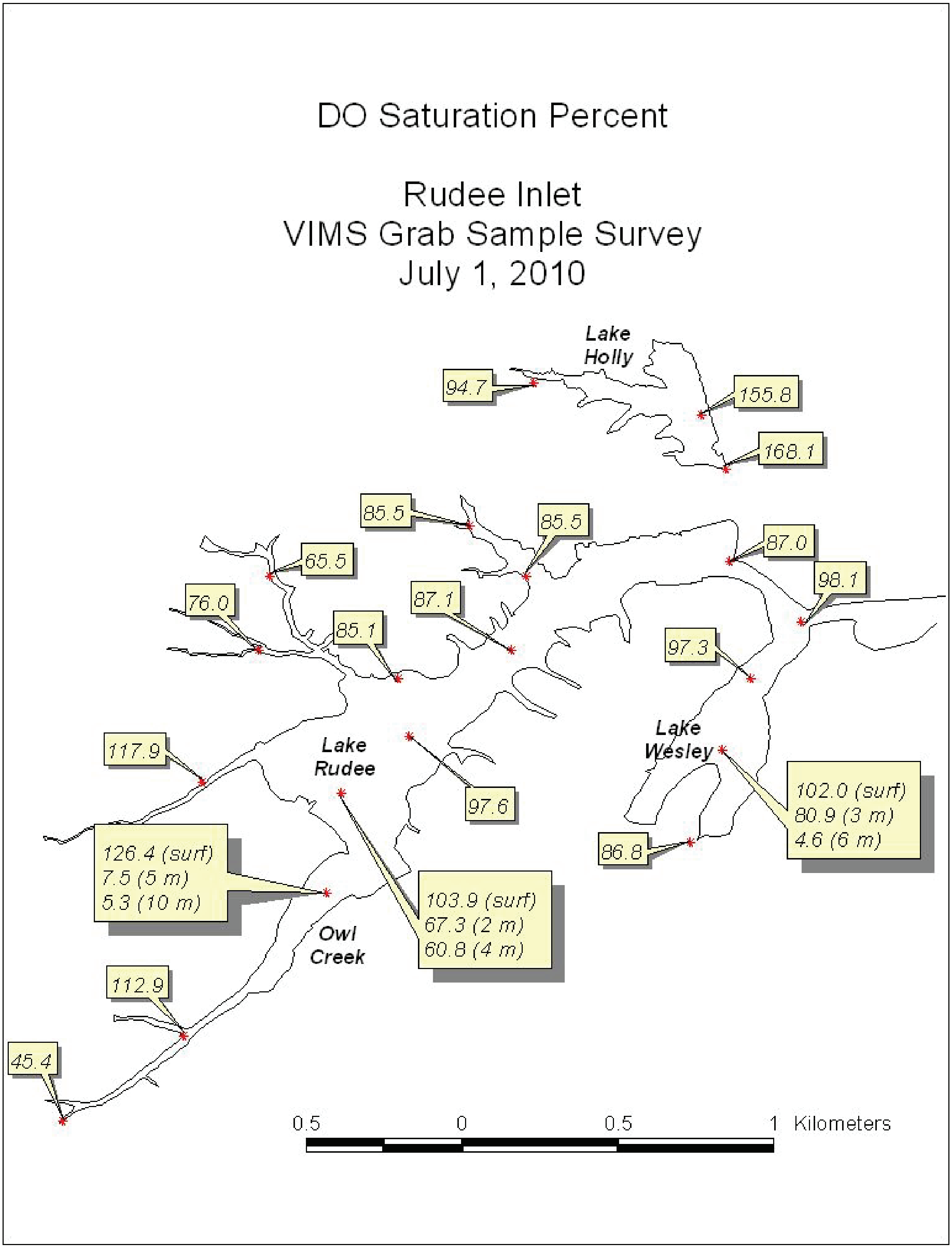


Figure II.45. Spatial plot of dissolved oxygen percent saturation from Rudee Inlet system grab samples, July 1, 2010.

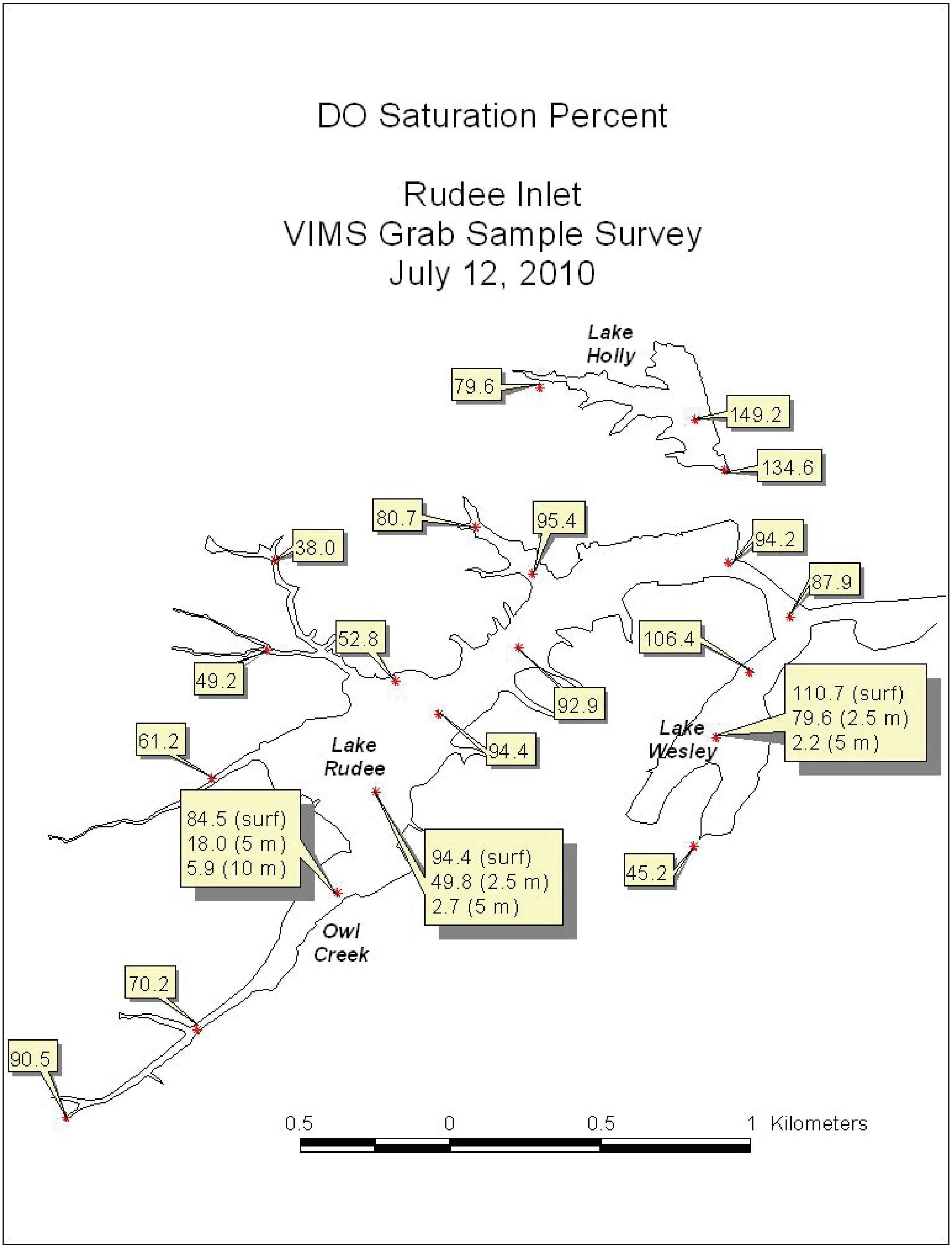


Figure II.46. Spatial plot of dissolved oxygen percent saturation from Rudee Inlet system grab samples, July 12, 2010.

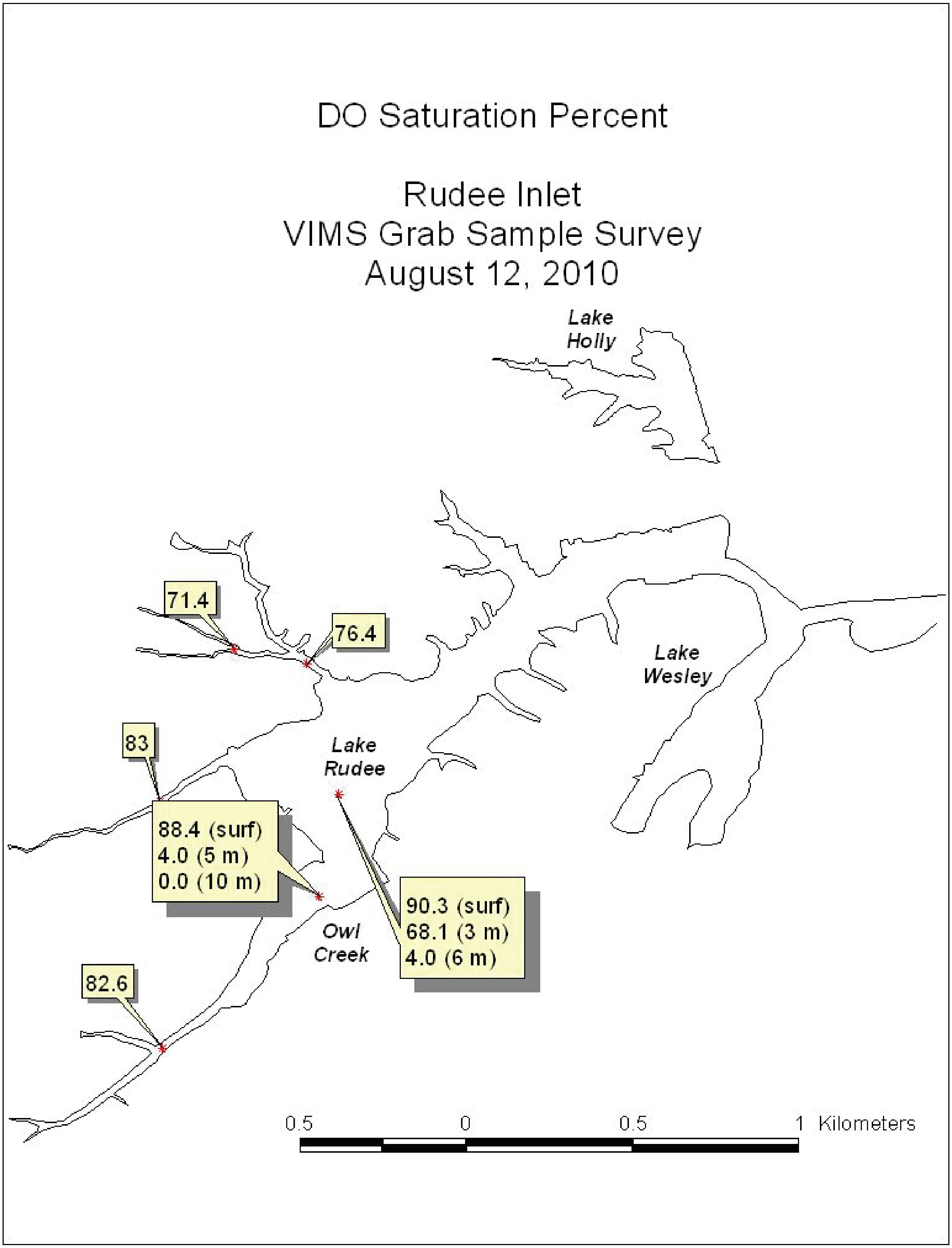


Figure II.47. Spatial plot of dissolved oxygen percent saturation from Rudee Inlet system grab samples, August 12, 2010.

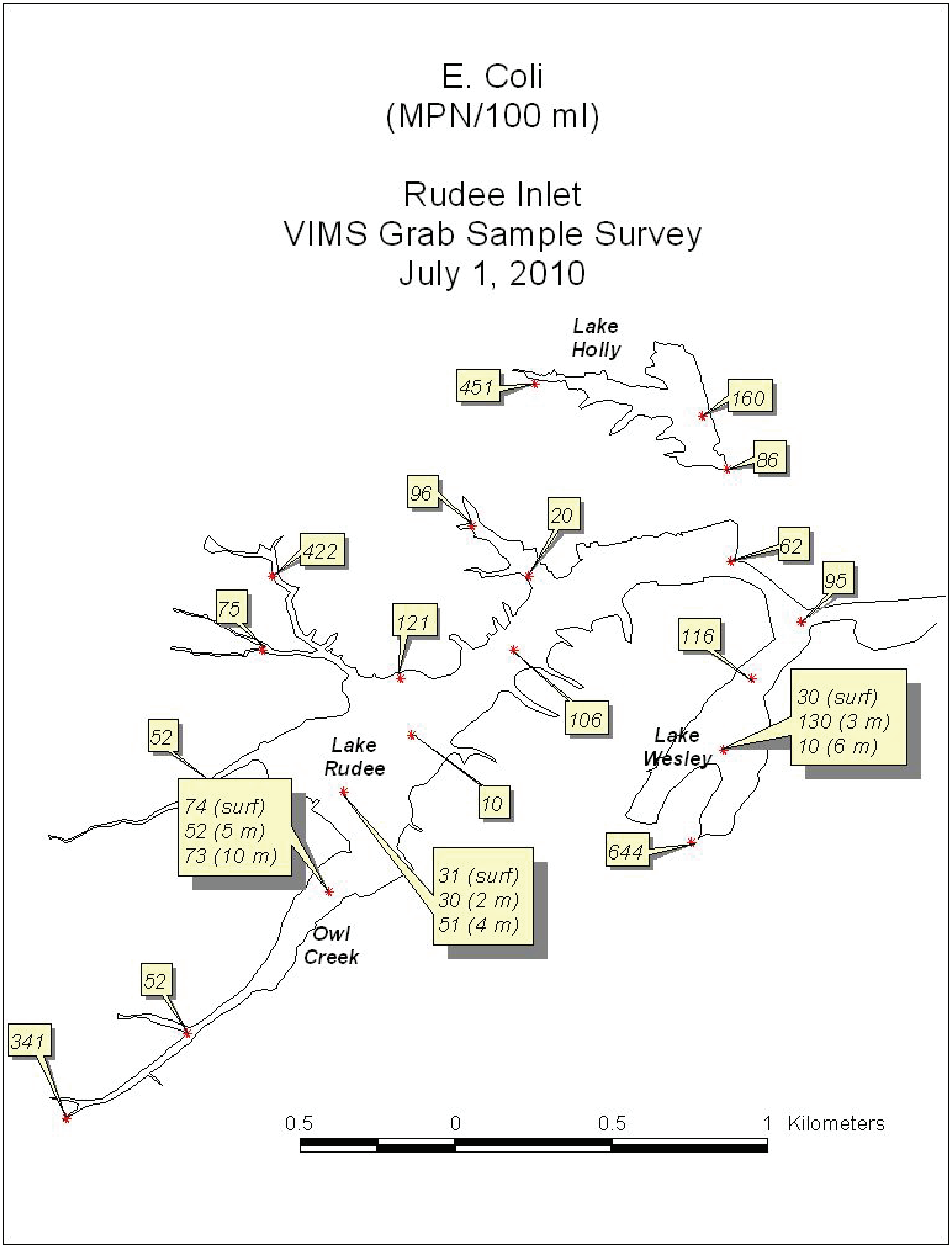


Figure II.48. Spatial plot of *E. coli* bacteria from Rudee Inlet system grab samples, July 1, 2010.

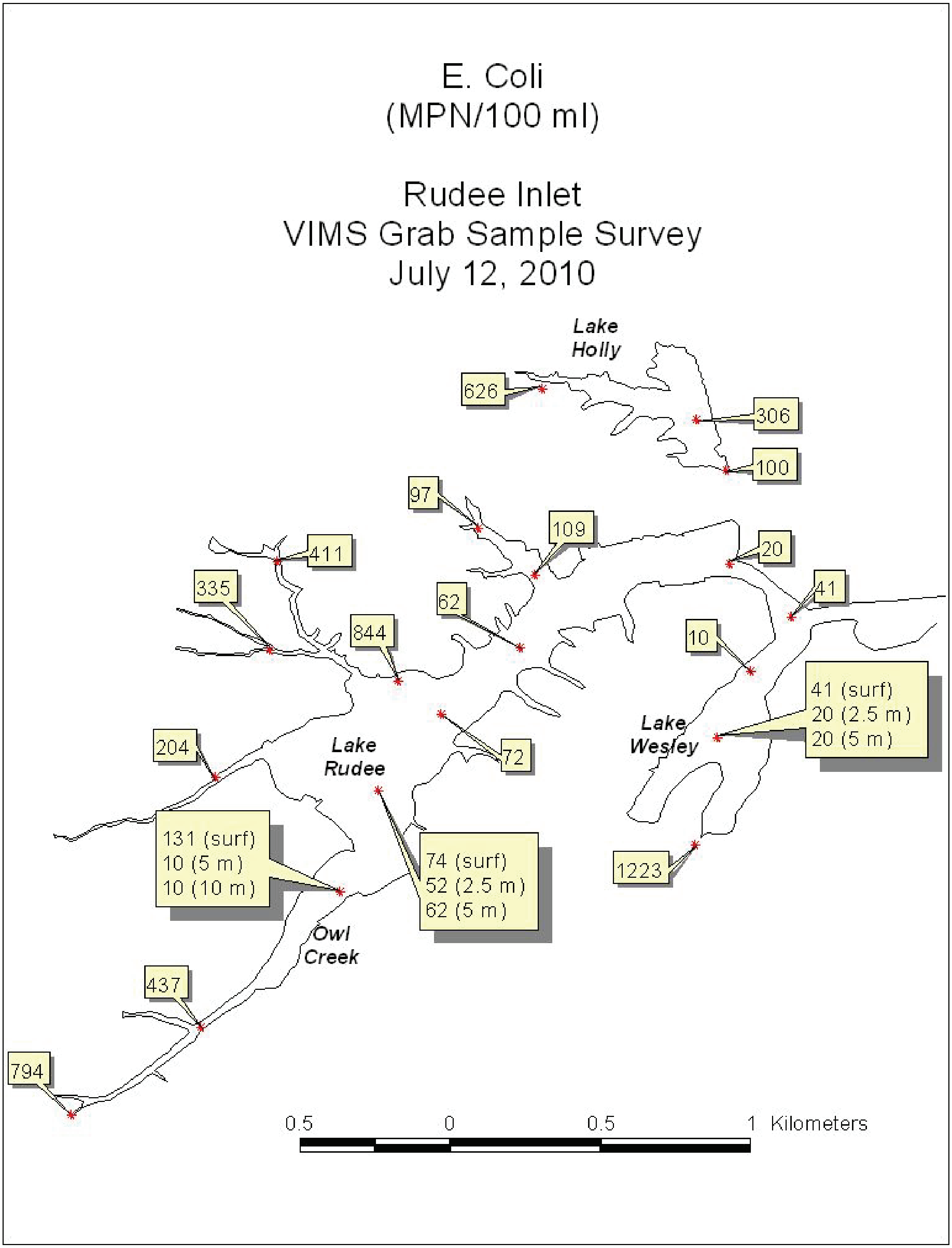


Figure II.49. Spatial plot of *E. coli* bacteria from Rudee Inlet system grab samples, July 12, 2010.

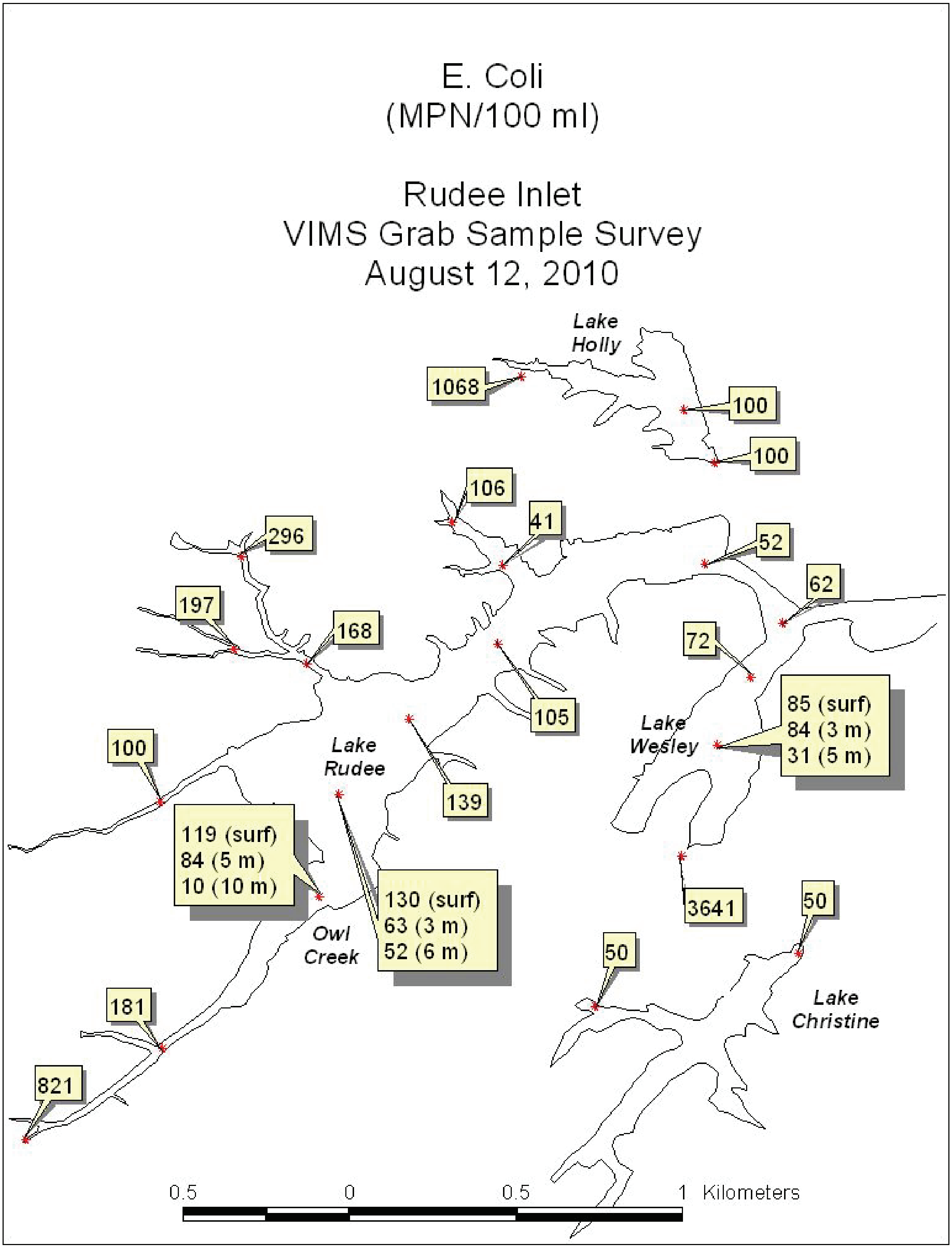


Figure II.50. Spatial plot of *E. coli* bacteria from Rudee Inlet system grab samples, August 12, 2010.

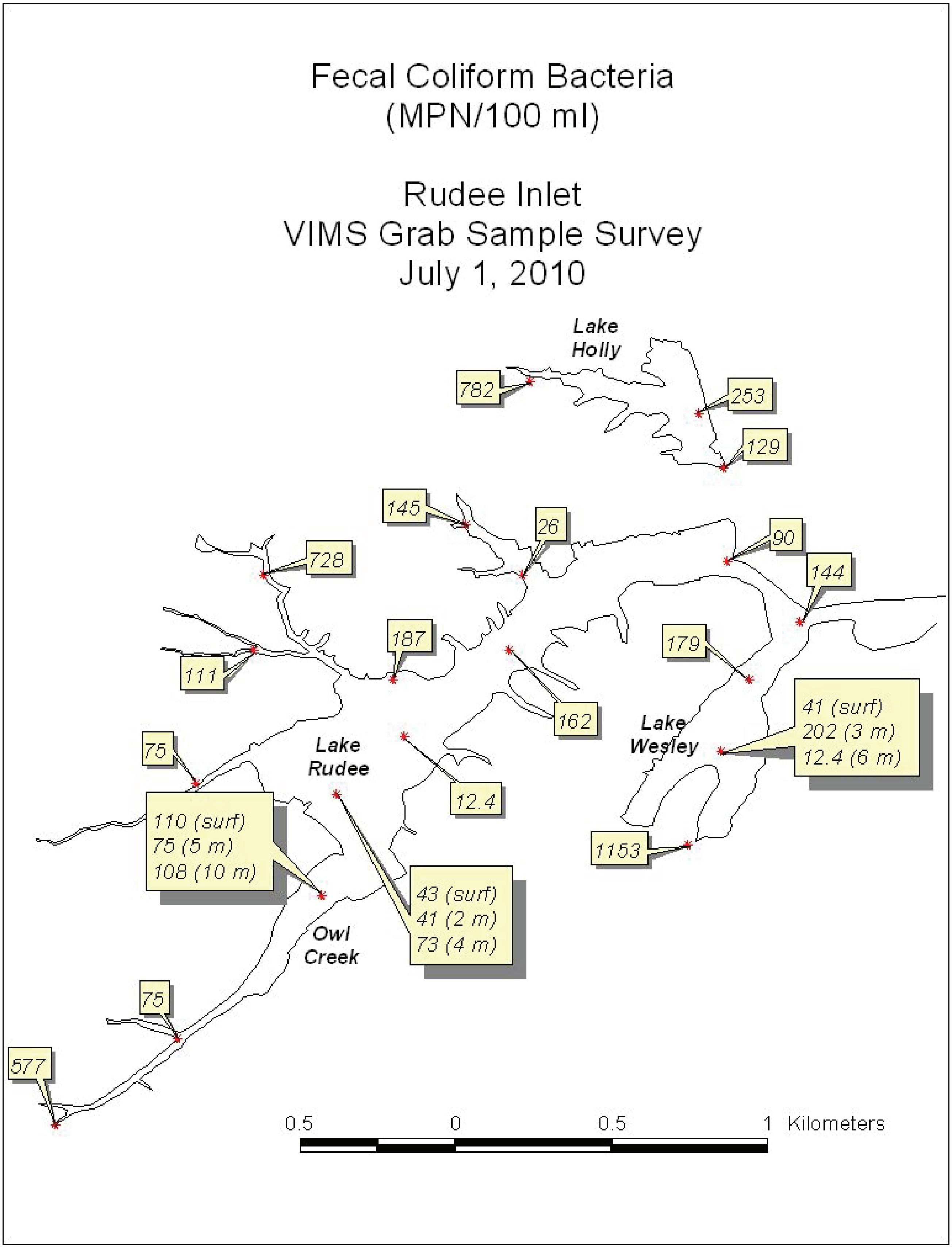


Figure II.51. Spatial plot of estimated fecal coliform bacteria from Rudee Inlet system grab samples, July 1, 2010.

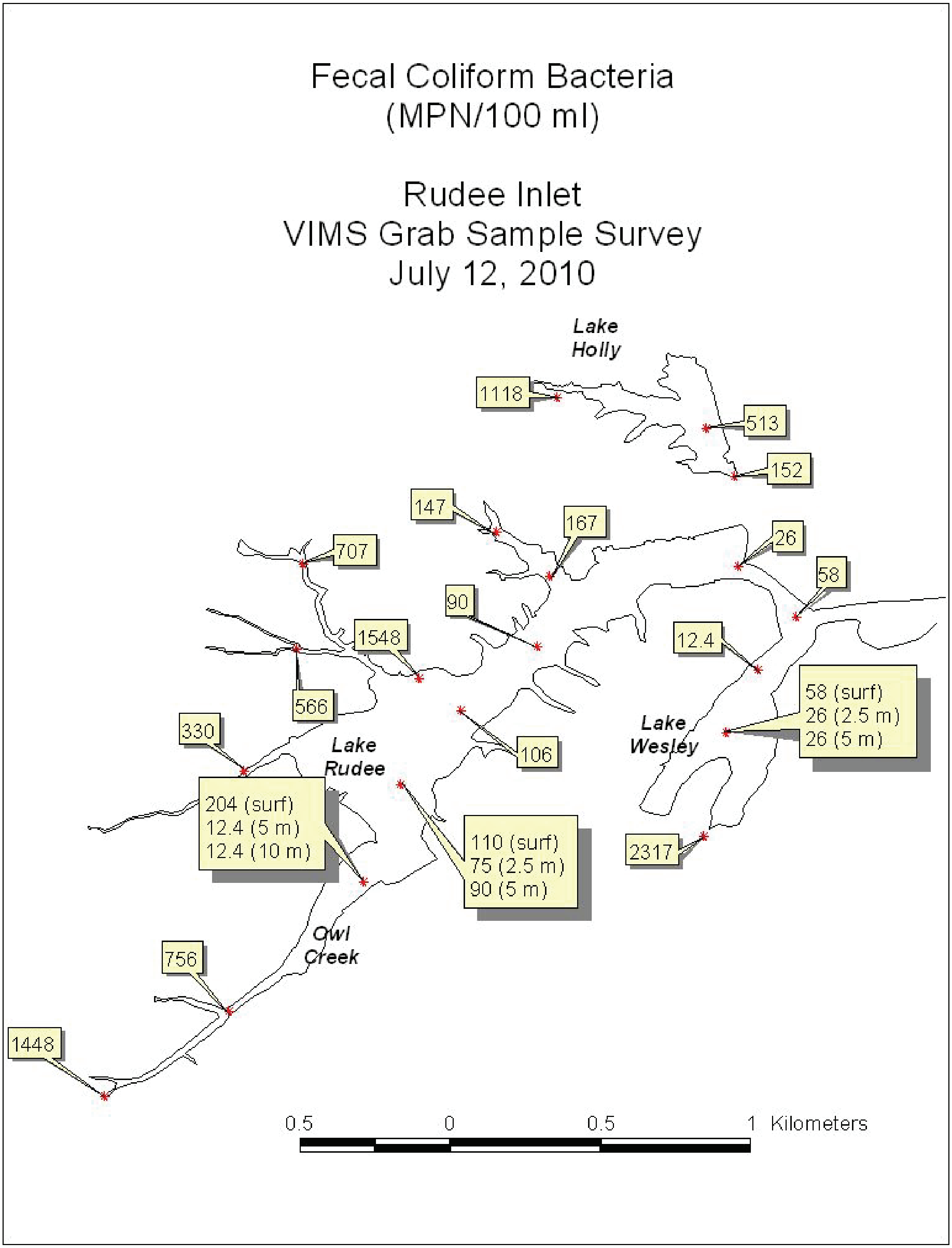


Figure II.52. Spatial plot of estimated fecal coliform bacteria from Rudee Inlet system grab samples, July 12, 2010.

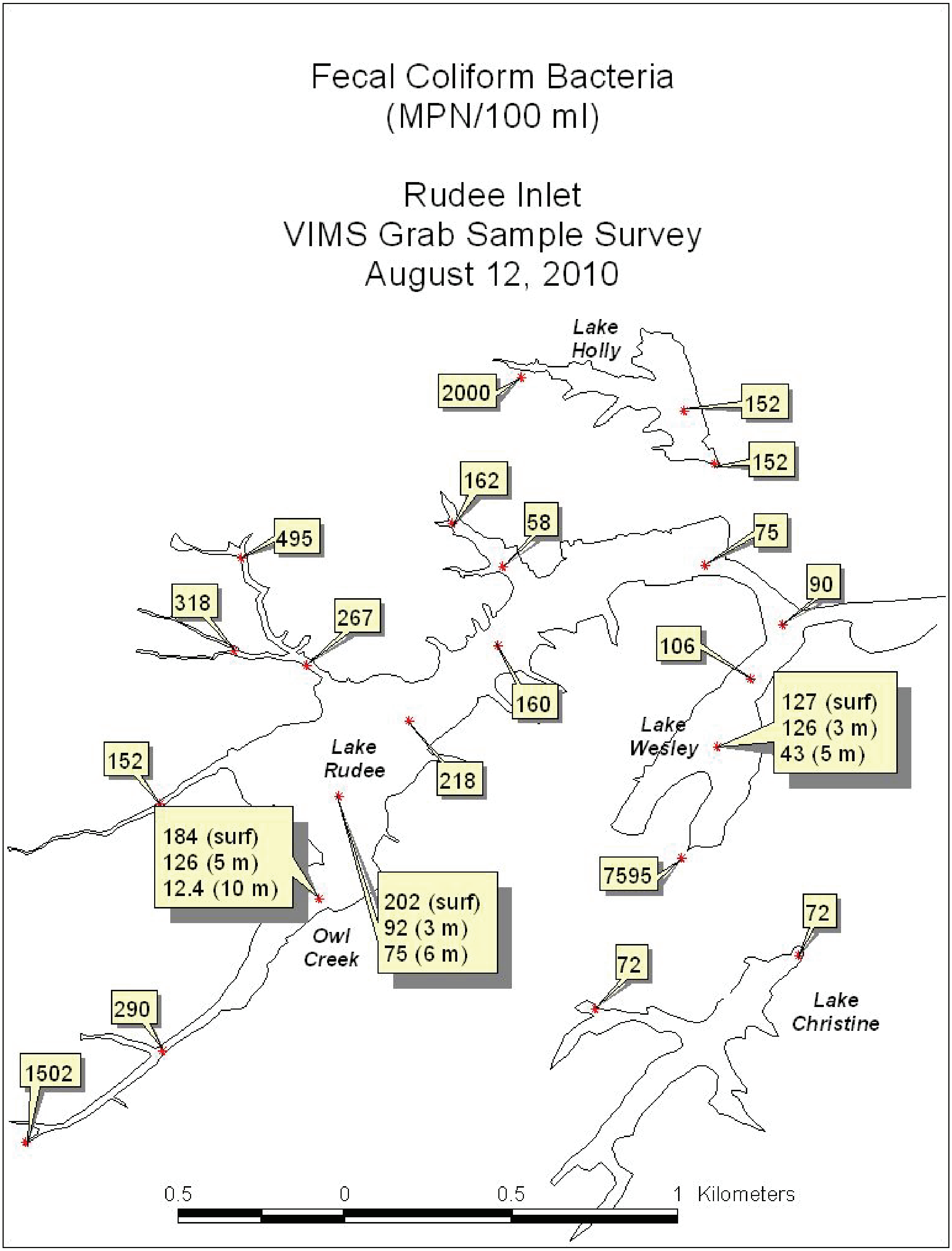


Figure II.53. Spatial plot of estimated fecal coliform bacteria from Rudee Inlet system grab samples, August 12, 2010.

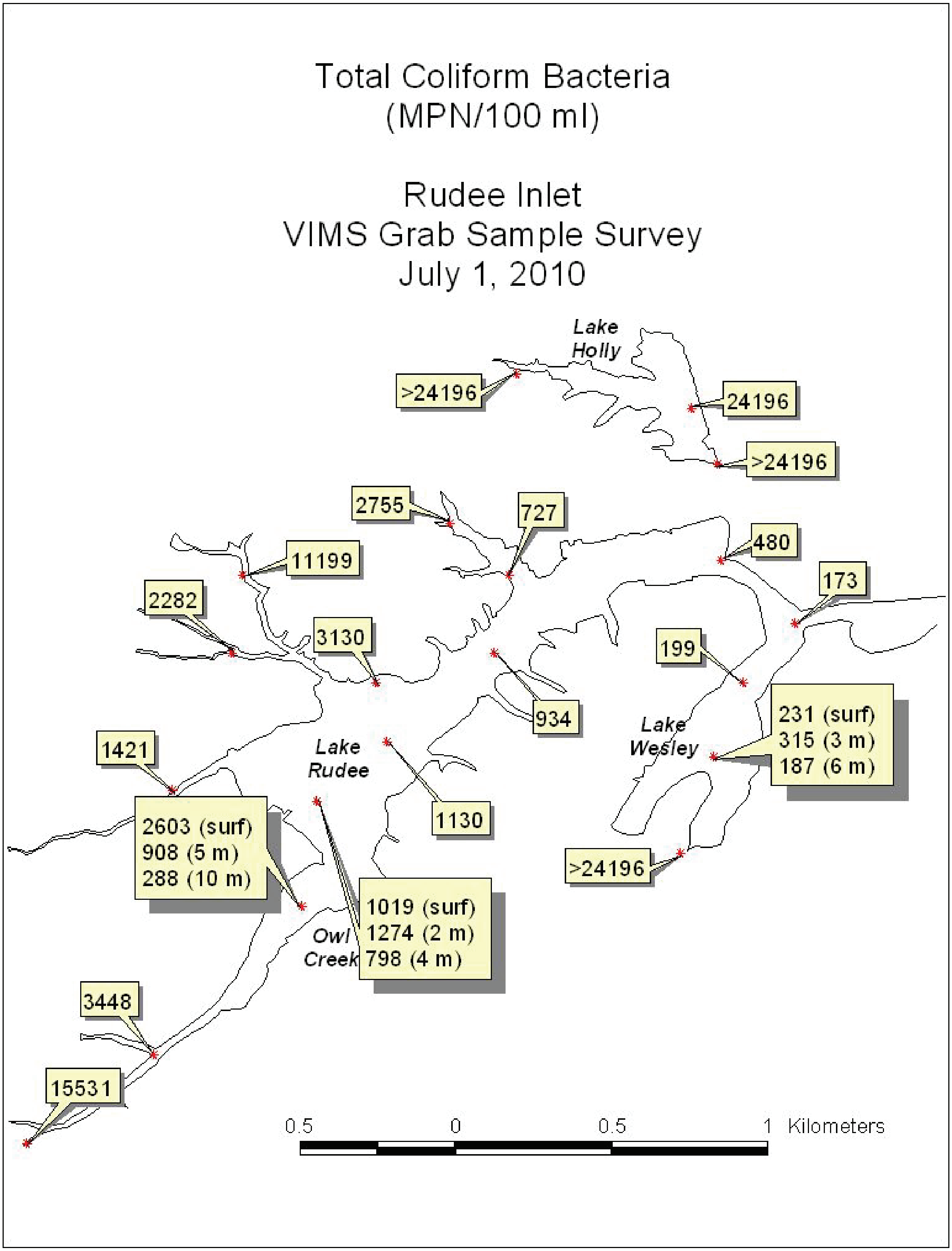


Figure II.54. Spatial plot of total coliform bacteria from Rudee Inlet system grab samples, July 1, 2010.

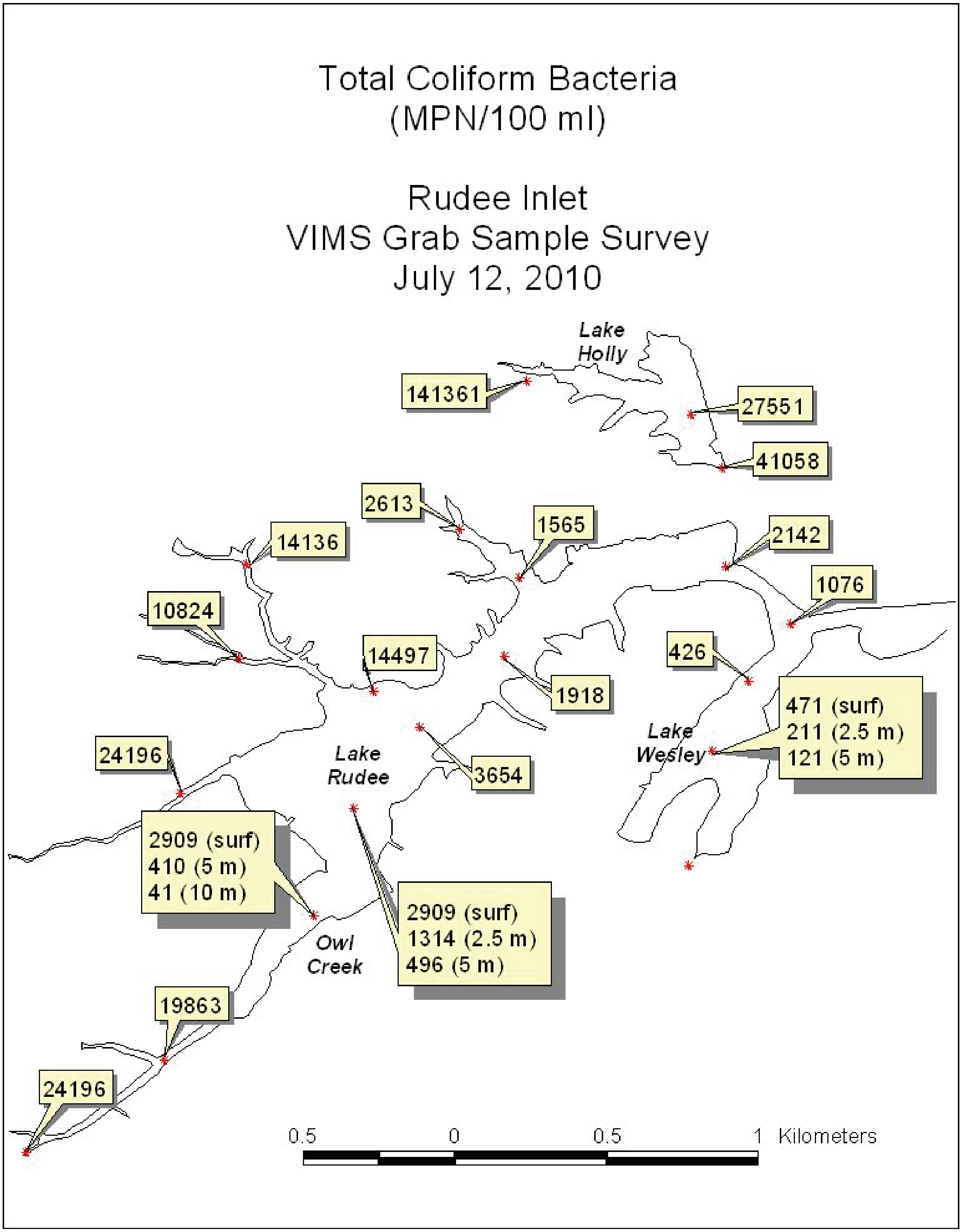


Figure II.55. Spatial plot of total coliform bacteria from Rudee Inlet system grab samples, July 12, 2010.

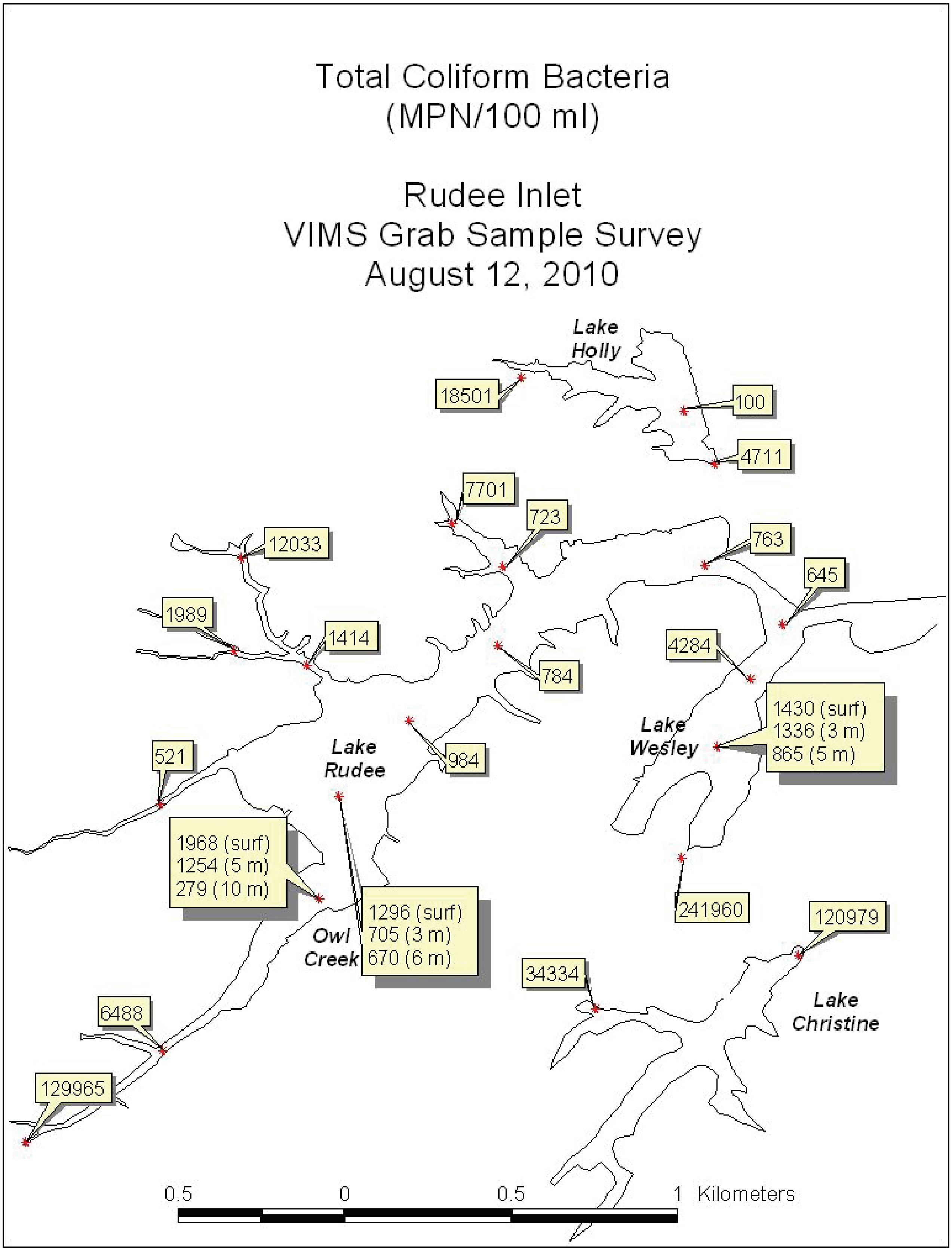


Figure II.56. Spatial plot of total coliform bacteria from Rudee Inlet system grab samples, August 12, 2010.

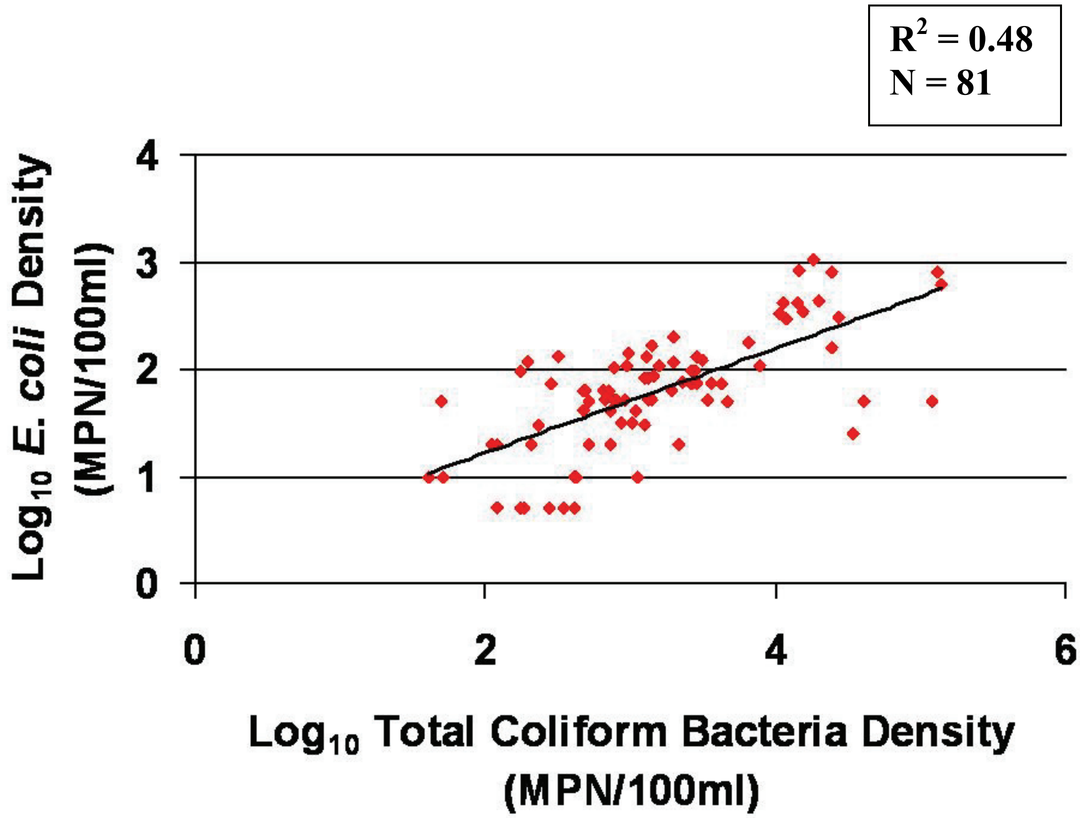


Figure II.57. Scatter plot depicting the relationship between log transformed TCB and *E. coli* densities for all samples collected within the Rudee Inlet system (including adjacent offshore waters, tidal waters within the Rudee Inlet system, and Lakes Holly and Christine). Values greater than maximum reportable values were deleted from analysis and values less than the minimum detectable limit were assigned a value equal to ½ the detection limit. A significant linear relationship ($p=0.00$; $r^2=0.48$, $N=81$) was found between log transformed TCB and E. coli densities for samples collected during this study period. Elevated counts of TCB and E. coli were associated with the upper reaches of selected tidal creeks and non-tidal freshwater sources.

II-6 Vertical Water Quality Profiles

Vertical profiles were collected when instrumentation for ConMon water quality stations were either deployed or collected. Profile data was collected on June 17 and 28, July 12 and 26, and August 10 and 23, 2010, under a variety of time of day and tidal stage conditions. Vertical water quality profiles, by sampling date are provided in Figures II.58-II.69.

The six ConMon water quality stations can be broadly classified as shallow (depths typically ≤ 3m; ConMon stations 1, 3 and 6) and deep water (depths > 5m; ConMon stations 2, 4 and 5) stations. With respect to temperature, salinity and water density, the shallow water stations were relatively well mixed. Temperature, salinity and density differences between surface and bottom waters were on the order <1 to 5 °C, <1 to 2 ppt, and <1 to 2 kg/m^3, respectively. The primary exception occurred at ConMon station 1 on June 28, 2010 where elevated temperature differences (on the order of 7 °C) were observed between surface and bottom waters, resulting in a more observable pycnocline at approximately 1.5 m in depth. Depth variations in pH were generally < 0.4 standard units at the shallow water stations. On many occasions, pH values increased 0.1 to 0.3 units within the upper 0.2 to 0.3 with no clear increasing or decreasing trend with depth. Dissolved oxygen concentrations were generally near saturated levels at the surface and showed a moderate decrease (down to 60-80% saturation limits) with depth. No hypoxia was observed during the vertical samplings at the shallow water stations.

In contrast to the shallow water stations, the deeper water stations (ConMon stations 2,4 and 5) exhibited moderate to strong vertical variations in water quality parameters. Water temperature commonly decreased between 8 to 12 °C from surface at bottom waters whereas salinity typically increased between 2 to 4 ppt. Due to the combination of decreased water temperatures and increased salinity, pycnoclines were more readily observed at the deeper water stations. Good examples of developed pycnoclines include ConMon station 2 on the July 26 sampling and ConMon station 5 on the July 12, July 26, and August 10 samplings. Stratification of the water column can lead to or exacerbate water quality degradation by reducing mixing between surface and bottom waters. pH values exhibited similar increases within the upper 0.5 m of water column and then decreased with depth to minimum bottom water levels on the order of 6.5 to 7.0 standard units. The greatest rate of pH decline was associated with the pycnocline region. Dissolved oxygen levels showed dramatic decreases with depth. In all cases, near surface dissolved oxygen levels were at or near saturation limits and decreased to hypoxic levels, defined as > 0 to < 30% $DO_{\%sat}$ and $DO_{conc} \leq 2.0\ mg \cdot L^{-1}$, below the pycnocline. As with pH, the greatest rate of dissolved oxygen decline was associated with the pycnocline region.

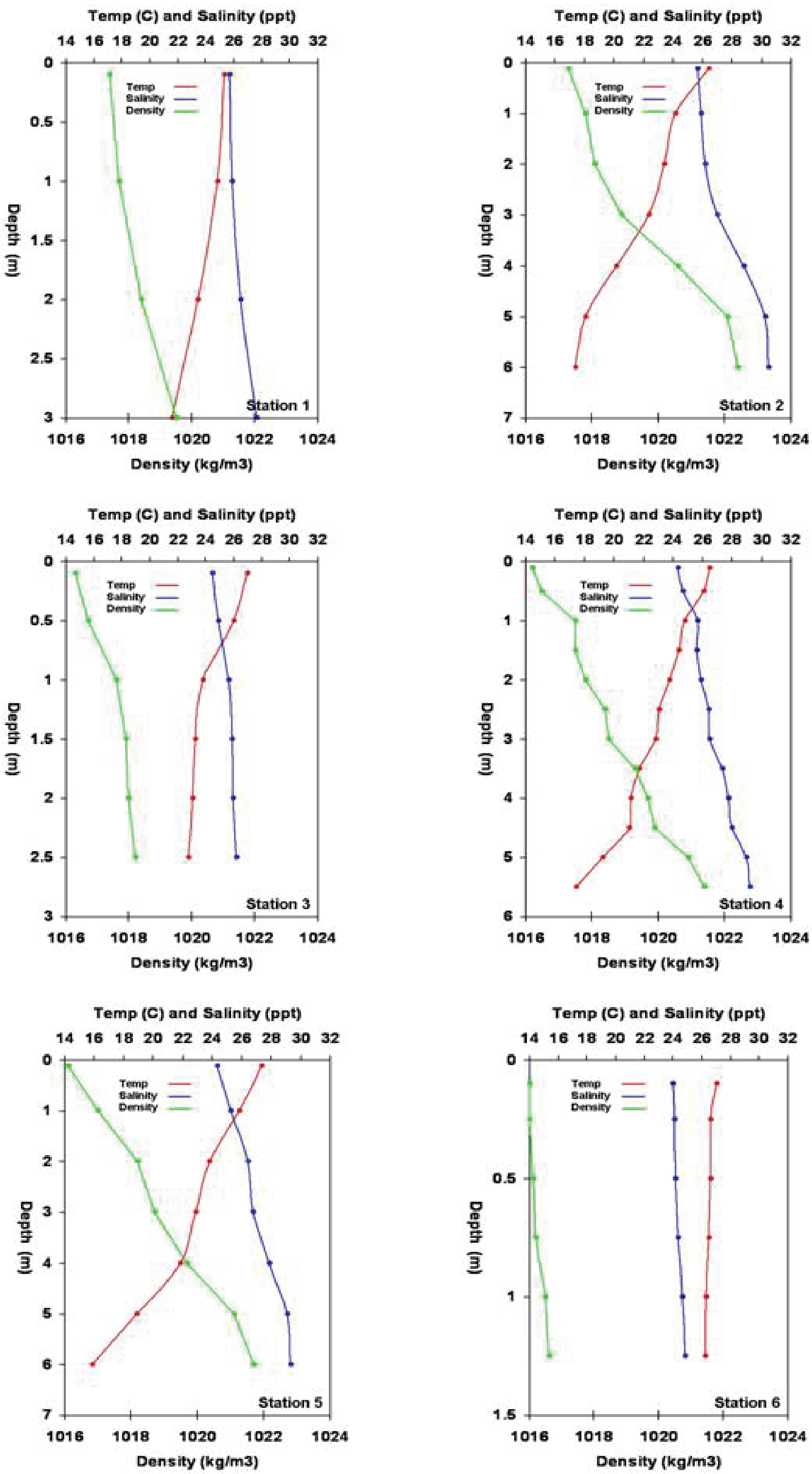


Figure II.58. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, June 17, 2010.

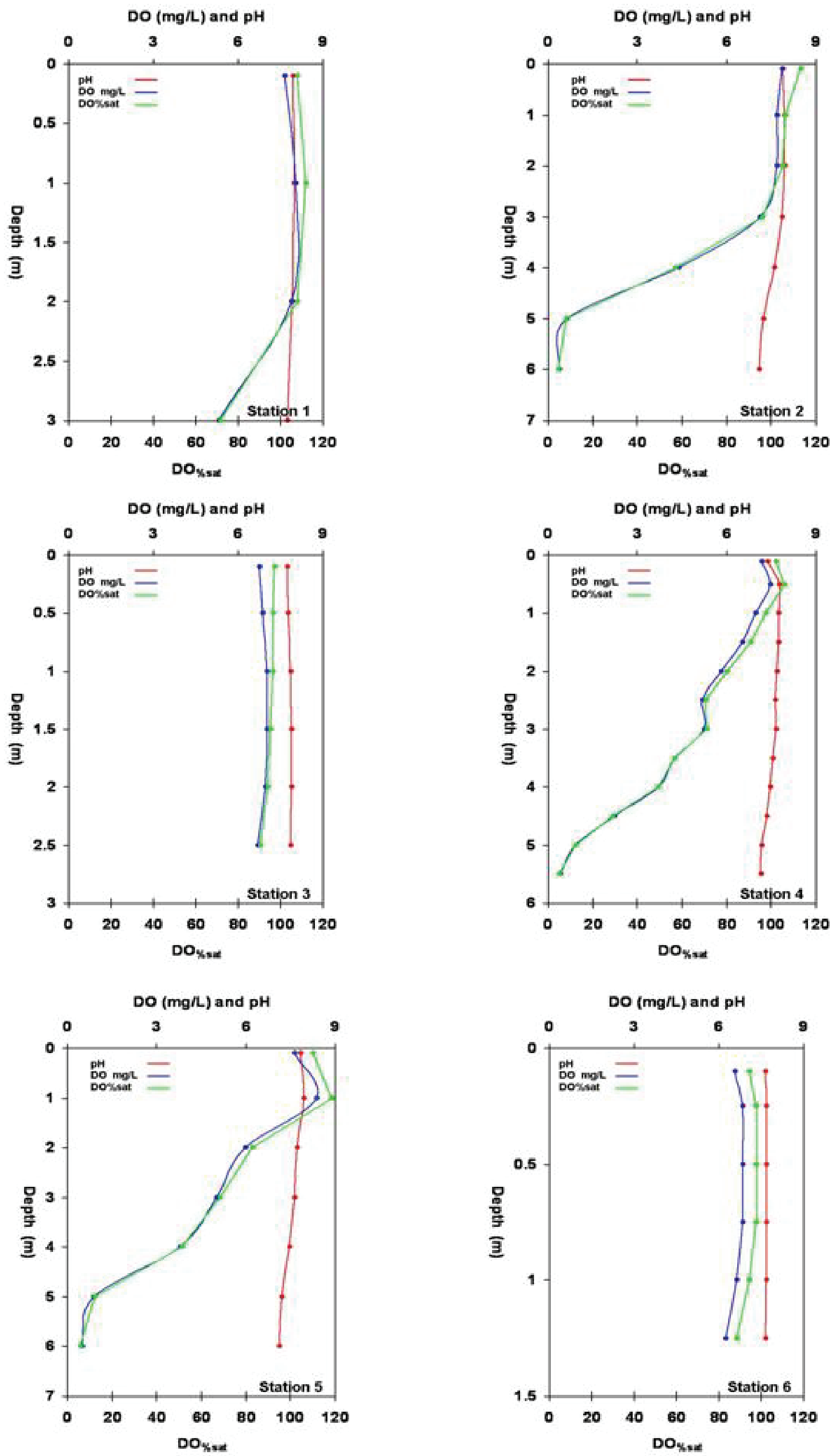


Figure II.59. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, June 17, 2010.

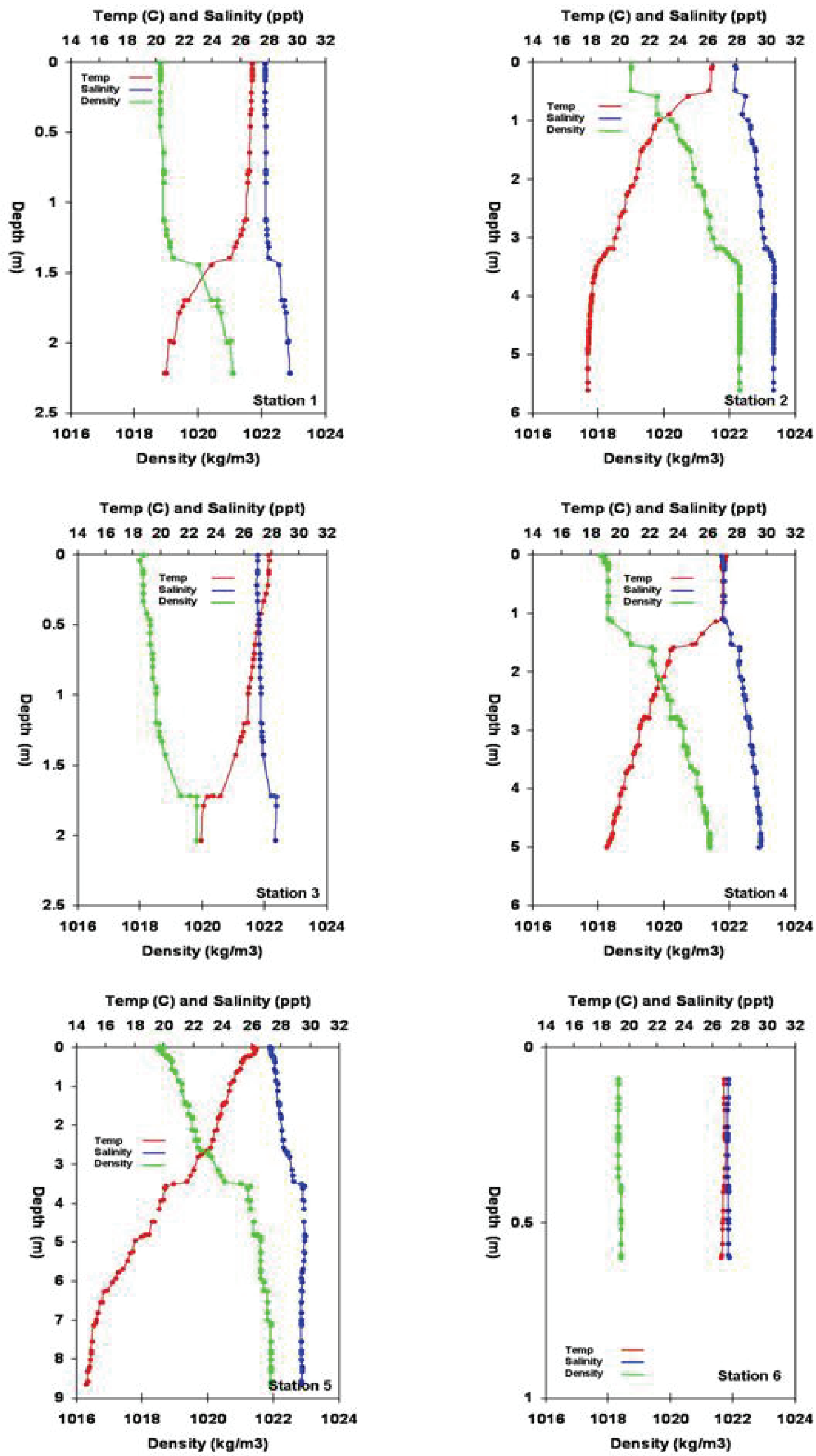


Figure II.60. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, June 28, 2010.

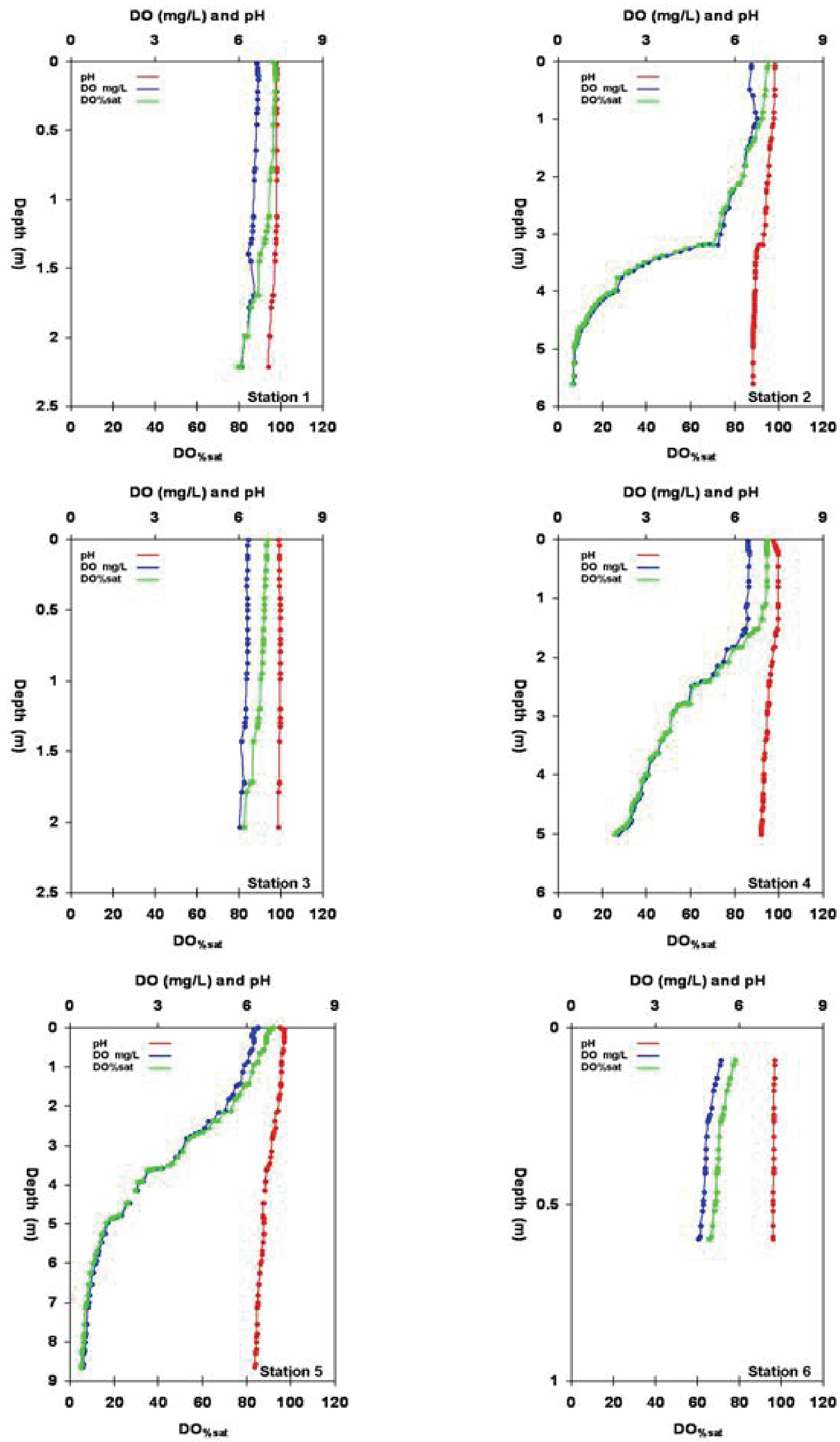


Figure II.61. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, June 28, 2010.

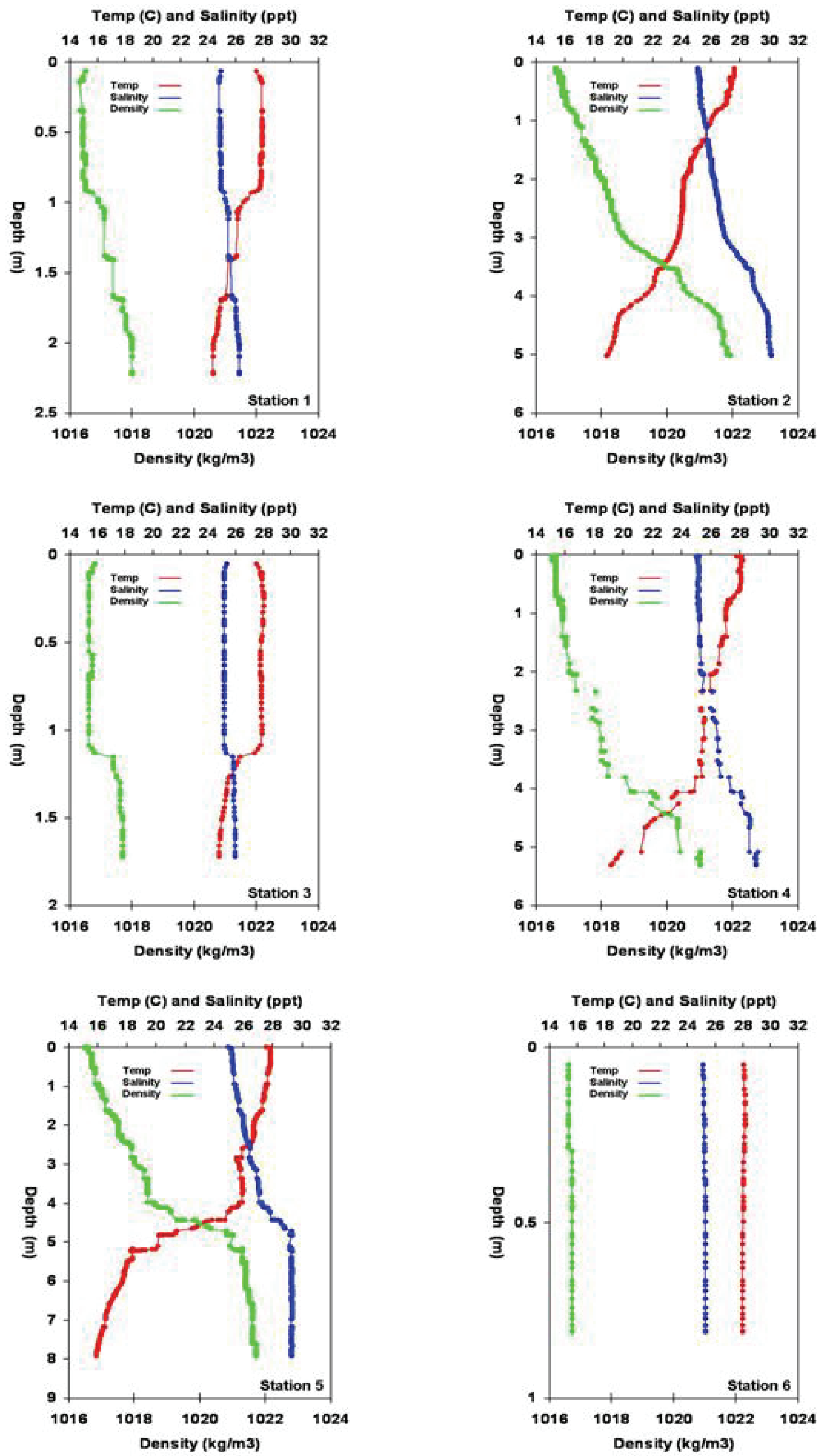


Figure II.62. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, July 12, 2010.

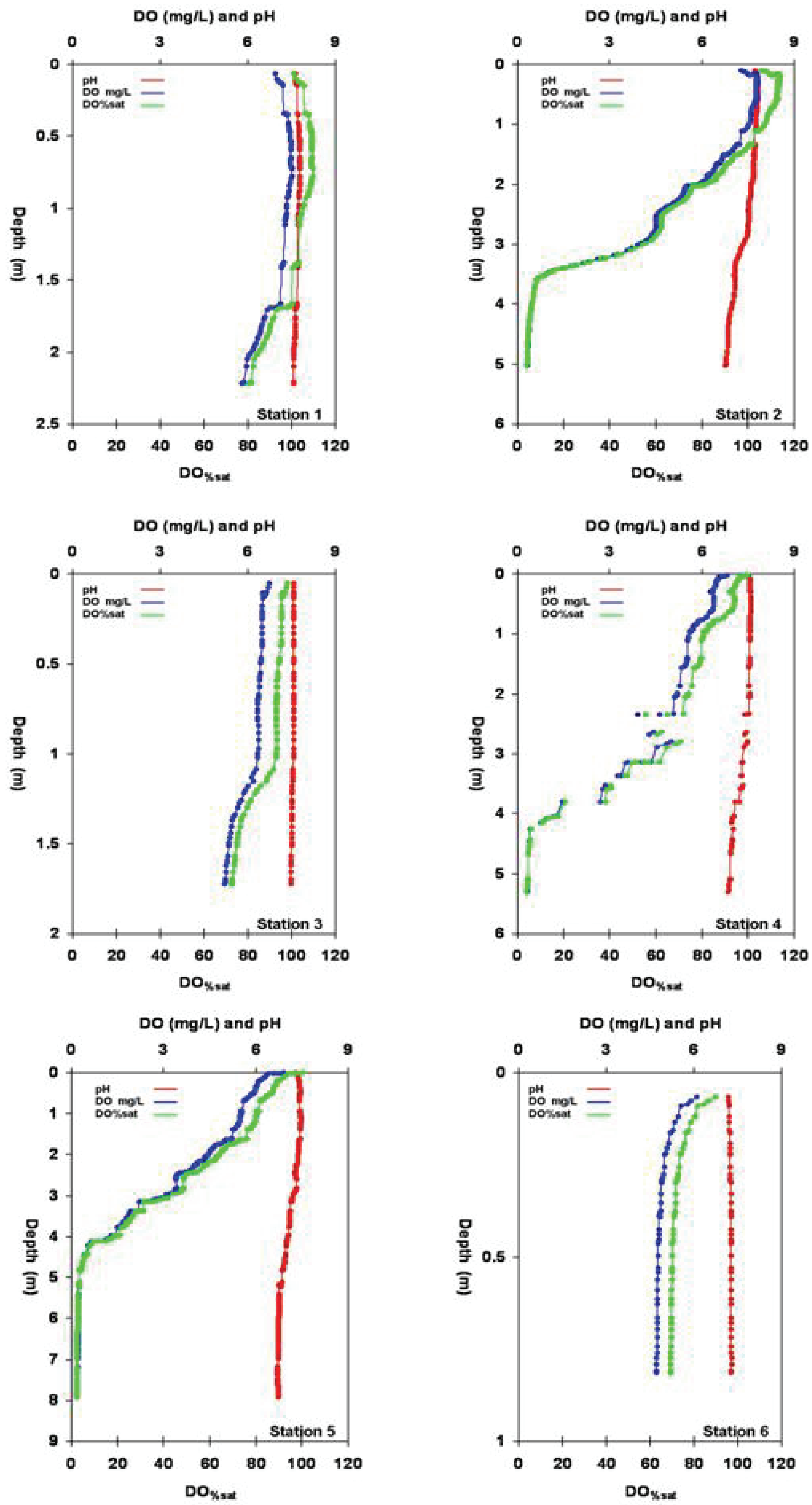


Figure II.63. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, July 12, 2010.

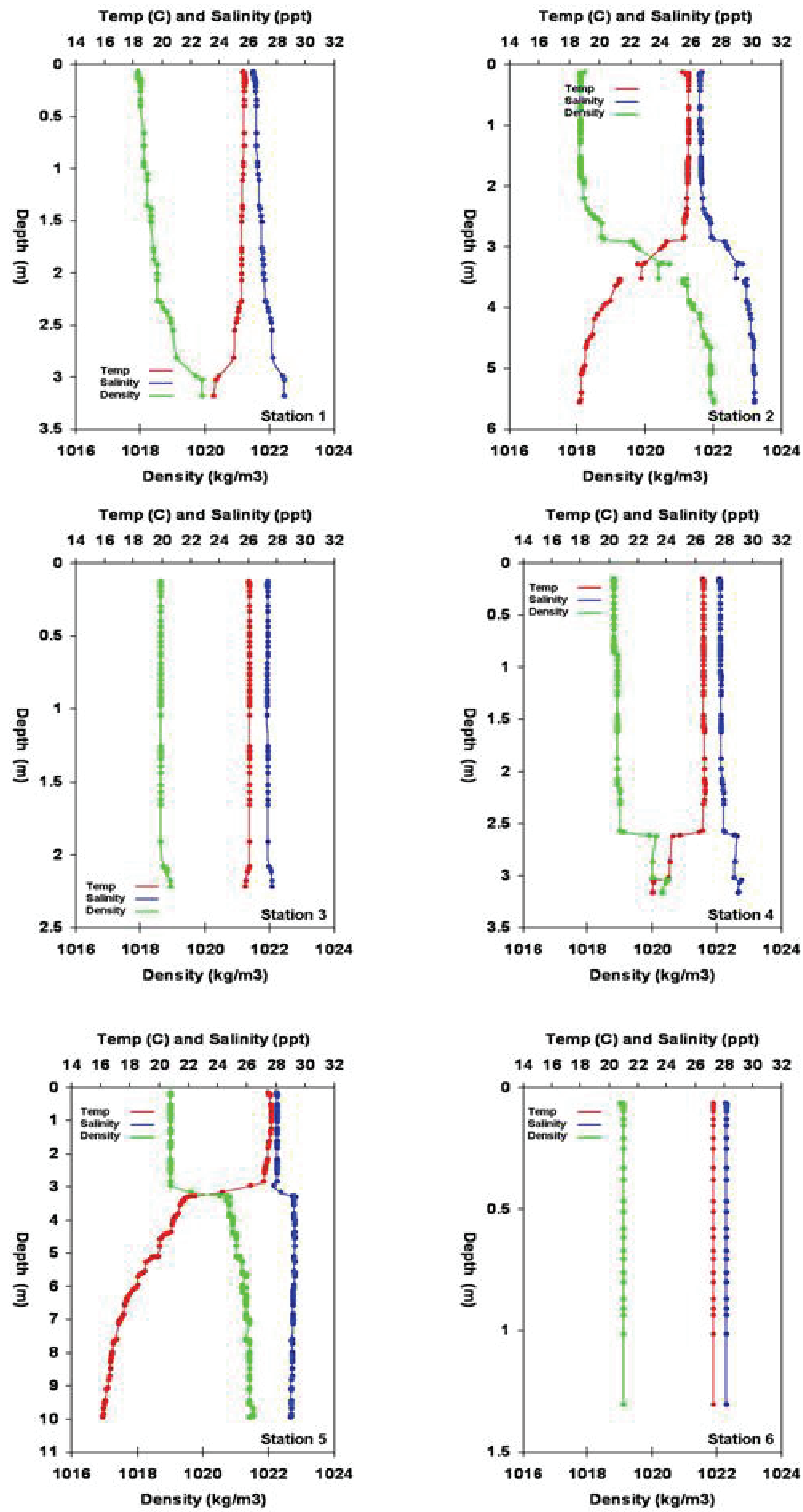


Figure II.64. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, July 26, 2010.

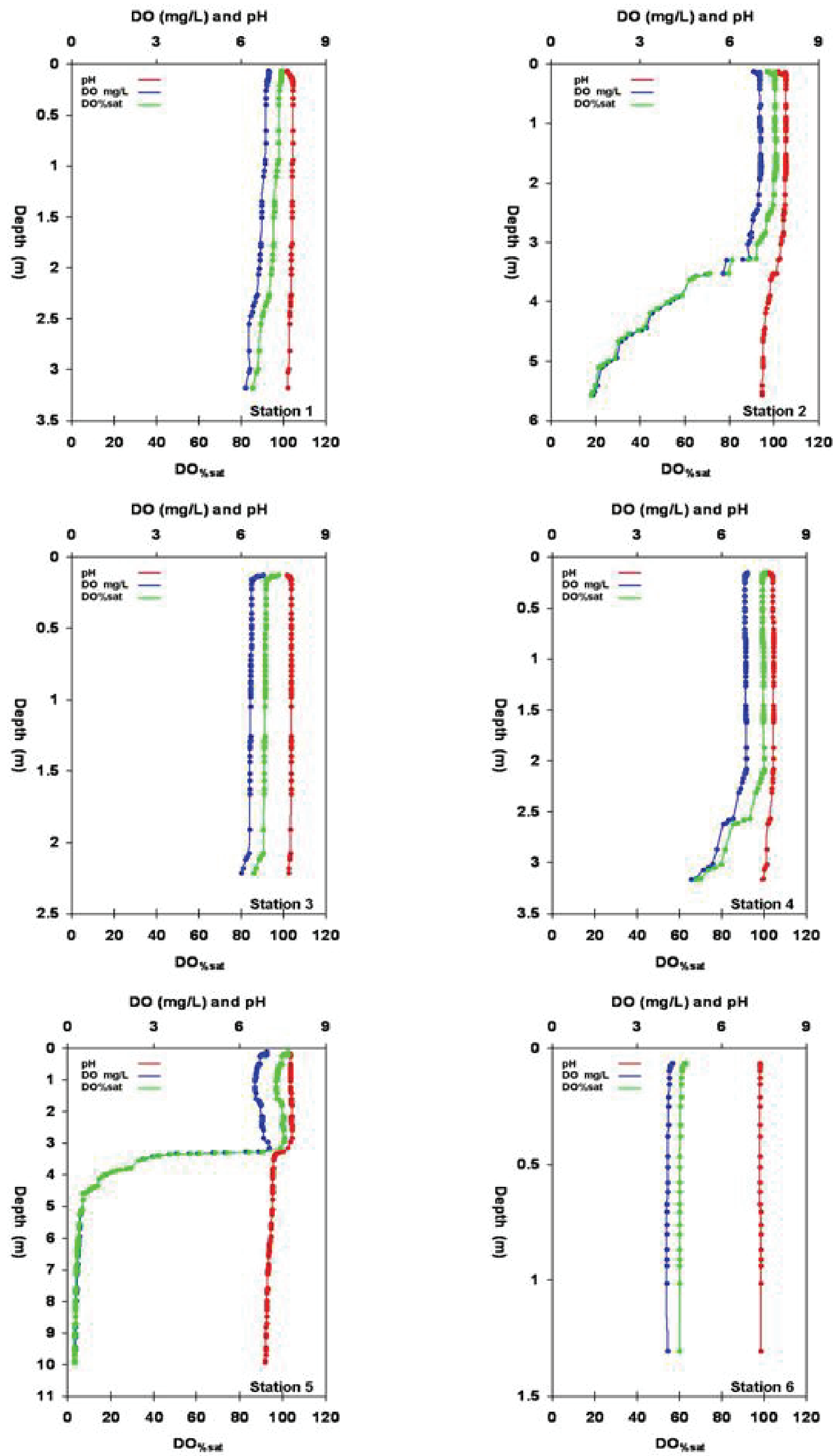


Figure II.65. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, July 26, 2010.

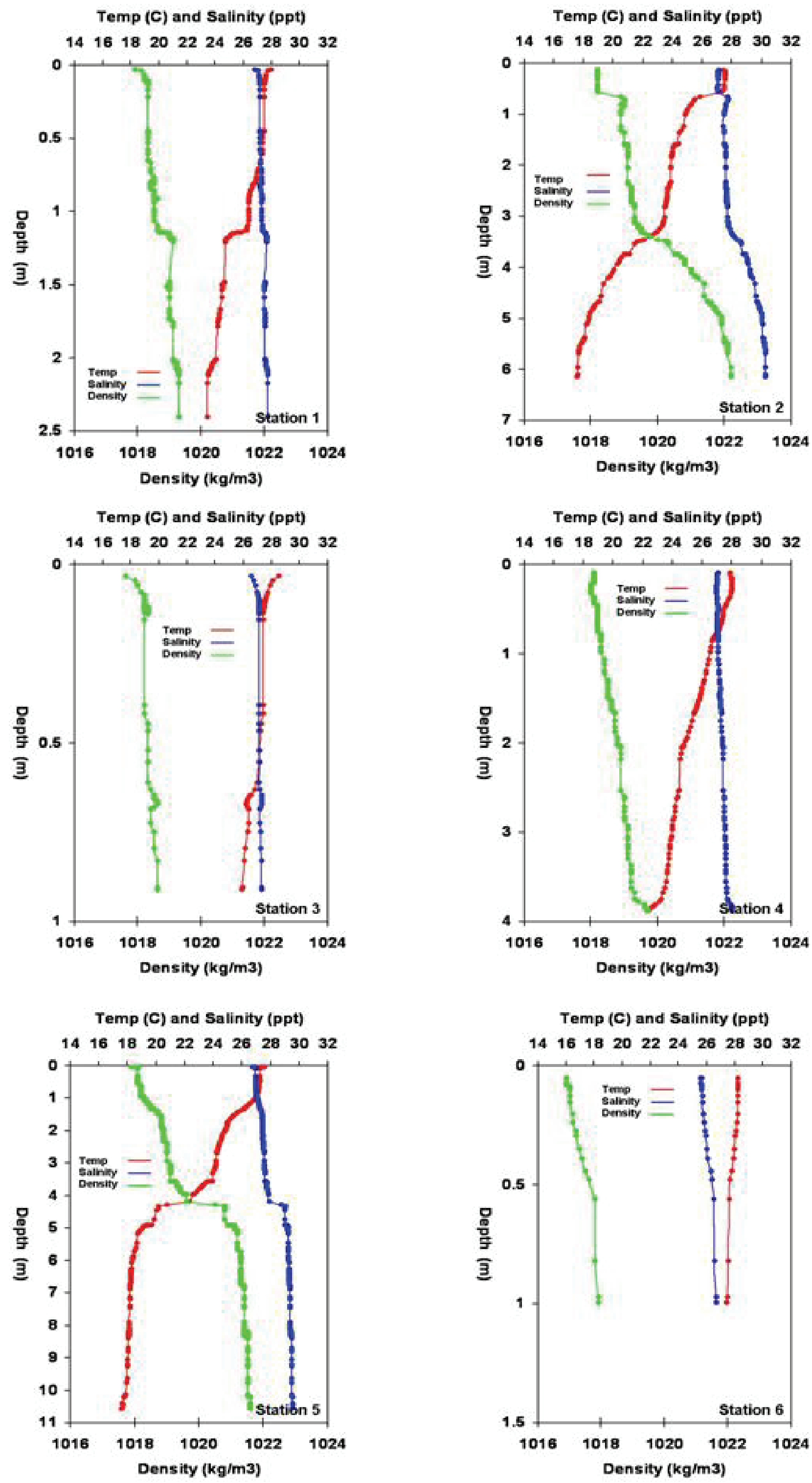


Figure II.66. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, August 10, 2010.

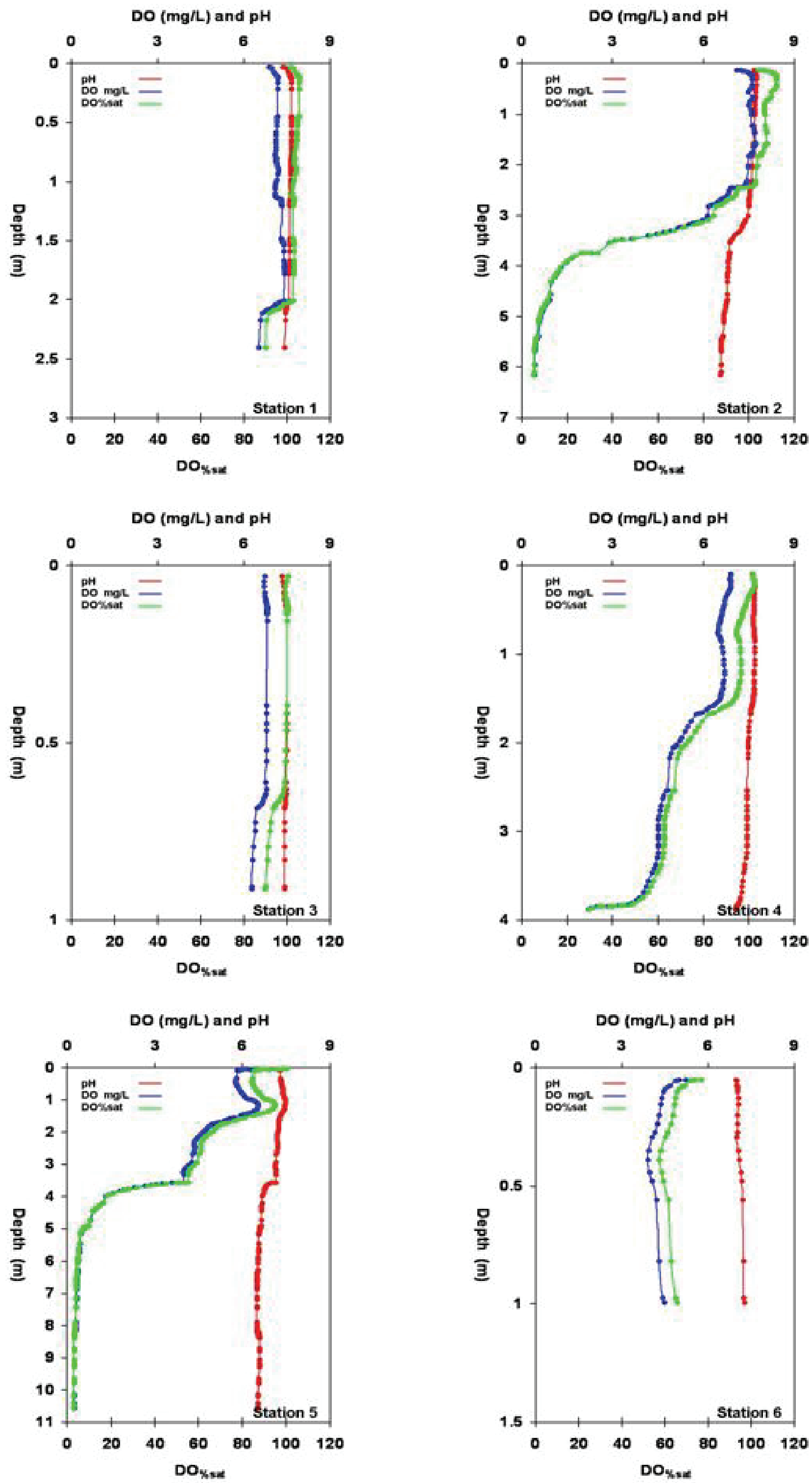


Figure II.67. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, August 10, 2010.

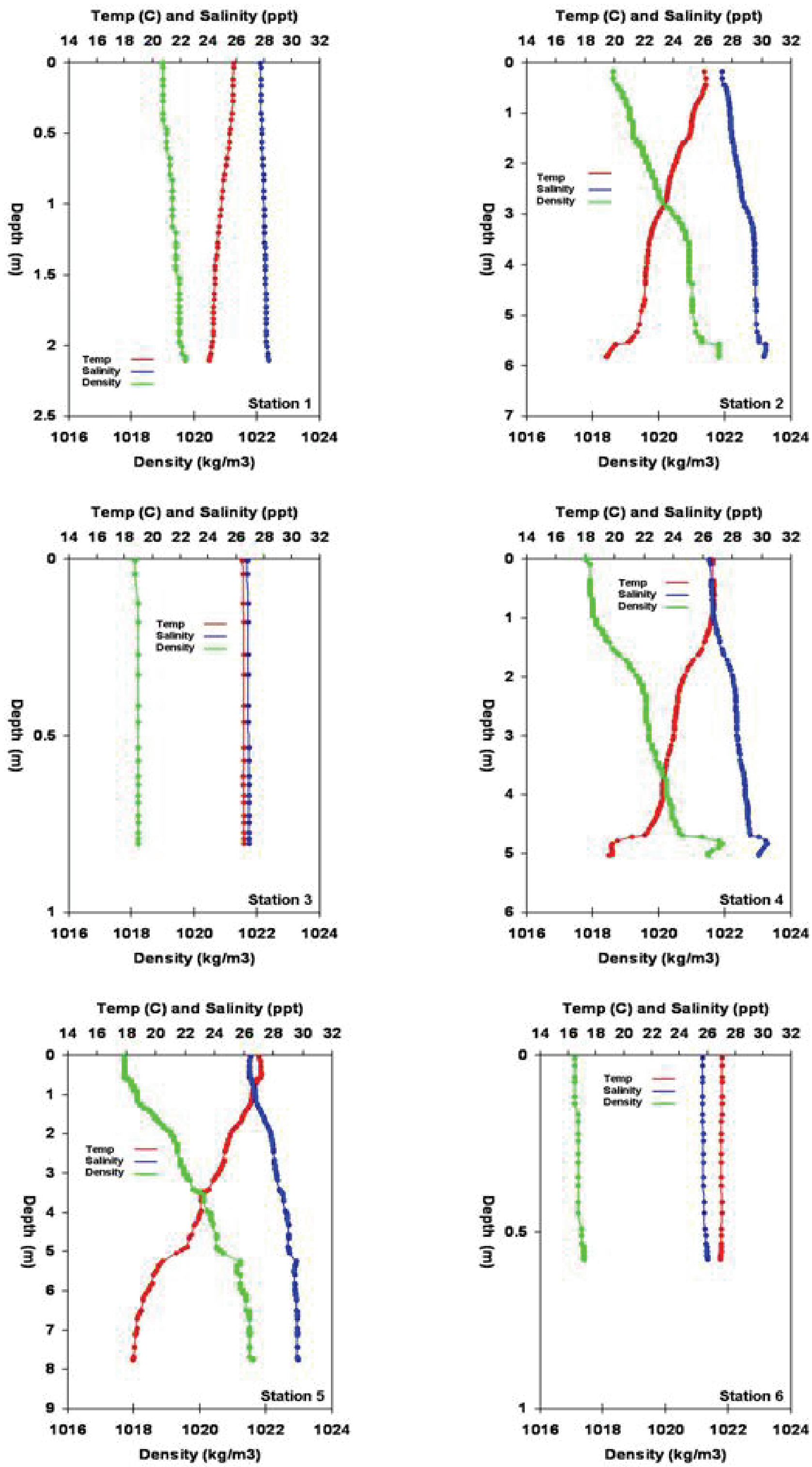


Figure II.68. Vertical profiles of water temperature (°C), salinity (ppt) and water density at the 6 primary ConMon water quality stations within the Rudee Inlet system, August 23, 2010.

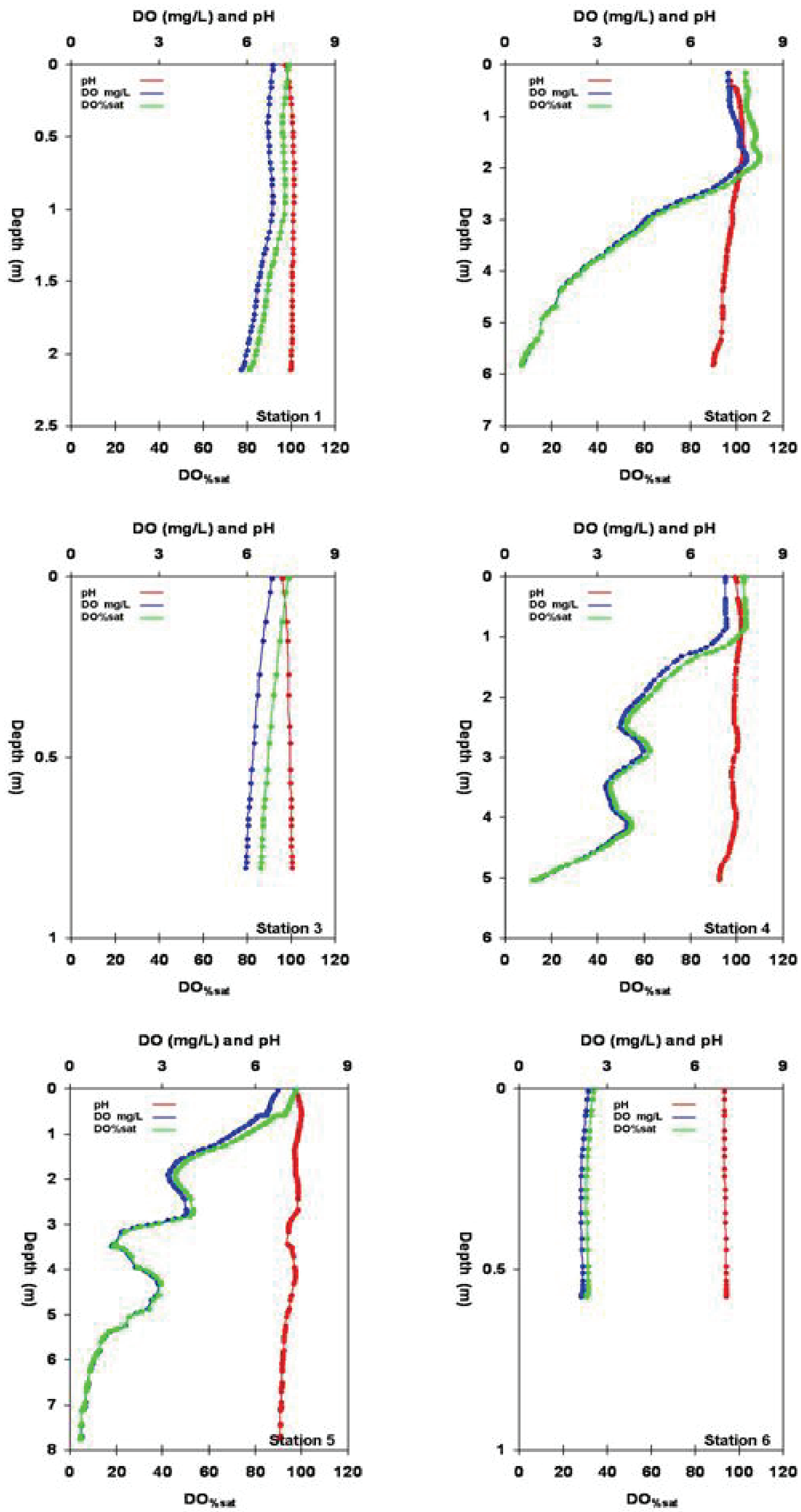


Figure II.69. Vertical profiles of pH, dissolved oxygen concentrations (mg/L) and percent saturation (%) at the 6 primary ConMon water quality stations within the Rudee Inlet system, August 23, 2010.

II-7 Summary and Key Findings

(1) The Rudee Inlet system consists of number of tidal creeks and two broader tidal embayments, Lake Rudee and Lake Wesley. The relatively shallow tidal creeks all feed into Lake Rudee. The exception is Owl Creek, the largest of the creek systems that has a deep (10 m or greater) hole near its mouth. Water depths in Lakes Rudee and Wesley can exceed 6 m.

(2) The tide has standing wave characteristics as it propagates between Rudee Inlet and the mouth of Owl Creek. Tidal range is on the order of 1.0 m and phase differences for most harmonic constituents were within several minutes. Sampled portions of the Rudee Inlet system were representative of polyhaline salinity regime conditions. Density gradients resulted in the formation of a pycnocline at the deep water stations.

(3) Dissolved oxygen patterns within the Rudee Inlet system were dynamic and shallow water stations exhibited a strong diurnal signal driven by water temperature variation and biological activities. Hypoxia (defined as DO_{conc} less than 2 mg L^{-1}) and anoxia was observed during the summer sampling period. The most severe and chronic low/no oxygen conditions occurred in bottom waters within Lake Wesley and Lake Rudee. Duration of low/no oxygen conditions in these regions persisted throughout entire deployment periods (> 10 days).

(4) *E. coli* samples from tidal waters of the Rudee Inlet system varied from <10-844 MPN 100 ml^{-1} during the summer of 2010. *E. coli* densities within the upper reaches of selected tidal creeks (stations OC-3 and UN1-3) were elevated as compared to more open waters. Likewise, elevated *E. coli* densities (range: 644-3641 MPN 100 ml^{-1}) were observed at a non-tidal freshwater source (station LW-3) that drains into Lake Wesley.

CHAPTER III. NUMERICAL MODELING METHODOLOGY

III-1. Description of Numerical Modeling Framework

Numerical modeling, in a broad sense, is a process of building a mathematical abstraction of an actual system. In the estuarine and coastal environmental context, the system consists of components that are interactive and feed back on one another. The numerical modeling framework used for the prediction of fecal coliform in the Rudee Inlet system requires both a watershed model and the hydrodynamic model modified to predict fecal coliform concentrations:

1) The hydrodynamic model for providing mass transport and
2) the Loading Simulation Program in C++ (LSPC) watershed model for freshwater discharge and fecal coliform loadings.

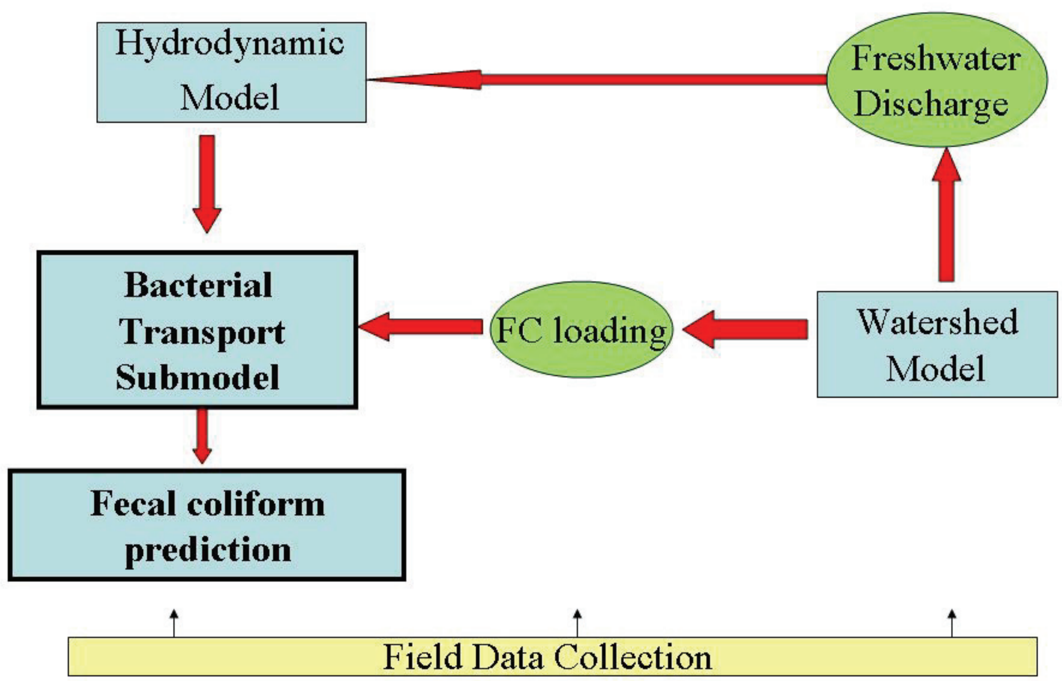


Figure III.1. The modeling approach used for the Rudee Inlet fecal coliform prediction model.

III-2. The HEM-3D hydrodynamic model

The Virginia Institute of Marine Science (VIMS) has worked with the Army Corps of Engineers and the City of Virginia Beach personnel to utilize the calibrated Hydrodynamic Eutrophication Model in 3 dimensions (HEM-3D) for the environmental assessment of the Rudee Inlet system. The original HEM-3D model was developed and refined at VIMS over the period 1988-1995 (Hamrick, 1992; Park et al., 1995). It is a multi-parameter finite difference model representing estuarine flow and material transport in three dimensions. Wind stress and momentum transfer can also be represented as input at the air-water interface with salinity and freshwater discharge handled as inputs at the appropriate longitudinal boundaries. Tidal input can be represented at the downstream open boundary by either a specific time history of water level or a simulated tide based on one or a combination of multiple tidal constituents of known amplitude and phase.

The code is written in standard FORTRAN 77 and is highly portable to UNIX or DOS platforms. It is computationally efficient due to the programmer's avoidance of logical operators, and it economizes on required storage by maintaining only active water cell variables in memory. This code was written to be highly vectorizable, anticipating upcoming developments in parallel processing. Due to a well-designed user interface, the internal source code remains the same from application to application. The HEM-3D model can be quickly converted to a 2D model either horizontally or vertically for preliminary testing. The model's most unique features include the mass conservative scheme that it uses for drying and wetting in shallow areas. It also incorporates vegetation resistance formulations (Hamrick, 1994). The most valuable feature is the model's ability to couple with both water quality and sediment transport models. The model uses a stretched (i.e., "sigma") vertical coordinate system and a curvilinear-orthogonal horizontal coordinate system to solve vertically hydrostatic, free surface, variable density, and turbulent-averaged equations of motion. This solution is coupled with a solution of the transport equations for turbulent kinetic energy, solving the equations of motion. Integration over time involves an internal-external mode splitting procedure separating "the internal shear or baroclinic mode" from the external turbulent length scale, salinity, and temperature. A staggered grid provides the framework for the spatial finite differencing (second order accurate) used by the numerical scheme to "free surface gravity wave or barotropic mode" (Hamrick and Yang, 1995).

For a full description of the formulation of the governing equations and numerical solution techniques for both the equations of motion and the transport equations for salinity, temperature, and turbulence intensity, the reader is referred to Chapter III (methodology) of Sisson et al. (2008), available online at

http://www.vims.edu/GreyLit/VIMS/sramsoe400.pdf.

III-3. Description of the watershed model for the Rudee Inlet system

The Loading Simulation Program in C++ (LSPC) watershed model was used to simulate flow and bacteria loading from the watershed. The LSPC model is a stand-alone, personal computer-based watershed modeling program developed in Microsoft C^{++} (Shen et al., 2005). It includes selected Hydrologic Simulation Program FORTRAN (HSPF) algorithms for simulating hydrology, sediment, and general water quality on land, as well as a simplified stream transport model (USEPA, 2004; Shen et al., 2002; USEPA, 2001). Like other watershed models, LSPC is a precipitation-driven model and requires necessary meteorological data as model input.

The LSPC was configured for Rudee to simulate the watershed as 56 sub-watersheds (SWS) (Figure III.2). The sub-watersheds were used as modeling units for the simulation of flow and bacteria loads based on meteorology and landuse applications. The simulated freshwater flow and bacteria loadings for each sub-watershed were fed into the adjacent hydrodynamic model segments of the receiving water. In simulating nonpoint source pollutants from the watershed, LSPC uses a traditional buildup and washoff approach. Pollutants from various sources (wildlife, human, agricultural, etc.) accumulate on the land surface and are available for runoff during rain events. Different landuses are associated with various anthropogenic and bacterial processes that determine the potential pollutant load. The pollutants contributed by interflow and groundwater are also modeled in LSPC for each landuse category. Pollutant loadings from surface runoff, interflow, and groundwater outflow are combined to form the final loading output from LSPC. In summary, nonpoint sources from the watershed are represented in the model as land-based runoff from the landuse categories to account for their contribution (USEPA, 1998).

For this study, the watershed processes were simulated based on buildup and washoff processes. The final loads were converted to model accumulation rates (ACQOP, units of lb/acre/day). The ACQOP can be calculated for each landuse based on all bacterial sources contributing to the land surface. The parameters used in the Lynnhaven (URS) were used in this model simulation. Venous sources including wildlife, human/dog, etc. are summarized together to derive the accumulation rates for different land uses. These loading parameters were adjusted accordingly during model calibration. The loads discharged to the stream were estimated based on model simulation results (see model simulation section). The other two major parameters governing water quality simulation, the maximum storage limit (SQOLIM, unit in lb/acre/day) and the washoff rate (WSQOP, unit in inches/hour), were specified based on soil characteristics and landuse practices, and further adjusted during the model calibration. The WSQOP is defined as the rate of surface runoff that results in 90% removal of pollutants in one hour. The lower the value, the more easily washoff occurs.

The calibration process involved adjustment of the model parameters used to represent the hydrologic processes until acceptable agreement between simulated flows and field measurements were achieved. Since there is no USGS gage or any other continuous flow data available in the Rudee Inlet system, the model parameters used for other nearby areas including Lynnhaven and Mill Creek on the Eastern Shore were used. A coupled modeling calibration using receiving water was conducted based on the salinity simulation. Bacterial simulations were conducted for 4 years from 1996-1999. The watershed model was run first and bacterial loadings are supplied to the 3D hydrodynamic model, which simulates the bacterial transport. The watershed model parameters are adjusted based on the 3D model simulation results. The first-order decay parameters are used in the 3D model.

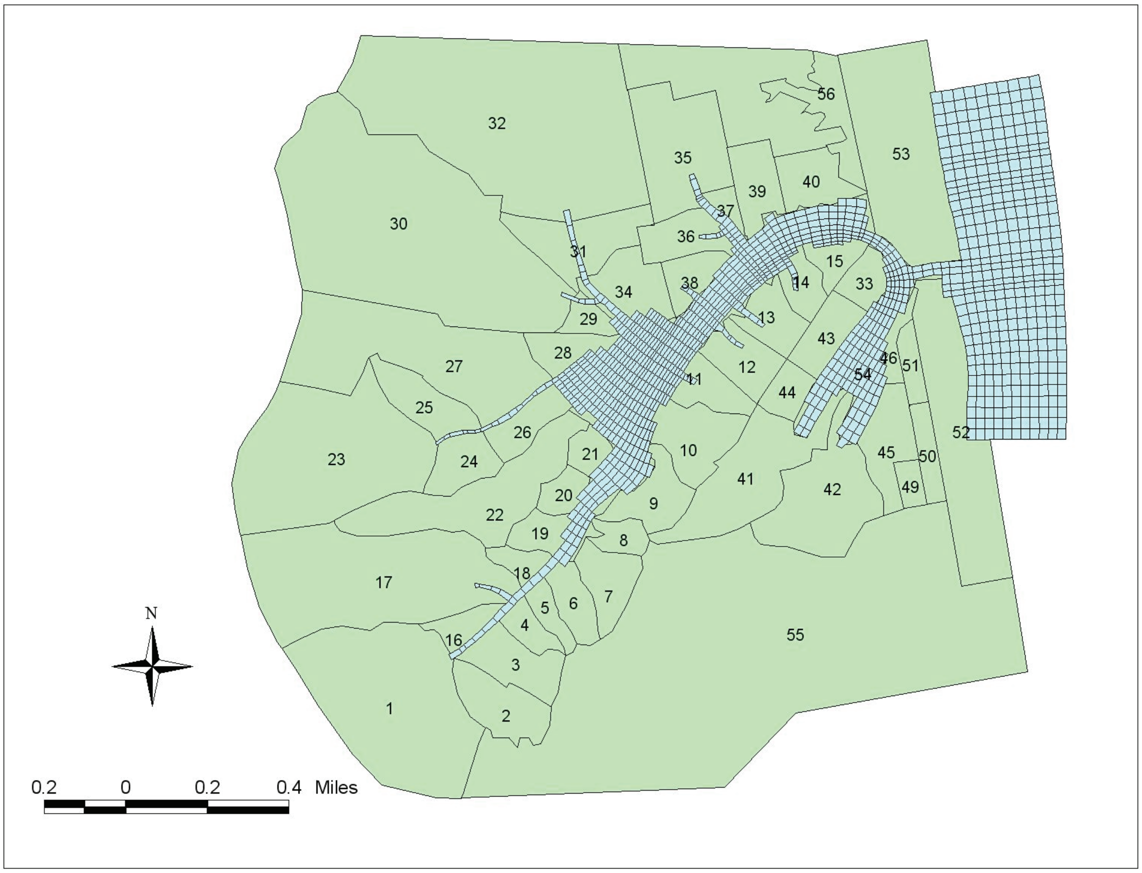


Figure III.2. The 56 subwatersheds of the Rudee Inlet Basin.

Land use descriptions are shown on the pie chart in Figure III.3 and the acreages associated with each land use are shown in Tables III.1 and III.2.

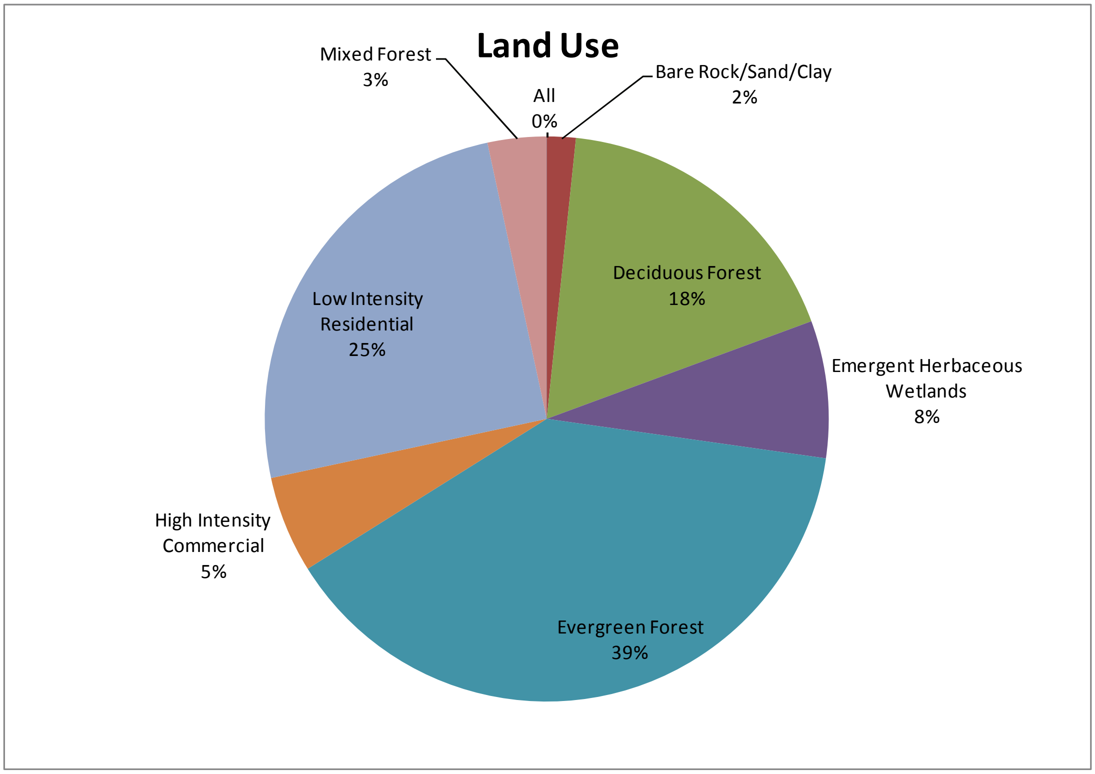


Figure III.3. Land uses in the Rudee Inlet watershed shown by areal percentage.

Table III.1. Land uses and associated acreages in the Rudee Inlet watershed.

Land Use Description	Area (acre)
Bare Rock/Sand/Clay	16.90
Deciduous Forest	181.05
Emergent Herbaceous Wetlands	80.07
Evergreen Forest	397.03
High Intensity Commercial	56.50
Low Intensity Residential	255.12
Mixed Forest	34.48
Open Water	58.94
Other Grasses	2.22
Pasture/Hay	2.00
Row Crops	90.75
Transitional Barren	67.17
Woody Wetlands	1.56
Total	1243.81

Table III.2. Land uses further grouped into 8 categories for modeling purposes.

Land Use Description	Area (acre)
Barren	84.08
Cropland	90.75
Forest	612.56
Pasture	4.23
UrbanImpervious	201.10
UrbanPervious	110.52
Water	58.94
Wetlands	81.63
Total	1243.81

III-4. Fecal coliform model

Transport with first-order decay of fecal coliform is incorporated into the hydrodynamic prediction model and is treated by the model like a dissolved substance. The decay of fecal coliform, which is a combination of die-off, settling, and both salinity and temperature influences. The decay rate is estimated based on literature values and the field measurements conducted in the Lynnhaven in 2006. For the current application, neither the growth of bacteria in the sediment nor sediment re-suspension was considered. The model is capable of handling both point and non-point sources.

CHAPTER IV. HYDRODYNAMIC MODEL CALIBRATION AND VALIDATION

The hydrodynamic model applied to the Rudee Inlet system was developed using the framework outlined in Chapter III. The calibration is a process by which the performance parameters are constrained by comparing the model predictions with the field measured observations. For example, the bottom friction parameters were adjusted during the calibration process. A calibration assures that the model will produce results that meet or exceed some defined criteria with a specified degree of confidence.

The hydrodynamic model was calibrated with observed surface elevations and salinities using VIMS survey data collected during the summer of 2010. The calibration consisted of comparison of model predictions and high-frequency observed water surface elevation and salinity data for a total of 18 time series each, with each deployment time series ranging from 10-16 days.

IV-1 Boundary conditions

For the application of the HEM-3D hydrodynamic model to the Rudee Inlet system, it was necessary to specify the downstream boundary condition where the Inlet enters into the Atlantic Ocean. The downstream boundary conditions consisted of specifications of time series of surface elevation and salinity along the exterior row of grid cells at the eastern extent of the model grid, as shown in Figure IV.1. These data were derived from the water depth measurement as well as salinity measurements at the most downstream ConMon water quality stations, shown earlier in Figure II.2.

IV-2 Freshwater discharge

There are no USGS gauges recording freshwater inflow to any of the lakes in the Rudee Inlet system. For this reason, the hydrodynamic model for the Rudee Inlet system was dependent upon the watershed model LSPC for its freshwater discharge inputs. As discussed in Section III-3, the LSPC model calculated hourly freshwater discharge values derived from a total of 56 catchment areas surrounding the Rudee Inlet system.

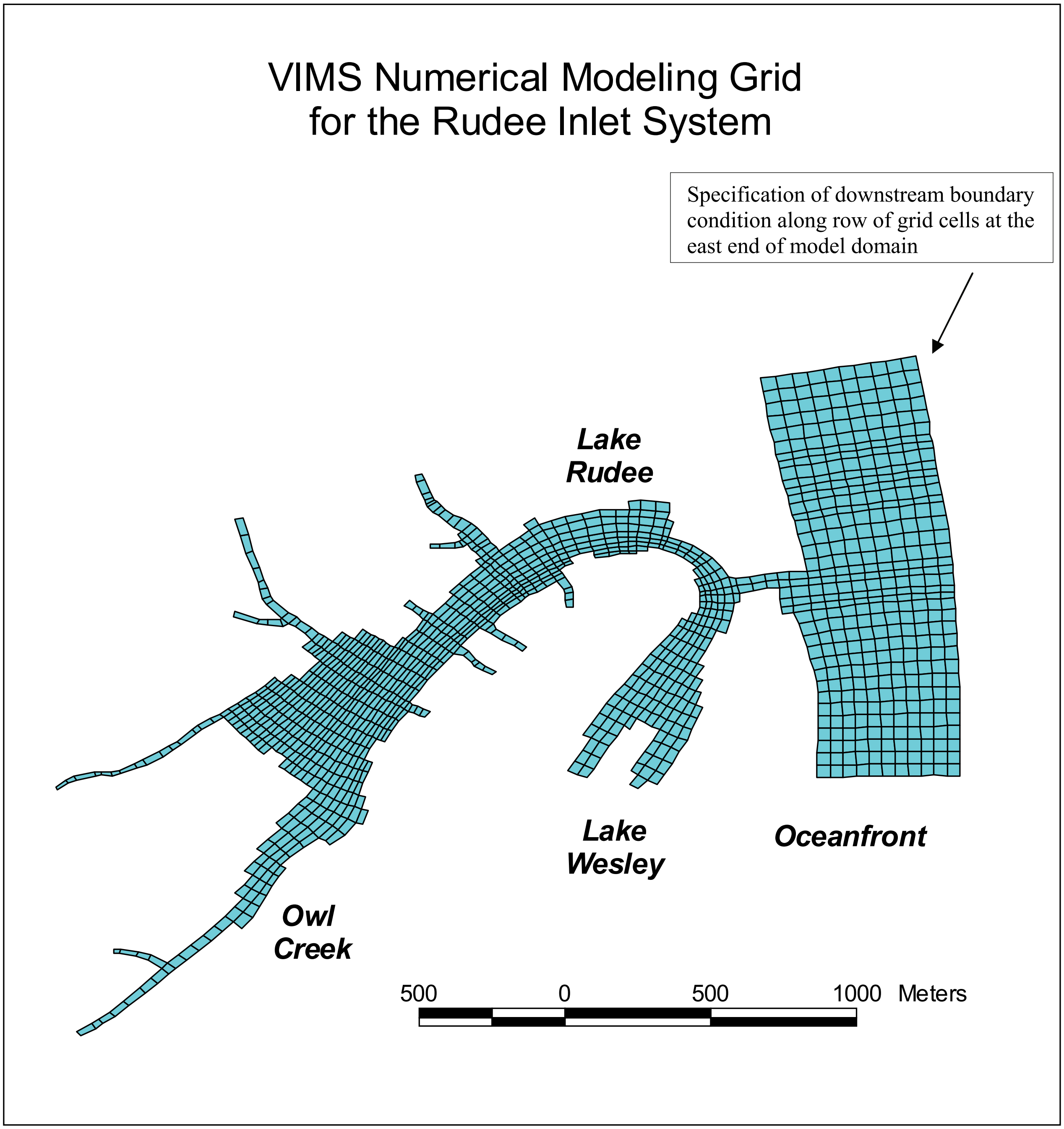


Figure IV.1. The structured HEM-3D numerical model grid used for the Rudee Inlet model.

IV-3 Calibration for surface elevation

For the calibration of water surface elevation in the Rudee Inlet system, VIMS compared model predictions to observed high-frequency surface elevations for the 3 deployments at 6 locations ranging from 10 to 16 days in duration. These deployments are listed in Table IV.1.

Table IV.1. Locations and dates of comparison for predicted vs. observed surface elevation in the Rudee Inlet region.

Deployment	Locale	Survey Dates	Location Map	Results
1	ConMon Sta. 1	06/17-06/28/10	Figure II.1	Figure IV.2
1	ConMon Sta. 2	06/17-06/28/10	Figure II.1	Figure IV.2
1	ConMon Sta. 3	06/17-06/28/10	Figure II.1	Figure IV.2
1	ConMon Sta. 4	06/17-06/28/10	Figure II.1	Figure IV.2
1	ConMon Sta. 5	06/17-06/28/10	Figure II.1	Figure IV.2
1	ConMon Sta. 6	06/17-06/28/10	Figure II.1	Figure IV.2
2	ConMon Sta. 1	07/12-07/26/10	Figure II.1	Figure IV.3
2	ConMon Sta. 2	07/12-07/26/10	Figure II.1	Figure IV.3
2	ConMon Sta. 3	07/12-07/26/10	Figure II.1	Figure IV.3
2	ConMon Sta. 4	07/12-07/26/10	Figure II.1	Figure IV.3
2	ConMon Sta. 5	07/12-07/26/10	Figure II.1	Figure IV.3
2	ConMon Sta. 6	07/12-07/26/10	Figure II.1	Figure IV.3
3	ConMon Sta. 1	08/10-08/23/10	Figure II.1	Figure IV.4
3	ConMon Sta. 2	08/10-08/23/10	Figure II.1	Figure IV.4
3	ConMon Sta. 3	08/10-08/23/10	Figure II.1	Figure IV.4
3	ConMon Sta. 4	08/10-08/23/10	Figure II.1	Figure IV.4
3	ConMon Sta. 5	08/10-08/23/10	Figure II.1	Figure IV.4
3	ConMon Sta. 6	08/10-08/23/10	Figure II.1	Figure IV.4
4	Rudee Inlet Marina	05/26-06/28/10	Figure II.2	Figure IV.8
4	Virginia Aquarium	05/26-06/28/10	Figure II.2	Figure IV.9

Real-time comparisons of predicted vs. observed surface elevations at stations throughout the Rudee Inlet system are shown in Figure IV.2 (June 17 to June 28, 2010), Figure IV.3 (July 12 to July 26, 2010), and Figure IV.4 (August 10 to August 23, 2010). It should be noted that some measurements, particularly at Station 6, only show water level variations during high tide. The surface elevation becomes constant or very small during low tide, because the instrument floated at the water surface when water depths become shallow. The model captures the tidal variations during high tide well at Stations 1-5. Overall, the model captured the semi-diurnal peaks and troughs and the phases of the observations quite well.

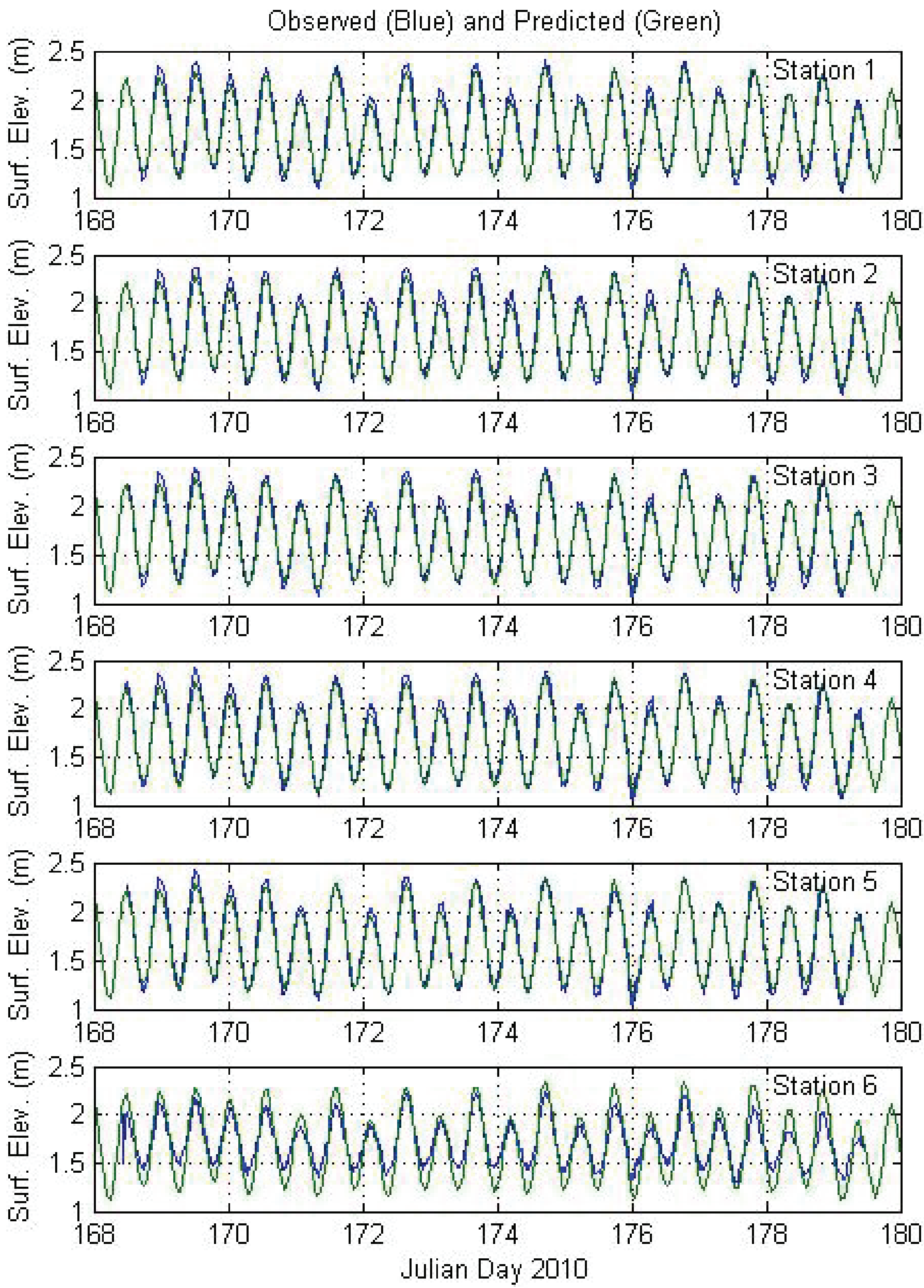


Figure IV.2. Predicted (green) vs. observed (blue) surface elevation – Rudee Inlet system Deployment 1, June 17 to June 28, 2010.

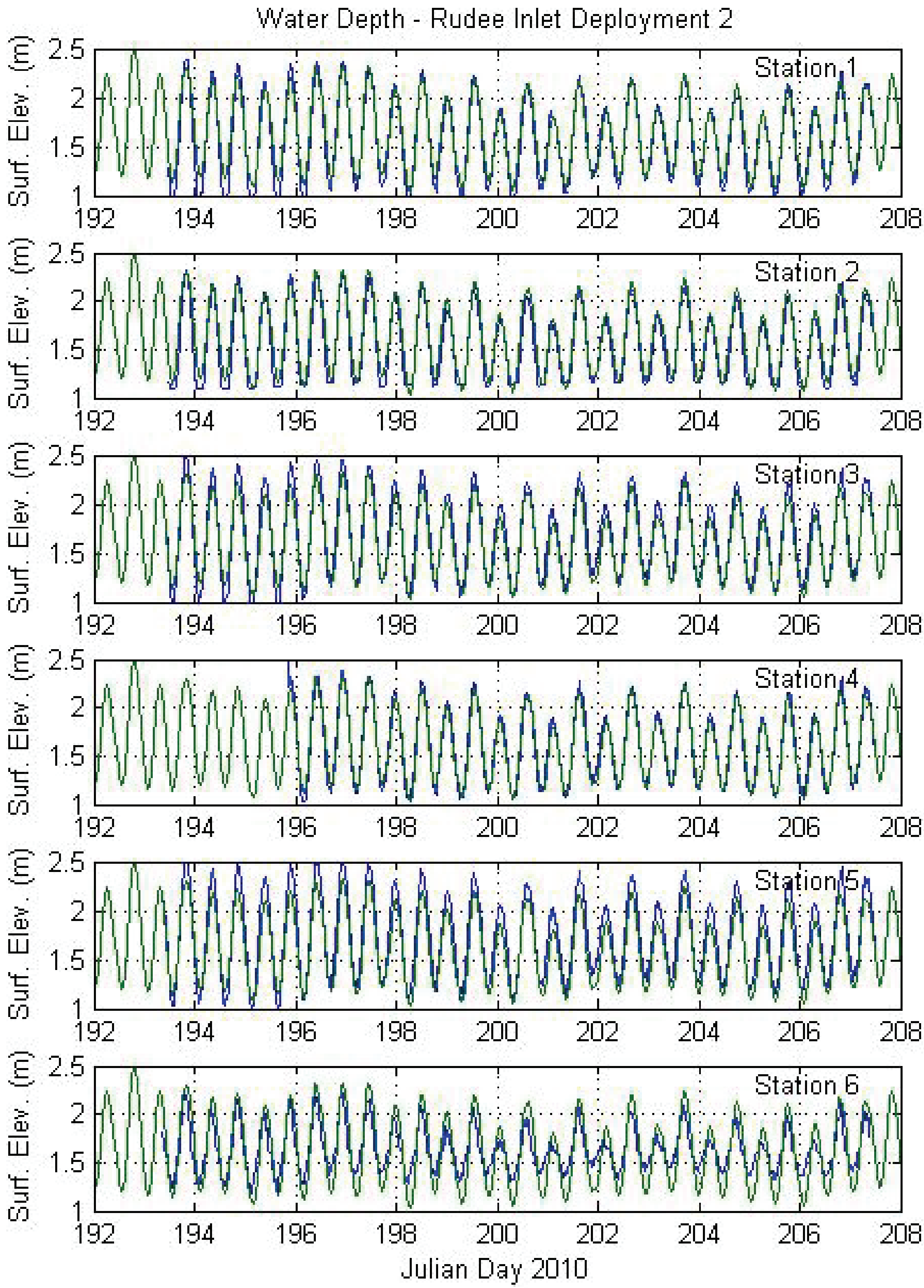


Figure IV.3. Predicted (red) vs. observed (blue) surface elevation in Rudee Inlet system Deployment 2, July 12 to July 26, 2010.

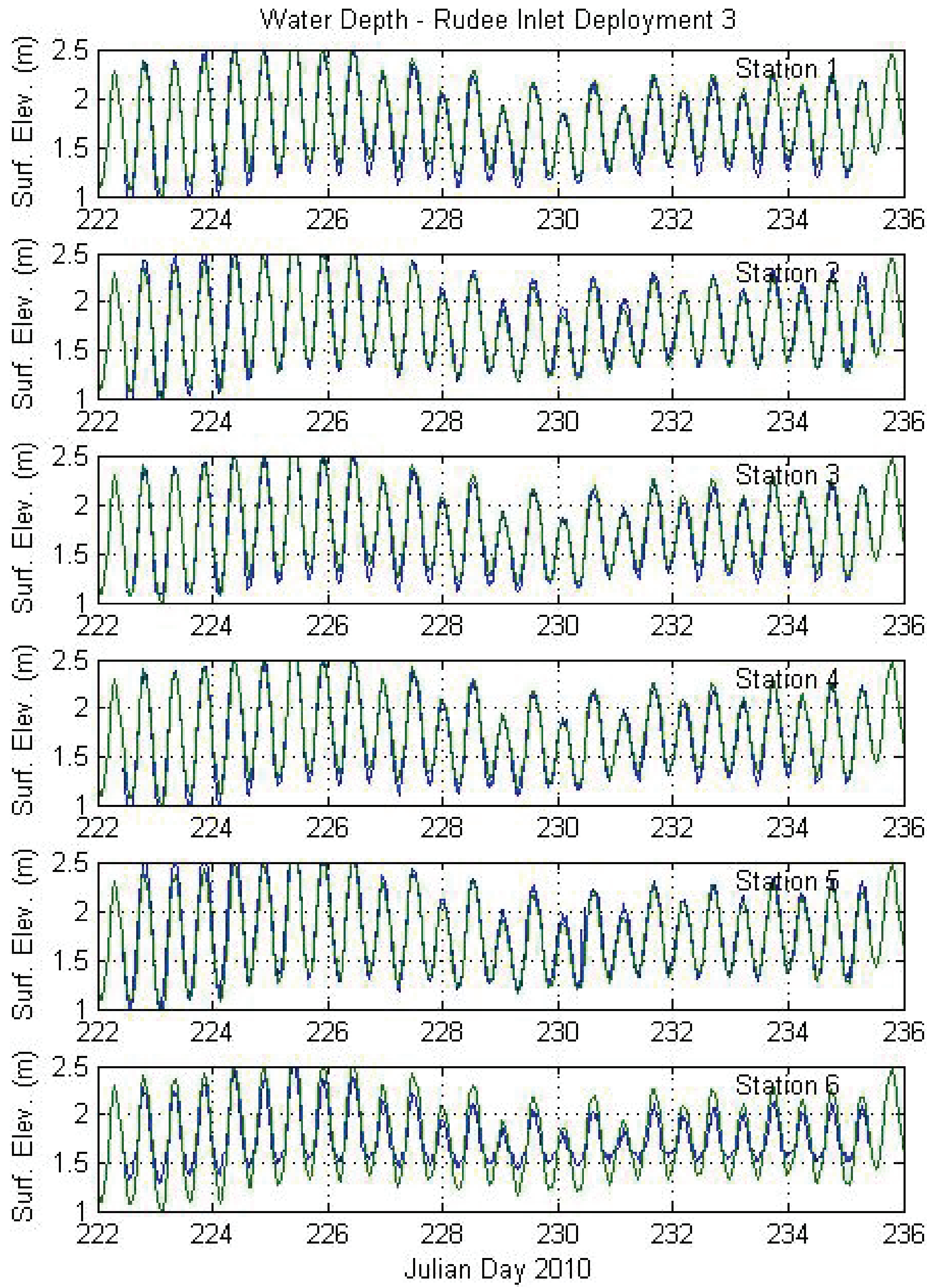


Figure IV.4. Predicted (green) vs. observed (blue) surface elevation – Rudee Inlet system Deployment 3, August 10 to August 23, 2010.

IV-4 Calibration for salinity

Real-time comparisons of predicted vs. observed salinity for the Rudee Inlet system are shown in Figures IV.5 through IV.7 for all ConMon water quality stations for Deployments 1, 2, and 3, respectively. Because portions of the system are shallow, it is very susceptible to the freshwater pulse. Any deviation of the freshwater discharge can affect the salinity. Therefore, the model may miss some events when the modeled freshwater discharge deviates from the actual freshwater discharge, particularly in the upstream locations. It can be seen that the model captures the general trend of salinity fluctuations and matches all stations to within approximately 2 ppt throughout the deployments.

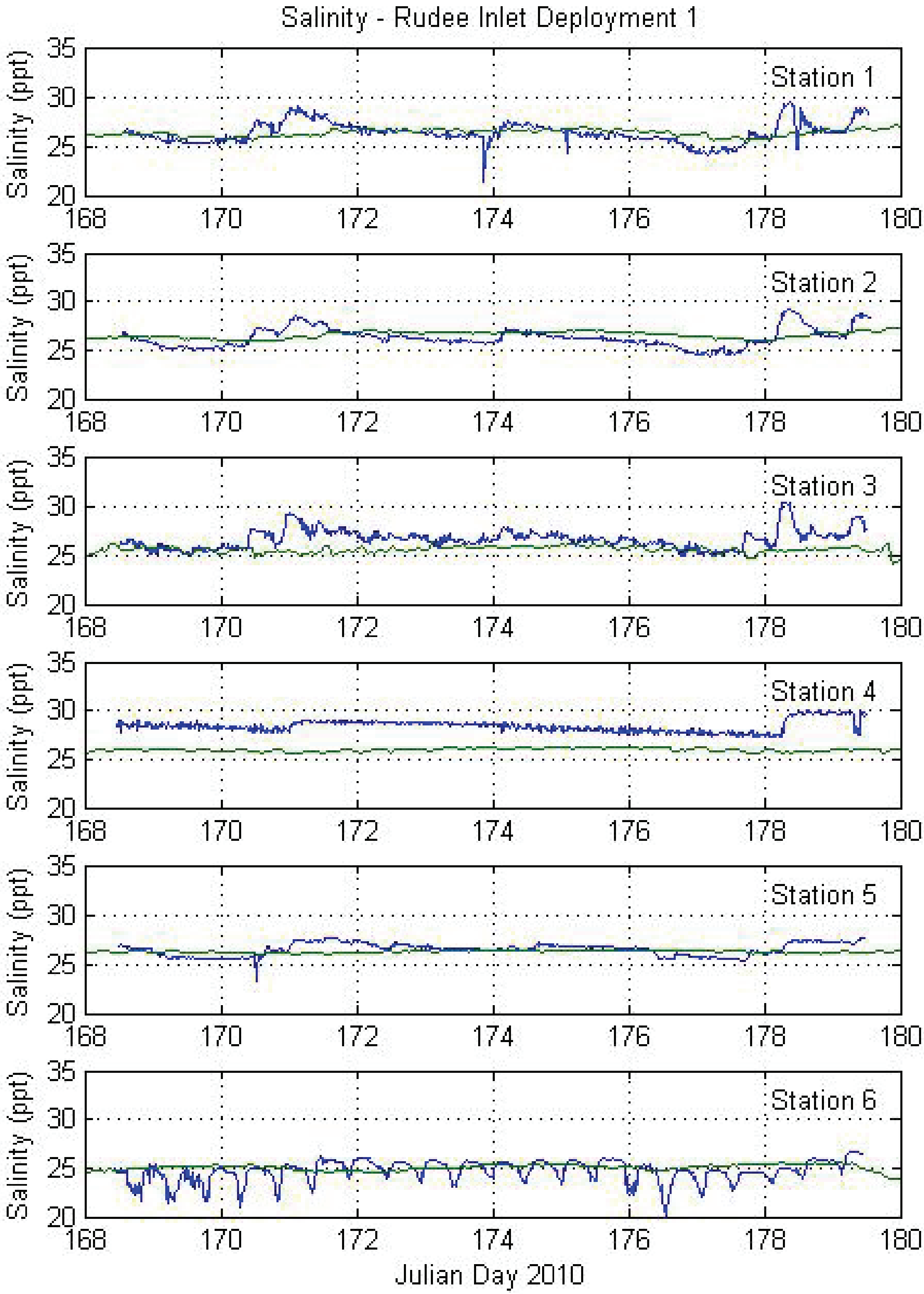


Figure IV.5. Predicted (green) vs. observed (blue) salinity, Rudee Inlet system Deployment 1, June 17 to June 28, 2010.

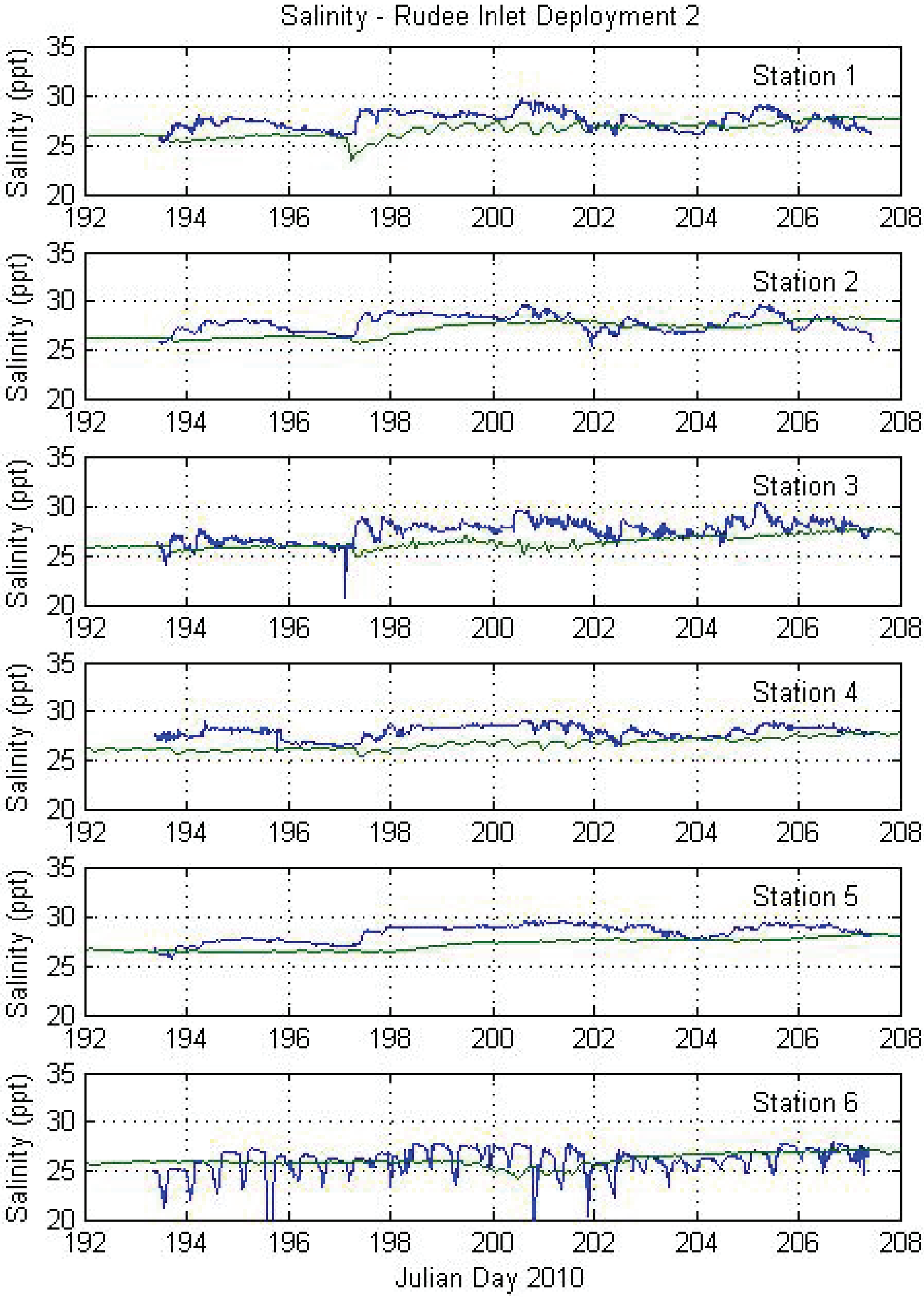


Figure IV.6. Predicted (green) vs. observed (blue) salinity, Rudee Inlet system Deployment 2, July 12 to July 26, 2010.

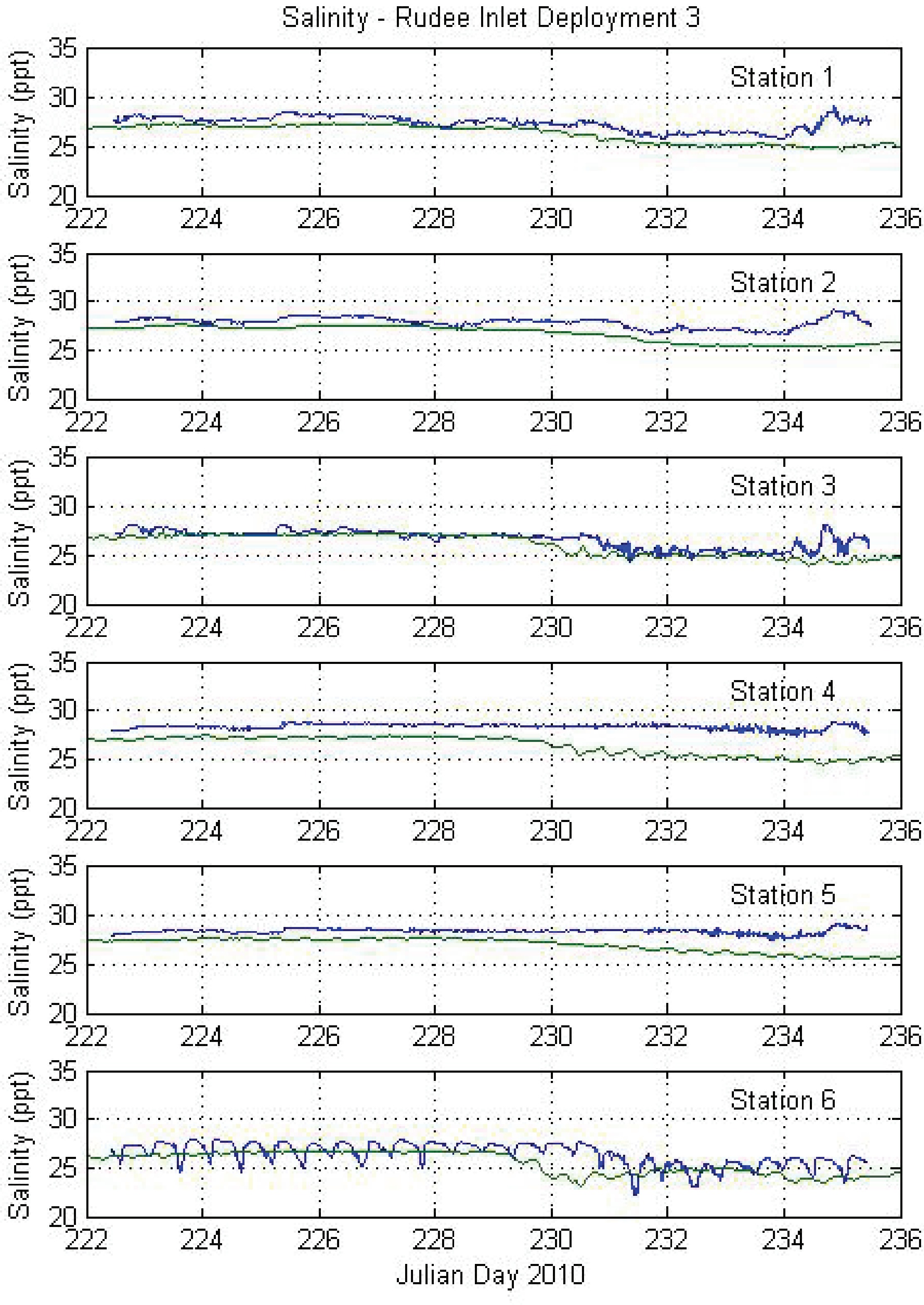


Figure IV.7. Predicted (green) vs. observed (blue) salinity – Rudee Inlet system Deployment 3, August 10 to August 23, 2010.

IV-6 Validation for surface elevation

Validation of the model's ability to predict water surface elevation was performed by comparing model results against the 30-day high-frequency observations at 2 locations in the Rudee Inlet system. This deployment of tidal gauges at two locations occurred over the period from May 26 through June 28, 2010, as shown earlier in Table IV.1, and comparisons to model predictions are shown below in Figures IV.8 and IV.9.

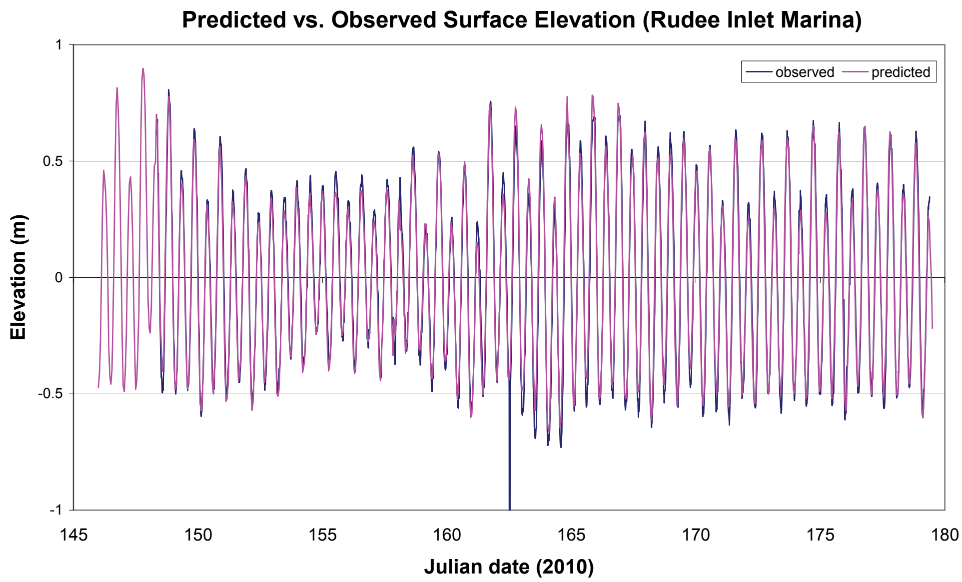


Figure IV.8. Predicted vs. observed surface elevation at the Rudee Inlet Marina, May 26 – June 28, 2010.

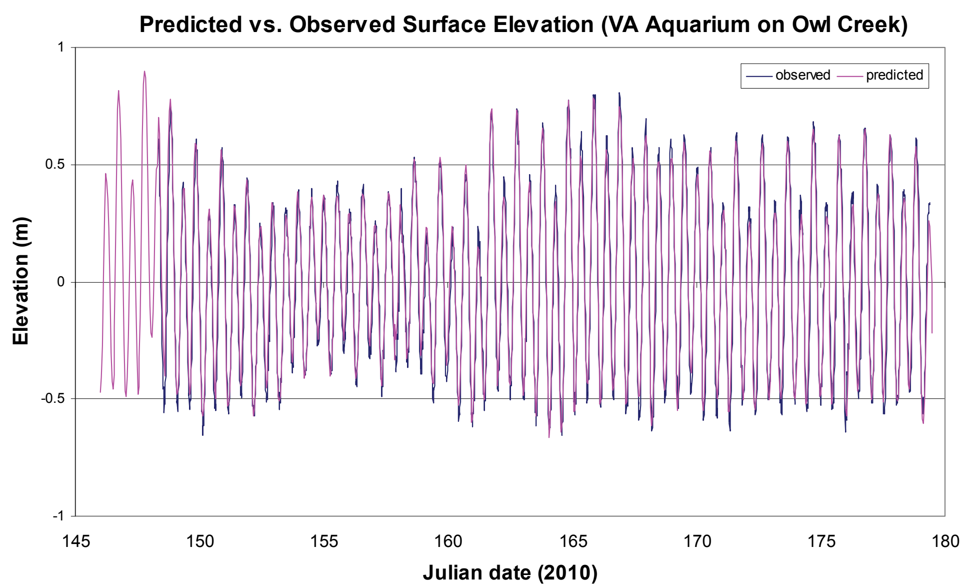


Figure IV.9. Predicted vs. observed surface elevation at the Virginia Aquarium on Owl Creek, May 26 – June 28, 2010.

CHAPTER V. FECAL COLIFORM MODEL CALIBRATION AND VALIDATION

Both the upper and lower portions of Owl Creek, as well as lower Lake Rudee and the upper branches of Lake Wesley, are on the 303D List as impaired waters for fecal coliform (City of Virginia Beach, List of Impaired Waters, 2008). Suitable long-term observation data for the Rudee Inlet system included 7 years of data at each of 6 VA-DEQ stations as well as 25 years of data at one VA-DSS station (discussed in Chapter I). For the model calibration and validation in this study, the strategy was to compare model predictions to the long-term VA-DEQ observations, and then to compare the model's predictions of fecal coliform spatial distributions against the observations made during VIMS grab sample surveys for this project in the summer of 2010.

V-1 Selection of the period for calibration

The calibration of modeled fecal coliform within a system such as Rudee Inlet must be performed over a period that includes sufficient monitoring data. The VA-DEQ data collected from 1996-2003 fulfilled this condition. The precipitation record is another important consideration, since it is preferable to include at least a period of relatively high rainfall within the period of model calibration. The annual rainfall totals measured at the Oceana Naval Air Station near Rudee Inlet are shown for the period 1996-2008 in Figure V.1. It can be seen that 1998-1999 were relatively wet years. The period selected for fecal coliform calibration in the Rudee Inlet system was 1996 through 1999.

V-2 Calibration of the fecal coliform model

The overall objective of the model calibration is to compare the model simulated fecal coliform levels to the observed data utilizing a set of model coefficients and parameters that are consistent with field measurements and are within the general ranges of values accepted by the modeling community as reported in the literature.

The main steps involved in the calibration of the fecal coliform model are: 1) the appropriate boundary condition has to be chosen, 2) the external fecal coliform loads have to be included, 3) the reasonable initial condition has to be specified, and 4) the suitable parameter values have to be estimated.

V-2-1 Boundary condition

The boundary condition used for the numerical modeling of fecal coliform in the Rudee Inlet system is a radiation boundary condition specified along the downstream (eastern) boundary of the model domain. Average long-term values of fecal coliform as measured by VA-DSS and VA-DEQ were then specified as boundary conditions. As the model open boundary extends downstream from Owl Creek and Lake Rudee, the specification of the open boundary condition has less influence on the interior of the model domain.

V-2-2 External loading

There is no specific FCB point source input into the Rudee Inlet system. The non-point fecal coliform loadings from the watershed were obtained from the output of the watershed model LSPC. The spatial distribution of these loadings, averaged over the 5-year period 1996-2000, is shown in Figure V.2. Nonpoint source loads enter the fecal coliform model through specification of fecal coliform loading calculated through freshwater discharge and the concentration of fecal coliform at model grid cells adjacent to the land. The procedure involves mapping of the model grid with 44 hydrologically connected subwatershed areas adjacent to the receiving waters (of a total of 56). These nonpoint source inputs are specified at the surface of the model cells at the locations of discharge. The watershed model uses a daily time increment for FCB loading inputs.

V-2-3 Initial condition

As simulations for fecal coliform are long-term (i.e., multi-year) and, as the model domain responds reasonably rapidly to external loading inputs, it was sufficient to specify an initial concentration of 0 $MPN \cdot 100\ ml^{-1}$ throughout the computational domain. Upon attaining dynamic equilibrium, the values of all computed model cell outputs from prior model results were used to specify a suitable initial condition. In our simulation, a FCB value of 20 $MPN \cdot 100\ ml^{-1}$ was used.

V-2-4 Estimation of parameters

The major parameters used for the fecal coliform model are the decay rate and the mixing parameter. The survival of bacteria in natural waters depends on the particular type of water body and associated phenomena that influence the growth, death, and total loss of organisms. In general, the factors that influence the decay rate include: sunlight, temperature, salinity, predation, nutrient, settling, resuspension and after-growth. In the previous fecal coliform simulations of Lynnhaven River and the adjacent Back Bay, we have tested the various decay rates and found that 1.0 day^{-1} during the summer generates reasonable results. This value is consistent with estimated values from previous extensive surveys of fecal coliform in the Lynnhaven River. This same value was used in the Thalia Creek and Thurston Branch fecal coliform simulations. The major mixing parameter is the eddy diffusivity, which is calculated by a two-equation turbulence closure scheme using the Mellor-Yamada formulation.

V-2-5 Model Calibration Results

The calibration of the fecal coliform model in the Rudee Inlet system included a full 4-year (i.e., 1996-1999) comparison of model predictions to observations made at all 6 VA-DEQ stations. This comparison of predicted vs. observed values of fecal coliform is shown in Figures V.3 through V.8. Data analysis shows that the fecal coliform distribution is similar during these years with fecal coliform values ranging from approximately 10 to 1200 $MPN \cdot 100\ ml^{-1}$. The simulation of the period 1996-1999 is representative of the current condition.

Figures V.3 through V.8 display the customary log-scale for fecal coliform values. It can be seen that the model predictions (shown in black) vary over several orders of magnitude (from 1 to 10,000 MPN·100 ml^{-1}) over short periods of time. Similarly, observed data values (shown by the red circles) also vary from 10 MPN·100 ml^{-1} to 1200 MPN·100 ml^{-1}, with the latter being the maximum observation detection limit using current measurement procedures. This is partly due to the fact that fecal coliform concentrations are often event-driven, with high concentrations following significant rainfall that delivers fecal pollutants from the watershed to the receiving waters. In the primarily shallow Rudee Inlet system, these events can occur with as little as 0.5 inches of rainfall. The 30-day geometric mean (heavy blue line) is also plotted, as are the criteria values of 14 MPN·100 ml^{-1} (shellfish harvesting standard) and 43 MPN·100 ml^{-1} (90^{th} percentile criterion).

V-2-6 Fecal Coliform Model Validation Results

To validate the Rudee Inlet system fecal coliform model, it was necessary to compare predictions to an entirely independent data set. These data were those collected during the July and August grab sample surveys of this project reported in Chapter II (see Figures II.51 through II.53. Again, it should be noted that FCB values were calculated from *E. coli* densities. The "snapshots" (average of the day) of model predictions throughout the domain are compared to the grab sample survey data for July 1, 2010, July 12, 2010, and August 12, 2010 in Figures V.9 through V.11, respectively. It is noted that, in these figures, the observed values are printed out adjacent to sampling locations (red squares) whereas the predicted values are shown throughout the model domain by the circles with a color-coding indicating their values, as shown by the figure legend.

Since the watershed model provides the daily fecal coliform loadings, the model-predicted values presented in Figures V.9 to V.11 are the daily averages while the observed data are instantaneous values at the time of sample collection. Therefore, these figures provide only the comparison of spatial pattern, rather than the exact magnitude of the values. Figures V.9 and 10 show generally good overall agreement between predicted and observed spatial patterns. The highest observations of fecal coliform (generally between 800 and 1200 MPN·100 ml^{-1}) correspond closely with the darkest coloration of the legend.

Figure V.11 shows a poorer comparison between the model results and field observation in August 2010. This might be due to the contribution of a non runoff-related source of fecal coliform loadings which is not accounted for by the watershed model. Figure II.7 shows that there is very little rainfall during the August survey. Therefore, the non-point sources from the watershed had a minor contribution. This suggests the existence of an unaccounted source inside the lake system. In fact, the historical data show high fecal coliform concentration at all stations in August regardless of precipitation (see Chapter I). That points to the non runoff-related sources, such as boating activities, wildlife in inter-tidal areas, and so forth.

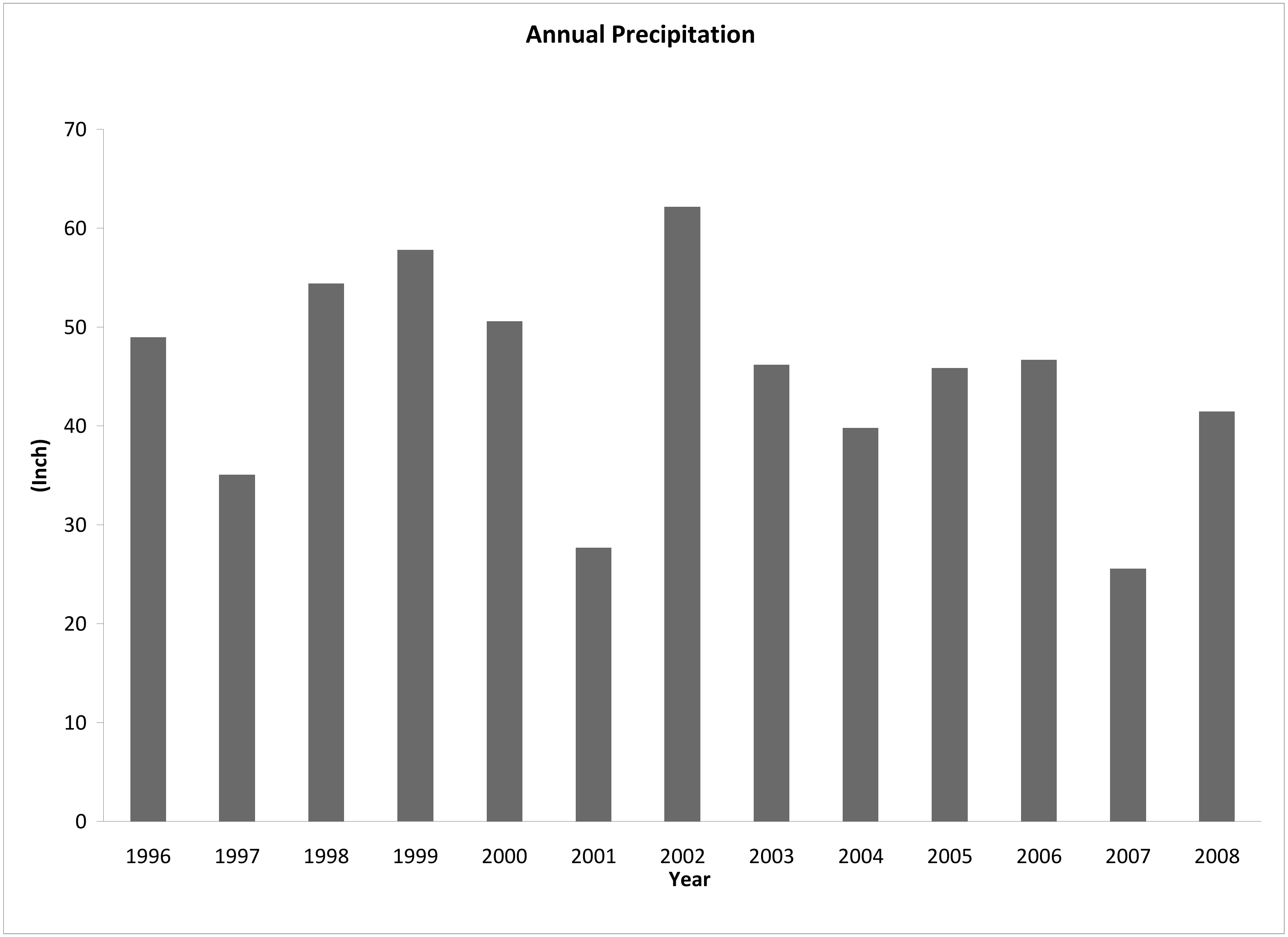


Figure V.1. Annual precipitations measured at the Oceana Naval Air Station for the period 1996-2008.

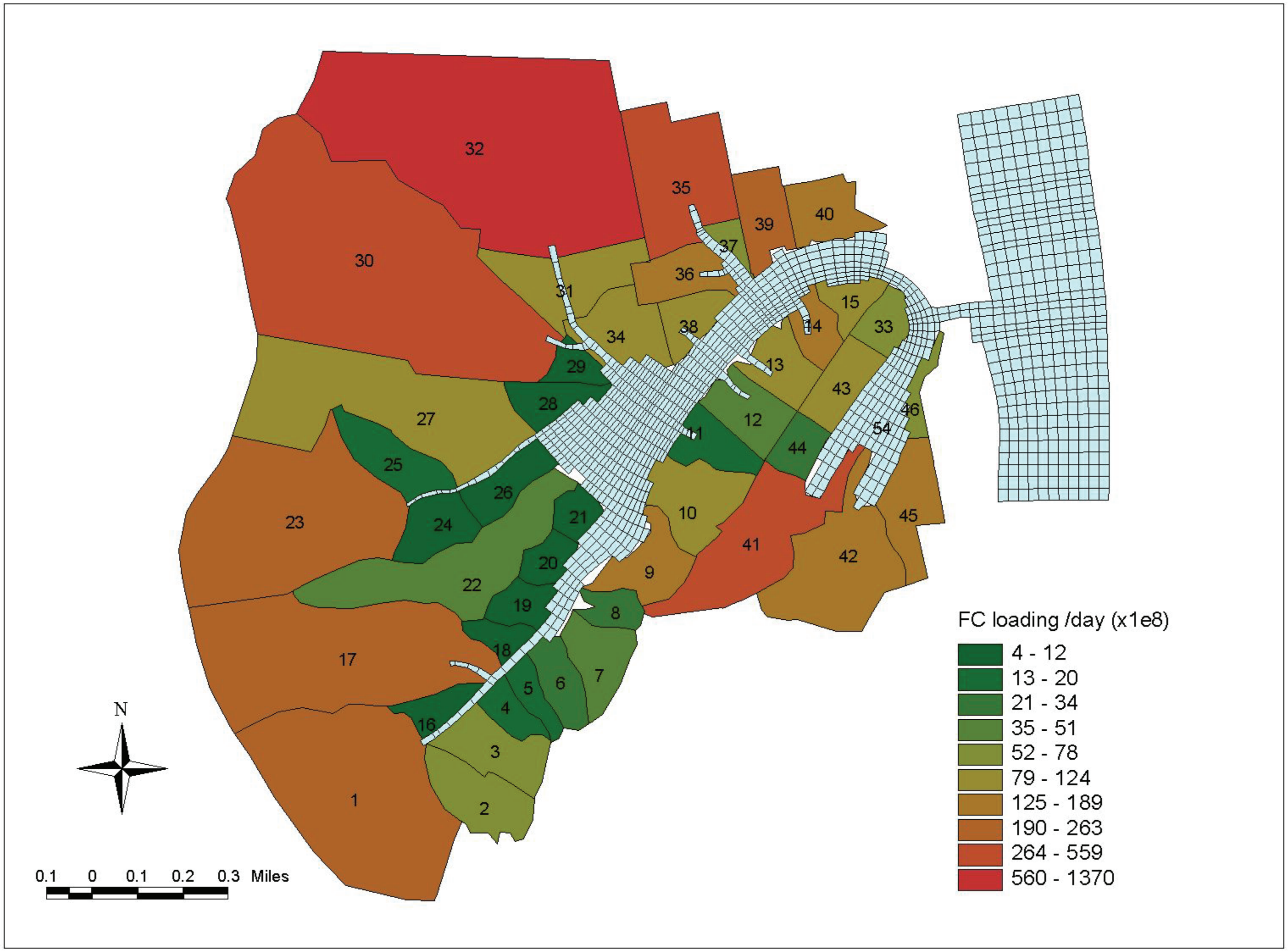


Figure V.2. Average fecal coliform loading (counts/day) from the Rudee Inlet subwatersheds.

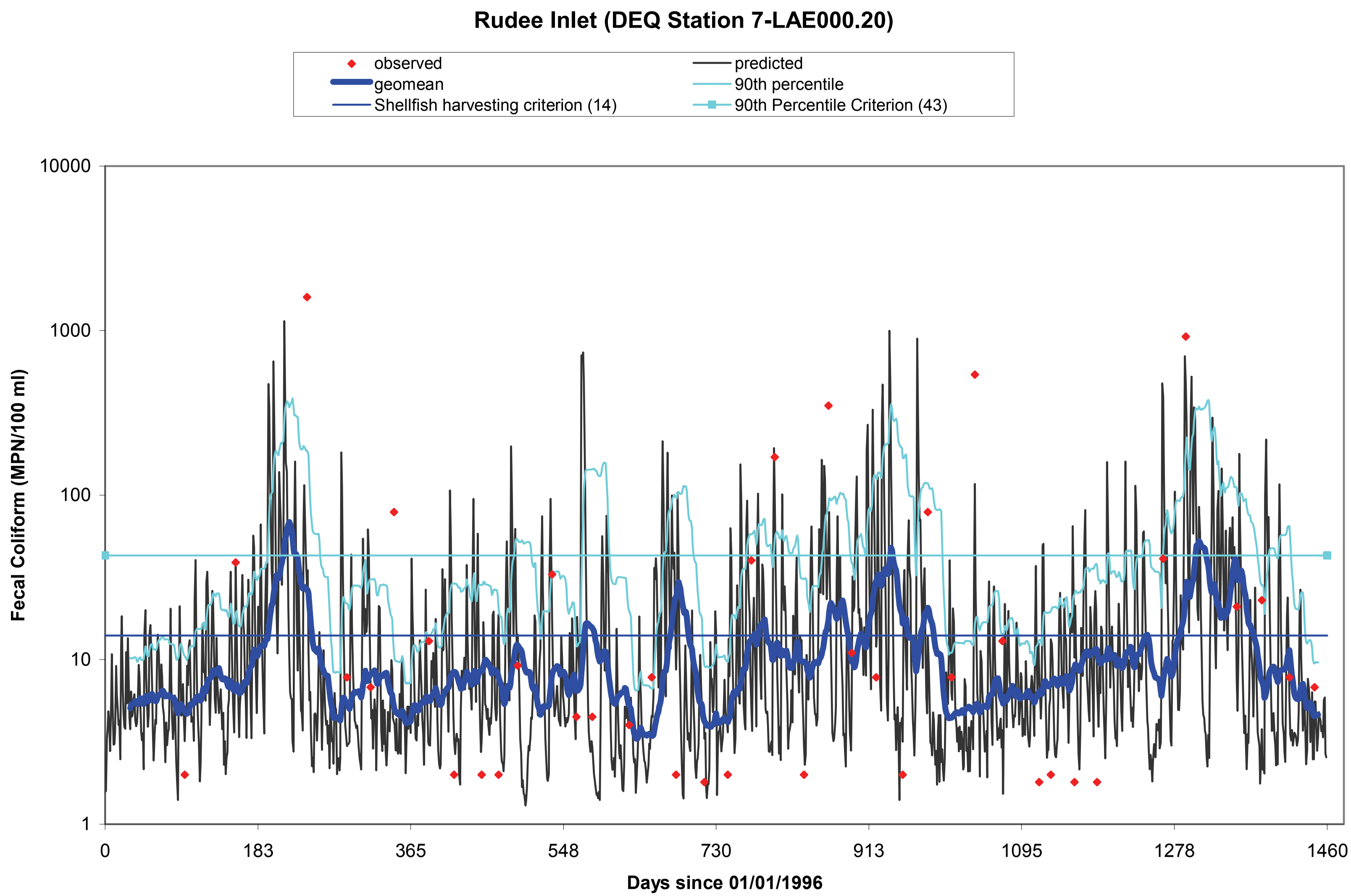


Figure V.3. Observed vs. predicted fecal coliform at VA-DEQ Station 7-LAE000.20 for 1996-1999 calibration.

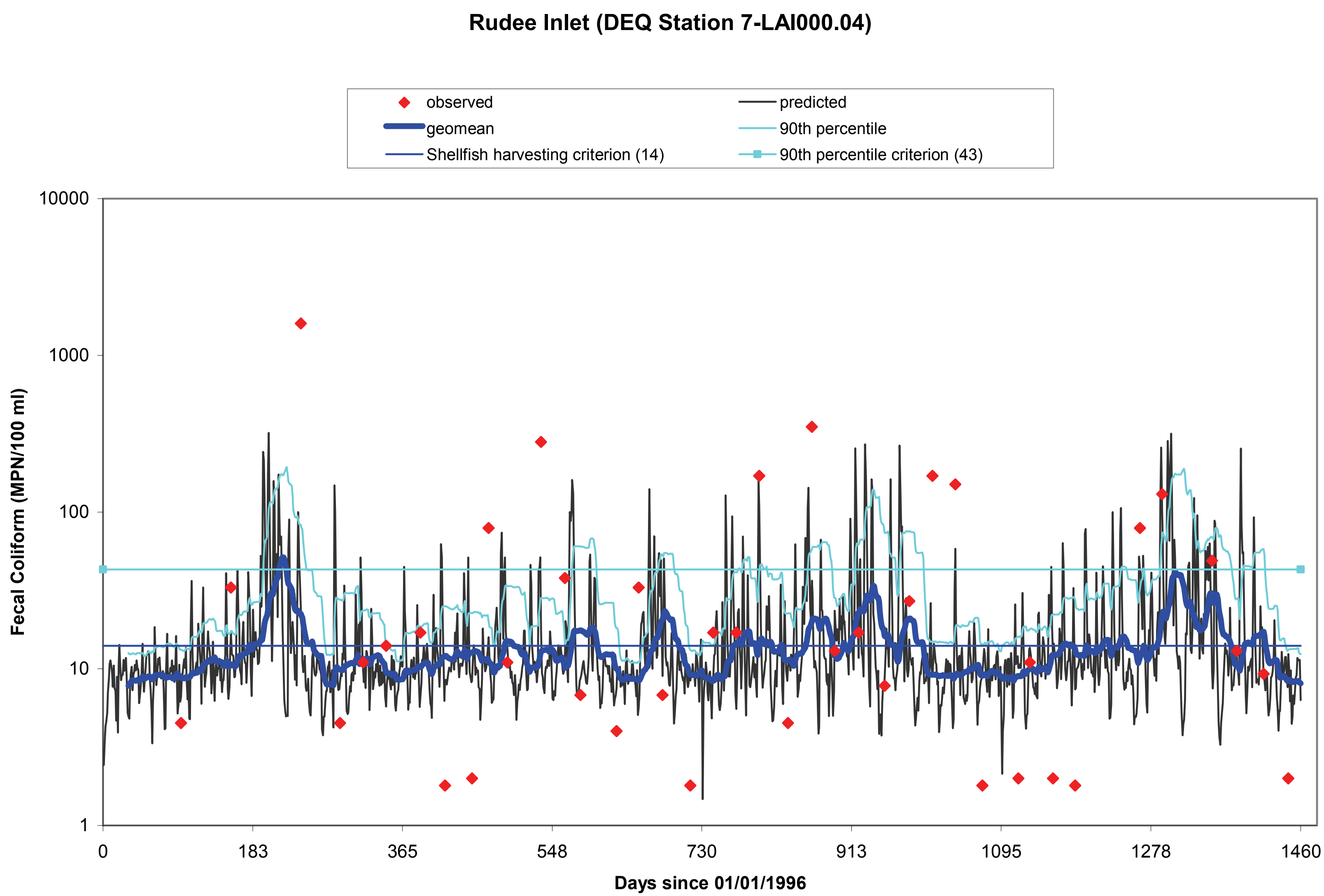


Figure V.4. Observed vs. predicted fecal coliform at VA-DEQ Station 7-LAI000.04 for 1996-1999 calibration.

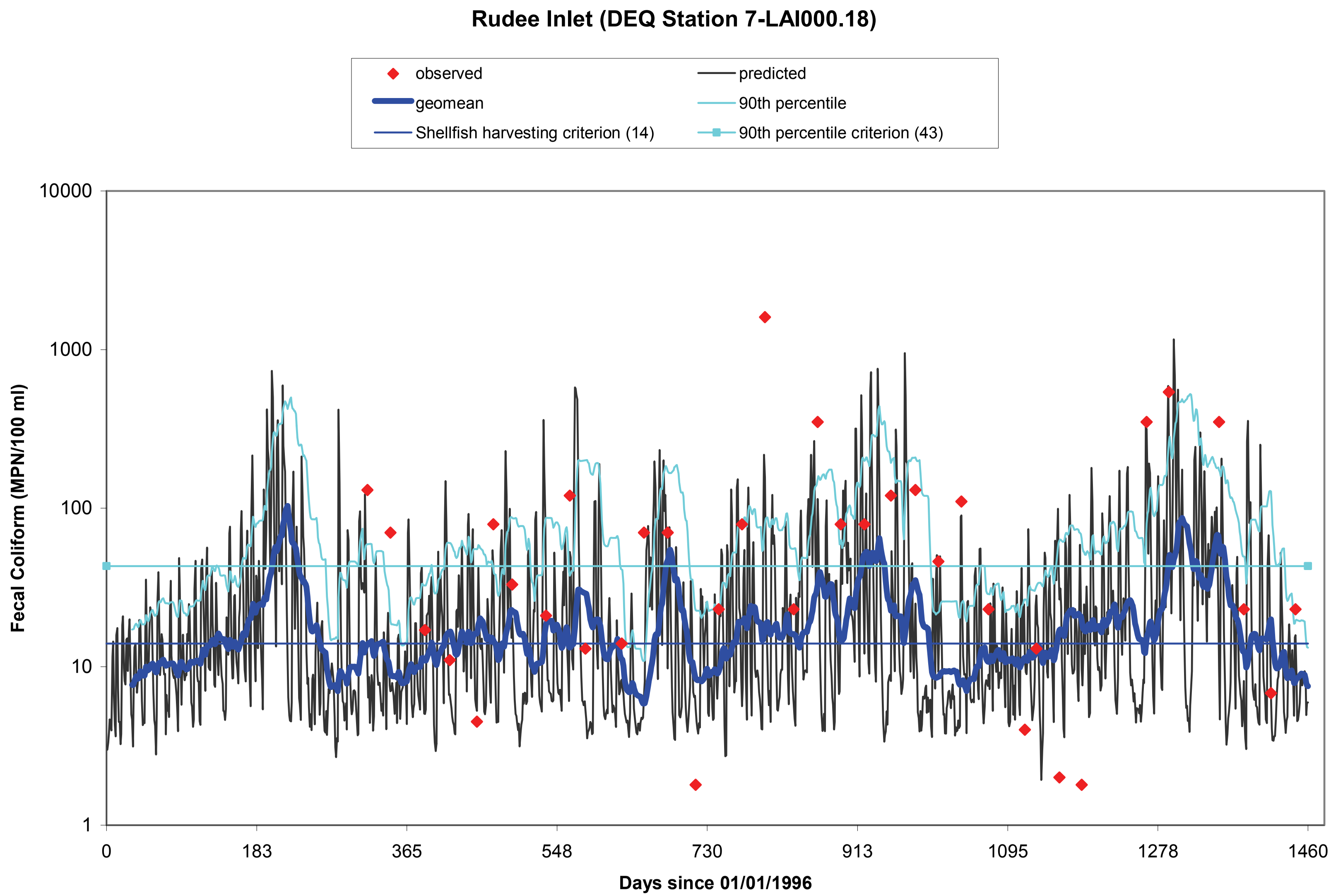


Figure V.5. Observed vs. predicted fecal coliform at DEQ Station 7-LAI000.18 for 1996-1999 calibration.

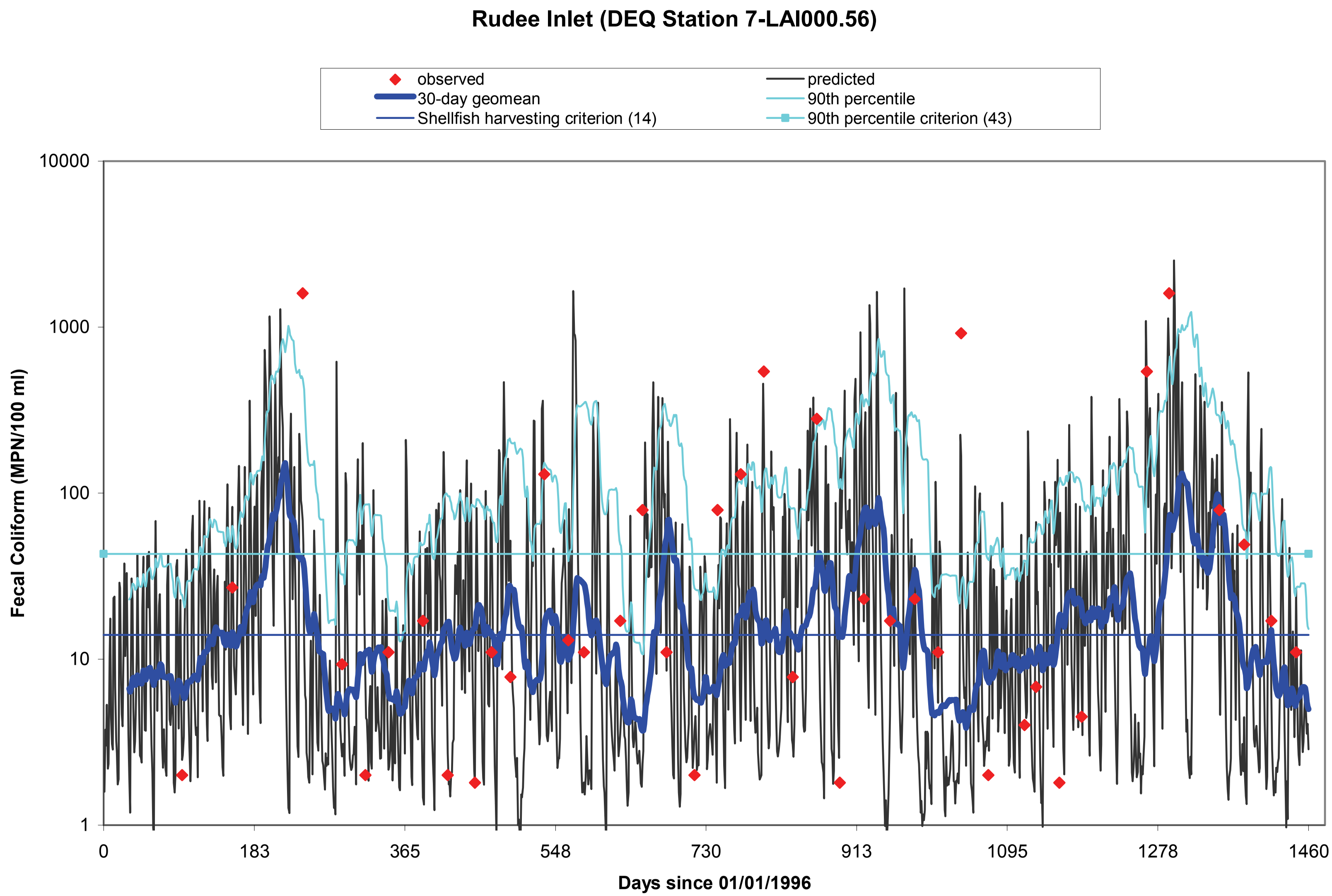


Figure V.6. Observed vs. predicted fecal coliform at DEQ Station 7-LAI000.56 for 1996-1999 calibration.

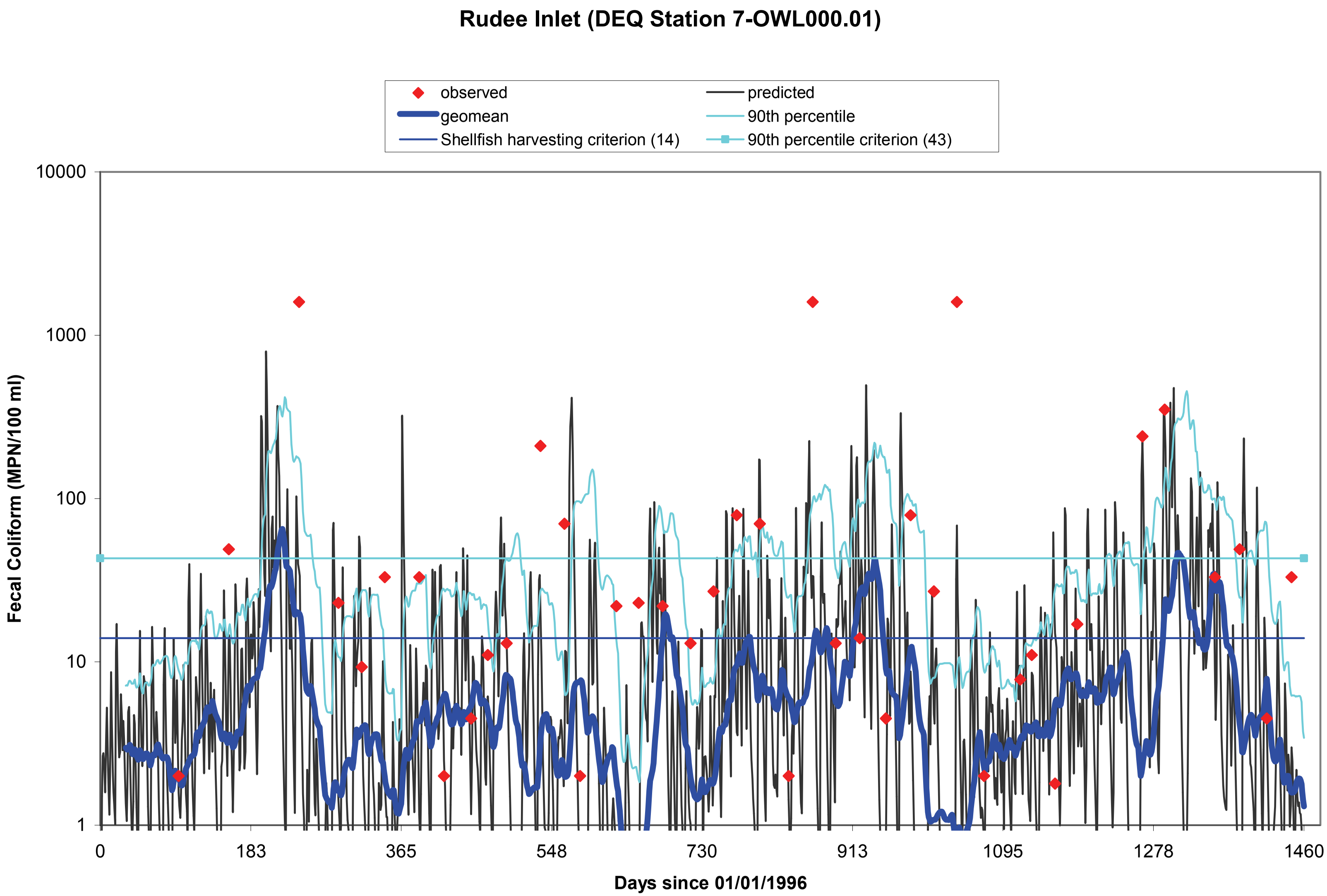


Figure V.7. Observed vs. predicted fecal coliform at DEQ Station 7-OWL000.01 for 1996-1999 calibration.

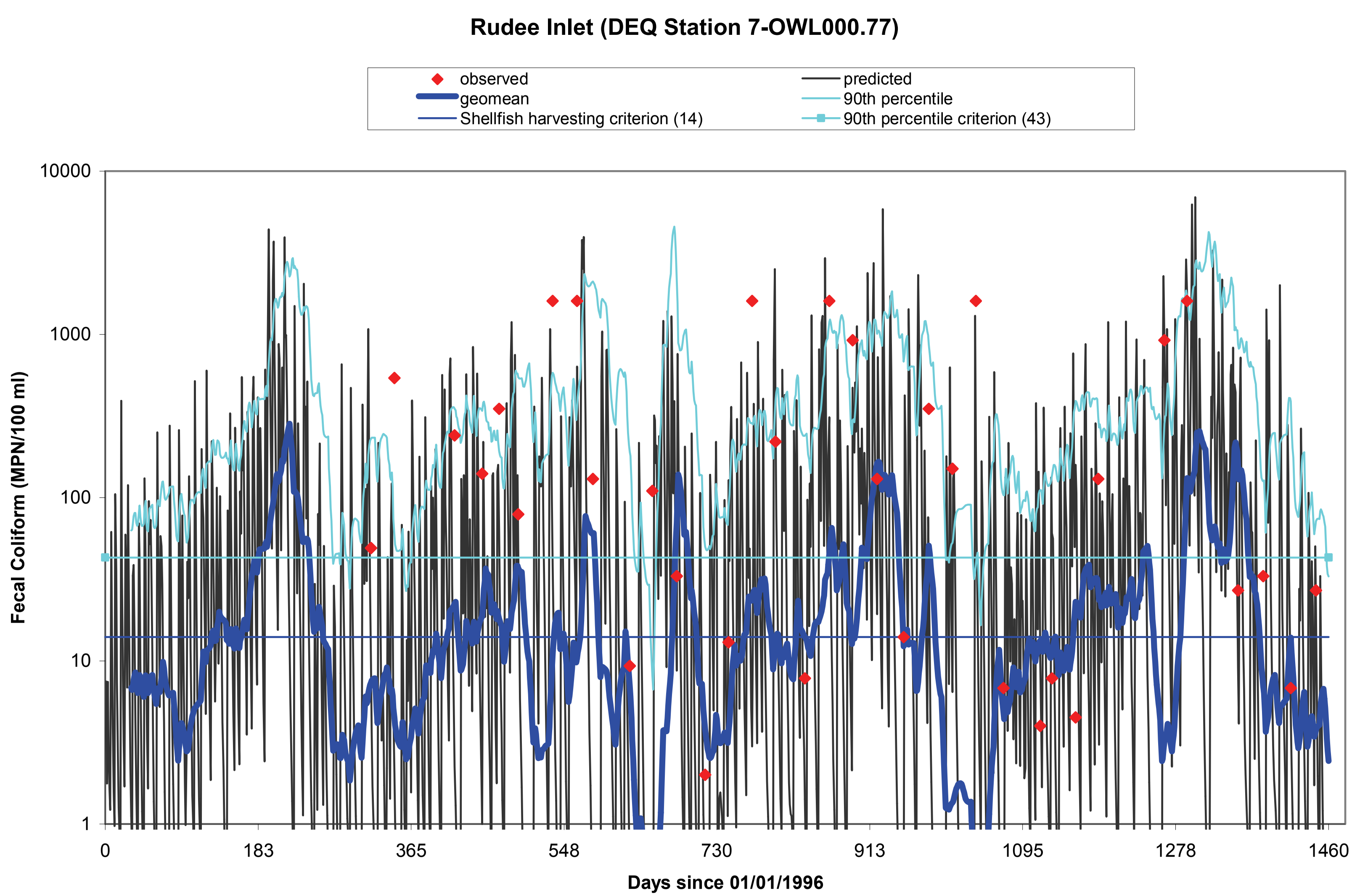


Figure V.8. Observed vs. predicted fecal coliform at DEQ Station 7-OWL000.77 for 1996-1999 calibration.

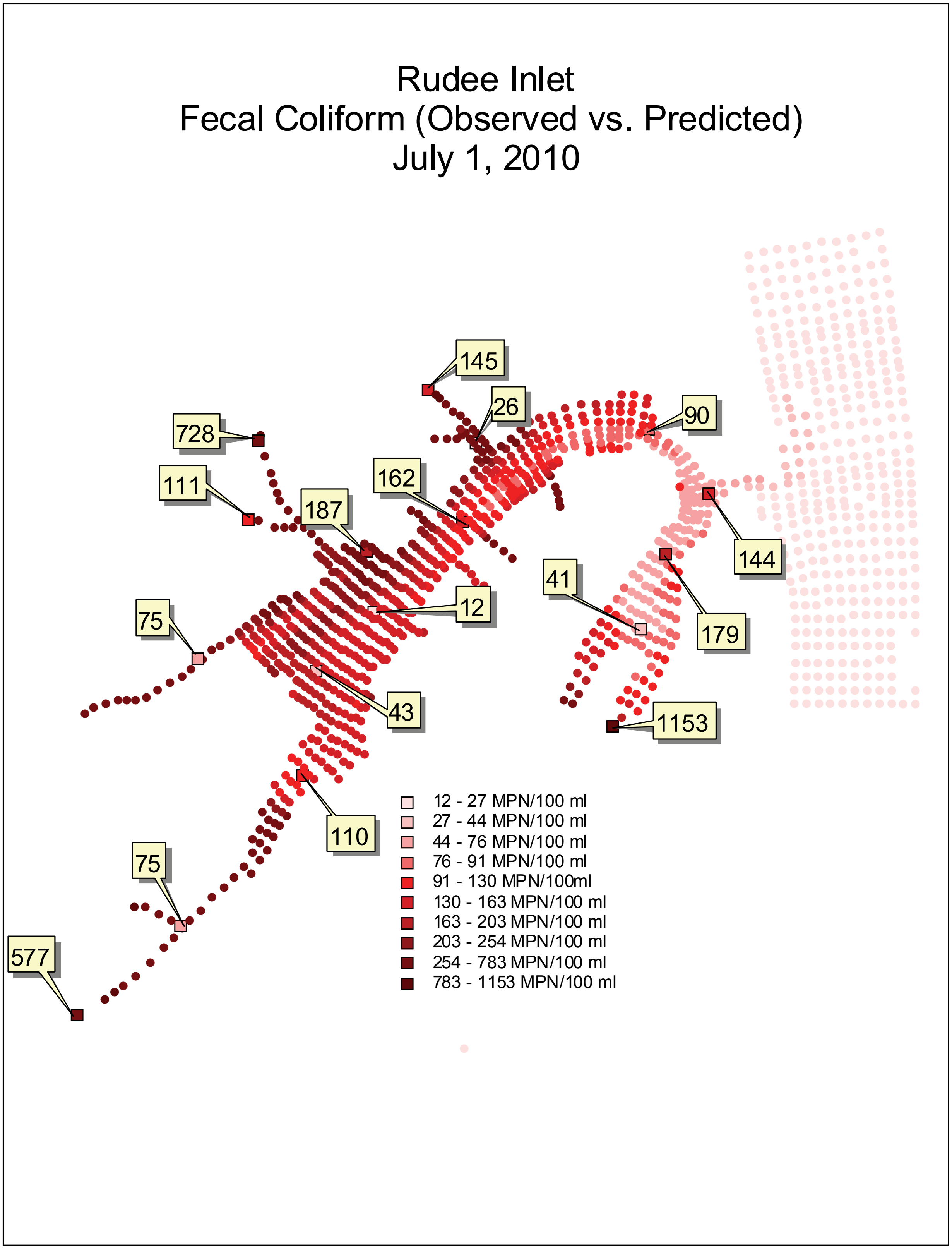


Figure V.9. Observed vs. predicted fecal coliform concentrations throughout the Rudee Inlet system on July 1, 2010 [Note: observed values printed, predicted values color-coded to legend].

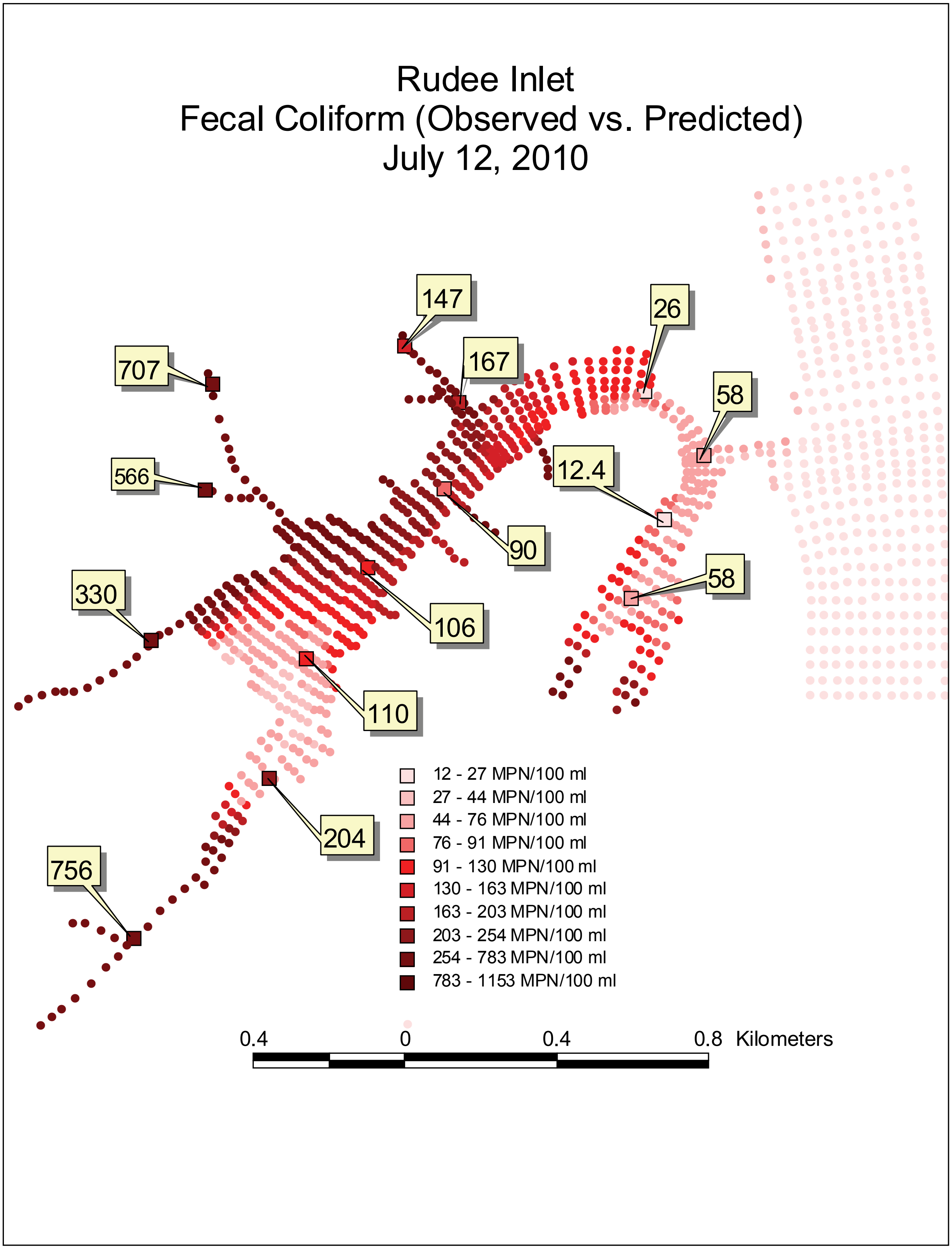


Figure V.10. Observed vs. predicted fecal coliform concentrations throughout the Rudee Inlet system on July 12, 2010. [Note: observed values printed, predicted values color-coded to legend].

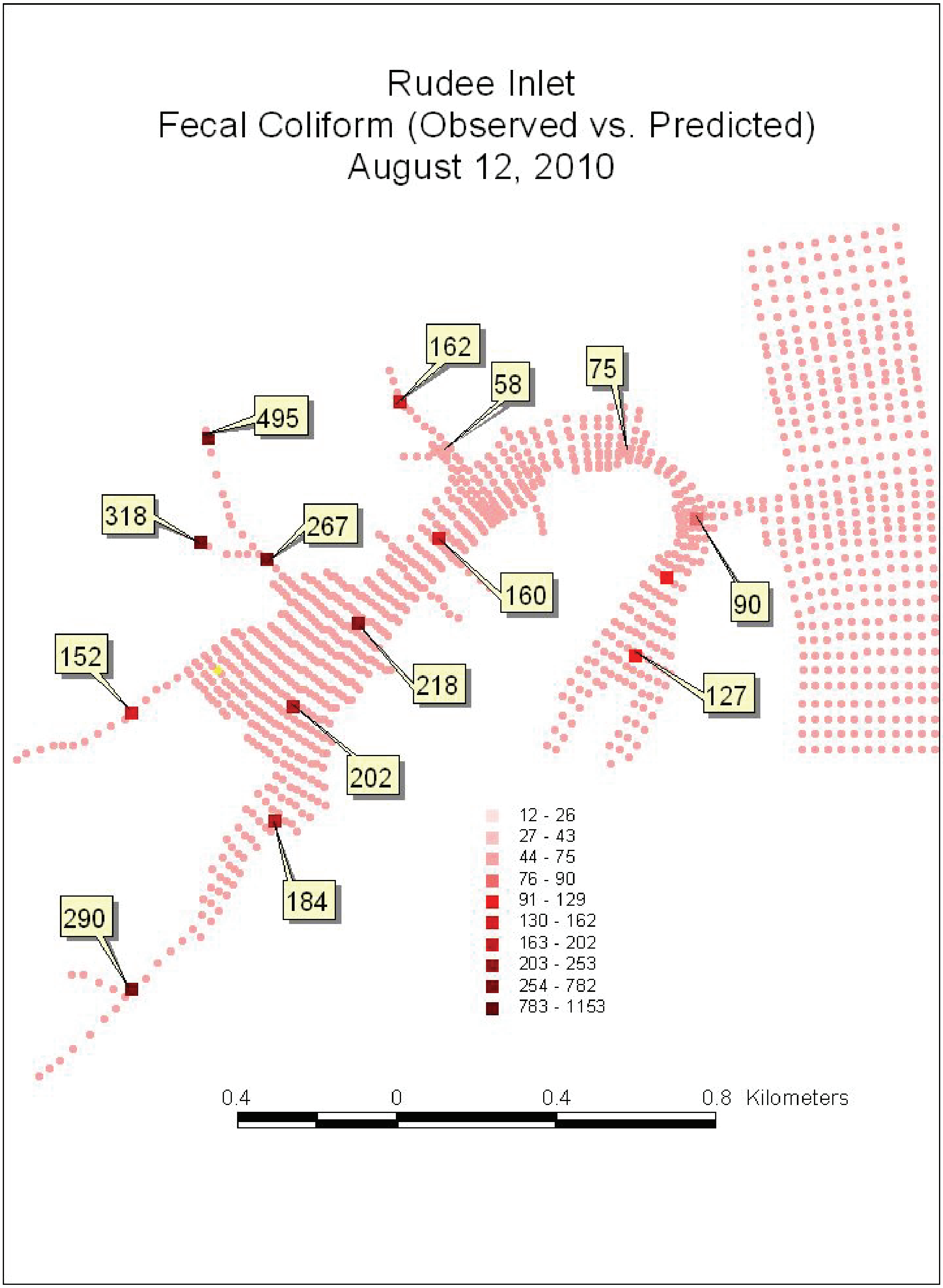


Figure V.11. Observed vs. predicted fecal coliform concentrations throughout the Rudee Inlet system on August 12, 2010. [Note: observed values printed, predicted values color-coded to legend].

CHAPTER VI. MODEL APPLICATIONS

With the modeling framework in place and the model having undergone calibration and validation, one of the most advantageous elements of the modeling is the ability to simulate hypothetical conditions. A good example of how the model, once calibrated and validated, can be applied is through *sensitivity* testing. Model inputs can be individually assessed by comparing model results with and without these inputs.

For the present modeling project of the Rudee Inlet system, the calibrated model was used to assess the conditions that would occur under reduced loadings of fecal coliform from the watershed. Reductions of first 90% and then 95% were made and analyzed to determine if compliance with state water quality regulations was being met. These reductions are discussed below in sections VI-1 and VI-2.

During the fecal coliform modeling effort, one question that arose was the relative contribution of urban land use areas compared to portions of the watershed dominated by marshlands. A sensitivity test reducing the loading from urban sources by 90% is discussed in Section VI-3.

Lastly, in Section VI-4, the base case condition release of fecal coliform is compared with 3 hypothetical non-point source release scenarios in an effort to identify the regions of influence associated with types of fecal coliform loading from the Rudee Inlet watershed. Spatial distributions of fecal coliform levels from each non-point source are contrasted with that of the base case.

VI-1 Fecal coliform load reduction sensitivity (90% load reduction)

Using the current fecal coliform calibration predictions in the Rudee Inlet system as the base condition, sensitivity runs were made using both 90% and 95% reduction scenarios over the 1997-1999 portion of the calibration period. The predictions of these scenarios at the 6 VA-DEQ stations in the system, along with their associated 30-day geometric means and 90th percentiles, are shown in Figures V1.1 through V1.6.

On each of these figures, the associated 30-day geometric mean of model predictions is plotted for comparison to the shellfish harvesting criterion of 14 $MPN \cdot 100\ ml^{-1}$. Also, the 30-day 90th percentile value of the predictions is plotted for comparison to the 90th percentile criterion of 43 $MPN \cdot 100\ ml^{-1}$. Figures VI.1 through VI.6 show occasional violations of both of these standards, with the more stringent 90th percentile standard being violated more often and last longer for the 90% load reduction for the Rudee Inlet watershed.

VI-2 Fecal coliform load reduction sensitivity (95% load reduction)

The scenario reducing the fecal coliform loading from the Rudee Inlet watershed by 95% was executed next. The predictions of fecal coliform levels, and their geometric means and 90th percentiles, at the 6 VA-DEQ stations, are shown in Figures V1.7 through V1.12.

An inspection of Figures VI.7 through VI.12 shows that increasing the load reduction to 95% eradicates almost all of the violations shown earlier in the 90% load reduction scenario. The one exception to this occurs at the most upstream station, 7-OWL000.77, located in upper Owl Creek in a region dominated by marshlands and not having much circulation, or flushing capability.

VI-3 Fecal coliform load reduction sensitivity (90% load reduction, urban sources)

The next scenario that was executed targeted the isolation of urban impacts in the Rudee Inlet system by reducing the fecal coliform urban loading sources by 90%. The revised distribution of loading resulting from this reduction can be seen by comparing the average loads resulting from the 90% reduction in urban loads (shown in Figure VI.13) with the normal loads shown earlier in Figure V.2. Predictions at the 6 VA_DEQ stations for this scenario are shown in Figures VI.14 through VI.19.

Comparisons of model predictions from this scenario with those of the overall load reduction scenarios show that the impact from urban sources of the Rudee Inlet watershed has a much smaller effect than that from the overall load reduction.

VI-4 Regional assessment of non-point source influence

One important capability of the calibrated model is being able to isolate various inputs to determine their impacts to conditions within the model domain. This has been done for the Rudee Inlet watershed loadings to determine impacts of FCB loadings from key subwatersheds.

A base case condition was executed and fecal coliform spatial distributions were saved in order to compare to 3 hypothetical non-point source releases of fecal at key locations along the shoreline. Shown in Figure VI.20 are 3 regions (labeled “West”, “Northwest”, and “Upstream Marsh”) that correspond to the high loading subwatersheds illustrated in Figure VI.13 (i.e., subwatersheds 1, 30, and 32). These regions were isolated by making 3 scenario runs with fecal coliform loading exclusively at these locations. The results, shown in Figures VI.21 through VI.24, indicate the spatial extents and concentrations that these non-point source releases of fecal coliform can generate. It can be seen that concentrations can spread throughout most of the Lake Rudee region within a couple of days prior to their reductions due to decay. The main conclusion drawn from these scenarios is that it may be important to address simultaneous loading reductions in all three of these regions.

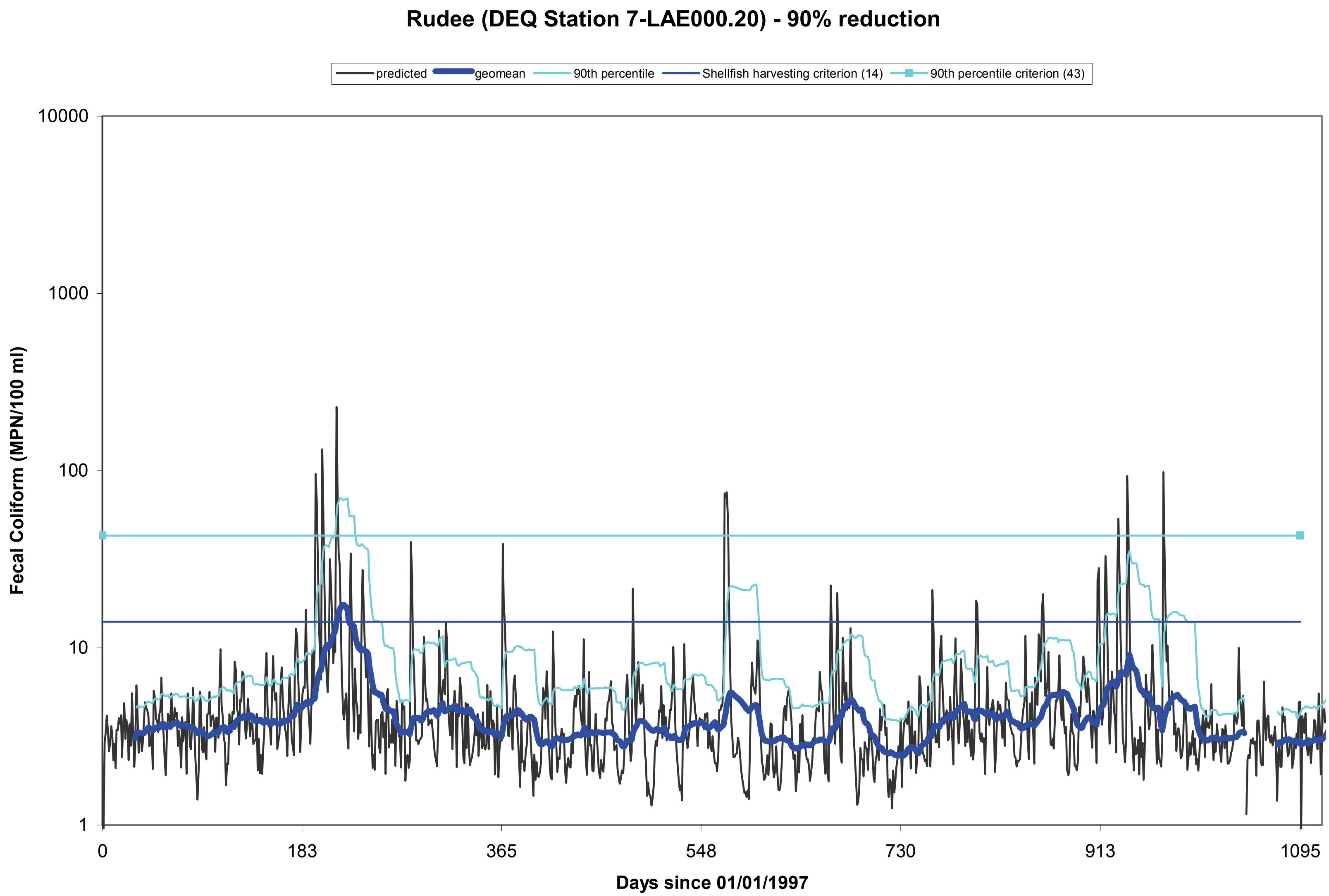


Figure VI.1. Fecal coliform predictions at VA-DEQ Station 7-LAE000.20 using a 90% load reduction for the 1997-1999 simulation.

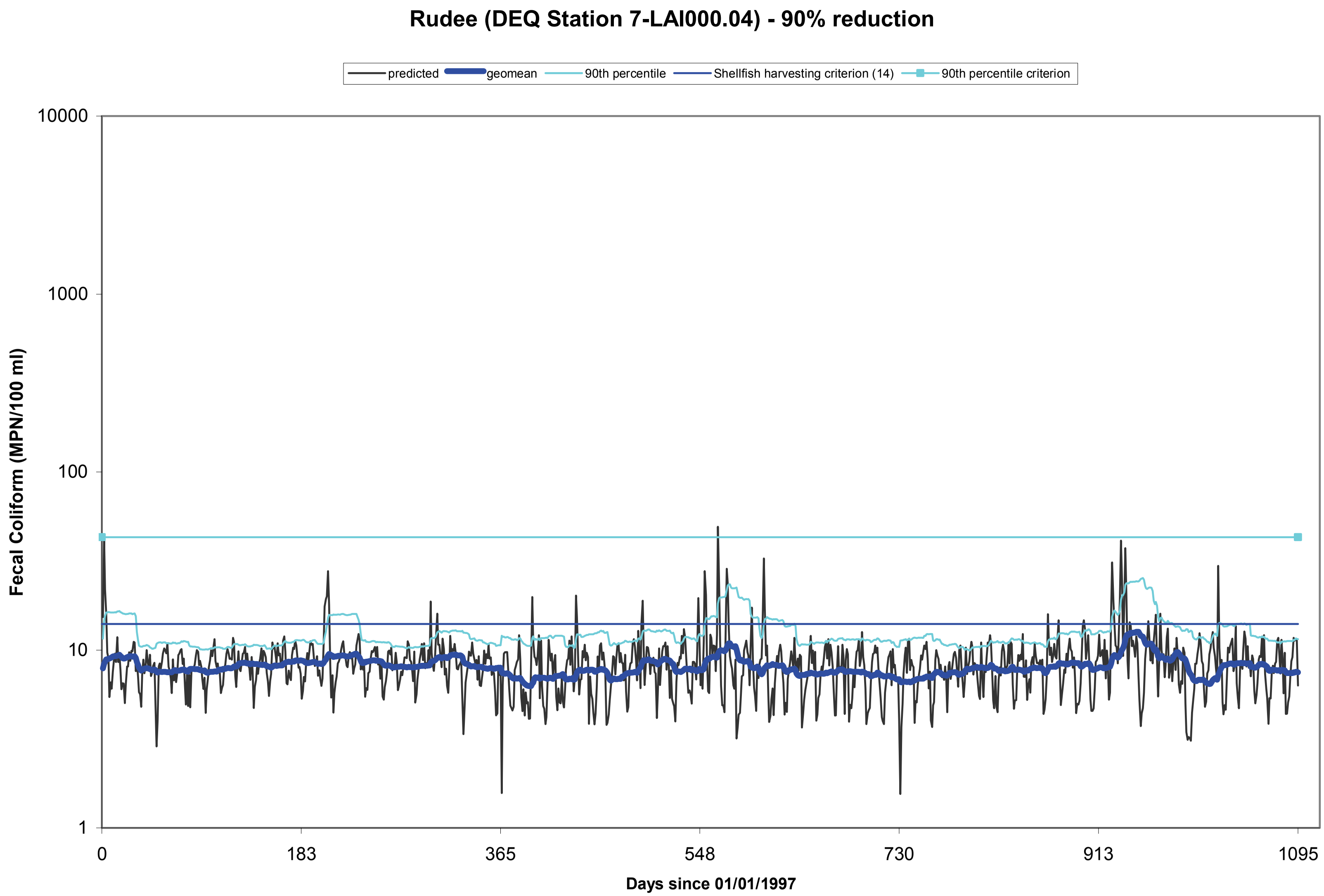


Figure VI.2. Fecal coliform predictions at VA-DEQ Station 7-LAI000.04 using a 90% load reduction for the 1997-1999 simulation.

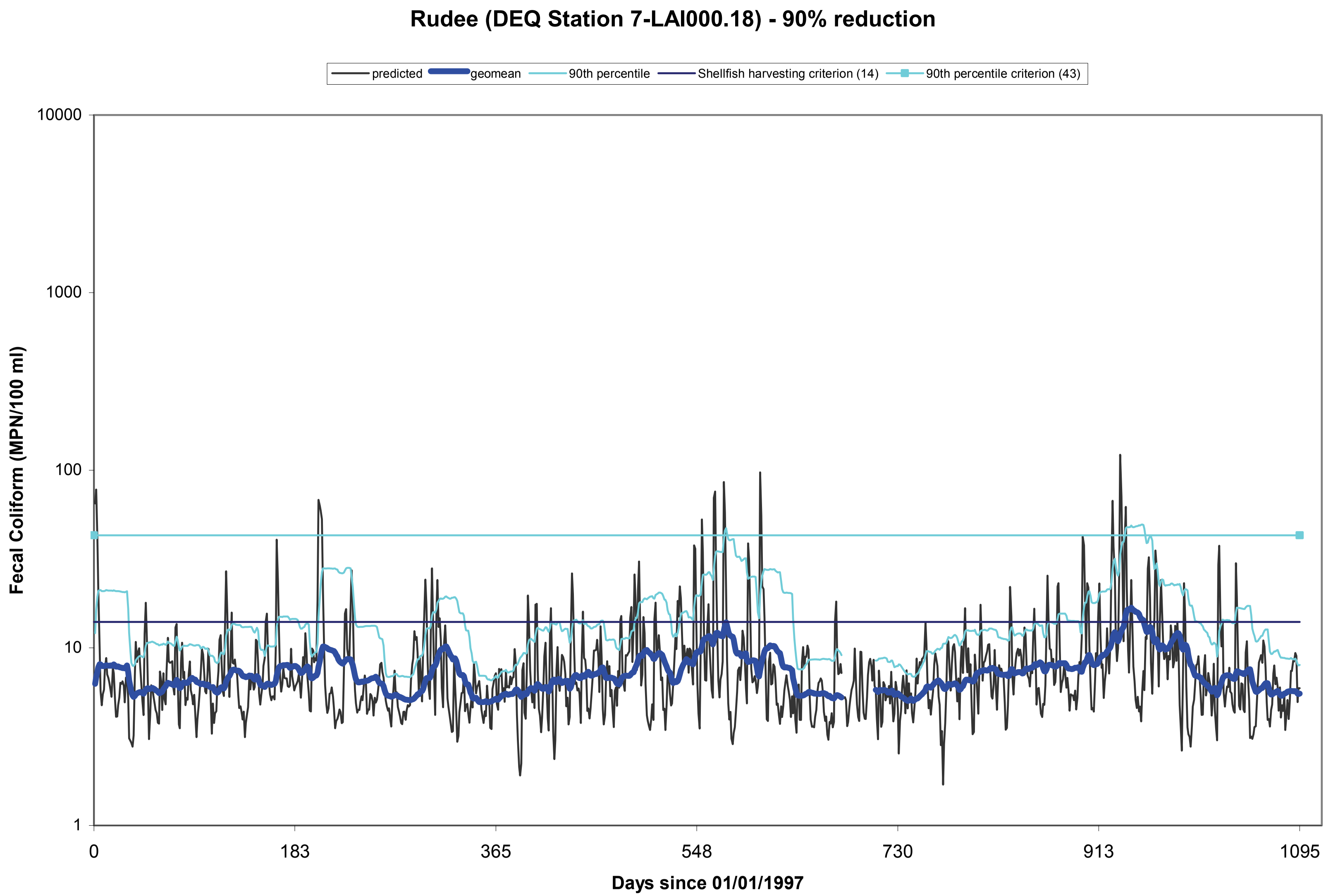


Figure VI.3. Fecal coliform predictions at VA-DEQ Station 7-LAI000.18 using a 90% load reduction for the 1997-1999 simulation.

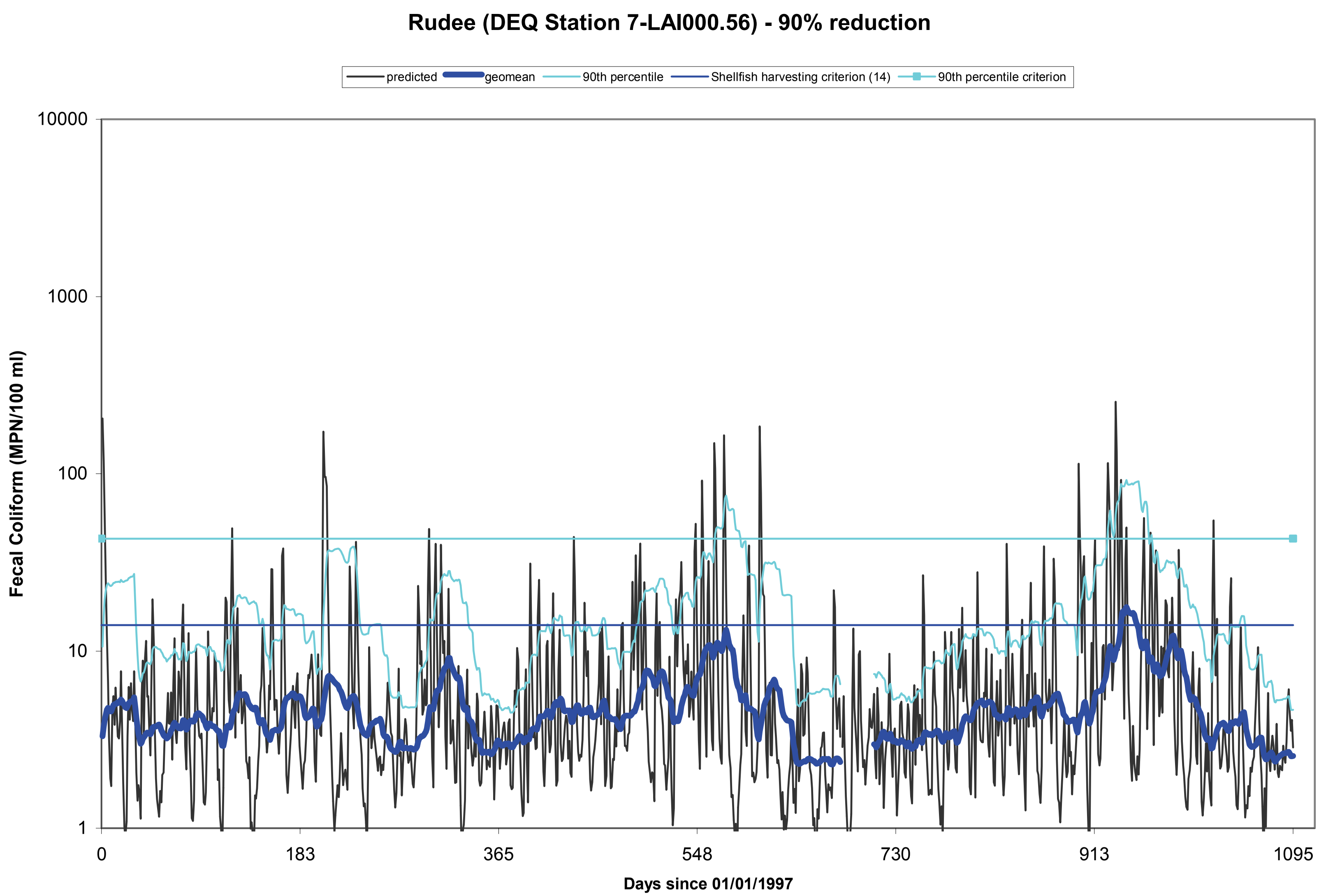


Figure VI.4. Fecal coliform predictions at VA-DEQ Station 7-LAI000.56 using a 90% load reduction for the 1997-1999 simulation.

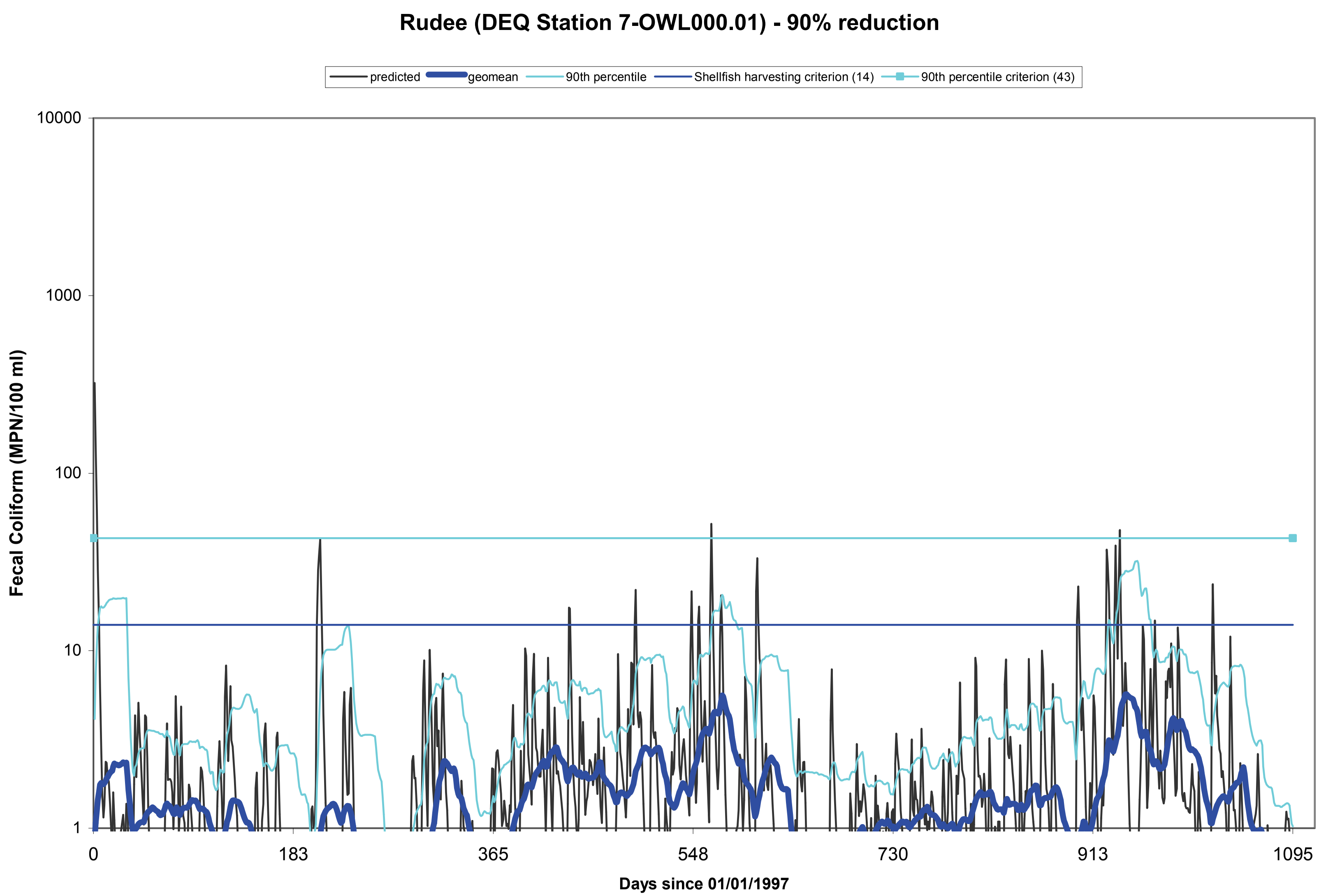


Figure VI.5. Fecal coliform predictions at VA-DEQ Station 7-OWL000.01 using a 90% load reduction for the 1997-1999 simulation.

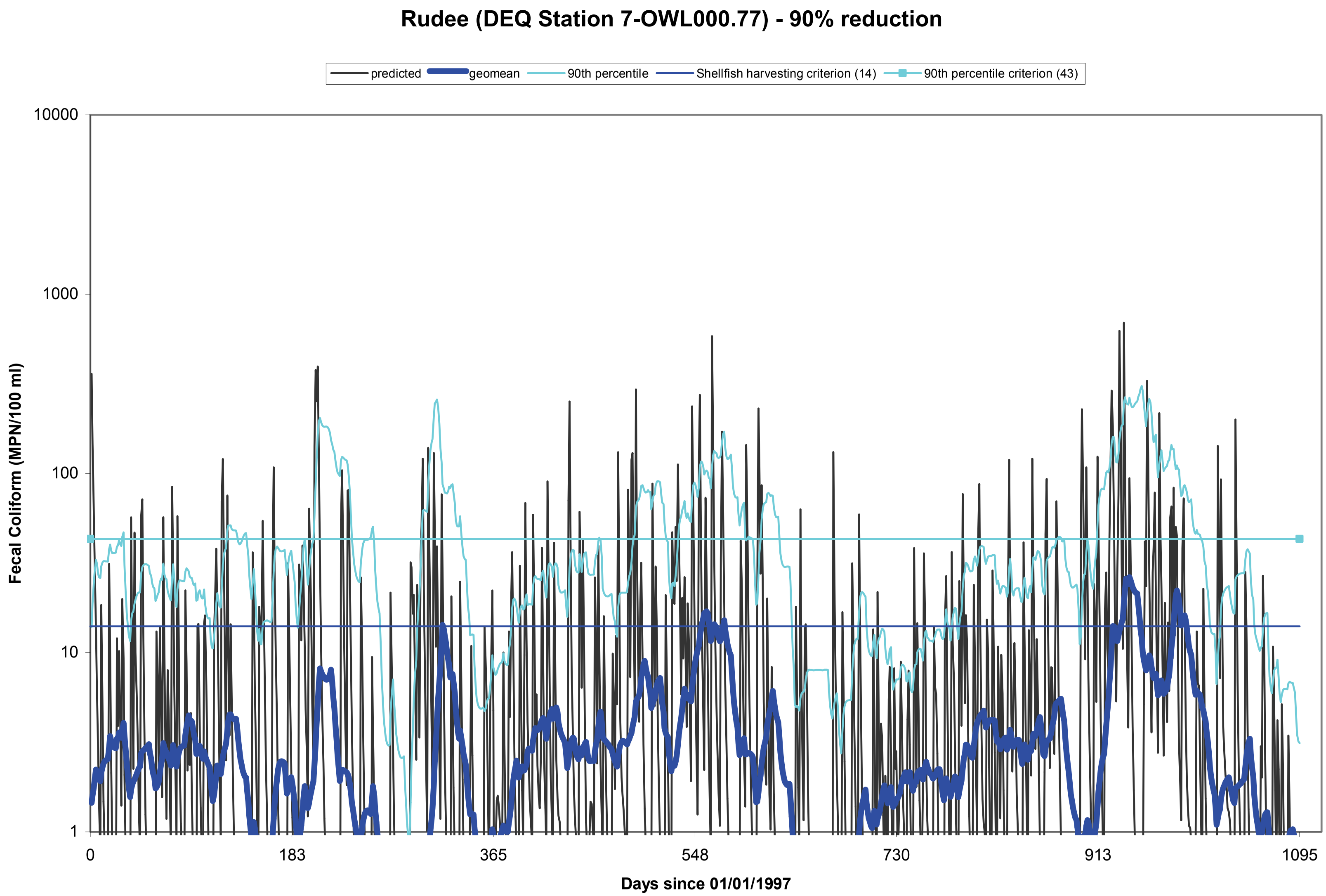


Figure VI.6. Fecal coliform predictions at VA-DEQ Station 7-OWL000.77 using a 90% load reduction for the 1997-1999 simulation.

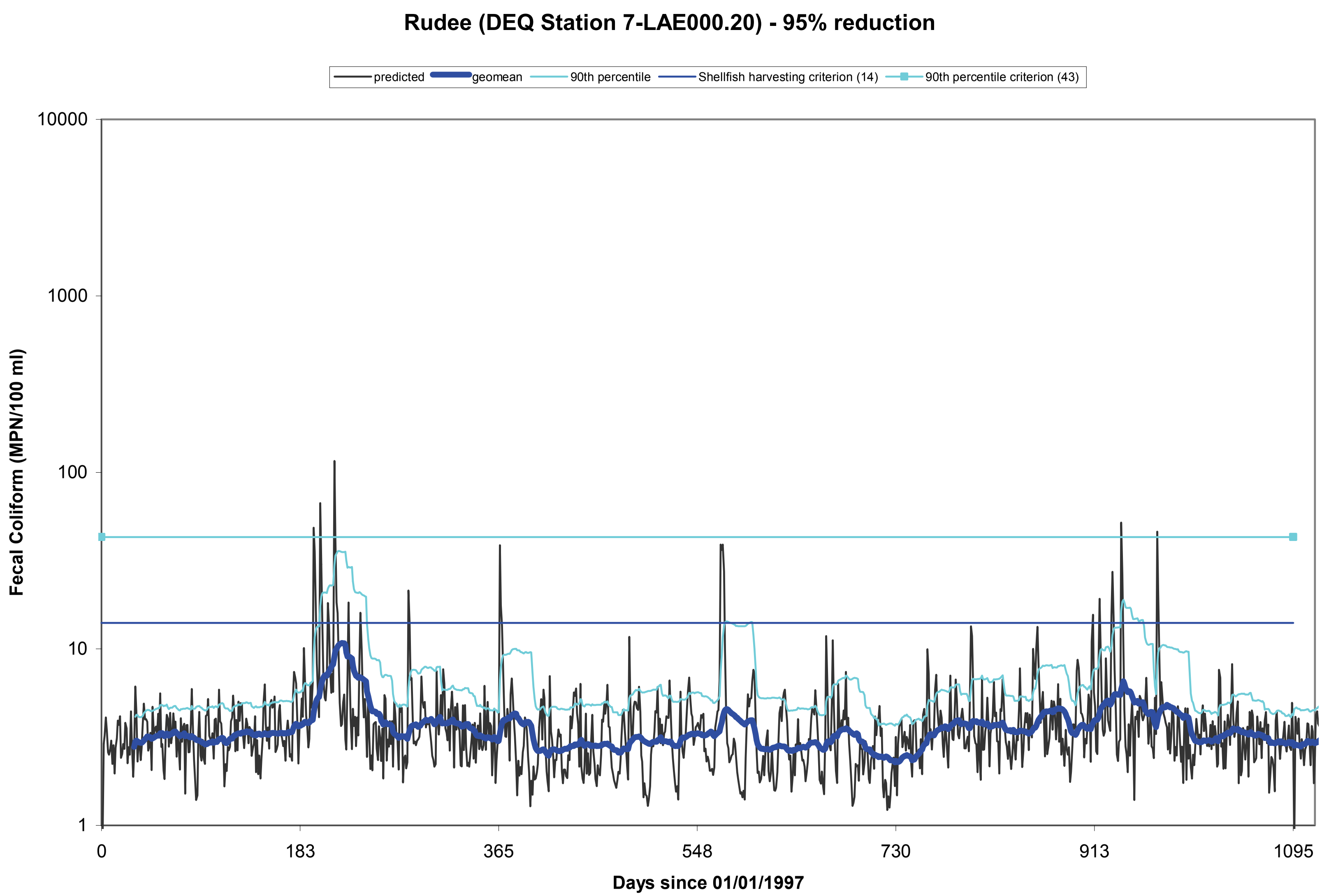


Figure VI.7. Fecal coliform predictions at VA-DEQ Station 7-LAE000.20 using a 95% load reduction for the 1997-1999 simulation.

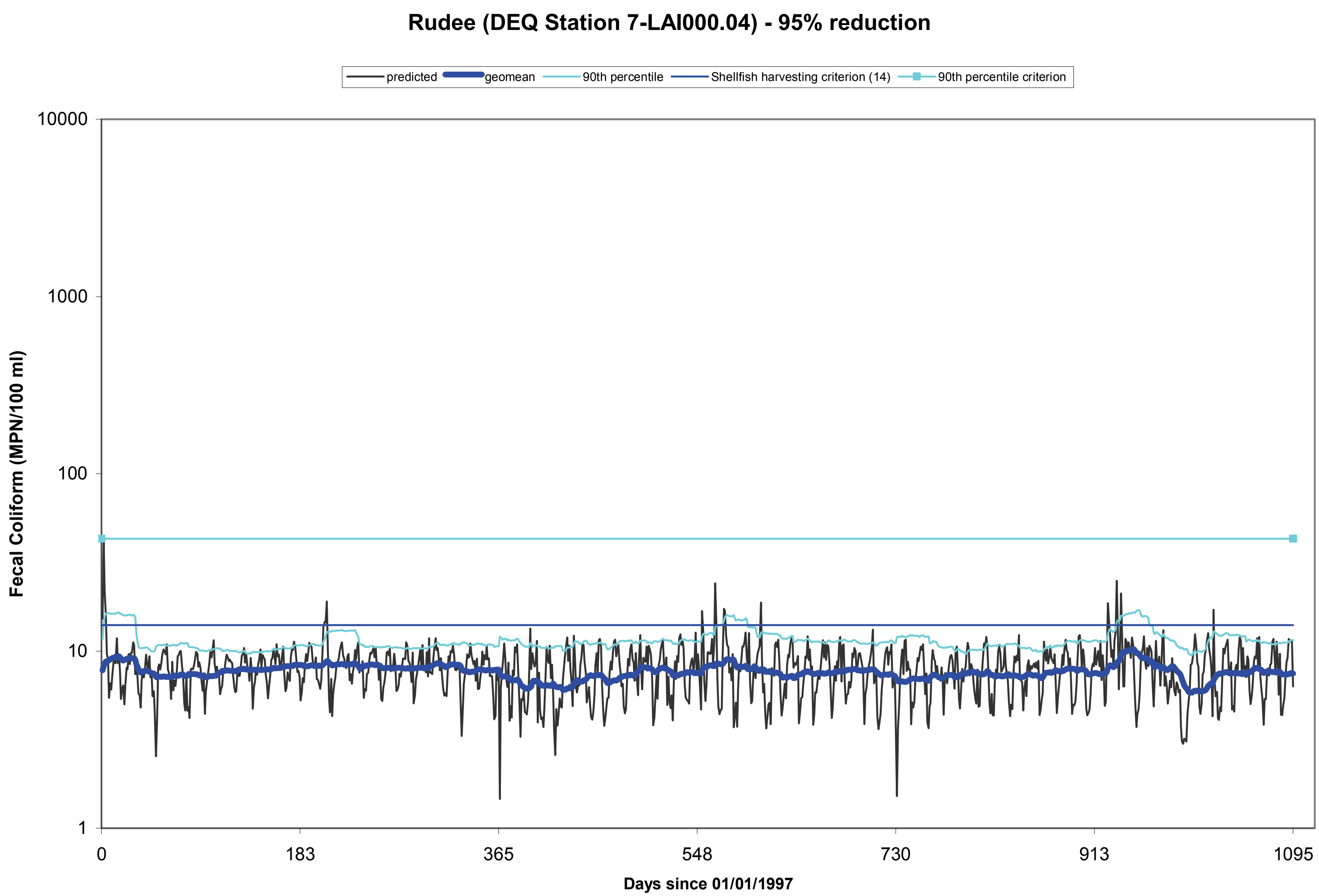


Figure VI.8. Fecal coliform predictions at VA-DEQ Station 7-LAI000.04 using a 95% load reduction for the 1997-1999 simulation.

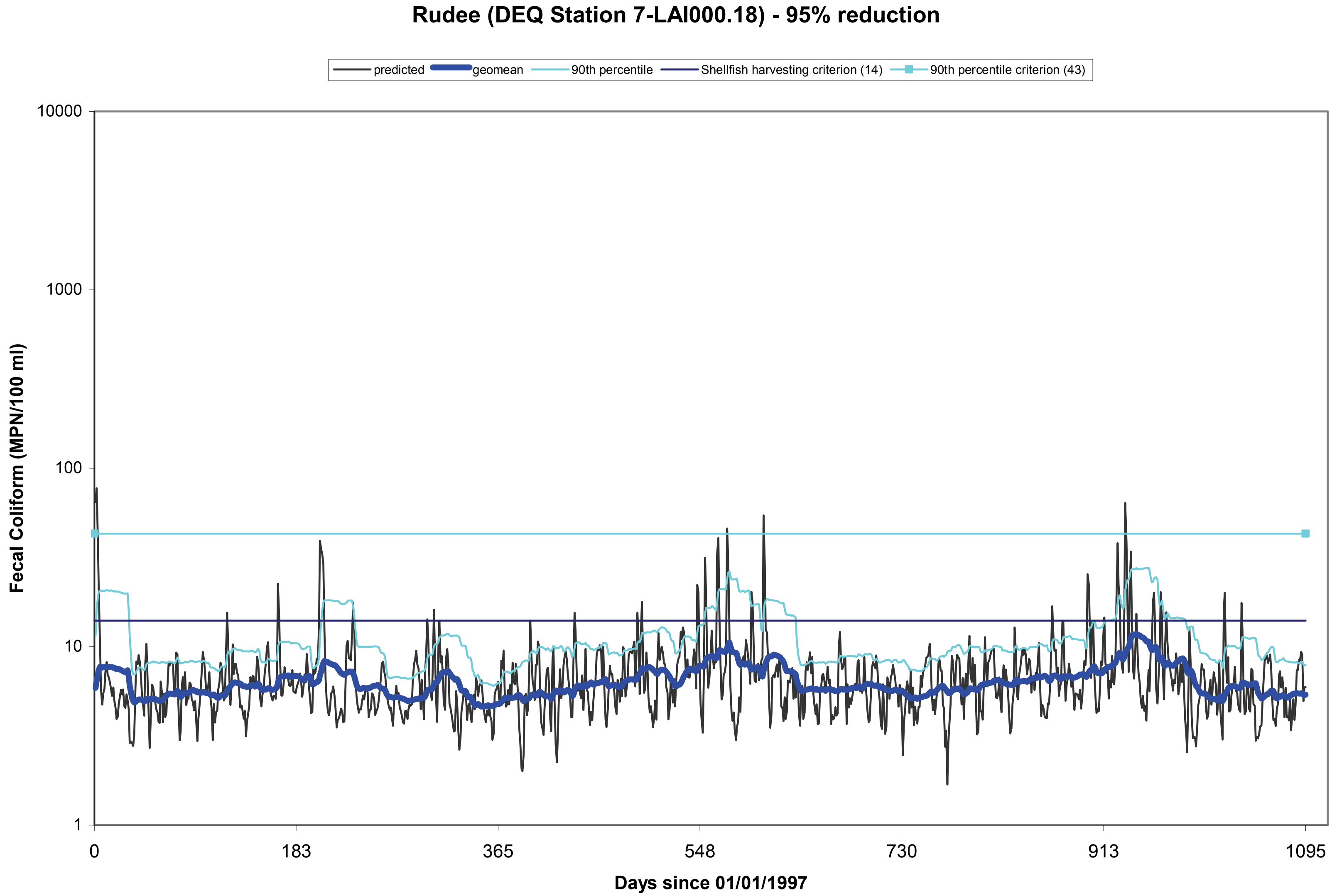


Figure VI.9. Fecal coliform predictions at VA-DEQ Station 7-LAI000.18 using a 95% load reduction for the 1997-1999 simulation.

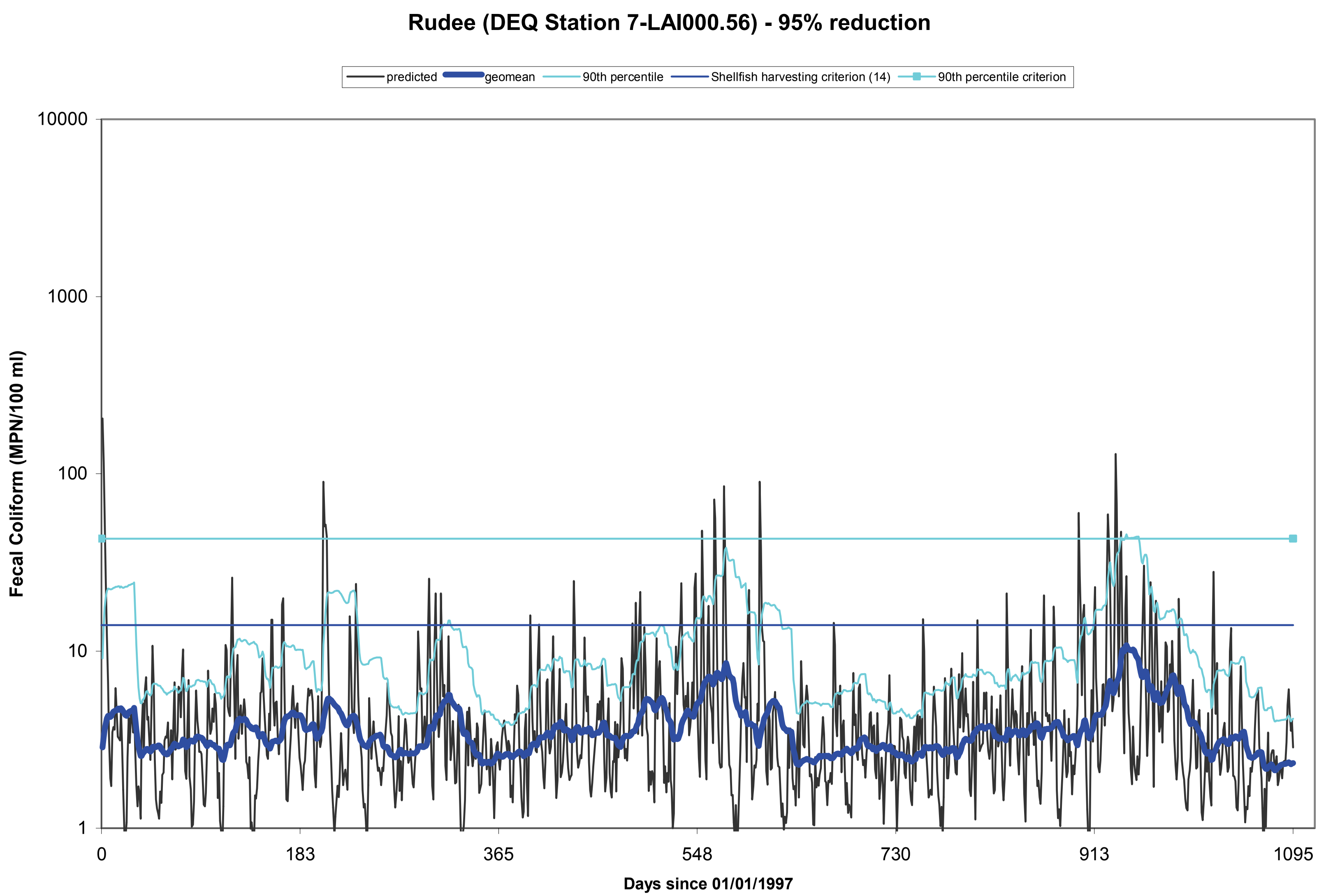


Figure VI.10. Fecal coliform predictions at VA-DEQ Station 7-LAI000.56 using a 95% load reduction for the 1997-1999 simulation.

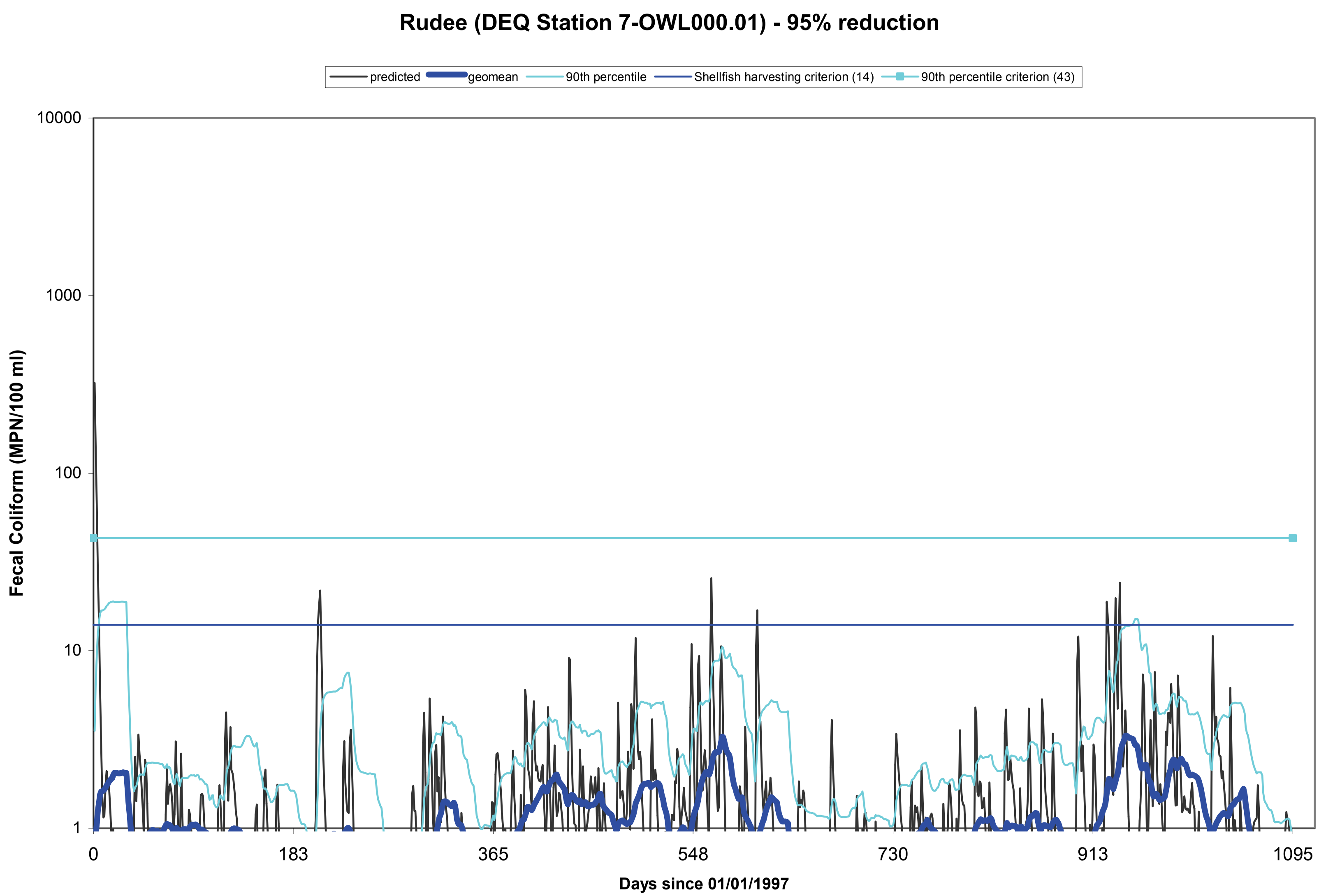


Figure VI.11. Fecal coliform predictions at VA-DEQ Station 7-OWL000.01 using a 95% load reduction for the 1997-1999 simulation.

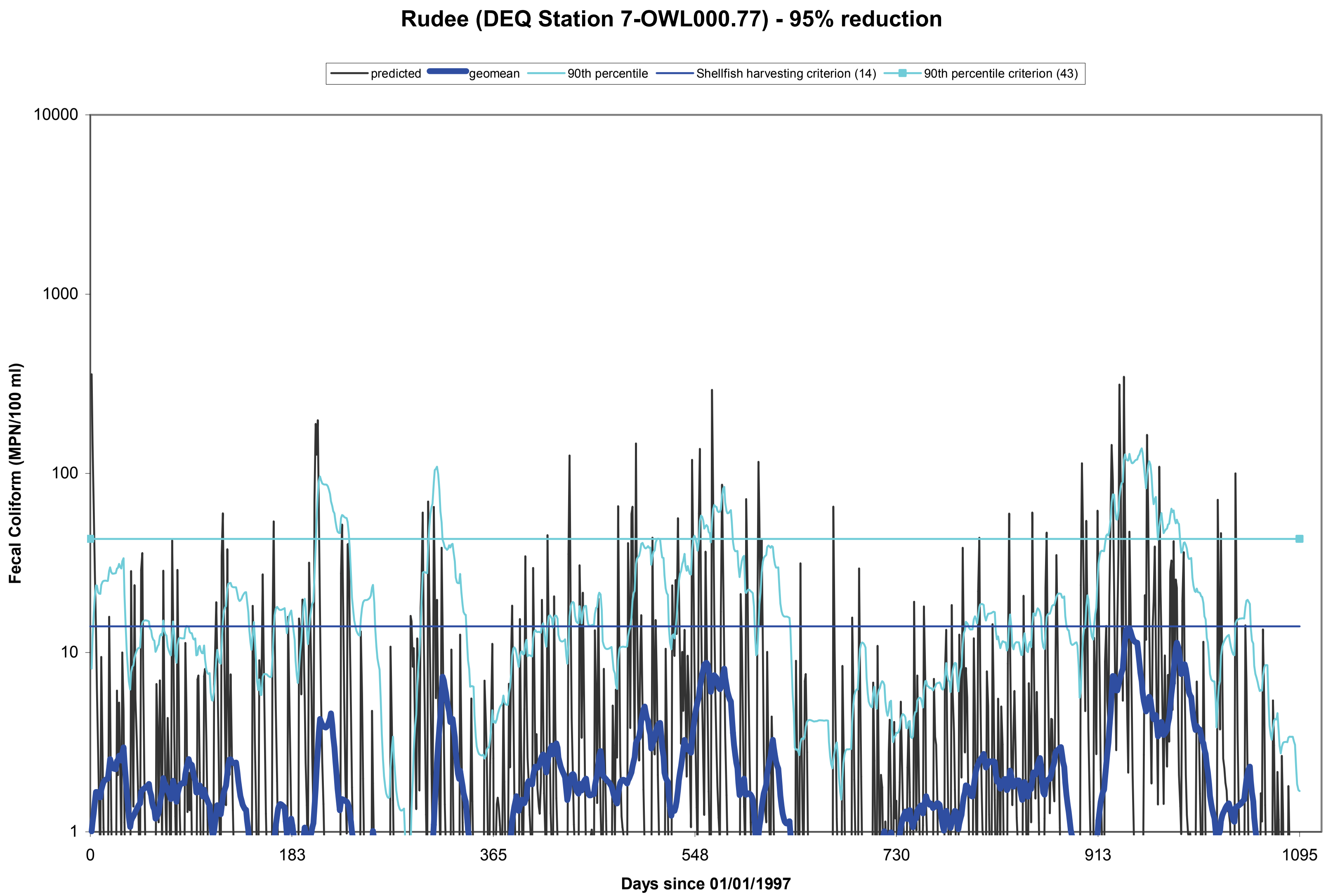


Figure VI.12. Fecal coliform predictions at VA-DEQ Station 7-OWL000.77 using a 95% load reduction for the 1997-1999 simulation.

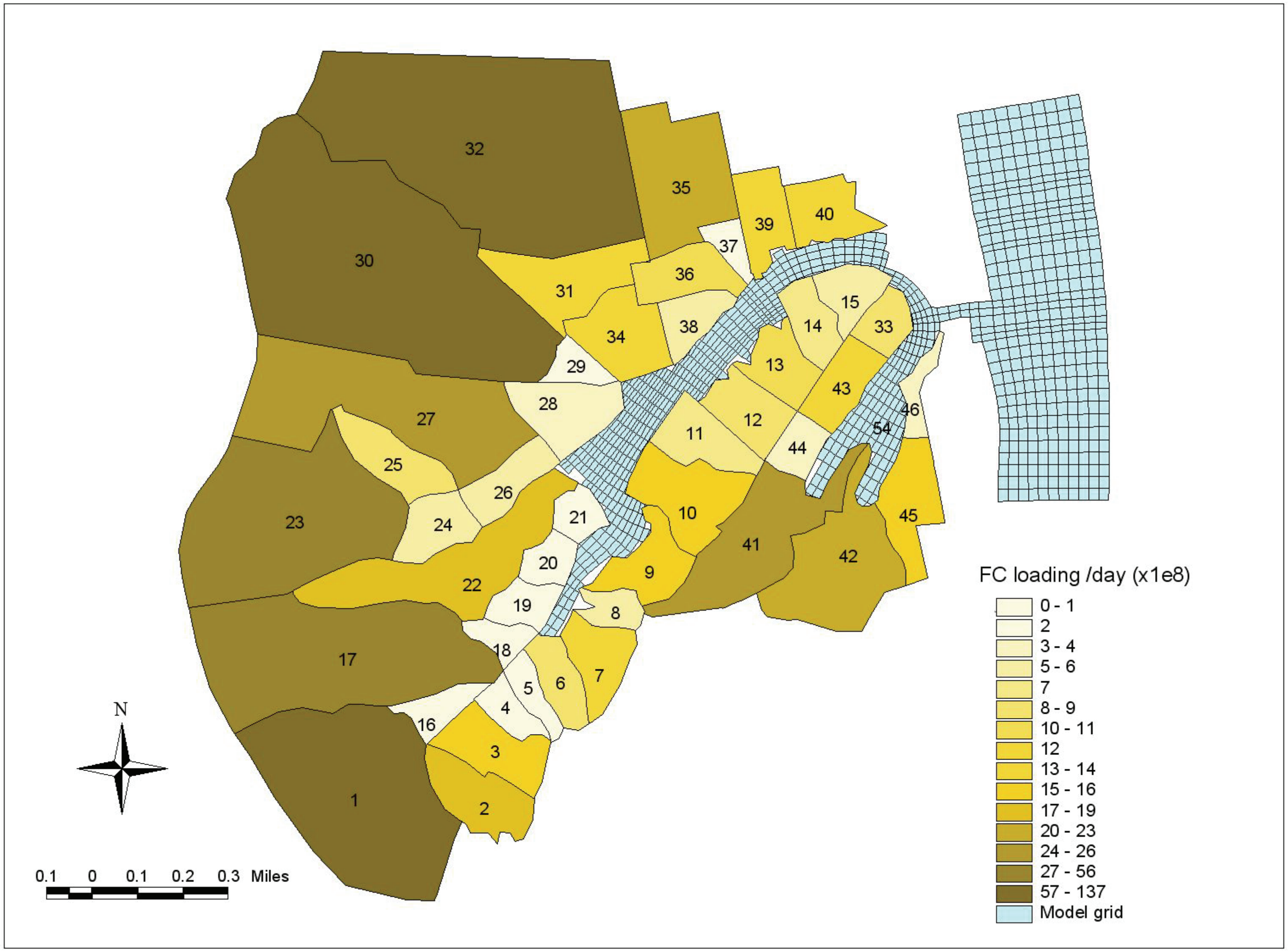


Figure VI.13. Average fecal coliform loading (counts/days) for the Rudee Inlet subwatersheds with a 90% reduction in urban source loading.

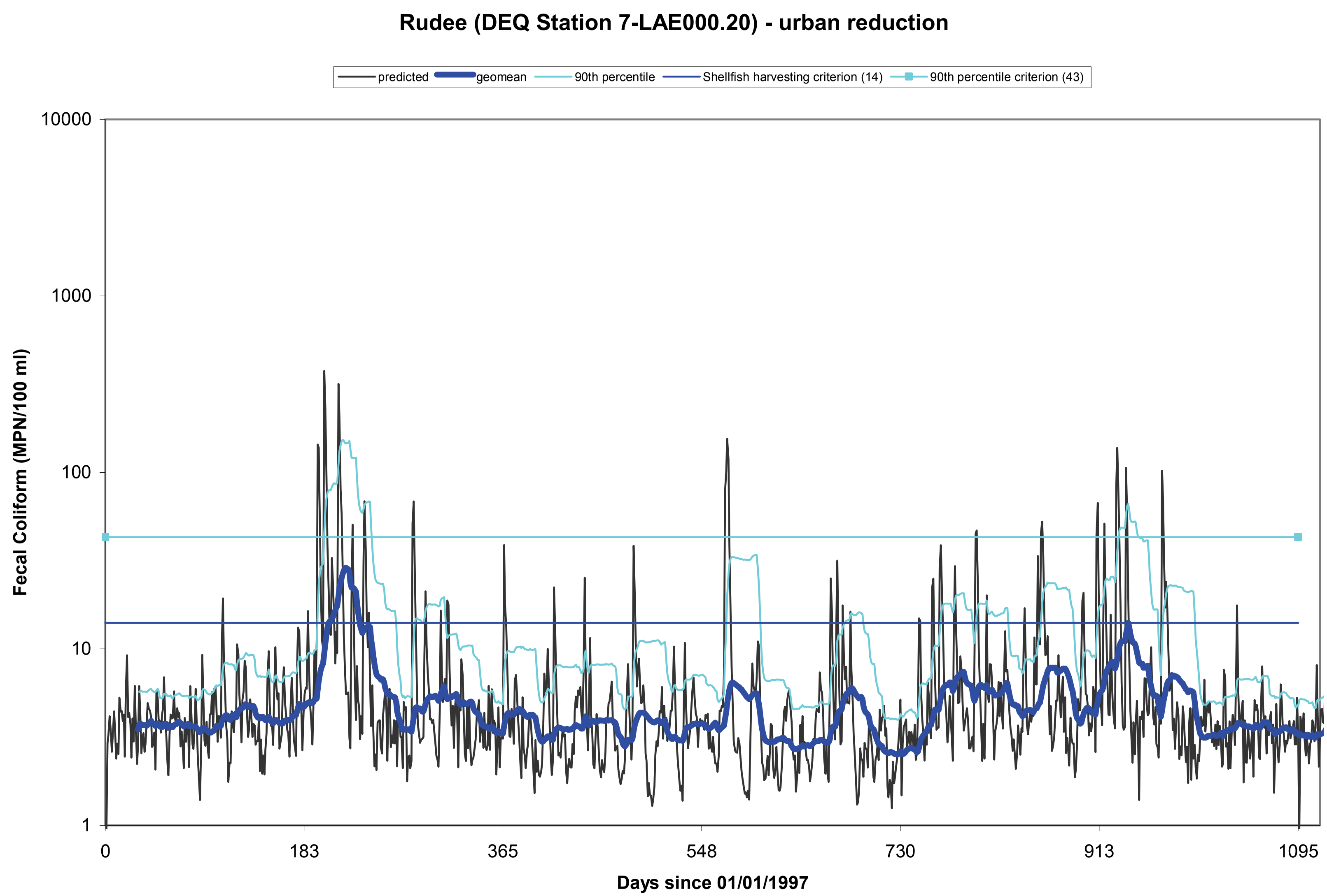


Figure VI.14. Fecal coliform predictions at VA-DEQ Station 7-LAE000.20 using a 90% load reduction from urban sources for the 1997-1999 simulation.

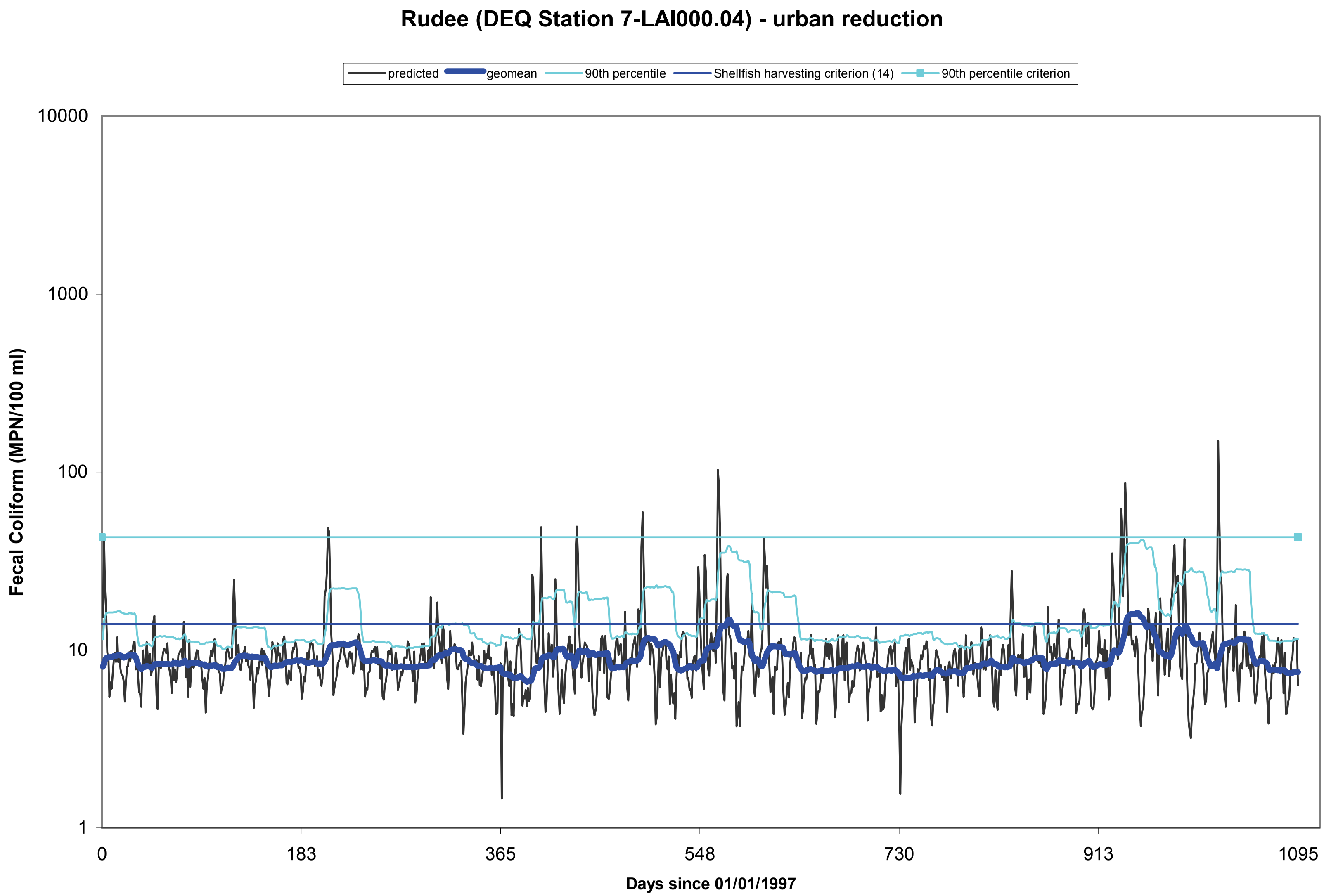


Figure VI.15. Fecal coliform predictions at VA-DEQ Station 7-LAI000.04 using a 90% load reduction from urban sources for the 1997-1999 simulation.

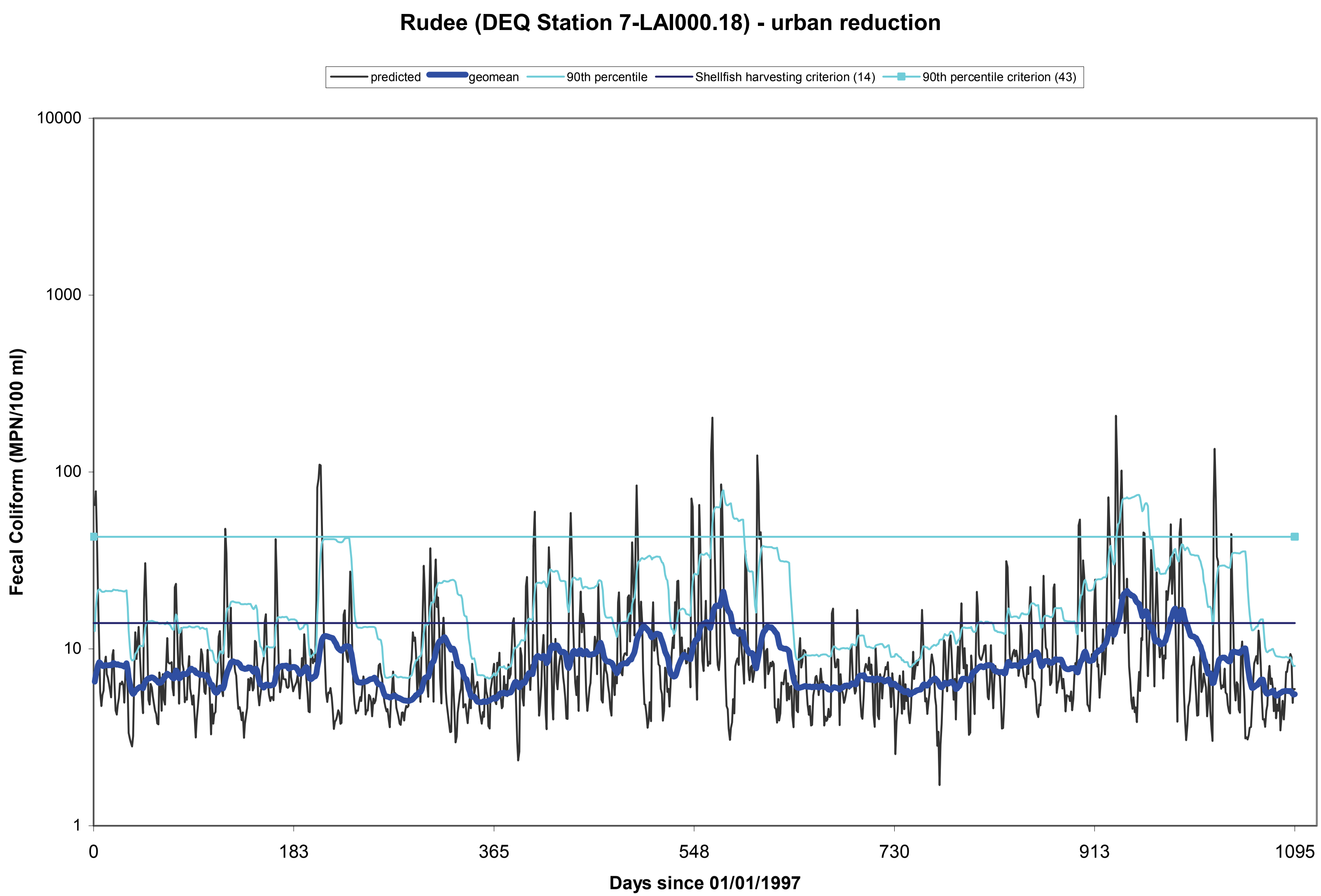


Figure VI.16. Fecal coliform predictions at VA-DEQ Station 7-LAI000.18 using a 90% load reduction from urban sources for the 1997-1999 simulation.

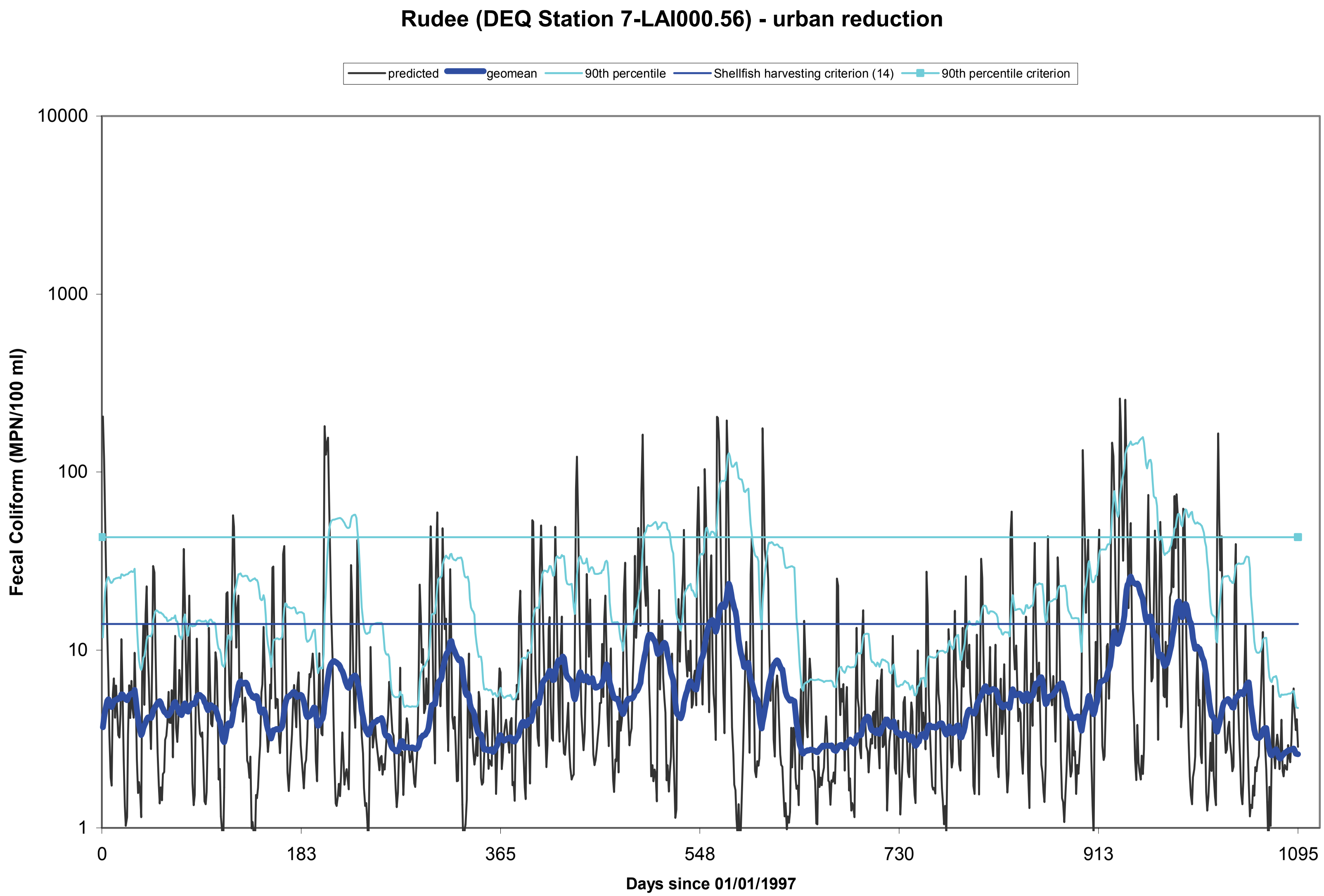


Figure VI.17. Fecal coliform predictions at VA-DEQ Station 7-LAI000.56 using a 90% load reduction from urban sources for the 1997-1999 simulation.

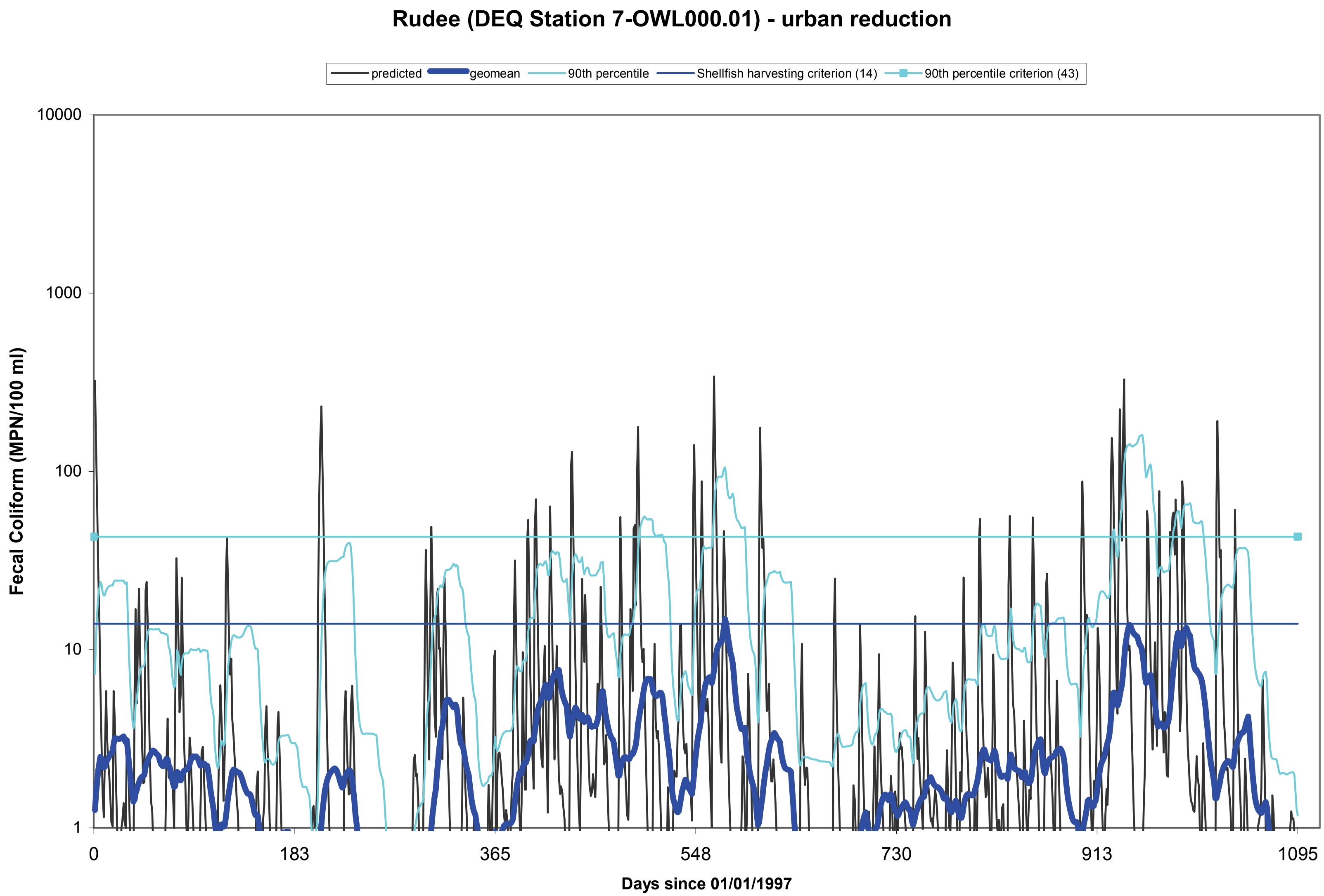


Figure VI.18. Fecal coliform predictions at VA-DEQ Station 7-OWL000.01 using a 90% load reduction from urban sources for the 1997-1999 simulation.

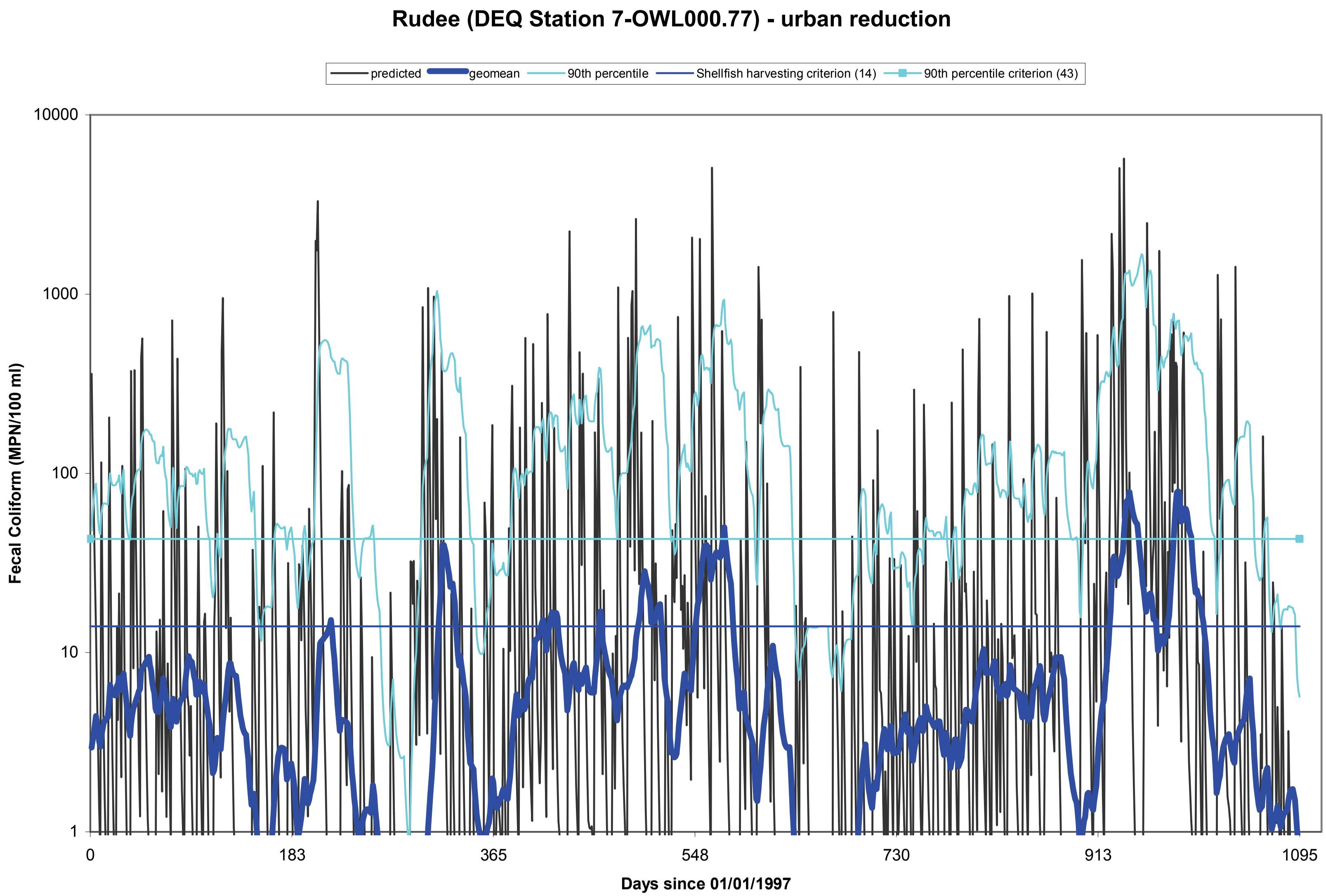


Figure VI.19. Fecal coliform predictions at VA-DEQ Station 7-OWL000.77 using a 90% load reduction from urban sources for the 1997-1999 simulation.

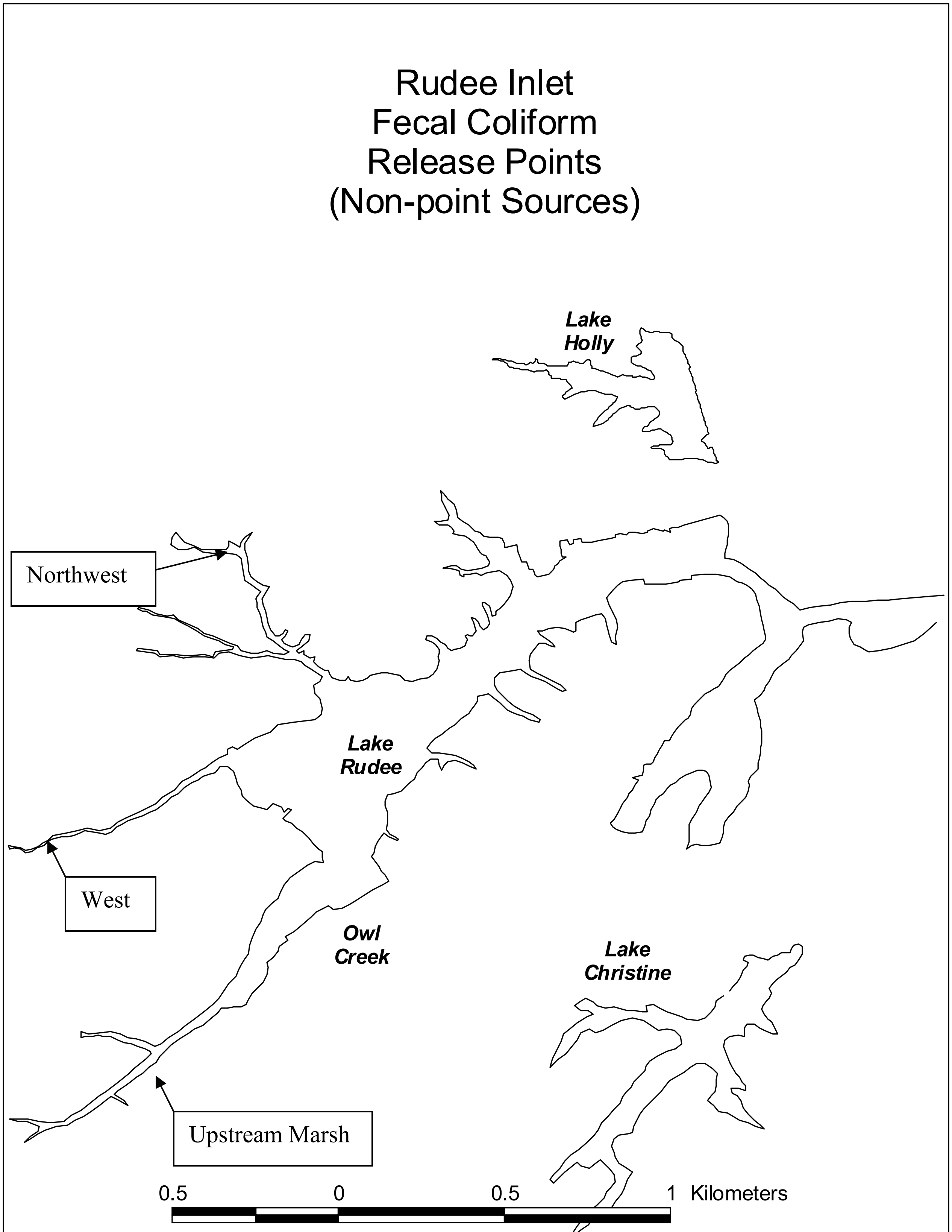


Figure VI.20. Locations of fecal coliform non-point source releases in Rudee Inlet.

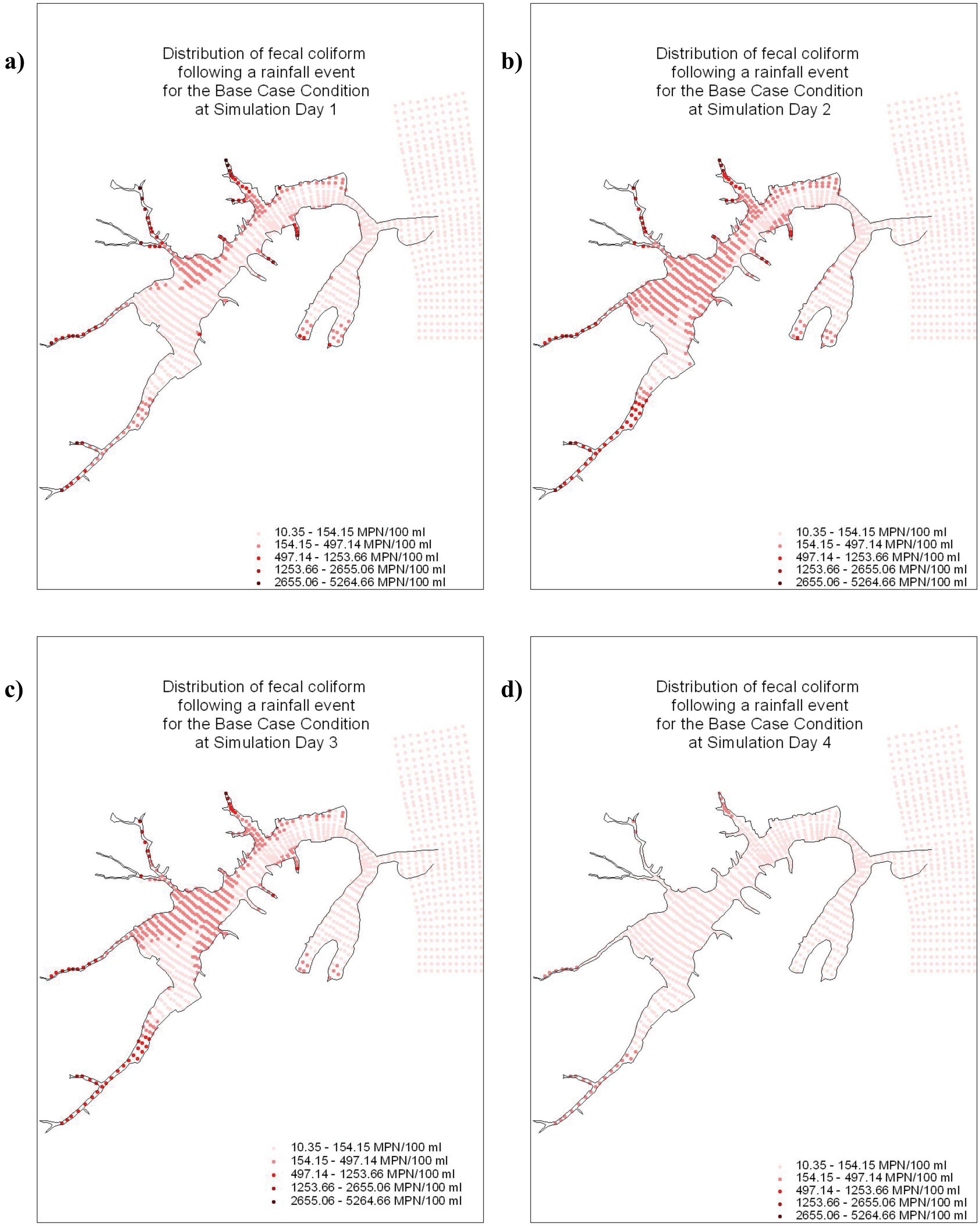


Figure VI.21. Spatial distributions of fecal coliform at simulation times a) Day 1, b) Day 2, c) Day 3, and d) Day 4 after a rainfall event for the base case condition.

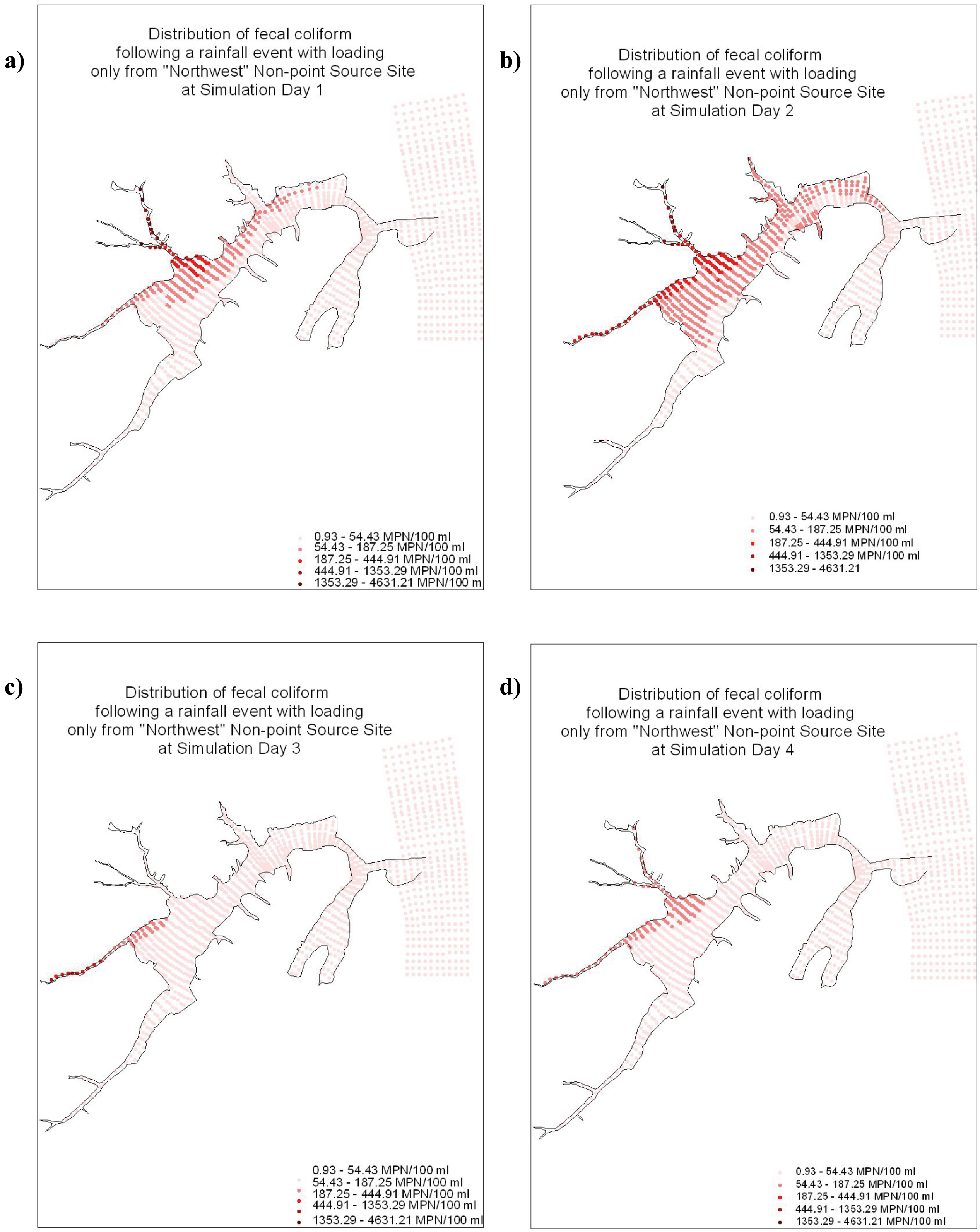


Figure VI.22. Spatial distributions of fecal coliform at simulation times a) Day 1, b) Day 2, c) Day 3, and d) Day 4 after a rainfall event with loading only from the "Northwest" site.

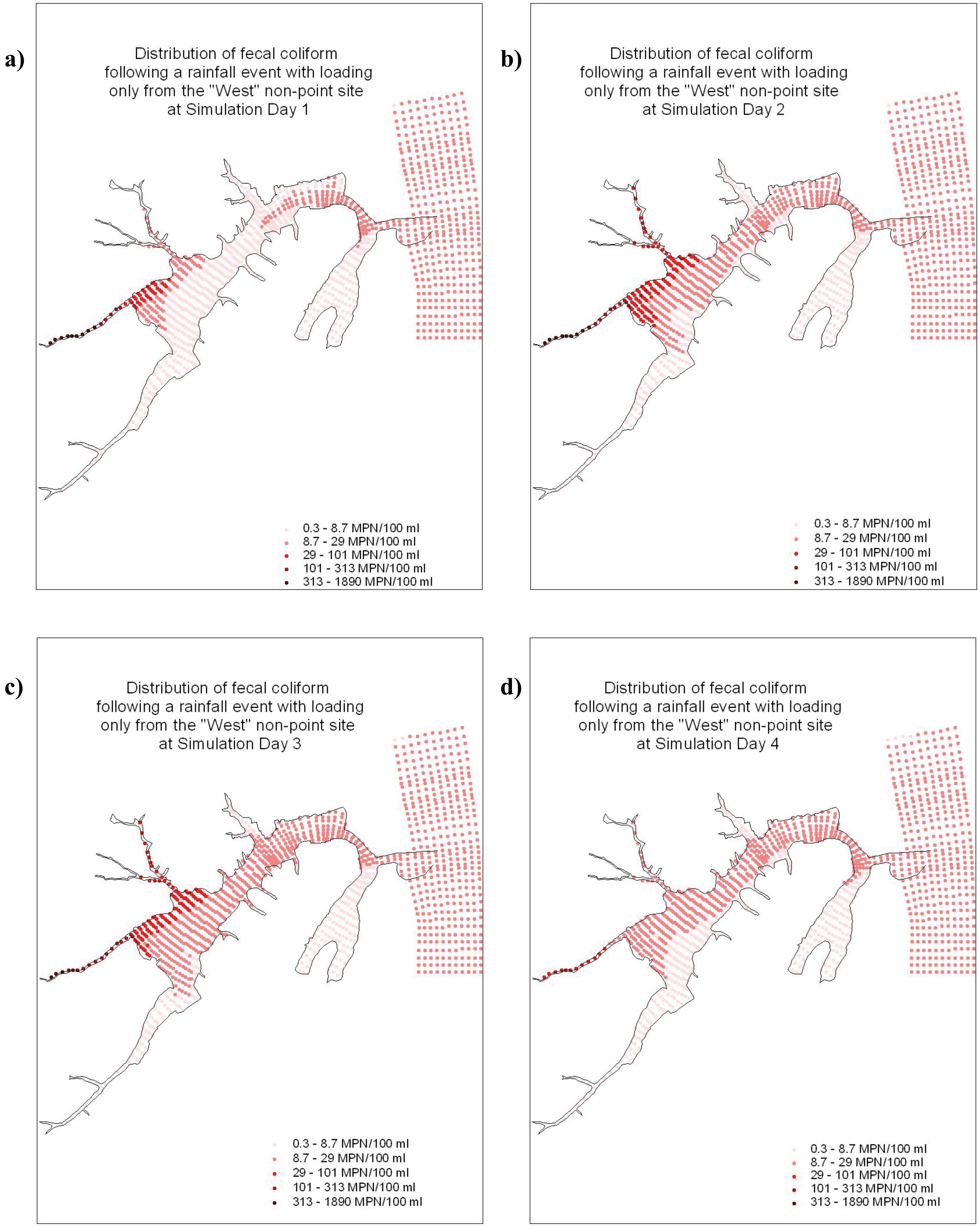
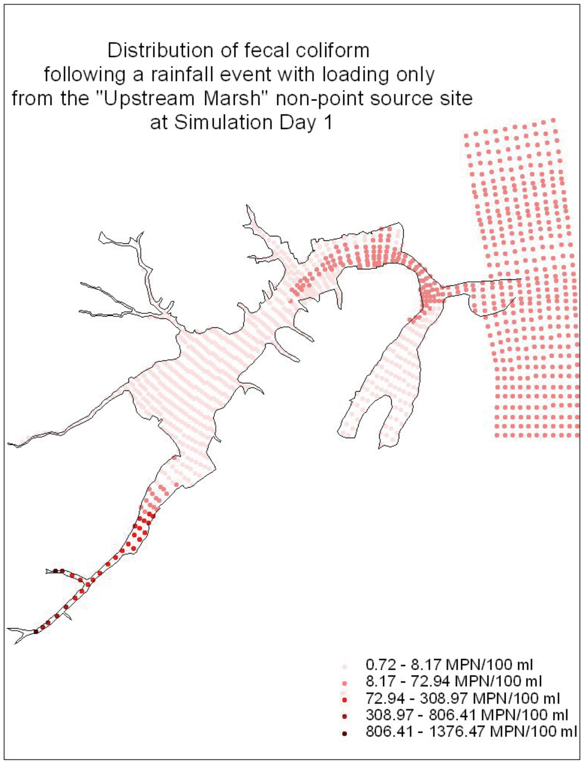
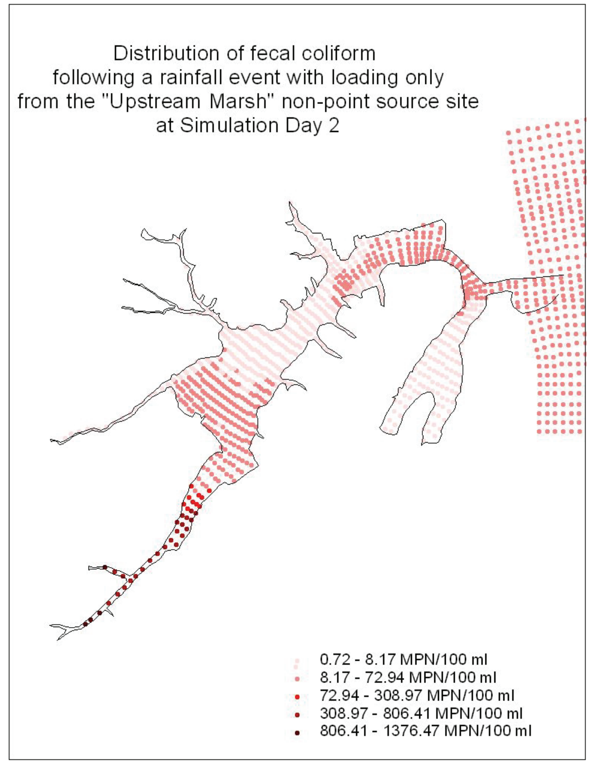


Figure VI.23. Spatial distributions of fecal coliform at simulation times a) Day 1, b) Day 2, c) Day 3, and d) Day 4 after a rainfall event with loading only from the "West" site.

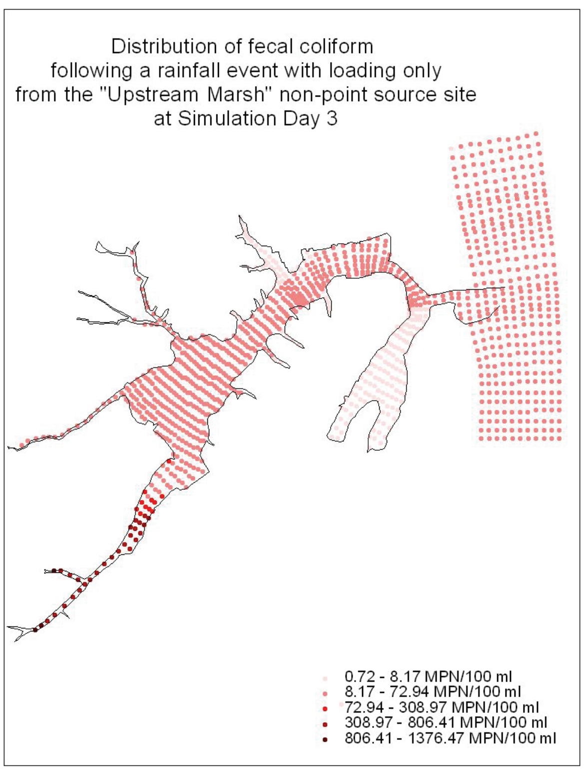
a)



b)



c)



d)

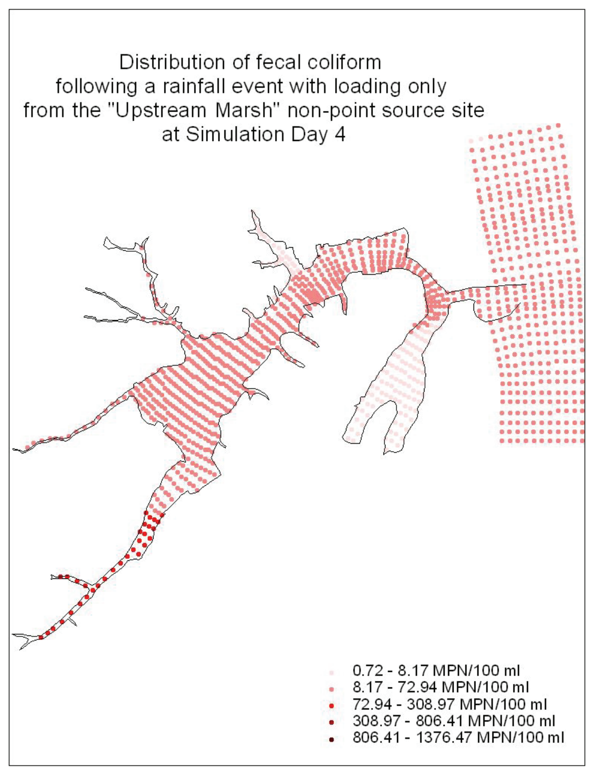


Figure VI.24. Spatial distributions of fecal coliform at simulation times a) Day 1, b) Day 2, c) Day 3, and d) Day 4 after a rainfall event with loading only from the "Upstream Marsh" site.

CHAPTER VII. SUMMARY AND CONCLUSIONS

This report provides the results of VIMS efforts as related to the collection of temporally high-resolution hydrodynamic data, grab sample surveys for key parameters, and the hydrodynamic and fecal coliform bacteria (FCB) prediction by integrated numerical modeling exercises. The objectives of these efforts were to assess the roles of non-point source and internal loadings of FCB in support of efforts to determine a management plan that could target FCB issues within the Rudee Inlet system.

VIMS performed field surveys in summer 2010 spanning the Rudee Inlet system. High-frequency measurements of depth (surface elevation), salinity, water temperature, dissolved oxygen, chlorophyll, and turbidity were made at 6 locations in this region for periods of approximately ten days to two weeks each commencing in June, July, and August of 2010. Grab sample surveys were conducted at over 20 locations spanning this region on July 1, July 12, and August 12, 2010. These grab samples were each analyzed for water temperature, salinity, pH, dissolved oxygen, dissolved oxygen percent saturation, *E. Coli,* and total coliform. The parameter of fecal coliform was then calculated from these measurements. Two 30-day, high-frequency tide gauge deployments were conducted at locations of the Rudee Inlet Marina and the Virginia Aquarium on Owl Creek in the spring of 2010. All these data were added to the VIMS Lynnhaven River database.

Calculated fecal coliform bacteria (FCB) densities exceeded Commonwealth contact standards (> 200 MPN 100· ml^{-1}) in the upper reaches of Owl Creek on a routine basis while the lower and more open reaches of Lakes Rudee and Wesley typically exhibited FCB densities between shellfish waters and recreational contact standards (> 14 MPN to ≤ 200 MPN·100 ml^{-1}). Findings are consistent with an increased "land effect" due to increases in the ratio of shoreline to water volume in the upper tidal reaches. Elevated FCB densities were also observed after periods of high rainfall. TCB and *E. coli* densities varied between 173-129,965 MPN·100 ml^{-1} and 10-844 MPN·100 ml^{-1}, respectively, in tidal waters of the Rudee Inlet system. A significant linear relationship ($p=0.00$; $r^2=0.48$, N=81) was found between log transformed TCB and *E. coli* densities for samples collected during this study period. Elevated counts of TCB and *E. coli* were associated with the upper reaches of selected tidal creeks and non-tidal freshwater sources. Analysis of historical VA-DEQ and DSS data supported the observation of higher coliform bacteria (FCB) in upstream regions and that summer months exhibited elevated average monthly densities as compared to other seasons. Sources of FCB to the Rudee Inlet system include nonpoint source runoff from urbanized and natural lands, direct domestic and wild animal loadings, and direct discharge from vessels. Additional study is required to source track and differentiate FCB loadings and to determine if true health concerns exist.

VIMS has completed a successful application of a hydrodynamic numerical model for the Rudee Inlet system. This application utilizes a watershed model to simulate bacterial processes in the watershed and discharge to the Rudee Inlet system, and a high-resolution 3D hydrodynamic model (HEM-3D hydro) that provides the required transport for a submodel simulating the fecal coliform bacteria levels. The model underwent an extensive calibration for surface elevation and salinity, as well as for fecal coliform bacteria.

A fecal coliform model was also developed, as a submodel of HEM-3D hydro, for the Rudee Inlet system and simulations were performed for the fecal coliform load reductions. A long-term calibration was performed comparing model predictions with monthly observations at 6 VA-DEQ stations in the Rudee Inlet system for the period 1996-1999. Additionally, spatial comparisons were made between fecal coliform model predictions and the observations at more than 20 grab sample locations for three surveys (July 1, July 12, and August 12, 2010). The calibrated model was then used to assess fecal coliform loading reductions of 90% and 95%. It was determined that the shellfish harvesting criteria (14 MPN·100 ml^{-1} for 30-day geometric mean and 43 MPN·100 ml^{-1} for the 90^{th} percentile) could be attained with approximately a 95% load reduction.

Model applications included additional sensitivity testing for fecal coliform load reduction. A scenario reducing fecal coliform loadings from urban sources by 90% was performed, but little impact was noted in the long-term fecal coliform levels. Assessments of isolated non-point sources of fecal coliform loadings indicated very localized impacts to FCB levels. Model results suggest that loadings from marsh-wetland regions have a higher impact on the system, and in particular, those from small up-reach branches. The study also points to the existence of non runoff-related sources in the summer season, such as boating activities, wildlife in inter-tidal areas, and so forth, which would require more study to identify these sources.

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