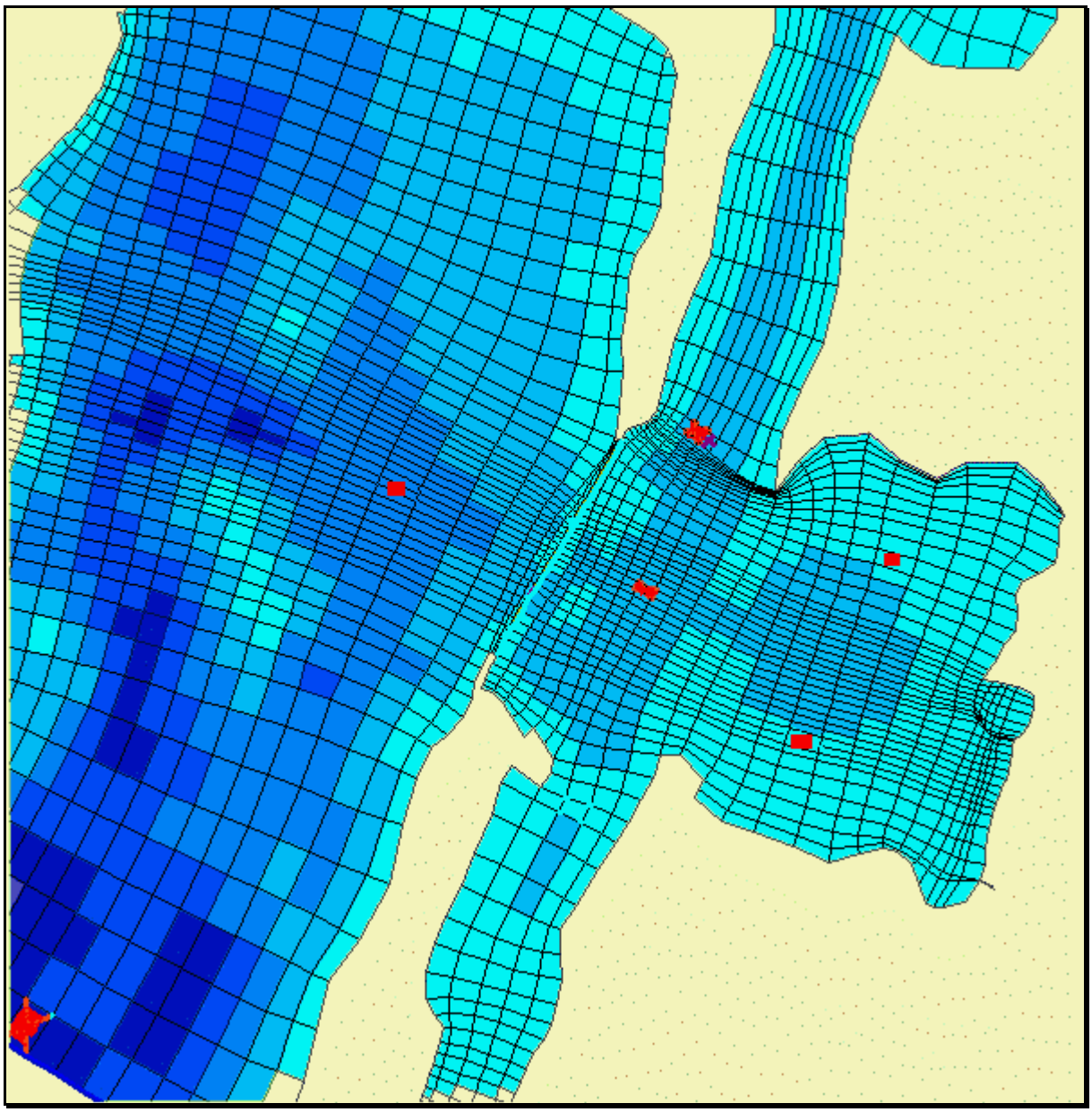

Carry Bay Causeway

A Field Study and Hydrodynamic Model

Prepared for the Vermont Department of Environmental Conservation — January 2004

BINKERD ENVIRONMENTAL Inc

Table of Contents

Table of Contents 2
Table of Figures 3
Abstract 4

1.0 INTRODUCTION 5
1.1 Objectives 5
1.2 Overall Study Plan 5
1.3 Related Studies and Reports 6
1.4 Methodology 7

2.0 FIELD METHODS AND OTHER DATA SOURCES 8
2.1 Study Area and Sampling Stations 8
2.2 Carry Bay Causeway – Physical Description 11
2.3 Currents 11
2.4 Water Quality 12
2.5 Other Sources of Data 13

3.0 OVERVIEW OF FIELD MEASUREMENTS 15
3.1 Current Measurements 15
3.2 Water Quality Measurements 15

4.0 DISCUSSION OF FIELD RESULTS 16
4.1 Water Quality 16
4.2 Currents - General 27

5.0 MATHEMATIONAL MODEL AND SIMULATIONS 39
5.1 Application of the Mathematical Model to Carry Bay 39
5.2 Preliminary Model Considerations 39
5.3 Calibration and Acceptance 43
5.4 Simulations of Proposed Modifications 44

6.0 WAVE ANALYSIS 57

7.0 SUMMARY OF RESULTS AND CONCLUSIONS 58
7.1 Survey Results 58
7.2 Model Results 59
Acknowledgements 62

[Note: This paper was published as an Adobe 5.0 PDF file in color because many of the charts rely on color to present data. If the paper is viewed in black and white, this information will not be available. When viewing the file, it is suggested that the Adobe Reader Zoom factor be set at 100% to maintain the original image quality. If you wish to enlarge a section, we suggest you use 200%. Copies of this report are available at http://www.binkerd.com/carrybay*]*

Table of Figures

Figure 2.1: Overall View of Survey Area 8
Figure 2.2: Detail of Northern Portion of Survey Area 9
Figure 2.3: Detail of Southern Portion of Survey Area 10
Figure 2.4: Missisquoi River Discharge – Summer 2003 13
Figure 2.5: Lake Champlain Water Levels at Richelieu River – Summer 2003 14
Figure 4.1: Temperature vs. Depth Station 24 (July) 17
Figure 4.2: Temperature vs. Depth Station1 (July) 18
Figure 4.3: Temperature vs. Depth Station 2 (July) 18
Figure 4.4: Temperature vs. Depth Station 3 (July) 19
Figure 4.5: Temperature vs. Depth Station 4 (July) 19
Figure 4.6: Temperature vs. Depth Station 5 (July) 20
Figure 4.7: Temperature vs. Depth Station 33 (August) 21
Figure 4.8: Temperature Contour La Motte Passage 21
Figure 4.9: Temperature Contour La Motte Passage 22
Figure 4.10: Temperature Contour Carry Bay 22
Figure 4.11: Temperature Contour Carry Bay 22
Figure 4.20: Chloride & Phosphorous – La Motte Passage 24
Figure 4.21: Chloride & Phosphorous – Alburg Passage 25
Figure 4.22: Chloride & Phosphorous – Carry Bay 25
Figure 4.23: Chloride – Alburg Passage (July) 26
Figure 4.80: Current & Wind at Isle La Motte Causeway – Station 7 28
Figure 4.30: Current with 10-foot Pole – Station 24 29
Figure 4.31: Current with 10-foot Jug – Station 24 30
Figure 4.32: Current with 20-foot Jug – Station 24 30
Figure 4.33: Current with 35-foot Jug – Station 24 30
Figure 4.34: Current with 50-foot Jug – Station 24 31
Figure 4.35: Current with 100-foot Jug – Station 24 31
Figure 4.40: Current with 10-foot Pole – Station 3 32
Figure 4.41: Current with 20-foot Jug – Station 3 32
Figure 4.42: Current with 30-foot Jug – Station 3 32
Figure 4.60: Current with 10-foot Pole – Station 33 33
Figure 4.61: Current with 10-foot Jug – Station 33 33
Figure 4.62: Current with 20-foot Jug – Station 33 34
Figure 4.63: Current with 35-foot Jug – Station 33 34
Figure 4.64: Current with 50-foot Jug – Station 33 34
Figure 4.65: Current with 70-foot Jug – Station 33 35
Figure 4.50: Current and Local Wind Direction – Station 8 (July) 36
Figure 4.70: Current with 10-foot Pole (GPS) – Station 8 (August) 37
Figure 5.1: Predicted vs. Measured Chloride 44
Figure 5.2: Predicted Chloride – July Average 46
Figure 5.10: Model Chloride Predictions – Typical Summer Conditions 47
Figure 5.11: Model Chloride Predictions – Late Summer Conditions 48
Figure 5.20: Phosphorus Prediction – July 2003 Average 49
Figure 5.21: Change in Phosphorus Prediction – July 2003 Average 50
Figure 5.22 – Table of Change in Phosphorus – July 2003 Average 50
Figure 5.30 – Phosphorus Difference – Day 1 52
Figure 5.31 – Phosphorus Difference – Day 2 53
Figure 5.32 – Phosphorus Difference – Day 3 54
Figure 5.33 – Phosphorus Difference – Day 4 55
Figure 5.34 – Phosphorus Difference – Day 5 56

401

Abstract

Many years ago a causeway was constructed for a railroad across the western side of Carry Bay on Lake Champlain in North Hero, Vermont. The fill was large granite blocks and spanned 4,345 feet. Two openings, one 85 feet and the other 180 feet, were left to permit flow of water between Carry Bay and the main lake. The railroad has long ago ceased operation but the fill remains. Recently, residents in this area of North Hero, tired of poor water quality and looking for ways to improve the situation, thought that removing the fill and restoring the natural flows could improve water quality. Some of these residents formed the Northern Lake Champlain Restoration Committee and one of their first actions was to promote a bill in the Vermont legislature to fund a study to evaluate the impact of causeway removal. This report is the result of that study.

Field surveys conducted in July and August 2003 provided sufficient data to offer a realistic conceptual model of present conditions. Previous studies documented that the internal seiche in the main lake has an impact as far north as Point Au Roche. During this investigation internal seiche impacts were observed near Point Au Roche and further north into La Motte Passage and Carry Bay. Both temperature and current measurements made during the field study confirmed these internal seiche hydrodynamics.

One significant finding of this study was the impact of the main lake's internal seiche on current reversals at Carry Bay. Current reversals and the transport of main lake warm surface water (epilimnion water) into Carry Bay were measured on four occasions corresponding with a rapid fall of the thermocline in the main lake. The fall of the thermocline and the transport of upper layer epilimnion water north in La Motte Passage are characteristics of the internal seiche. Without current reversals and the inflow of main lake water into Carry Bay, dilution water would not enter Carry Bay and phosphorous levels would be even higher than they are now.

With the aid of a mathematical modeling tool, it was predicted that complete removal of the causeway would result in an average of 7% to 10% reduction in total phosphorous concentration for Pelots Bay, Carry Bay, and the lower portion of the Alburg Passage. This corresponds to a decrease in average total phosphorous concentration of about 1.6 to 2.5 µg/l. These predictions are based on summer 2003 conditions in Lake Champlain.

Another hypothesis that was developed with the mathematical model is that with Carry Bay causeway removed, more net flow from Missisquoi Bay will enter Alburg Passage and leave via Carry Bay. This increased net flow would transport a higher percentage of the net total phosphorus load from Missisquoi Bay though the Alburg Passage and into the main lake. This would result in a decrease in the total net phosphorus load transported into the Northeast Arm.

1.0 INTRODUCTION

The Vermont Department of Environmental Conservation (VT DEC) released a request for proposals on 13 December 2002 titled "Hydrodynamic and Water Quality Modeling of Causeway Removal at Carry Bay in Lake Champlain (North Hero, Vermont)." ***BINKERD ENVIRONMENTRAL, Inc.*** submitted a proposal on 7 February 2003 that was selected by the VT DEC. A contract based on a modified proposal (April 28, 2003) was finalized in early June 2003.

A public information meeting on the project was held on July 2, 2003 at the North Hero Elementary School. At this meeting Roger C. Binkerd presented a project overview that included scope of work, methodology, field measurement techniques, field schedule, and description of the mathematical tools used in the analysis phase. Information presented at this meeting was posted at www.binkerd.com along with survey data and newspaper articles as they became available throughout summer. A link at this site provided access to e-mail ***BINKERD ENVIRONMENTAL, Inc.***

1.1 Objectives

The objective of the study is to determine if causeway removal (partial or complete) would lower phosphorous concentration in the area east of the causeway, i.e., Carry Bay, Pelots Bay, and Alburg Passage.

Wave effects are the second part of the project objectives. Complete or partial removal of the causeway would allow previously blocked waves from La Motte Passage to enter Carry Bay resulting in larger waves in Carry Bay and portions of the Alburg Passage. The objective is to quantify this expected change in wave height.

1.2 Overall Study Plan

Field surveys and mathematical modeling techniques were utilized to achieve these project objectives. Field surveys were conducted during summer conditions in July and August 2003 to obtain information to better understand the flow patterns and water quality in the vicinity of Carry Bay. An understanding of summertime flow patterns provided the basis for formulating a conceptual model. Data gathered from various sources during the summer were then applied to a mathematical model. After observed summer conditions were duplicated in the model, the geometry of the model was modified to reflect partial and complete removal of the causeway. Impact on water quality is evaluated by a direct comparison of simulated conditions with and without the Carry Bay Causeway in place.

The mathematical model utilized in this study is Delft3D written by Delft Hydraulics Institute, www.wldelft.nl. This mathematical model is a time dependent integrated model for hydrodynamics, water quality, particle tracking, water quality, waves, sediment transport, morphology, and ecology.

One four-day field study was planned in July with one additional survey day planned in late August. A four-day survey was needed due to the internal seiche, which is known to have a period of just over four days. Although the internal seiche is known to have a dramatic impact on main lake hydrodynamics, it was not known if it would have any impact on water transport through the openings in the Carry Bay Causeway that separates Carry Bay and La Motte

Passage. In the results section of this report it will be shown that current reversals at both passages in the Carry Bay Causeway are often due to the dynamics of the internal seiche.

1.3 Related Studies and Reports

The earliest scientific study of Lake Champlain that included Carry Bay was by Glenn E. Myer, 1977.[1] Alburg Passage, Carry Bay, and the Gut were included in Myer's study and were referred to as "gaps between lake components." The components referred to by Myer were the main lake and the Northeast Arm. Myer measured current reversals at Carry Bay Causeway and concluded that these events were due to water elevation differences created by the relaxation of forced surface seiches in the main lake in conjunction with those in the Northeast Arm.

The next major study that included the Northeast Arm and areas near Carry Bay began in the early 1990's as a result of the Lake Champlain Basin Program. This program is a joint effort between Vermont, New York and Canada with the goal to clean up Lake Champlain. After several years of study and data collection a report was released (VT DEC & NY DEC, 1997).[2] This VT & NY DEC study included all of Lake Champlain and was the most comprehensive water quality study of Lake Champlain conducted to date. The nearest water quality stations to Carry Bay were in Missisquoi Bay and south and north of Isle La Motte in the main lake.

During this same time period Middlebury College began an investigation of volume flows in Alburg Passage and the Gut (Perry, 1995).[3] Perry documented frequent current reversals at Alburg Bridge and the Gut. In Perry's' search for environmental forcing functions that would produce observed periods at these locations he concluded, "…the 4.1-4.2 day period could be explained by the internal seiche of the main lake, which has a period of about 4 days."

Applied Science Associates wrote two reports on water quality impacts of Missisquoi Bay causeway removal in 1997.[4] In ASA's model study area Carry Bay formed one of three boundaries that connected Missisquoi Bay with the main lake. In ASA's reports very little information was included for Carry Bay since the focus of the ASA reports was on impacts on Missisquoi Bay due to the proposed removal of the bridge and causeway that connects West Swanton and East Alburg.

---

[1] Myer, G. E., 1977. "Currents of Northern Lake Champlain." Department of Earth Sciences, State University of New York. Proceedings of the 1977- Fourth Annual Lake Champlain Basin Environmental Conference.

[2] Vermont DEC, New York DEC. "A phosphorus budget, model, and load reduction strategy for Lake Champlain: Lake Champlain diagnostic-feasibility study final report, 1997."

[3] Perry, B., 1995. "Estimational Flow volumes between the Northeast Arm and main body of Lake Champlain, Vermont." Department of Geology, Middlebury College, Middlebury, Vermont.

[4] Applied Science Associates, Inc., 1997. "Hydrodynamic modeling of Missisquoi Bay in Lake Champlain," by D. Mendelsohn, C. Swanson, and T. Isaji for Vermont Geological Survey & Vermont Agency of Natural Resources; "Missisquoi Bay field study and hydrodynamic model verification," by D. Mendelsohn, H. Rines, and T. Isaji for Vermont Geological Survey & Vermont Agency of Natural Resources, 1997.

1.4 Methodology

The methodology is summarized by the following steps:

- Review available literature on hydrodynamics and water quality in the vicinity of Carry Bay;
- Obtain local knowledge from residents through meetings such as the July 2nd Project Information meeting and through discussions with fisherman, boaters, and marina operators;
- Measure and observe water currents and water quality in Carry Bay and adjacent areas;
- Formulate a conceptual model based on all information gathered;
- Using field measurements and a conceptual model, apply a mathematical model to Carry Bay and simulate existing summertime conditions;
- Change the geometry in the model to reflect complete and partial removal of the Carry Bay Causeway and repeat the simulations; finally,
- Compare results of simulations with the causeway in place and simulations without the causeway;
- Summarize conclusions on impact on predicted changes in water quality based on all information obtained.

2.0 FIELD METHODS AND OTHER DATA SOURCES

2.1 Study Area and Sampling Stations

The overall survey area is depicted in Figure 2.1. Figures 2.2 and 2.3 show the north and south survey areas in more detail. Stations shown are used for water quality measurements of total phosphorous, chloride and/or temperature and for current measurements.

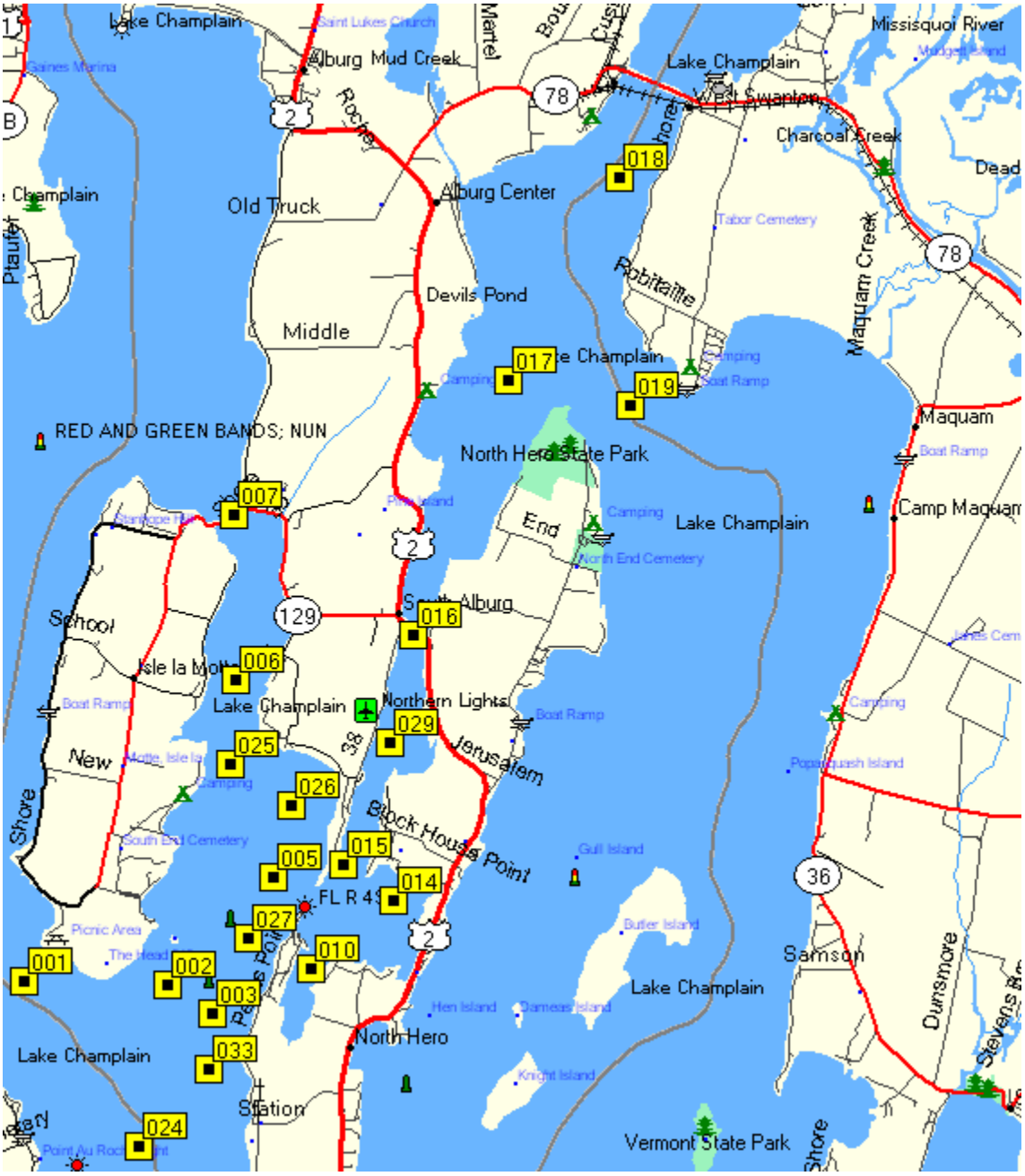

Figure 2.1: Overall View of Survey Area

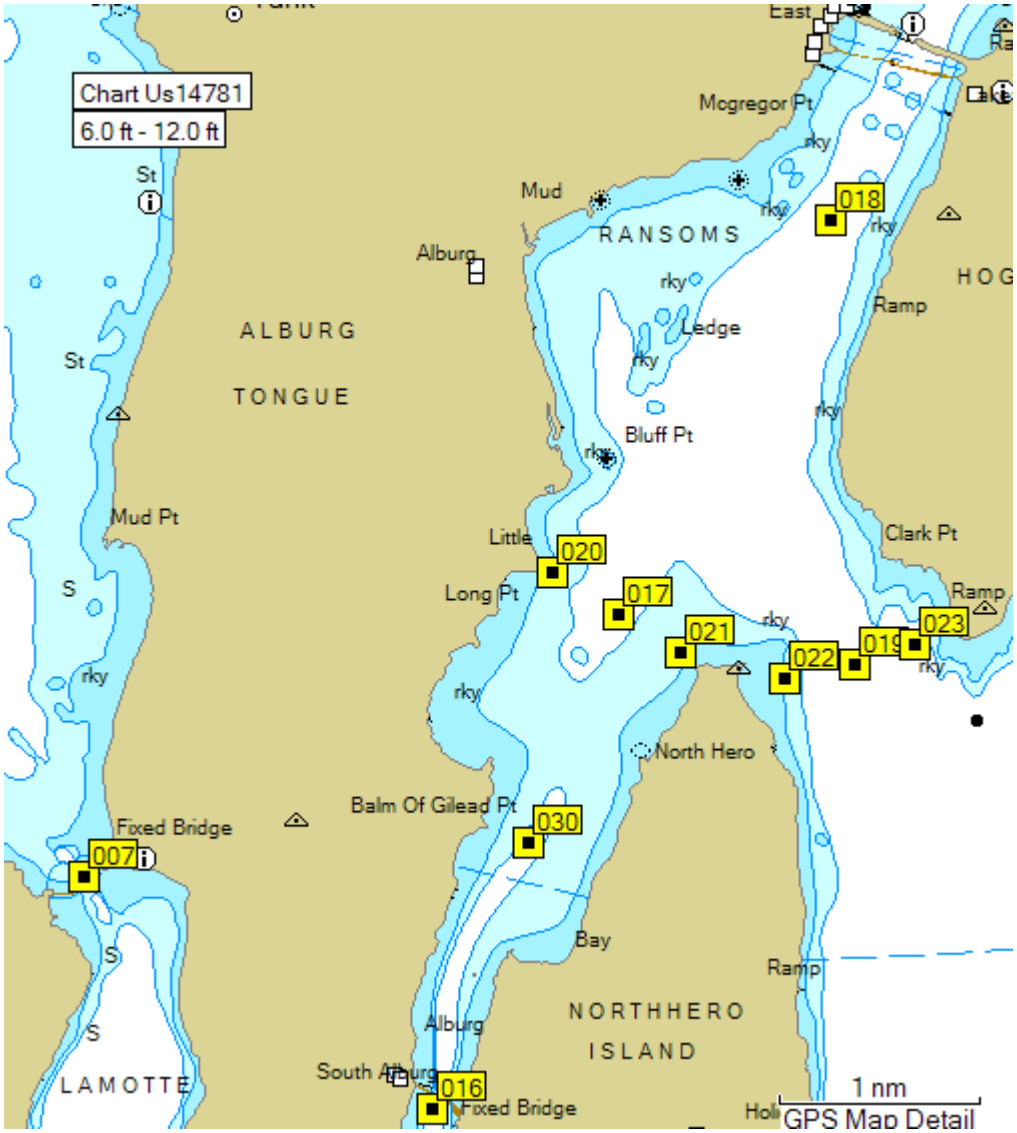

Figure 2.2: Detail of Northern Portion of Survey Area

Station #1 is located in the channel of the main lake that leads to the Richelieu River. This location is the western boundary of the survey area. The northern extent of the survey area is near the Missisquoi Bay Bridge where Station #18 is located. The eastern boundary is at the entrance to the Northeast Arm where Station # 19 is located. All of La Motte Passage, Carry Bay, and Alburg Passage are included in the survey area.

The southern extent of the survey area is opposite Point Au Roche where Station #24 is located. Station #24 is near the most northern station used for a long-term current and temperature monitoring station by Saylor (1999).[5] In Saylor's study the dynamics of the internal seiche were observed near Point Au Roche.

[5] Saylor, J. H., et al., "Gravity currents and internal bores in Lake Champlain," in Lake Champlain in Transition, From Research Toward Restoration, editors T. O. Manley and Patricia L. Manley, 1999.

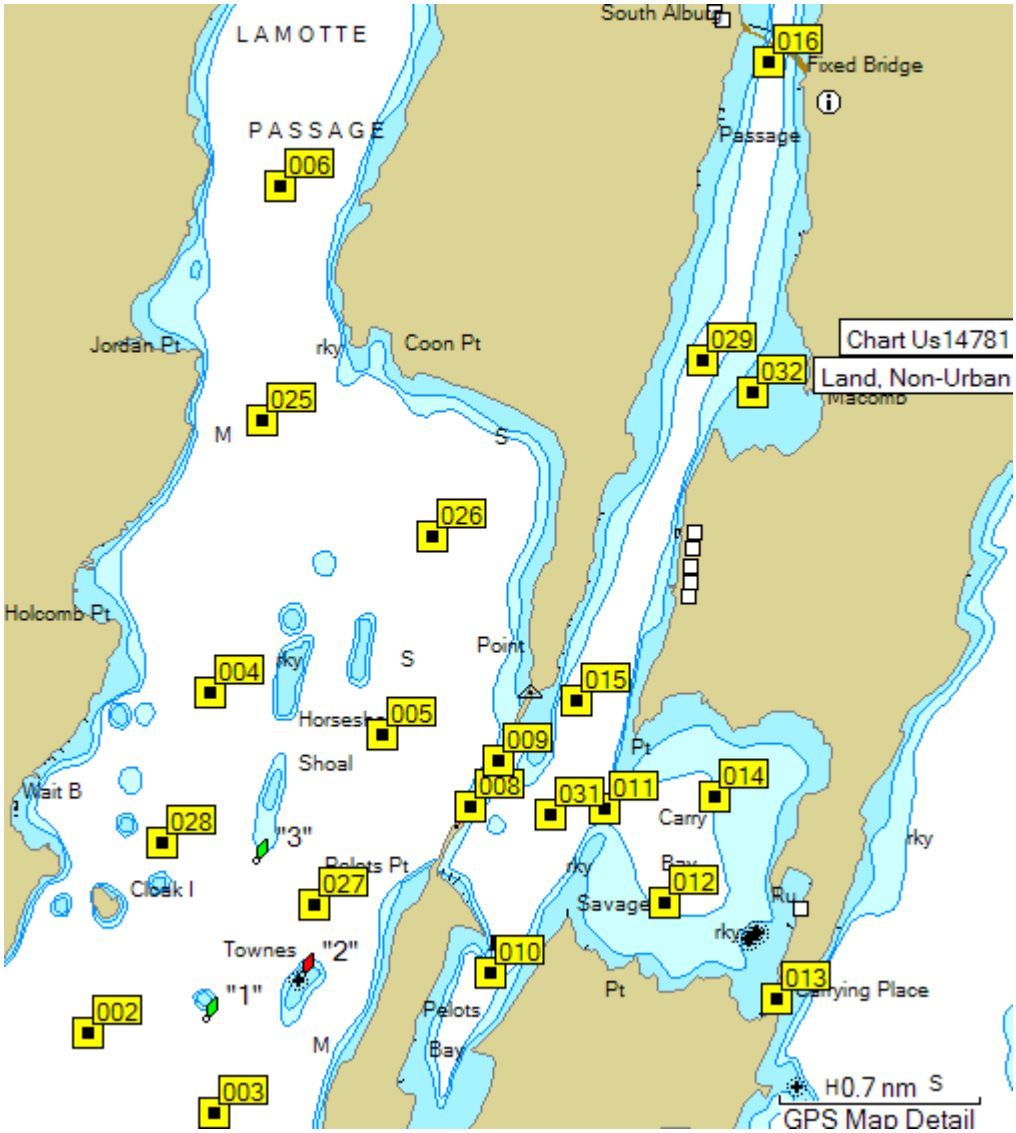

Figure 2.3: Detail of Southern Portion of Survey Area

2.2 Carry Bay Causeway – Physical Description

The Carry Bay Causeway was constructed as part of a railroad line that traversed South Hero, Grand Isle and North Hero.

The total length of the Carry Bay Causeway is about 4,345 feet (1,325 meters) long. There are two openings (passages) in the Carry Bay Causeway. The north passage is 85 feet (26 meters) wide and small boats can pass under the bridge that spans this opening. The width of the south passage is 180 feet (55 meters). These two passages represent about six percent of the total length of the causeway. The middle section, i.e., between the two passages, is 1,053 feet (321 meters) long. The width of the causeway is about 50 feet (15 meters).

Near the south and north abutments in the south passage depths are 15.5 feet at 93.0 feet MSL (mean sea level) above LLL (low lake level). Near the center of the south passage depth at LLL is 7.5 feet. East and west of the south passage depths increase to 16.5 feet LLL. Water depth at the north passage is 10 feet at 93.0 feet MSL. West and east of the north passage depths increase to 11.5 feet LLL.

The combined cross-sectional area of the south and north passages at LLL is about 2,900 square feet. With the middle section removed the cross-sectional area would increase to about 10,800 square feet. Complete removal of the causeway, as defined in this study, would remove the middle section, all but 490 feet (150 meters) of the south section, and all but 245 feet (75 meters) of the north section. The width of the opening at complete removal would increase to 3,600 feet (1,100 meters). The cross-sectional area of the opening with complete causeway removal would increase to over 25,000 square feet.

For comparison, the cross-sectional area at LLL at the drawbridge between North Hero and Grand Isle (the Gut) is about 1,200 square feet. At Alburg Bridge the cross-sectional area is about 10,500 square feet.

2.3 Currents

Water currents were measured using drogues. Drogues are submerged floats that drift with water currents. Two drogue designs were used: poles and jugs. Poles are designed to measure the average water current over the length of the pole and jugs are designed to measure the water current at a specific depth.

Poles were 10 feet long, 1½-inch diameter PVC pipes. They were capped and sealed using PVC cement at one end. For ten foot long PVC poles a hole was drilled about 40 inches from the top cap. When placed in the water air was captured in the space above the drilled hole. This trapped air provided buoyancy to offset the weight of the PVC pole. The pole was designed to float vertical with about 2 to 3 inches of PVC pole above the water surface. To provide added visibility plastic orange flags about 3 by 4 inches in size on a thin metal rod was taped to the pole.

Jugs were 5-gallon plastic water containers. When filled completely with water the jugs were slightly negatively buoyant. To offset this negative buoyancy a small float was attached to the jug with a nylon 3/16-inch diameter string. The length of the string determined the depth of the jug below the water surface. The jug was much larger than the surface float, and since drag

forces are directly proportional to frontal cross-sectional area, the jug moved with the current at depth and the surface float was pulled along with negligible resistance.

A drogue was placed in the water and its start position was obtained using a hand held Global Positioning System (GPS) unit. After an arbitrary amount of time a second measurement of location and time was recorded. The current measurement is the distance traveled divided by the elapsed time. The drogue could then be retrieved or left in the water to obtain additional location observations and make a track of pole position versus time. This method assumes that the drogue travels in a straight line and at a constant speed between any two observations. This assumption is appropriate for relatively small elapsed times. In a situation where a drogue is place in the water and left unobserved for several hours, the assumption of straight line and constant speed becomes less reliable. All current measurements in July were obtained using this procedure.

After the July survey GPS units were physically attached to the top of the pole.[6] GPS units were programmed to record location and time of day at 1 to 5 minute intervals. Using this method a pole drogue could be released and recovered several hours later with precise data on its movement between deployment and retrieval. Jugs, and on occasion poles, were also used in the August survey without attached GPS units.

Data recorded in the field were entered into spreadsheets. An algorithm was written to compute speed and direction traveled relative to true north. The data obtained with GPS attached pole drogues were transferred to a PC and currents were computed using manufacturer-supplied software.

2.4 Water Quality

Water quality measurements included temperature, total phosphorous, and chloride. Temperatures were measured with an Omega Series 700 thermister probe connected to a digital readout. Vermont DEC personnel collected water samples for total phosphorous and chloride analysis. Grab samples were collected using a Kemmerer water bottle from a depth of two meters. Water samples were analyzed at the Vermont Department of Environmental Conservation R. A. LaRosa Environmental Laboratory. Total phosphorous was analyzed using method USEPA 365.1[7] and chloride by method USEPA 325.2.[8] Quality control samples include duplicate water samples, equipment blanks, and internal laboratory control samples.

---

[6] Larry Dupont, Chairman, Northern Lake Champlain Restoration Committee suggested this technique.

[7] U. S. Environmental Protection Agency. Methods for the determination of inorganic substances in environmental samples. EPA/600/R-93/100. Office of Research and Development, Washington, D. C.

[8] U. S. Environmental Protection Agency. 1983. Methods for the chemical analysis of water and wastes. EPA/600/4-79/020. Office of Research and Development, Washington, D. C.

2.5 Other Sources of Data

2.5.1 Hydrological

Hydrological data were obtained from USGS Internet sites for discharge of the Missisquoi River. A link to real time data at the gauge in Swanton, VT is http://nh.waterdata.usgs.gov/nwis/dv/?site_no=04294000.

Missisquoi River discharge is depicted from May to October 2003 in the following chart obtained from the USGS web site, Figure 2.4.

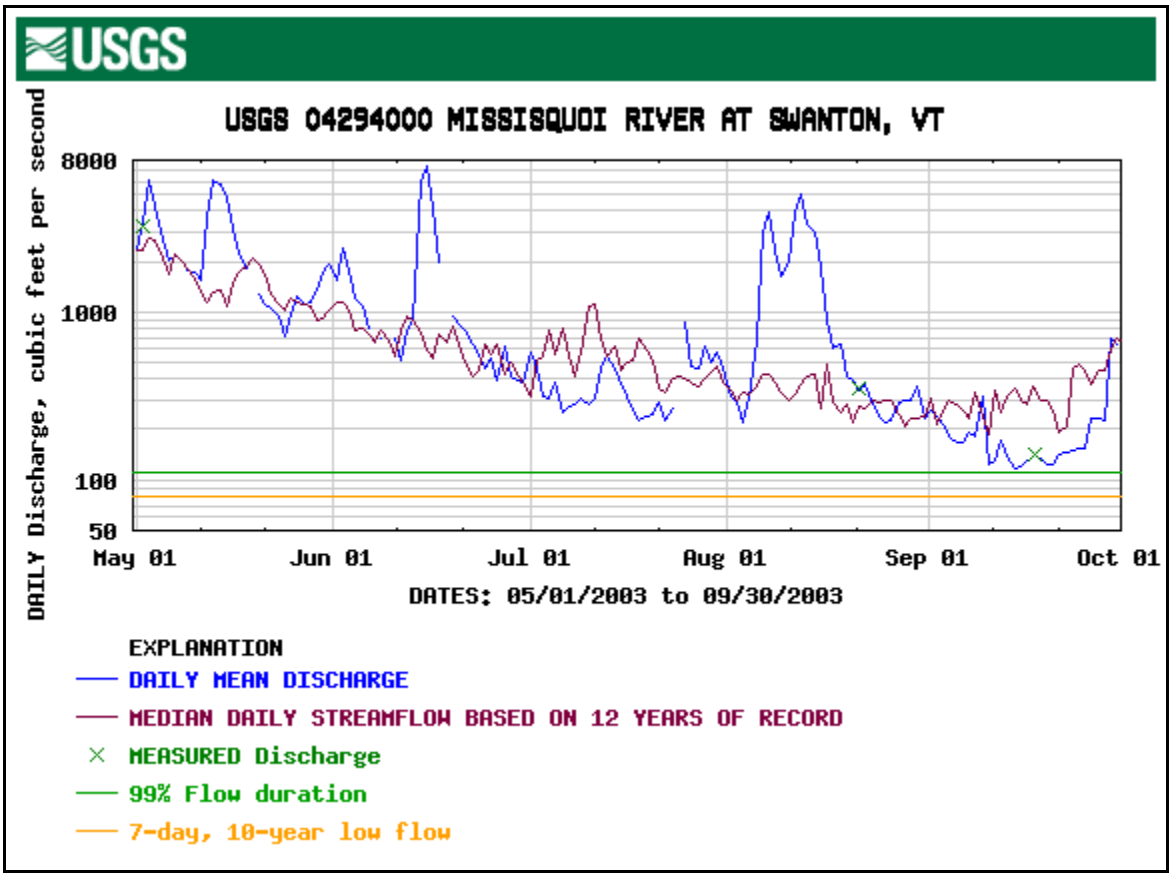

Figure 2.4: Missisquoi River Discharge – Summer 2003

Lake Champlain water levels at Rouses Point New York are at http://waterdata.usgs.gov/nwis/uv?site_no=04295000, where the following data were obtained, Figure 2.5.

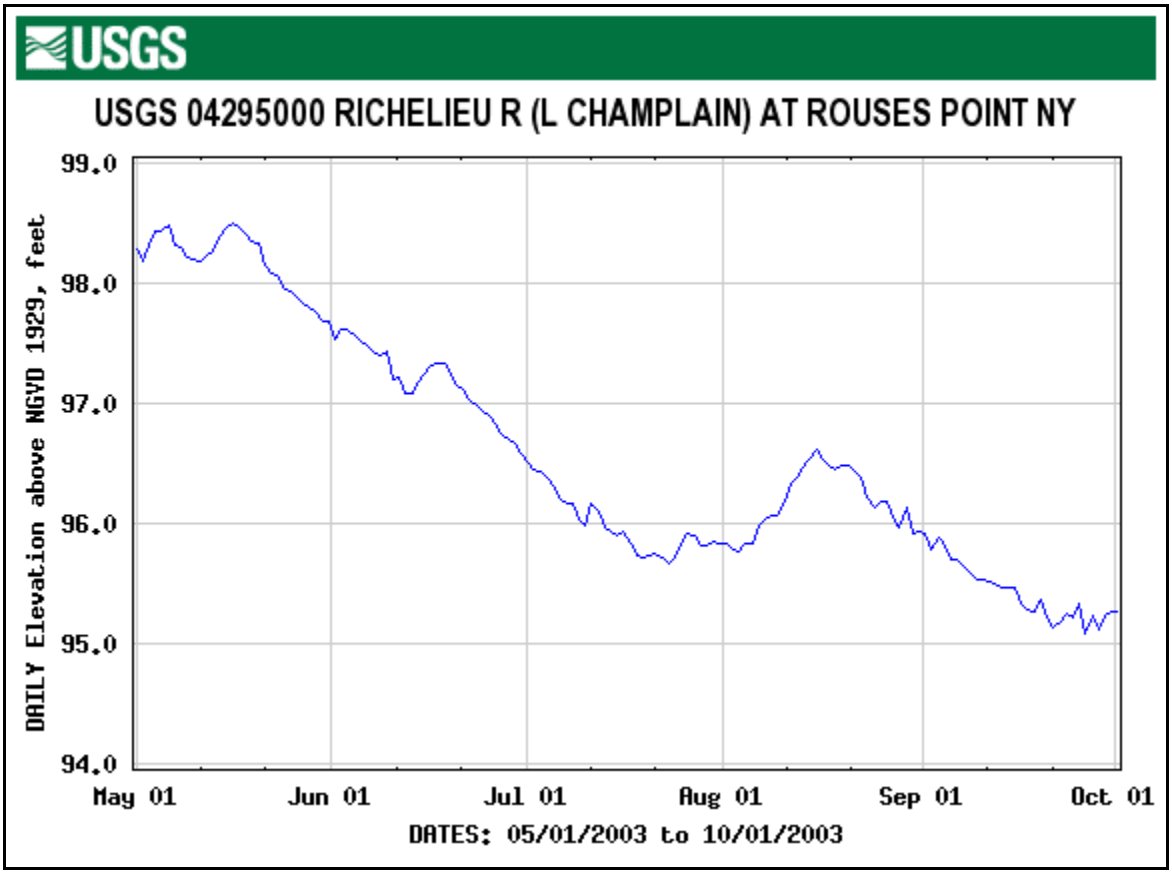

Figure 2.5: Lake Champlain Water Levels at Richelieu River – Summer 2003

2.5.2 Meteorological

The weather observations used in this project are from reports issued by the U.S. National Weather Service from the Plattsburgh (Clinton County), New York airport. The airport is 15 miles southwest of Carry Bay and is the closest source of reliable weather observations.

Regular METAR[9] reports are issued every hour, and SPECI (special) reports are issued whenever weather conditions change significantly. The wind speed and direction has been extracted from these reports for every 6 minute interval from May 1 to September 30, 2003.

[9] METAR is a French acronym which means "routine aviation weather observation."

3.0 OVERVIEW OF FIELD MEASUREMENTS

3.1 Current Measurements

Currents were measured each day from July 28th to 31st and August 14th to 22nd. During the July survey, pole and jug drogues were deployed and generally retrieved after about twenty minutes. One measurement at each station each day was the normal procedure. On occasion some drogues were deployed for several hours.

During the August, survey the common procedure was to release pole drogues with GPS units attached to them and not retrieve them until several hours later. One drogue with GPS attached was used at the south passage in the Carry Bay Causeway (Station #8) and it was deployed and retrieved many times during the day. At Station #3 and #16, pole and jug drogues were deployed to obtain velocity profiles.

In July currents were measured from Station #24 near Point Au Roche to Station #18 near Missisquoi Bay Bridge. During the August survey the focus shifted to the region near the Carry Bay Causeway. The extent of the August survey area was from entrance to La Motte Passage to Alburg Bridge. On seven of the nine days a current profile was obtained at Station #3 (entrance to La Motte Passage).

A current survey was conducted on August 2nd at the passage in the Isle La Motte Causeway (Station #7). Currents were measured at the bridge by dropping a five-foot pole drogue off the bridge and recording the time for the drogue to travel under the bridge. On this day currents were monitored continuously from 11 am to 3 pm. Previous to this survey only spot measurements were obtained at this station.

3.2 Water Quality Measurements

3.2.1 Temperature Measurements

During the first survey in July temperature profiles at Station #24 were measured daily for eight continuous days to document the position of the thermocline and determine from those measurements the phase of the internal seiche. Temperature measurements began on July 26th and ended on August 2nd.

During the four-day survey, July 28th to 31st, temperatures were measured at many more stations in La Motte Passage and from Carry Bay to the Missisquoi Bay Bridge.

In August, temperature profiles were collected at Station #33 which served as the southern extent of the August survey area. In August, it was not necessary to travel as far south as Station #24 to measure the internal seiche since in the July survey the internal seiche was also measured in the La Motte Passage. Station #33 provided a deep-water station closer to Carry Bay than Station #24.

3.2.2 Phosphorous and Chloride Measurements

Water samples for total phosphorous and chloride were collected each day of the four-day survey, July 28th to 31st. On July 28th only six samples were collected. On the following three days samples were collected at eighteen stations.

4.0 DISCUSSION OF FIELD RESULTS

4.1 Water Quality

4.1.1 Temperature

Temperatures shown in Figure 4.1 illustrate the rise and fall of the thermocline at Station #24.[10] As the thermocline rises in the Isle La Motte region of Lake Champlain water above the thermocline is generally moving south and water below the thermocline is moving north.[11] The rise in the thermocline appears to begin on July 27th and peaks sometime on July 29th. The fall and the associated northern flow of upper layer water occurred on July 30th.

Temperatures measured at Stations #1, #2 and #3 are plotted in Figures 4.2, 4.3 and 4.4, respectively. These figures illustrate a similar pattern as that shown at Station #24. About halfway up the La Motte Passage internal seiche activity is observed at Stations #4 (Figure 4.5) and Station #5 (Figure 4.6). At Station #6, further north, temperatures did not illustrate a well-defined thermocline.

On the other side of the Carry Bay Causeway water temperatures during the July survey were generally uniform and differences in top and bottom temperatures, when they were observed, could be attributed to solar heating.

---

[10] The thermocline is the region in the vertical thermal structure that has a rapid change in temperature with depth. This region is also called the metalimnion. Above the thermocline is warmer water associated with the epilimnion and below the thermocline is colder water associated with the hypolimnion.

[11] For a detailed description of the dynamics of the internal seiche throughout the main lake see Thomas O. Manley, K. L. Hunkins, J. H. Saylor, G. S. Miller and P. L. Manley, 1999. "Aspects of summertime and wintertime hydrodynamics of Lake Champlain." Lake Champlain in Transition: From Research Toward Restoration. Water Science and Application Volume 1, pages 67-115. American Geophysical Union. A more theoretical description is presented by Robert B. Prigo et al., 1996. "Linear, one-dimensional models of the surface and internal standing waves for a long and narrow lake." Am. J. Phys. 64 (3), March 1996.

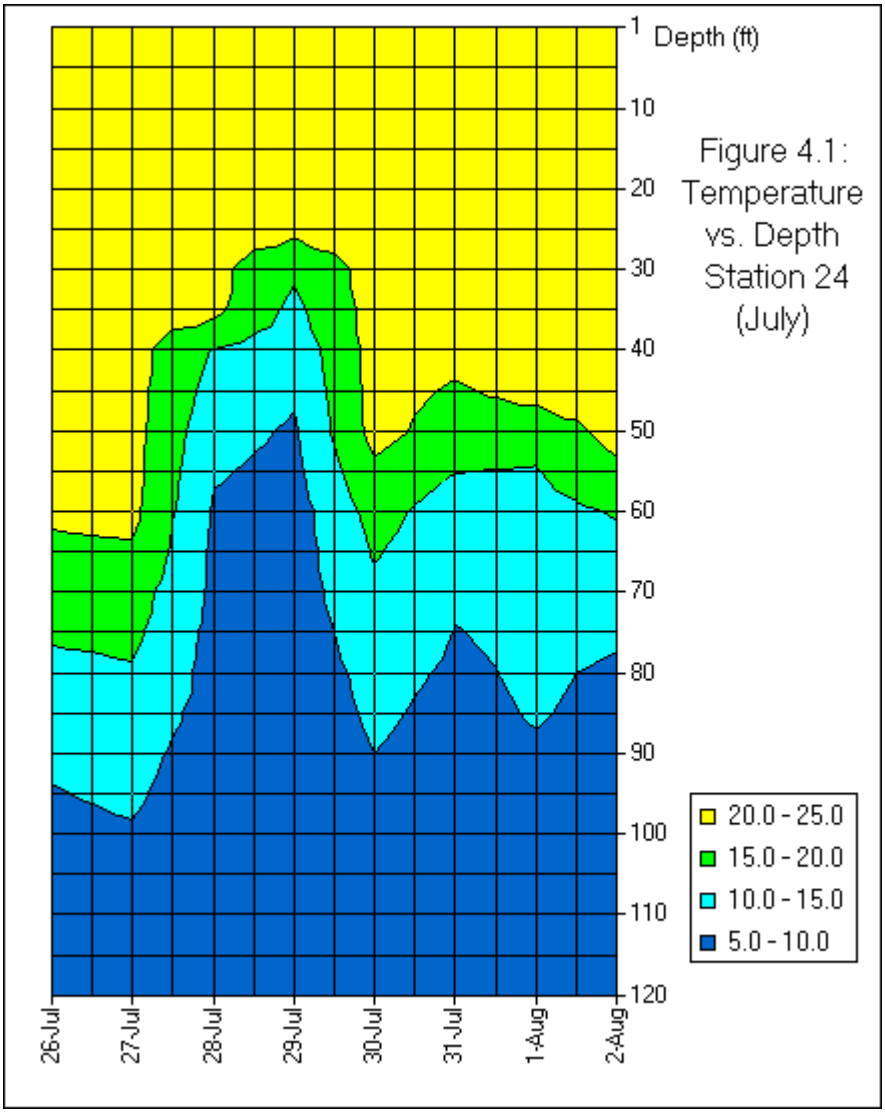

Figure 4.1: Temperature vs. Depth Station 24 (July)

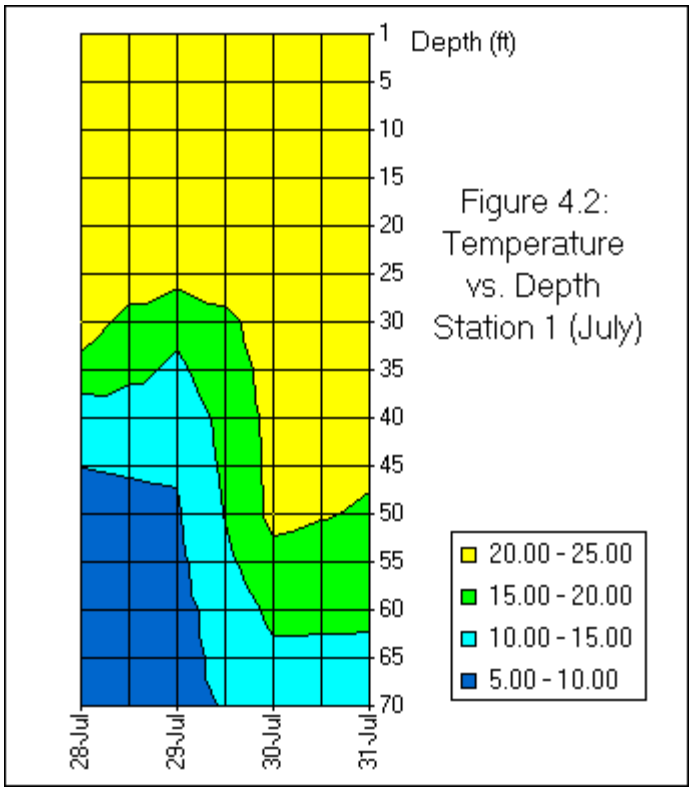

Figure 4.2: Temperature vs. Depth Station1 (July)

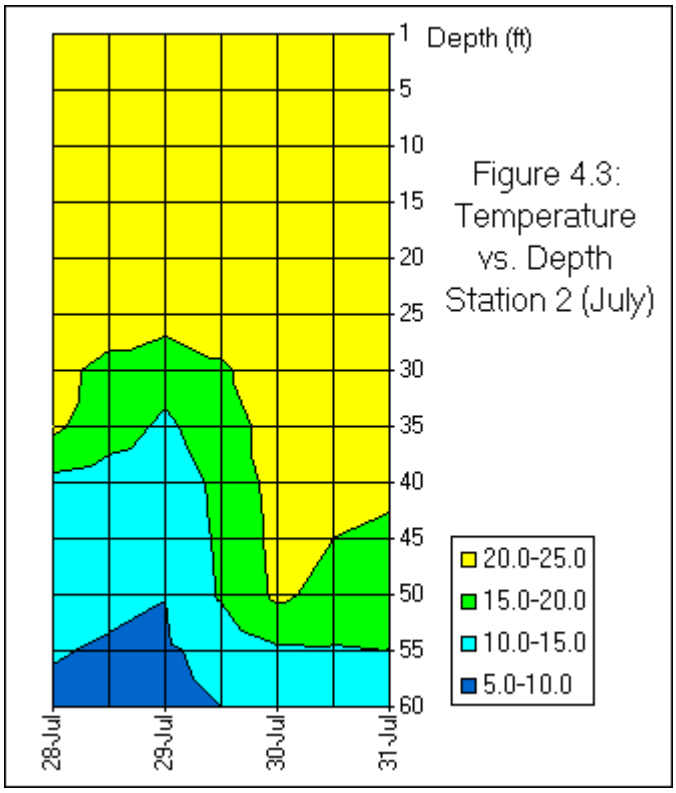

Figure 4.3: Temperature vs. Depth Station 2 (July)

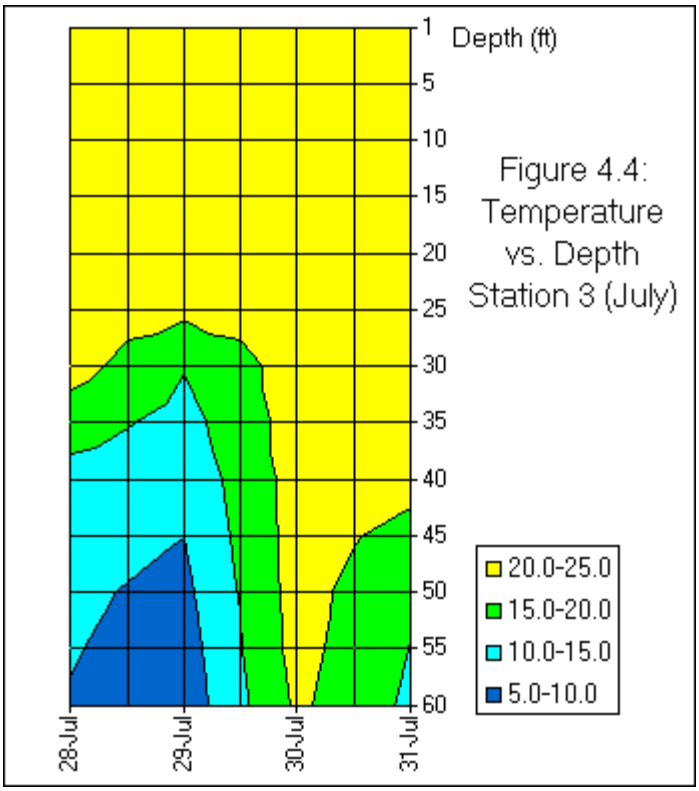

Figure 4.4: Temperature vs. Depth Station 3 (July)

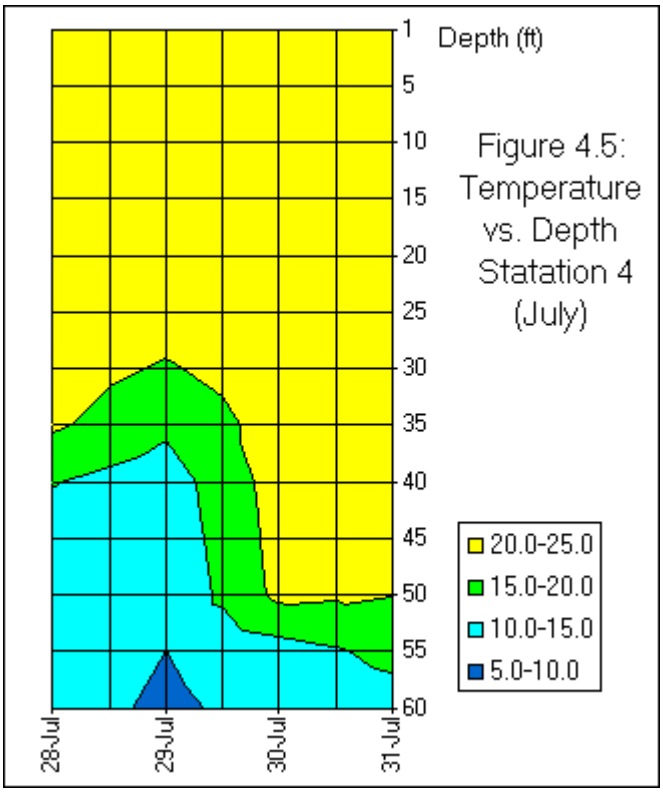

Figure 4.5: Temperature vs. Depth Station 4 (July)

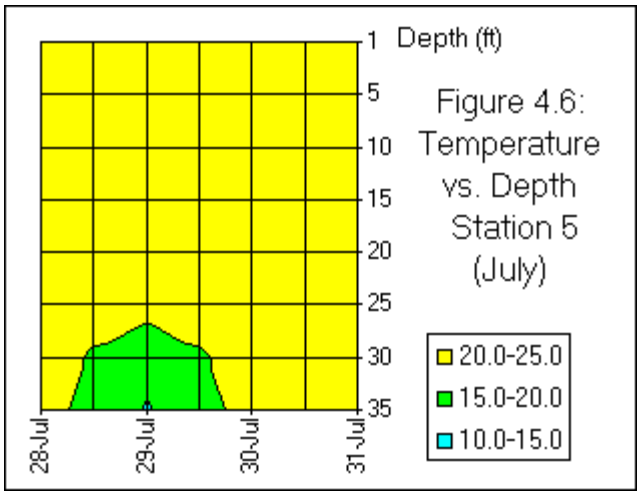

Figure 4.6: Temperature vs. Depth Station 5 (July)

Temperatures measured in August displayed a fall in the thermocline related to the northern flow of warm surface water on three occasions, 14th -15th, 18th -19th, and 21st-22nd. These falls in the thermocline are illustrated in Figure 4.7. Clearly the most dramatic drop in the thermocline occurred right in the middle of the August survey.

On August 18th temperatures were measured at several stations in La Motte Passage. These measurements indicate that the 20 degree C isotherm had penetrated the entire passage, Figure 4.8.

Also on August 18th vertical temperature profiles were measured west to east through the south passage (cut) in the Carry Bay Causeway. Temperatures displayed in Figure 4.10 indicate that cold bottom water between 10–15 degrees C moved west to east into Carry Bay from La Motte Passage.

On the following day most of the colder bottom water had left La Motte Passage and Carry Bay and was replaced with warmer surface water that flowed north corresponding with the fall of the thermocline. Figure 4.11 shows temperatures contours from west to east at the south passage on August 19th.

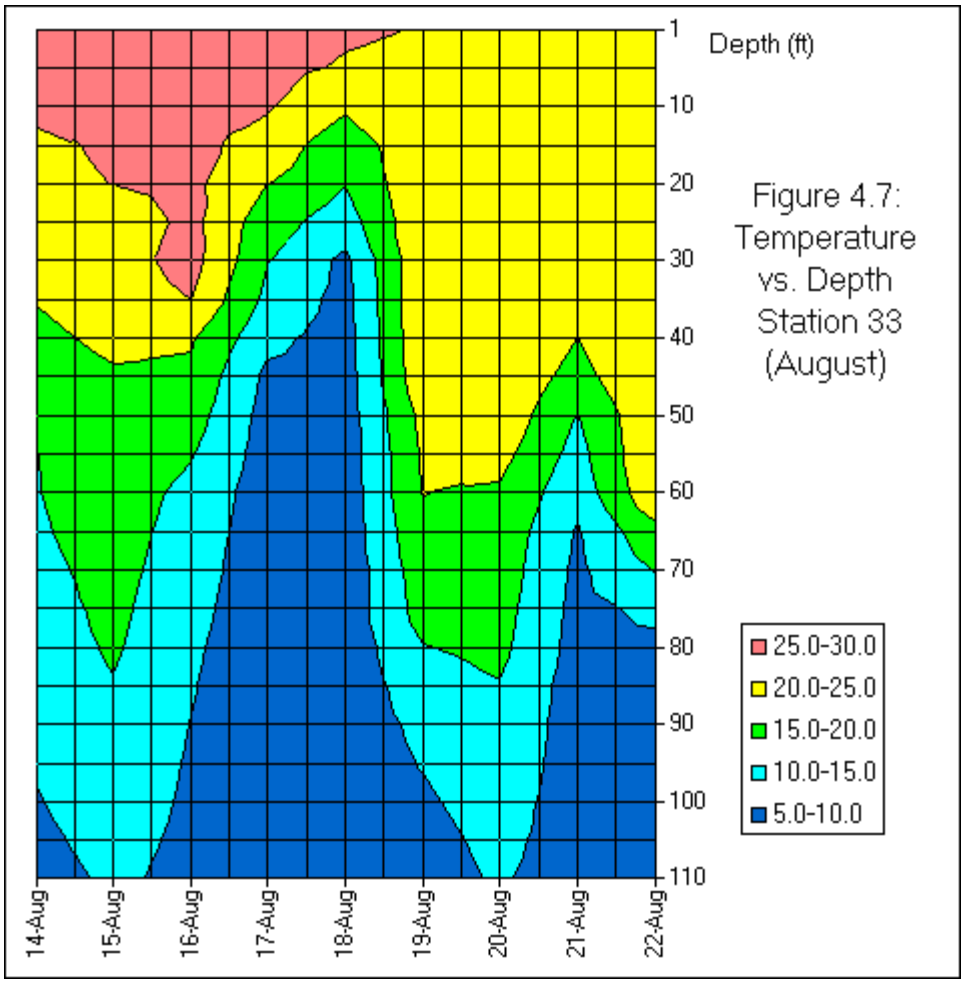

Figure 4.7: Temperature vs. Depth Station 33 (August)

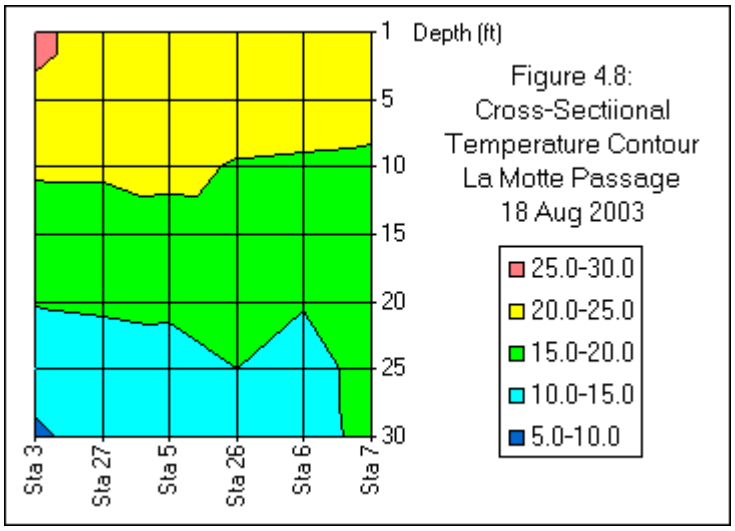

Figure 4.8: Temperature Contour La Motte Passage

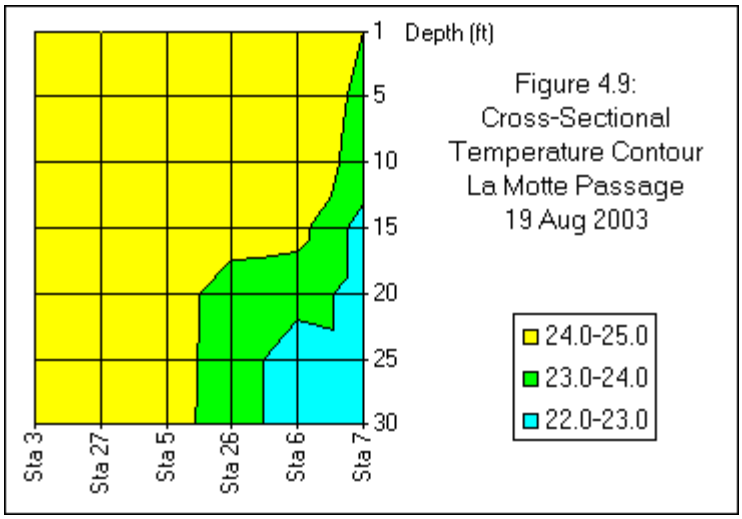

Figure 4.9: Temperature Contour La Motte Passage

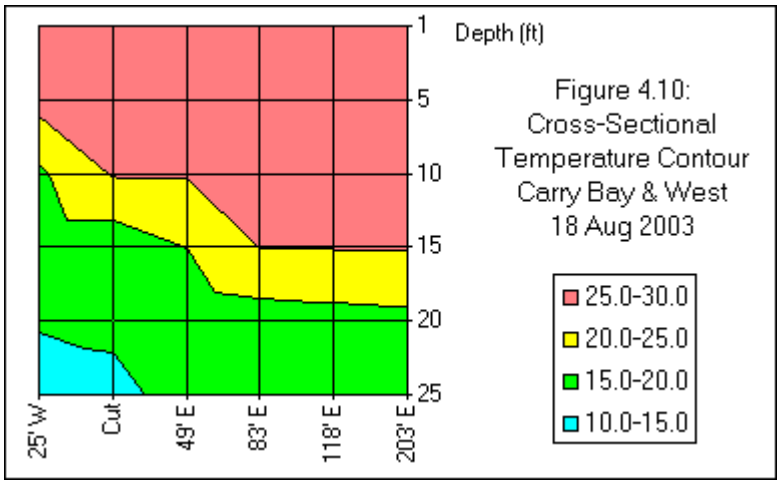

Figure 4.10: Temperature Contour Carry Bay

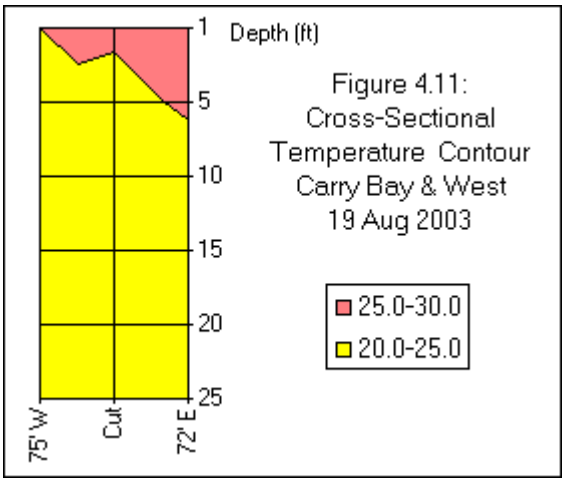

Figure 4.11: Temperature Contour Carry Bay

4.1.2 Phosphorus and Chloride

The lowest chloride concentrations were consistently measured at Station #18, near Missisquoi Bay Bridge, and the highest chloride concentrations were measured in the main lake. Chloride concentrations at Station #18 varied from 10.0 to 10.7 mg/l (milligram per liter) with a four-day average of 10.2 mg/l. At Station #24 chloride concentration was 14.5 mg/l for three consecutive days. At the southern entrance to La Motte Passage chloride ranged from 14.0 mg/l to 14.4 mg/l with a four-day average of 14.2 mg/l.

Chloride is conservative (slow to react in the environment) and provides an excellent tracer of transport characteristics in this situation where low chloride concentration from the Missisquoi Bay region mixes with higher chloride concentrations from the main lake.[12]

In Figure 4.20 both chloride and total phosphorous are plotted. The chloride scale in this graph is inverted, i.e., the top of the scale represents10 mg/l chloride and the bottom is15 mg/l. In the same graph, total phosphorous is plotted in the more traditional way with the lower values at the bottom. In the main lake chloride concentrations are high relative to concentration of chloride in waters of Missisquoi Bay, but the opposite is true for total phosphorous. As water from Missisquoi Bay moves through Alburg Passage and Carry Bay it mixes with lake water. For chloride concentrations this mixing results in an increase in concentration toward Carry Bay while the opposite is true for total phosphorous, i.e., total phosphorous decreases. To better illustrate relationship between these two variables and the impact of mixing with water from the main lake in this region the scale for chloride was inverted.

Figure 4.20 shows chloride concentrations from the main lake at Station #24 to the Isle La Motte Causeway at Station #7. As seen in this figure chloride decreases in concentration and tends to level off, whereas total phosphorous increases in concentration then levels off. Although the values are different the underlining reason for this observation is the same; water originating from Missisquoi Bay is being diluted with main lake water.

Total phosphorous is also plotted in Figure 4.20. The trend in total phosphorous in these measurements is opposite to chloride. The lowest concentrations of total phosphorous are observed in the main lake and an increase in concentration is observed north into La Motte Passage. The range is from 13.7 µg/l (microgram per liter) to just over 20 µg/l.

---

[12] Eric Smeltzer (VT DEC) and Scott Quinn (NY DEC) used the conservative properties and observed variability in chloride to estimate exchange rates between large segments of Lake Champlain. “A phosphorous budget, model, and load reduction strategy for Lake Champlain.” Journal of Lake and Reservoir Management, 12 (3): 381-393,1996.

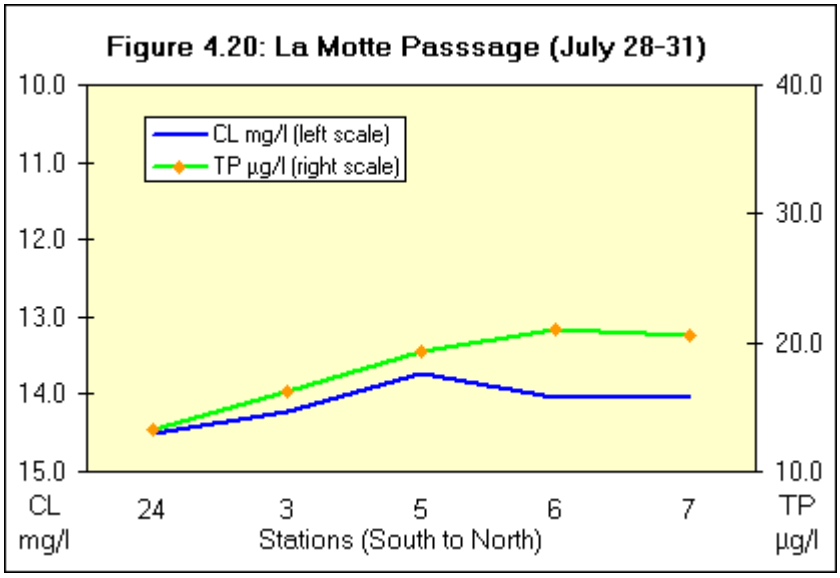

Figure 4.20: Chloride & Phosphorous – La Motte Passage

Chloride and total phosphorous are plotted in Figure 4.21 representing conditions measured in the Alburg Passage from Station #10 in Pelots Bay to Station #18 near Missisquoi Bay Bridge. The trends observed in the La Motte Passage are repeated, i.e., chloride concentrations decrease from south to north while total phosphorous increases. Chloride concentrations decrease from just over 13 mg/l to just over 10 mg/l while total phosphorous increase from 28 µg/l to 36 µg/l. The increase in chloride and the decrease in total phosphorous from north to south indicate dilution of water originating from Missisquoi Bay with main lake water. However, phosphorous concentrations do not decrease as rapidly as chloride indicating that other factors besides dilution may be impacting phosphorous concentrations. Other factors that affect phosphorous concentrations could be settling, re-suspension and chemical and biological interactions.

At the same location over three consecutive days in July total phosphorous was observed to vary widely. For example, measurements at Station #10 varied from 25 to 32 µg/l; at Station #16 – 26 to 36 µg/l; and at Station #17 – 26 to 33 µg/l. The largest change between two observations was at Station #11: 48 to 25 µg/l on consecutive days.

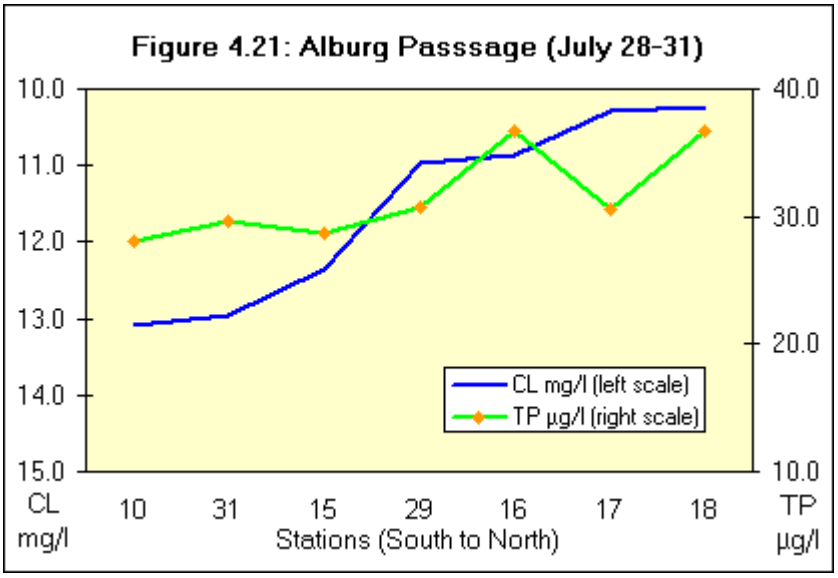

Figure 4.21: Chloride & Phosphorous – Alburg Passage

The next display of chloride and total phosphorous depicts concentrations along a west to east transect from La Motte Passage to Carry Bay. Chloride is observed to decrease toward Carry Bay while the opposite is observed for total phosphorous. The total phosphorous gradient is steepest near the Carry Bay Causeway.

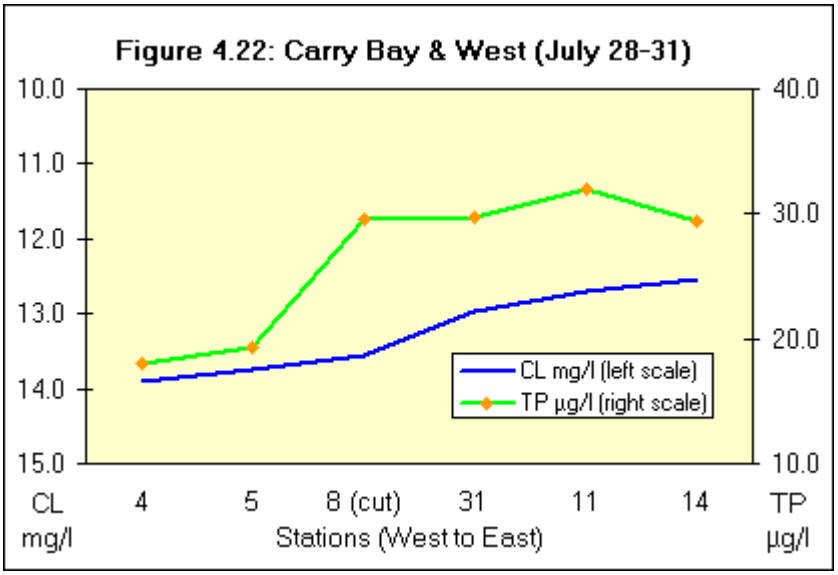

Figure 4.22: Chloride & Phosphorous – Carry Bay

Chloride measured at five stations in Carry Bay and Alburg Passage is plotted in Figure 4.23. These curves were developed from daily measurements at each station and illustrate that on July 30th there was an increase in chloride concentration followed by a decrease on the following day. This increase in chloride concentration was due to the inflow of main lake water to Carry Bay caused by the internal seiche.

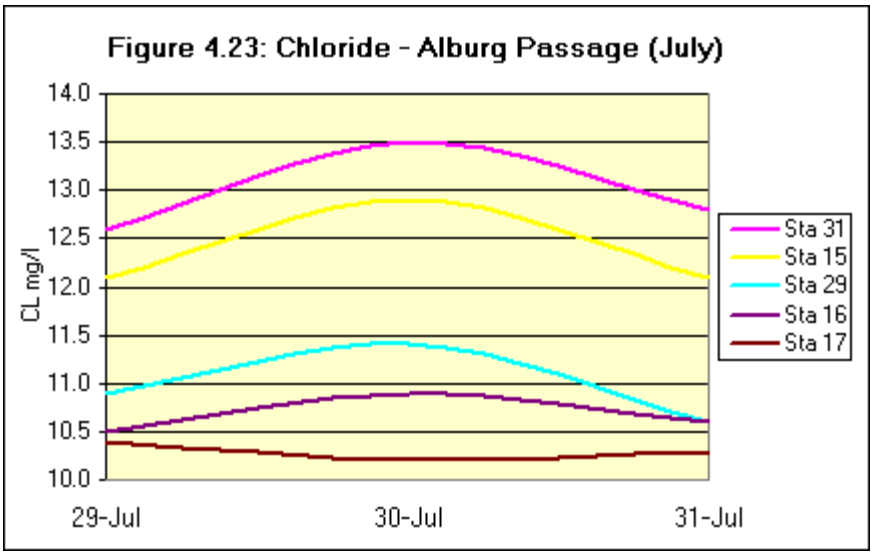

Figure 4.23: Chloride – Alburg Passage (July)

4.2 Currents - General

In Section 4.1 observed variations in water temperatures and the currents due to the internal seiche are discussed. Currents induced by the internal seiche are just one of several mechanisms contributing to lake circulation. Other mechanisms are net-advection flows from all sources of inflow and outflow such as rivers, surface runoff, precipitation and evaporation; wind driven currents; currents produced by surface seiche activity both directly and indirectly; and net transport due to waves.[13]

To provide continuity (water mass balance) for the lake as a whole the net inflow minus outflow must be zero over a long period of time. In this report, currents associated with river inflows are called net-advection flows.

Wind induced surface shear forces at the air-water interface produce currents and contribute to observed circulation patterns. Also, direct wind generated currents can result in currents in adjacent regions. For example, if strong south winds produce flows to the north in Alburg Passage, west to east currents may be observed at the south passage. In this case currents at the south passage are being indirectly induced by the wind.

Surface seiche and internal seiche induced flows can also be considered to be wind driven, since the primary forcing function of surface and internal seiches is the wind. Currents induced by surface seiche have a minor role in overall circulation patterns.[14]

In essence, one observes water motion, which is the sum effect of net-advection, direct and indirect wind, surface seiche and internal seiche induced flows. Determining which mechanism(s) is important for an individual observation leads to a correct interpretation of circulation patterns.

4.2.1 Currents at Isle La Motte Causeway

Currents under the bridge at the Isle La Motte Causeway were measured frequently leading up to and throughout the four-day July survey. Considerable effort went into these measurements since a correlation was being sought between the phases of the internal seiche and some other more easily observed measurement, such as the current direction at the Isle La Motte Causeway.

Figure 4.80 depicts observations at the Isle La Motte Causeway for eight consecutive days in July. On July 28th, a south current was measured at the Isle La Motte Causeway, and the rising thermocline in the main lake infers a south current in the La Motte Passage (see Section 4.1.1). On July 29-30th a north current was measured and the falling thermocline observed at the entrance to La Motte Passage on this date also infers a north current. Both of these observations are in phase with internal seiche surface flows. However, current measurements on the following days did not seem to relate to the internal seiche dynamics.

---

[13] A very brief description of lake circulation mechanisms is given here to define terms used in this report. For a description of Lake Champlain circulation patterns the reader is referred to Lake Champlain in Transition: From Research Toward Restoration, Water Science and Application 1. Editors, T. O. Manley and P. L. Manley.

[14] Hunkins, K., D. Mendelsohn, and Tatsu Isaji. "Numerical hydrodynamic models of Lake Champlain." Lake Champlain in Transition: From Research Toward Restoration, Volume 1, page 123.

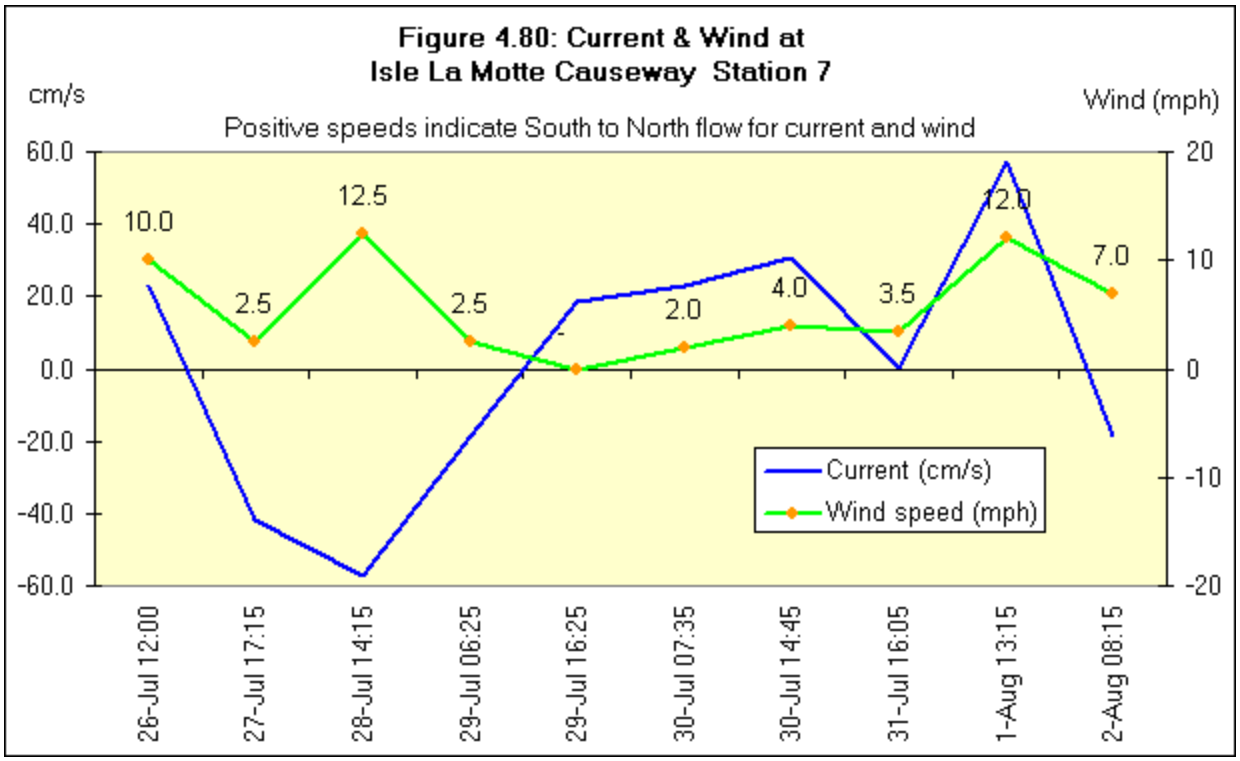

Figure 4.80: Current & Wind at Isle La Motte Causeway – Station 7

Net-advection transport could not explain observations at the La Motte Causeway since currents were observed moving in both directions. And, of these ten observations three had currents going against the wind. With internal seiche, wind and net-advection ruled out, the only remaining mechanism is surface seiches.

Surface seiches are relatively small surface waves with amplitudes of a few centimeters that travel the length of the lake and in local embayments such as the La Motte Passage. It is possible that a surface seiche in the main lake could result in water elevations on the main lake side of the causeway different than water elevations on the La Motte Passage side. If water elevations were different on either side of the causeway water would flow through the causeway in response to these changing water elevations. Since the periods of surface seiches in the main lake are about two hours or less, current reversals should occur in that same time period.[15]

To document the frequency of current reversals, continuous observation of currents began at 11:00 am until 3:10 pm on August 2nd. Winds were light from the south most of the day until going calm about 1:00 pm. Currents under the bridge at the Isle La Motte Causeway at 11:00 am were S-N (south to north). Twenty minutes later they reversed and stayed N-S for only 15 minutes before the current went slack and changed direction for only six minutes, S-N. After reversing this time currents stayed N-S from 11:41 am until 1:28 pm (1 hour 47 minutes) before changing again to the north. Flows were still going south to north at 3:10 pm when the station was abandoned. The frequency of these current reversals are similar to the periods of the

[15] Myer observed a period of 4.2 hours for the uninodal component along the south-north axis of the lake. That was the maximum period and other components (waves with more nodes) had periods of 2.2-2.5 hours, 1.6 hours, 1.1, and 0.87 hours. Myer, G. E., and G. K. Gruendling, 1979. Limnology of Lake Champlain. State University of New York, College of Arts and Science, Plattsburgh, NY.

surface seiche which indicates that the most likely cause of these observations was surface seiche induced water elevation differences between one side of the causeway and the other.

4.2.2 Point Au Roche and La Motte Passage

At Station #24 currents were measured for three consecutive days in July. Surface currents were measured with a 10-foot pole and jugs at depths of 10, 20, 35, 50 and 100 feet below the surface. Data are plotted in Figures 4.30, 4.31, 4.32, 4.33, 4.34 and 4.35, respectively, for each of these measurements.

The 10-foot pole and the 10-foot jug appear to depict similar currents in respect to both magnitude and direction. On July 29th and 31st surface currents were toward the E while on July 30 NNE currents were observed. The speeds indicate that currents were twice as strong on July 30 compared with those measured on July 29th and 31st. At depths of 20, 35 and 50 feet current direction at all depth were SE, N, then WSW with magnitudes again increasing on July 30th.

Currents at 100 feet showed a distinctly different pattern. Current speeds were low all three days at 100 feet and current direction at 100 feet was nearly opposite to those observed from the surface to 50 feet.

Clearly, the two-layer flow of the internal seiche is represented in these measurements. The current directions also agree with those inferred from temperature measurements (Section 4.1.1).

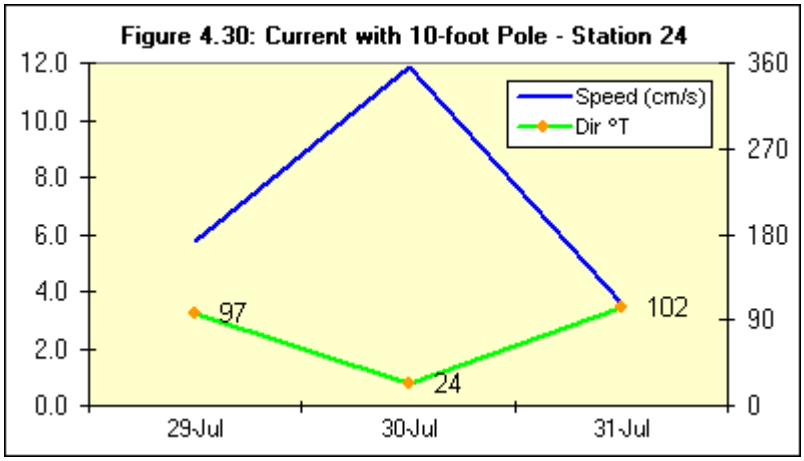

Figure 4.30: Current with 10-foot Pole – Station 24

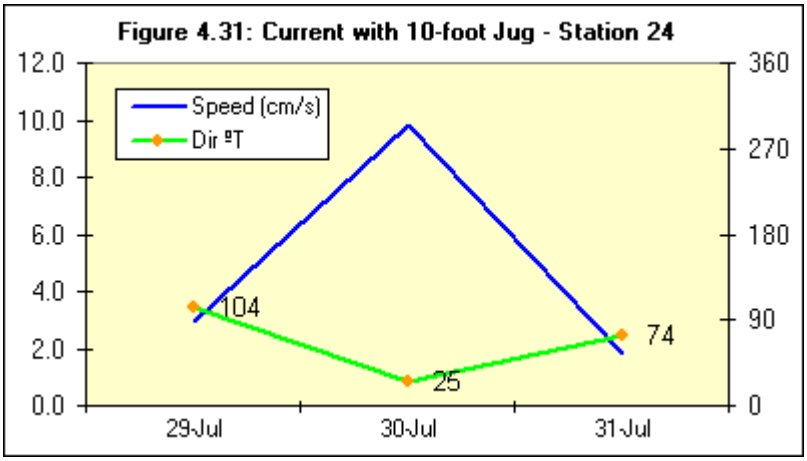

Figure 4.31: Current with 10-foot Jug – Station 24

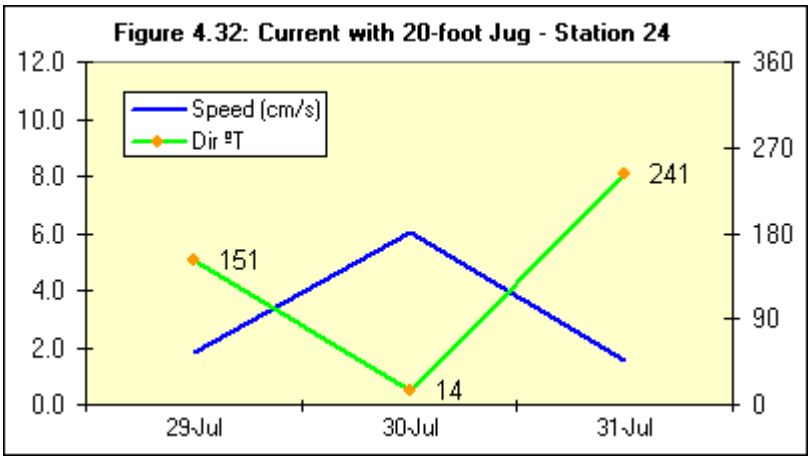

Figure 4.32: Current with 20-foot Jug – Station 24

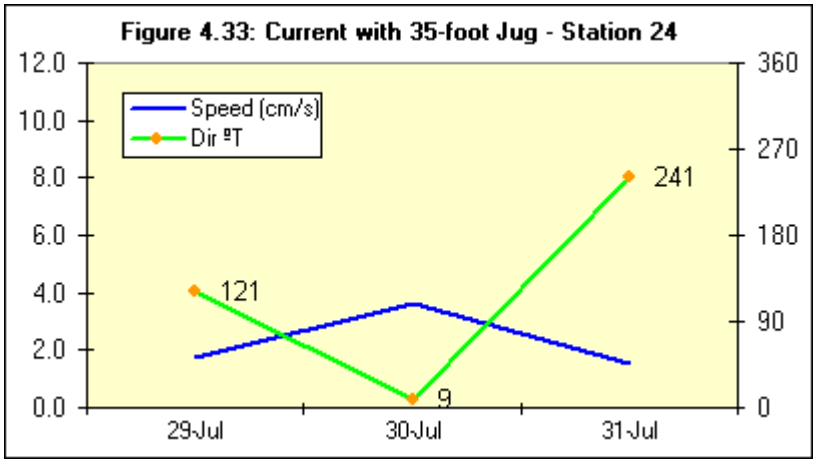

Figure 4.33: Current with 35-foot Jug – Station 24

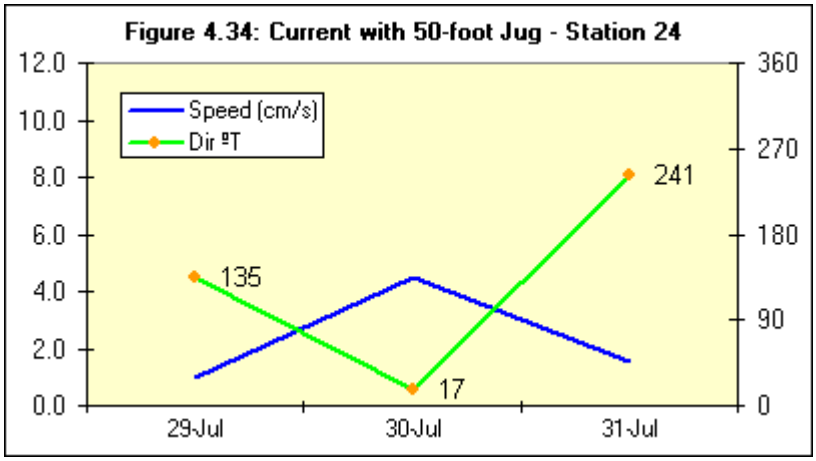

Figure 4.34: Current with 50-foot Jug – Station 24

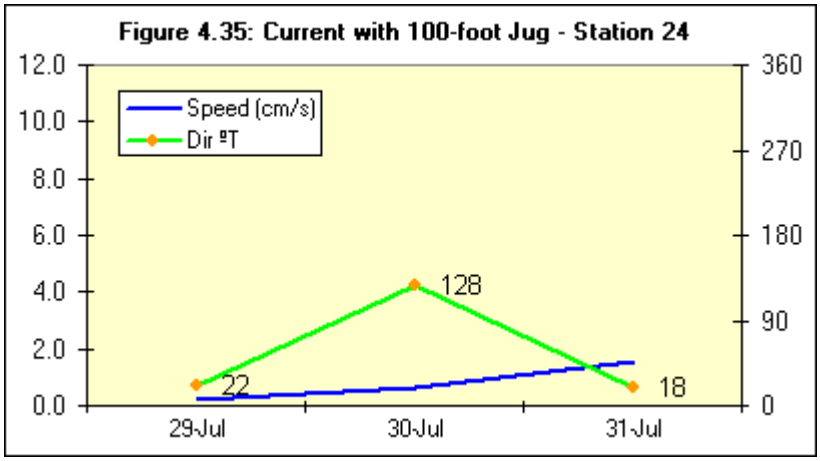

Figure 4.35: Current with 100-foot Jug – Station 24

Currents at Station #3 measured in July are plotted in Figures 4.40, 4.41 and 4.42 for a 10-foot pole drogue and jug drogues at 20 and 30 feet, respectively. Currents generally decrease with depth while maintaining a similar pattern. Current direction in these three figures are similar with SE, S an SW current direction observed on the first two days changing to NE on the third day, July 30th. As observed at Station #24, surface current direction toward the north correlates with the falling thermocline. On the fourth day, July 31st, surface currents again reversed direction and are generally moving ESE to SE.

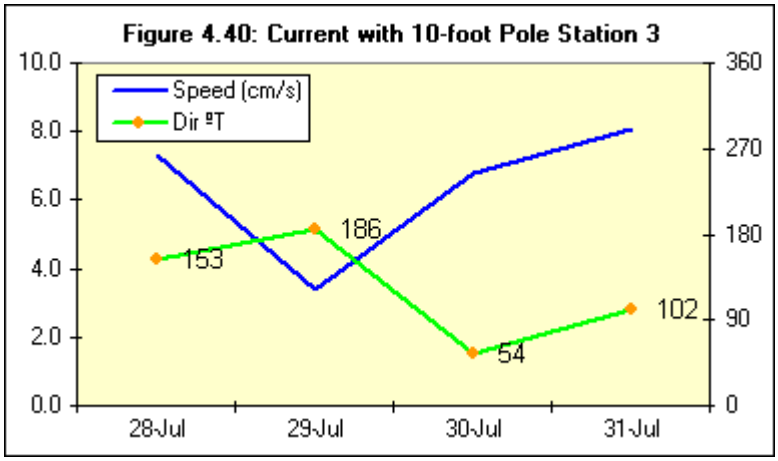

Figure 4.40: Current with 10-foot Pole – Station 3

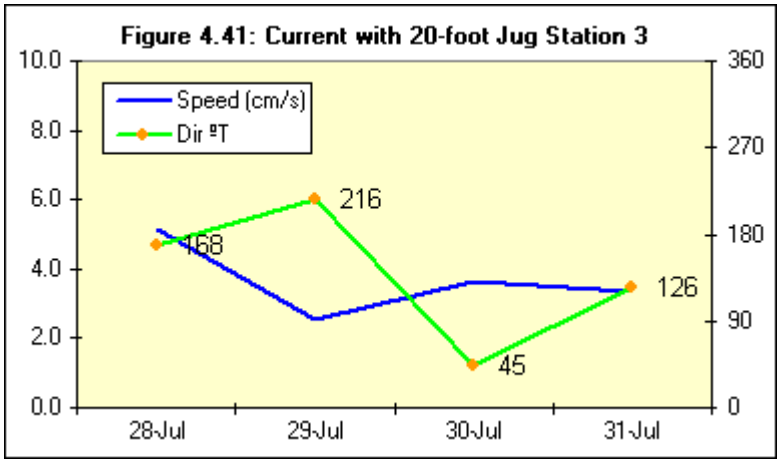

Figure 4.41: Current with 20-foot Jug – Station 3

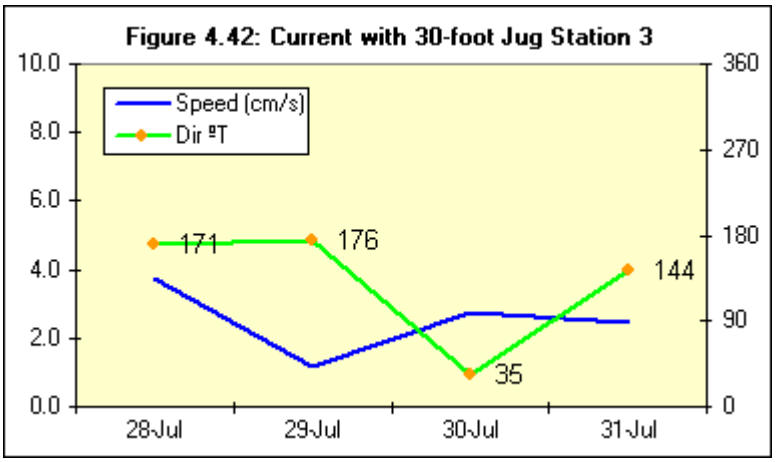

Figure 4.42: Current with 30-foot Jug – Station 3

In August a new station was added, Station #33. Depths at Station #3 were only about 50 feet so Station #33 was established where depths were about 100 feet. Station #33 is south of Station #3 but not as far as Station #24.

Each day from the August 14th to 22nd a vertical profile of temperature was measured at Station #33. Currents were also measured each day at this station but the current data for this last day was blown overboard.

Currents are depicted in Figures 4.60, 4.61, 4.62, 4.63, 4.64, and 4.65 for a 10 foot surface pole drogue, and jugs at depths of 10, 20, 35, 50, and 70 feet, respectively. One striking feature in these graphs is current reversals on August 15th – August 16th and August 19th. A third reversal in current direction occurred the night of August 21st and into August 22nd, which is documented with temperature data. The strongest currents observed occurred on August 19th during the fall of the thermocline from an elevation of about 10 feet to 60 feet deep.

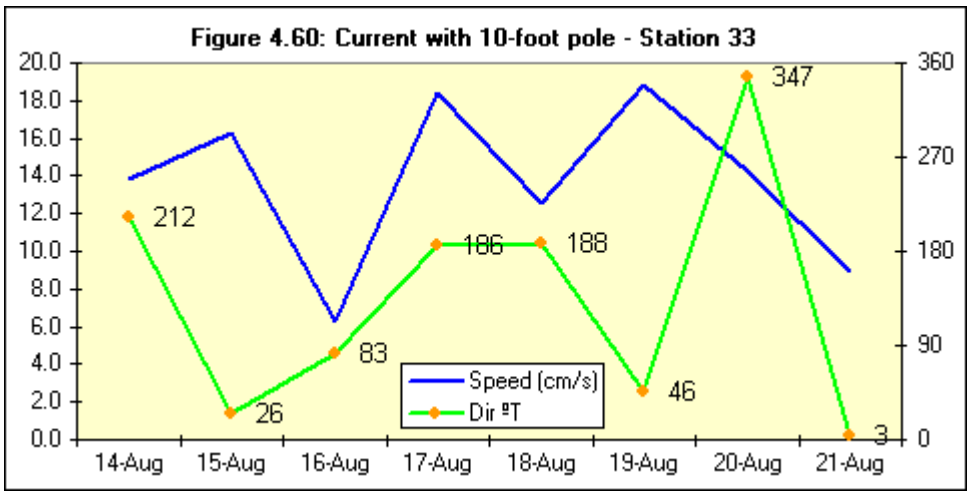

Figure 4.60: Current with 10-foot Pole – Station 33

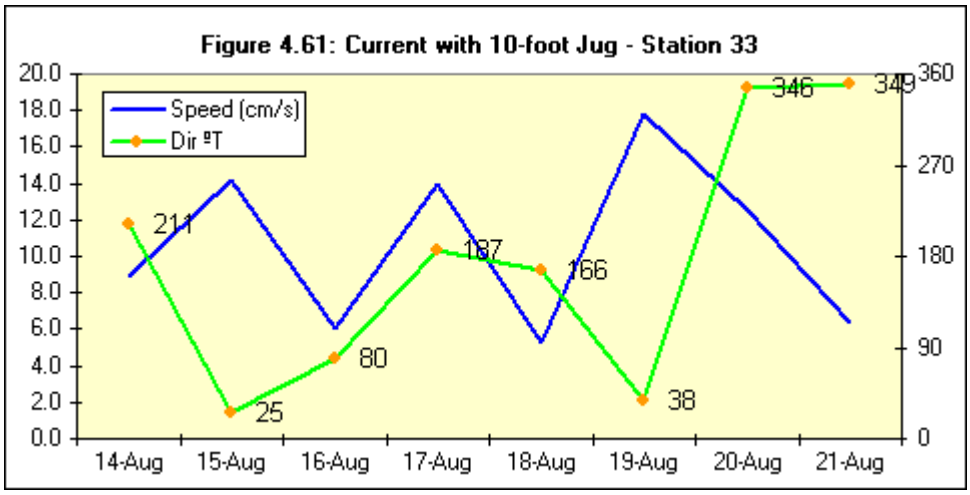

Figure 4.61: Current with 10-foot Jug – Station 33

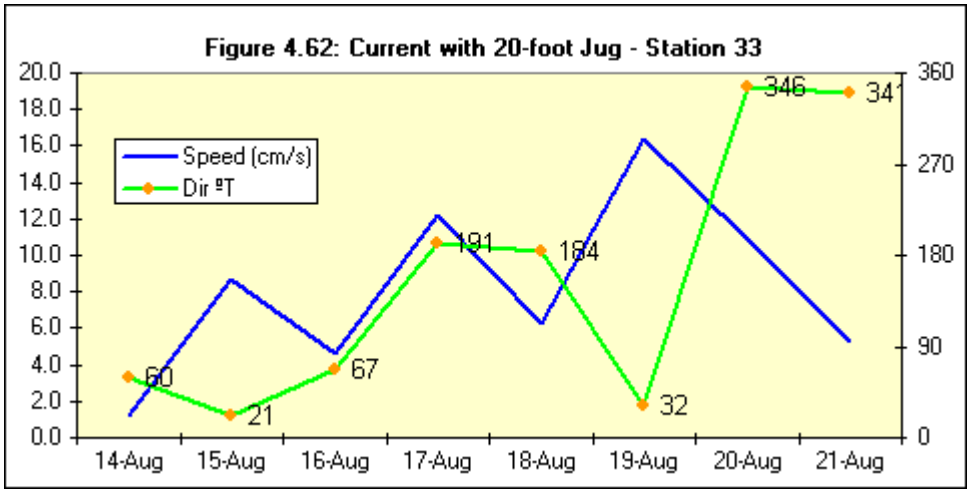

Figure 4.62: Current with 20-foot Jug – Station 33

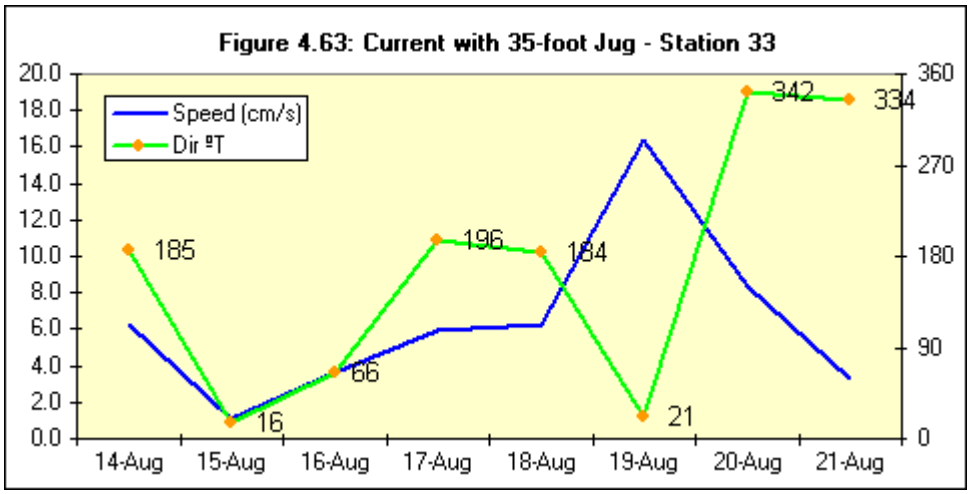

Figure 4.63: Current with 35-foot Jug – Station 33

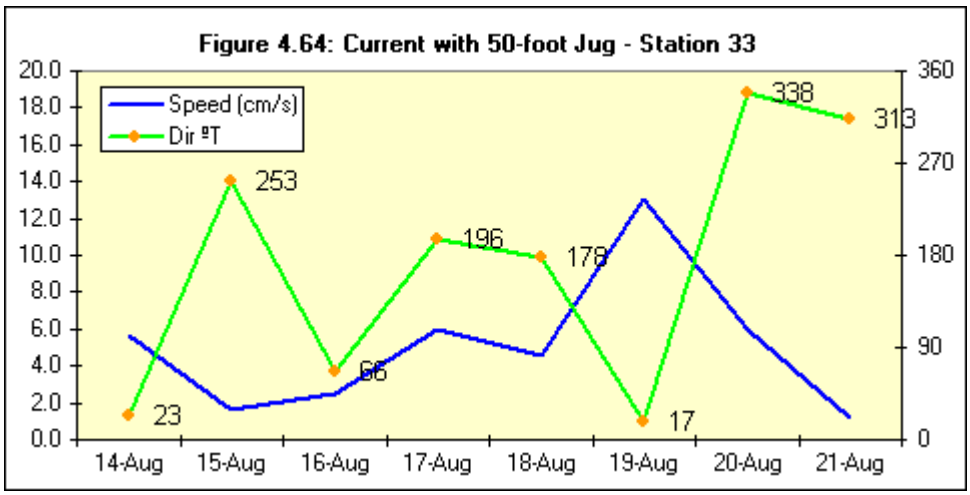

Figure 4.64: Current with 50-foot Jug – Station 33

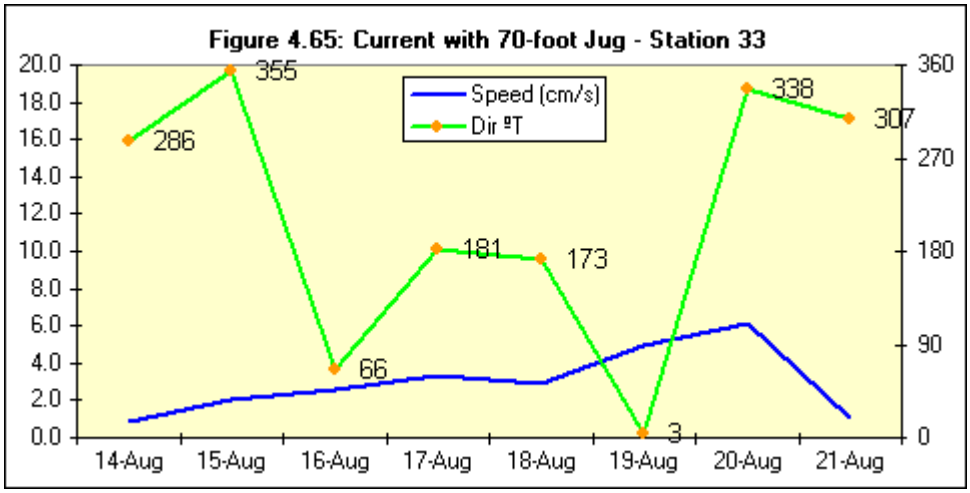

Figure 4.65: Current with 70-foot Jug – Station 33

4.2.3 Carry Bay Causeway

Current and temperature measurements were collected to identify the primary mechanisms influencing flows at the Carry Bay Causeway. As at the Isle La Motte Causeway investigation described in Section 4.2.1, the primary current mechanisms investigated were direct wind, net-advection, internal seiche, and surface seiche.

Currents were measured at the south passage in the Carry Bay Causeway for thirteen consecutive days, July 21st to August 2nd. Members of the Northern Lake Champlain Restoration Committee obtained current measurements from July 21st to July 25th. [16] Results of these measurements are in Figure 4.50.[17]

From July 21st to July 26th currents were consistently measured moving into Carry Bay from La Motte Passage. Measurements were collected once per day and currents were not observed between these daily measurements. Currents could have been moving both into and out of Carry Bay during this time period, but it is still remarkable that on six consecutive days spot observations of current showed water moving west to east into Carry Bay.

The first day of the 4-day survey, July 28th, winds were high and gusty from the north, northwest and west. At the time of the current measurement at the south passage, winds were from the west and the current was observed to move against the wind. Current moving opposite to the wind was a relatively common occurrence at both passages in the Carry Bay Causeway and early into the study it appeared that currents through these openings were most likely not entirely dominated by local winds.

---

[16] Members who participated in the collection off current and temperature data for this project were Larry Dupont, Ken Bassett and John Lambert.

[17] Currents at the north passage in the Carry Bay Causeway were often measured at nearly the same time as those at the south passage. Although speeds varied between these two stations the direction of travel was always the same.

Net-advection flows play a major part in currents at the Carry Bay Causeway. There are only three outlets between the Northeast Arm and the main lake: the opening in the Sandbar causeway, the Gut, and Carry Bay Causeway. Net-advection flow must leave the Northeast Arm and Missisquoi Bay via one of these three passages.

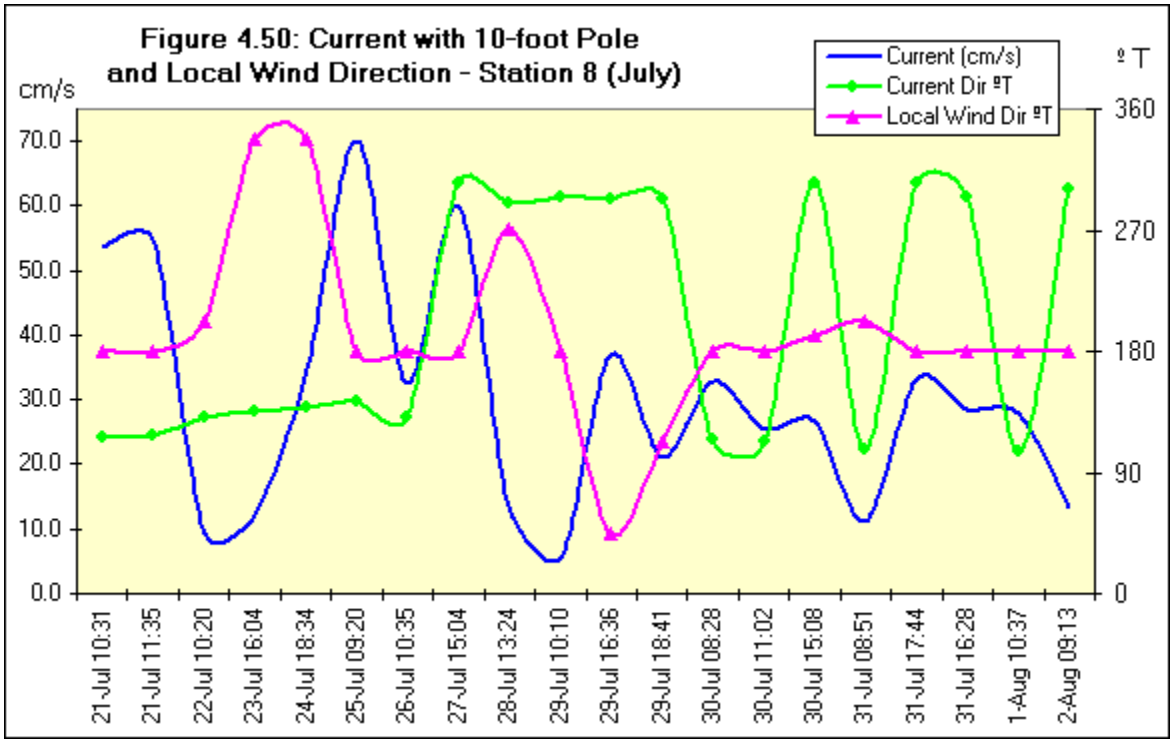

Figure 4.50: Current and Local Wind Direction – Station 8 (July)

The first indication that another mechanism besides net-advection was influential in transport at the south passage was on July 30th. This mechanism was the internal seiche in the main lake. On the preceding day, July 29th, three observations detected currents to be flowing to the west, out of Carry Bay. Meteorological conditions remained similar on July 30th but the measurement at 8:26 am indicated flow into Carry Bay. This pole drogue was not recovered after a few minutes as was the normal routine but allowed to drift throughout the day. At 15:44 pm the pole drogue released at the south passage in the causeway had moved 1.7 km (1 mile) north at an average speed of 6.2 cm/s and was observed in the Alburg Passage. The next observation of the pole drogue was at 17:06 pm and at that time it was south of the previous measurement. The path of the pole between these two observations is unknown but the 15:44 pm observation was most likely near its' maximum extent north since the currents at the south passage were decreasing in the late afternoon. As seen in Figure 4.1, the thermocline was falling on July 30thand surface water in Isle La Motte was moving north. This was the first indication that the internal seiche may have a role to play in current reversal at the Carry Bay Causeway.

In spite of there being several spot measurements of currents at the Carry Bay Causeway during this thirteen-day period, there was simply not enough information to formulate a conceptual model with certainty at the end of July. Up until the end of July, measurements at the south passage in the causeway were generally taken only once per day and there was no information available on currents between these daily spot measurements. The objective of the August survey was to obtain as continuous a record as possible of current speed and direction at the causeway, at least during daylight hours. To assist in this effort GPS receivers were

placed on pole drogues and the GPS receiver recorded location data. Using this technique, pole drogues could be left adrift unobserved for extended periods of time knowing that an accurate record of its location was being recorded. The August survey was from the 14th to the 22nd.

On 14 August currents were clearly east to west, out of Carry Bay. Corresponding with the fall of the thermocline as measured at Station #33 currents on August 15th reversed and flowed from west to east into Carry Bay throughout the day. The following three days, August 16th, 17th, and 18th, currents flowed from east to west as the thermocline rose dramatically. The rise of the thermocline to a depth of nine feet throughout much of La Motte Passage was caused by the steady north winds during this period of time. The north wind in phase with the south moving surface currents induced by the internal seiche, transported warm surface water in the main lake toward the south. In response, cool bottom water in the main lake was transported north resulting in the rise of the thermocline to within nine feet of the surface.

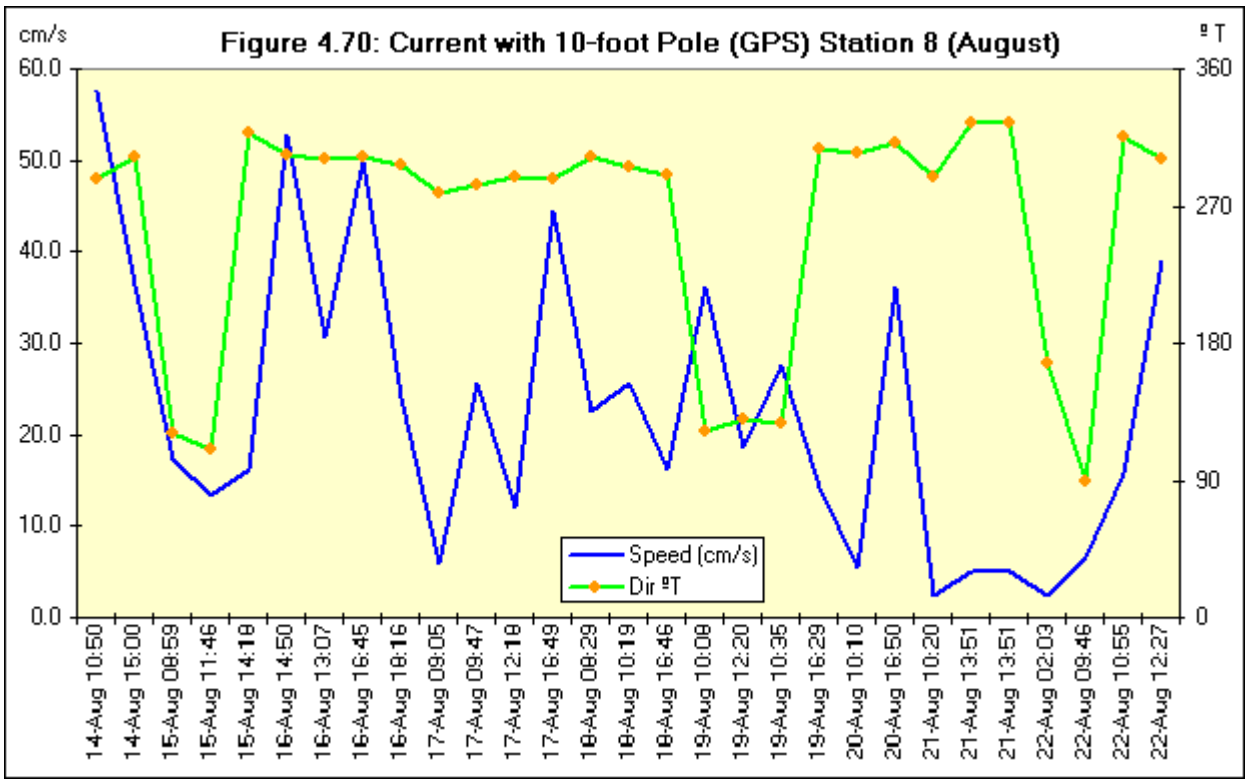

Figure 4.70: Current with 10-foot Pole (GPS) – Station 8 (August)

The fall of the thermocline on the night of August 18th and throughout most of August 19th was dramatic as reflected in the inflow observed to Carry Bay from La Motte Passage. Drogues released at the south passage were transported north to the entrance in Alburg Passage. On the following two days currents traveled east to west, again out of Carry Bay.

In anticipation of the fall of the thermocline during the night of August 21st a pole drogue was fixed by a 30-foot rope to a concrete block and anchored near the north end of the south passage. Data from this drogue indicated that a reversal due to the drop in the thermocline began about 2 am. Measurements in the morning on August 22nd indicated a west to east flow. Later in the morning currents were again moving out of Carry Bay as net-advection flows once again dominated the flow patterns.

As a result of this nine-day survey, and with the previous information obtained in July, hydrodynamics at the south passage in the Carry Bay Causeway at Carry Bay could be better explained. The dominant forces impacting currents at both passages in the Carry Bay Causeway during this nine-day August survey were internal seiche induced currents and net-advection currents. At times forces related to net-advection flows dominate and currents are east to west. When, the internal seiche surface induced flows dominate, currents entered Carry Bay.

As seen in Section 2.4.1, river discharge at Swanton was decreasing and relatively low during much of July. Specifically, the 15-day average discharge of the Missisquoi River preceding the July survey was 380 cfs compared with a fifteen-day average river discharge of 1,750 cfs in August. During the July survey, July 28th-31st, the average river discharge was 545 cfs compared with a nine-day average during the August survey of 940 cfs.

It appears that during the survey period in August only the momentum of the currents induced by the seiche were strong enough to overcome the increased flows due to net-advection. While in July, with lower river inflows, other mechanisms such as direct and indirect wind effects may have caused current reversals at the Carry Bay Causeway.

5.0 MATHEMATIONAL MODEL AND SIMULATIONS

5.1 Application of the Mathematical Model to Carry Bay

The mathematical model which is applied to the Carry Causeway site is Delft3D-Flow developed by Delft Hydraulics Institute. This mathematical model is based on physical laws of conservation of mass and momentum. Once the Dellft3D mathematical model is formulated with site-specific information about the geometry, initial conditions, and boundary conditions it is referred to as the Carry Bay model.

The first step in applying a general mathematical hydrodynamic model to situations such as estuaries, rivers, lakes, etc., and building a site-specific hydrodynamic model is the application and calibration process. A successful application of this or any mathematical model depends on accurate knowledge of local hydrodynamics. For example, prior to the field surveys in July and August 2003 there was no direct evidence that correlated the dynamics of the internal seiche in the main lake with current reversals at the passages in the Carry Bay Causeway. This phenomenon is an important aspect of hydrodynamics near Carry Bay and is necessary for realistic representation in the model.

Building the model involves progressive independent steps laying the foundation for the final model results. For example, bathymetry data need to be accurate since currents depend in part on correct geometry. The acceptance of a model application may ultimately depend on comparison of model results with field data, but building blocks of the model need to be individually examined.

The following sections describe the building of the Carry Bay model, its application to Carry Bay, and compares model results with field measurements. Finally, predictions of total phosphorous concentrations are presented for three scenarios: causeway in place, middle section removed, and complete removal.

5.2 Preliminary Model Considerations

5.2.1 Domain

The model domain is defined by the land boundary. Within the land boundary water depths are defined relative to a datum. Also, a grid is defined within the land boundary. The grid and sample depths are combined to form the computational grid. The grid is orthogonal curvilinear which enables high-resolution grids in areas of interest and less resolution elsewhere. It also allows the grid to conform to shoreline features.

In this application the model domain extends from the southern entrance of Isle La Motte Passage north to Isle La Motte Causeway. The domain includes Pelots Bay, Carry Bay and Alburg Passage, which form the main study area in this application. Missisquoi Bay and the Northeast Arm are also included in the model domain.

In the Delft model cells can be deactivated, i.e., removed from the computational process by a process of defining “dry points.” Similarly, a previously defined “dry point” cell can be activated and behave as any other computational cell. In this application the grid was specifically constructed to create one computational grid cell in the south passage of the causeway and one

cell in the north passage. In simulations involving the removal of the middle section of the causeway eleven additional cells are activated between these two cells. For complete removal twelve more cells are activated: five south of the south passage and seven north of the north passage.

The datum used in this application is the Vermont Plane Coordinate System in meters. The land boundary file was produced from digitized maps of Vermont Base Maps. The digitized data is available from the Lake Champlain Basin Program and the Vermont Center for Geographic Information. The land boundary file used to represent the domain contains over 26,000 records. This comprehensive land boundary file provides precise details for important geometric features such as the Carry Bay Causeway.

Lake water depths were obtained from National Oceanic and Atmospheric Administration (NOAA) charts of Lake Champlain. The plane of reference of these charts is low lake level (LLL) of 93.0 feet mean sea level (MSL) referenced to the National Vertical Geodetic Datum of 1929. A constant of 2.6 feet was added to chart depths to raise the model datum to mean lake level of 95.6 feet MSL. Depths in meters at mean lake level formed the depth sample file. From the depth sample file an interpolation scheme computed depths for each corner of every grid cell in the model domain.

The orientation of the model domain was true north at latitude 44.8 degrees North. The number of layers selected was one that resulted in parameters being averaged over the depth. This is a good approximation for the main area of interest near Carry Bay, Pelots Bay, and Alburg Passage where water quality parameters such as temperature, chloride, and phosphorous are well mixed.

5.2.2 Time Frame

The time frame for model simulation was May 1, 2003 to September 30, 2003. In nature time is a continuum, in the model time proceeds in discrete intervals. The time step (time interval) used for all simulations was six minutes. Map files representing the distributions of selected constituents were generally saved each hour after July 1st. History files representing the values of many parameters at one monitoring point were saved hourly for the five-month simulation period.

5.2.3 Processes

In this application two “processes” were selected: wind and constituent. Wind data were obtained from Plattsburg Airport for the time frame simulated. Recorded values were interpolated to 6-minute intervals since the model only accepts wind records at even multiples of the time step. If a computational time step fell between two wind observations, the value at the time step was estimated by linear interpolation using the two nearest recorded values.

Constituents represent tracers such as chloride. In the implementation of the model it is necessary to first identify by name any constituents and their attributes included in the scenario. For example, chloride was included as a conservative constituent in model calibration scenarios and total phosphorous was included for final model simulations. In this application the difference in total phosphorous concentration distributions are of primary concern, i.e., causeway in place compared with mid-section or total removal. Therefore, decay of phosphorous was not implemented, as the differences between scenarios would not be significantly affected.

5.2.4 Initial Conditions

Initial conditions in the model are defined depending on the scenario. For chloride the entire domain was defined at time equal zero at a uniform concentration closer to expected final concentrations rather than starting the model at a uniform concentration of zero. The initial condition for chloride was a uniform concentration of 10.2 mg/l; similarly, for total phosphorous initial conditions was defined at a uniform concentration of 36 µg/l.

5.2.5 Boundaries

A boundary condition must be specified at each opening in the land boundary file. For example a river presented a gap in the land boundary file and a boundary condition is required at that gap. At every boundary in the model a "flow boundary condition" is required. Flow boundary conditions selected in this model application to Carry Bay were of three types: discharge - time series, water level - time series, and harmonic. Also, for each constituent identified a "transport boundary condition" was assigned.

There are three passages from the Northeast Arm to the main lake: Carry Bay Causeway, the Gut, and Sandbar Causeway. The passages at Carry Bay are not boundaries in the Carry Bay model; the Gut and sandbar Causeway are boundaries. The Gut is defined as a discharge boundary with a daily discharge of 22% of the daily inflow to Missisquoi Bay. This value was selected, in part, based on the ratio of cross-sectional area at the drawbridge between Grand Isle and North Hero compared with the total cross-sectional area at Carry Bay Causeway plus the area at the drawbridge and at Sandbar Causeway (28%). Other considerations were their respective locations and information in the report by Perry.[18]

For simulations of both proposed modifications the discharge from the Gut was reduced to 11% of the daily discharge to Missisquoi Bay. This value was based on ratios of cross-sectional areas with proposed modifications. The ratio of the cross-sectional area at the drawbridge compared with the area at Alburg Bridge plus drawbridge is about 11%. The cross-sectional area at Alburg Bridge is used in this estimate since it would be less than the cross-sectional area for either proposed modification.

The passage at Sandbar Causeway is shallow and narrow. Flows at the Sandbar Causeway reverse quite often and correlated with wind direction[19] although, as observed at Carry Bay, wind may not be the only mechanism that could cause current reversals at the Sandbar Causeway. Based on a ratio of cross-sectional areas, net flow to the main lake is expected to be much lower at Sandbar Causeway than net flows at Carry Bay or the Gut. In this simulation the boundary at Sandbar is defined as a water level boundary, i.e., it is an open boundary where the water level is allowed to vary. A second water level boundary is defined at the north end of Isle La Motte Passage.

---

[18] Perry, B., 1995. "Estimational Flow volumes between the Northeast Arm and main body of Lake Champlain, Vermont." Department of Geology, Middlebury College, Middlebury, Vermont.

[19] Myer, G. E., 1977. "Currents of Northern Lake Champlain." Department of Earth Sciences, State University of New York. Proceedings of the 1977- Fourth Annual Lake Champlain Basin Environmental Conference, pages 223 & 224.

The southern boundary at Isle La Motte was simulated with a harmonic function (a simulated cosine wave). The angle of rotation was selected as 3.6 degrees per hour; therefore, one period (360 degrees) took 100 hours (4.16 days). The amplitude of the simulated cosine curve used in all simulations was 0.02 meters per second. In this manner the dynamics of the internal seiche were represented in the model. In some respects the dynamics of the internal seiche on currents at Carry Bay are similar to coastal tidal wave dynamics with a flood tide phase simulated by inflow to Carry Bay and an ebb tide phase simulated by outflow from Carry Bay.

There are five additional discharge boundaries in the application of the model located in Missisquoi Bay. Daily discharge data at the Swanton USGS gauge was used to define the discharge from each of these five boundaries. The USGS gauged discharge at Swanton was divided into three equal parts and each part assigned to one of the Missisquoi River discharges at the end of the delta formed in the bay by the Missisquoi River. For the Pike River 20% of the Swanton discharge was assigned and 5% was assigned to the Rock River.[20] The discharge entering Missisquoi Bay in all simulations was 125% of the recorded discharge at the Swanton Missisquoi River gauge.

5.2.6 Physical Parameters

There are several physical parameters in the model. Some are physical constants such as acceleration due to gravity (9.81 meters per square second), density of water (1000 kg/cubic meters) and density of air (1.000 kg/cubic meter). Others are selected, in part, based on calibration runs and include wind drag coefficients, bottom roughness, horizontal eddy viscosity and horizontal eddy diffusivity. Other considerations for selection are from previous studies and research.

Bottom roughness was formulated using the Chezy friction coefficient of 65. This is approximately equivalent to a Manning coefficient of 0.02 for depth of 10 meters. Bottom roughness was applied uniformly. The wind drag coefficient was selected at 0.0012 and applied uniformly. The horizontal eddy viscosity was constant at 1 m^2/sec in the model. Each of these values was selected after extensive sensitivity studies and is consistent with literature values.

The horizontal eddy diffusivity coefficient was originally set at 10 m^2/sec, but upon evaluation of mass distributions and current patterns, the diffusivity coefficient was reduced to 1 m^2/sec. The selection of a low value for diffusivity reflects the relatively small grid cells used in the vicinity of La Motte Passage, Carry Bay and the Alburg Passage.

5.2.7 Monitoring Points

Monitoring points are user-selected locations in the model domain where time history files are created during a simulation. These files are available for processing after the model has completed a simulation. For each observation point values of concentration versus time are obtained. Volume flux and mass transport (for constituents, if any) are obtained at cross-sections. Both types of monitoring points are useful for interpretation of model results. On a typical model run about ten monitoring points corresponding to station locations and eight cross-sections were selected for examination.

---

[20] Ratios of flows at the Pike, Rock and Missisquoi Rivers were obtained from page 52, “A phosphorus budget, model, and load reduction strategy for Lake Champlain: Lake Champlain diagnostic-feasibility study final report, 1997.” Vermont DEC, New York DEC.

5.3 Calibration and Acceptance

There are several ways for comparing model results with observations and determining if model results mimic reality sufficiently for acceptance. One way is qualitative and others are more quantitative. On a qualitative basis simulated results are examined for general and overall agreement with observed phenomena. On a quantitative basis simulated results and field observations are compared numerically.

Several qualitative and quantitative examples are available to illustrate that model results mimic observations. First, flows through the passages in the model display a pattern related to the period of the internal seiche. The driving force in the model at the south entrance resulted in a periodic reversal in the model similar to ones measured in the field. There were some differences as the model results were more coupled to a regular harmonic driving function whereas in reality the period of the internal seiche varies. Also, in reality the magnitude of the seiche currents vary. The model had a seiche driving force that had a constant period and amplitude representing the longer term mean conditions at this location. However, even with this steady periodic driving force the model observations at the passages showed considerable variation.

The other driving forces in the model were wind and river inflow. Wind speed and direction as simulated could vary every six minutes in the model; river discharge was steady for a 24-hour period. Both of these driving forces coupled with the periodic seiche period produced a dynamic simulation mimicking field observations. Modeled flows at the passages in Carry Bay Causeway did appear to last longer in the west to east direction than was observed in the field. It may be that the shorter duration of inflow to Carry Bay in reality is related to the fact that the internal seiche does not have perfect harmonic motion as was simulated.

Another qualitative example between field and model results occurred over a period of relatively high river inflows. On August 6th Missisquoi River discharge increased to 2,970 cfs from 686 cfs the day before. River discharge peaked at 3,960 cfs on August 7th, dropped below 2,000 cfs for two days, August 9th and 10th, before a second higher peak of 4,960 cfs was reached on August 12th. On August 15th discharge was again below 2,000 cfs and kept falling during the rest of the month. Model results indicate that after August 4th at 4pm lake water did not enter Carry Bay until August 9th at midnight. However, this modeled inflow was of short duration and quickly reversed direction. Model results indicate that the next reversal (flow into Carry Bay) was on August 15th at 8 am. No field measurements are available from August 2nd until August 14th when currents were observed to be flowing out of Carry Bay. The next day, August 15th, inflow to Carry Bay was measured early in the morning corresponding with the fall of the thermocline; and, also corresponding with model results. This field observation together with model results may indicate that very little lake water enters Carry Bay for Missisquoi River discharges over 2,000 cfs (total inflow to Missisquoi Bay about 2,500 cfs).

A comparison was made of modeled currents and measured currents at several stations and in all cases the agreement was very good; model results agreed with measured peak current speeds and seemed to vary around the same mean value.

The model is 100% accurate on continuity. Various combinations of accumulated flow at cross-sectional monitoring locations were compared and a discrepancy never appeared. For example, all simulations had a discharge into the model domain from rivers in Missisquoi Bay. This was the only location with net transport into the model domain but not the only exit. Volume balance was checked at Missisquoi Bay Bridge and found on a net basis equal to the net volume inflow

to Missisquoi Bay from the five river sources simulated. Over the entire model domain mass and volume balance was maintained.

Complete sets of chloride concentrations are available for three days in late July. An average of these chloride data were compared to model averaged chloride data obtained from July simulations. Measured chloride concentrations are shown in Figure 5.1. On a volume/volume comparison basis a value of 12.2 mg/l represents 50% lake water and 50% river water since the lake source was set at 14.2 and the river source set at 10.2 mg/l. The measured chloride concentrations at Station #10 in Pelots Bay and at Station #31 east of the causeway are both above 13 mg/l. Based on this analysis this indicates that there is more lake water than river water at these two locations. At Station #15 there is nearly 50% lake water and 50% river water while further north in the Alburg Passage river water dominates.

The Carry Bay model was run for a five-month period starting May 1st. By late June modeled results had stabilized and fluctuations in model parameters from then on responded to variations in modeled conditions such as river inflow, wind and internal seiche. Data from July were selected for comparison of modeled chloride and measured chloride. For each station along a transect from Pelots Bay (Station #10) to Stony Point (Station#17) concentration versus time was available hourly. The monthly average value for July at each of these stations was computed for comparison with a three-day average value of measurements obtained in the July survey.

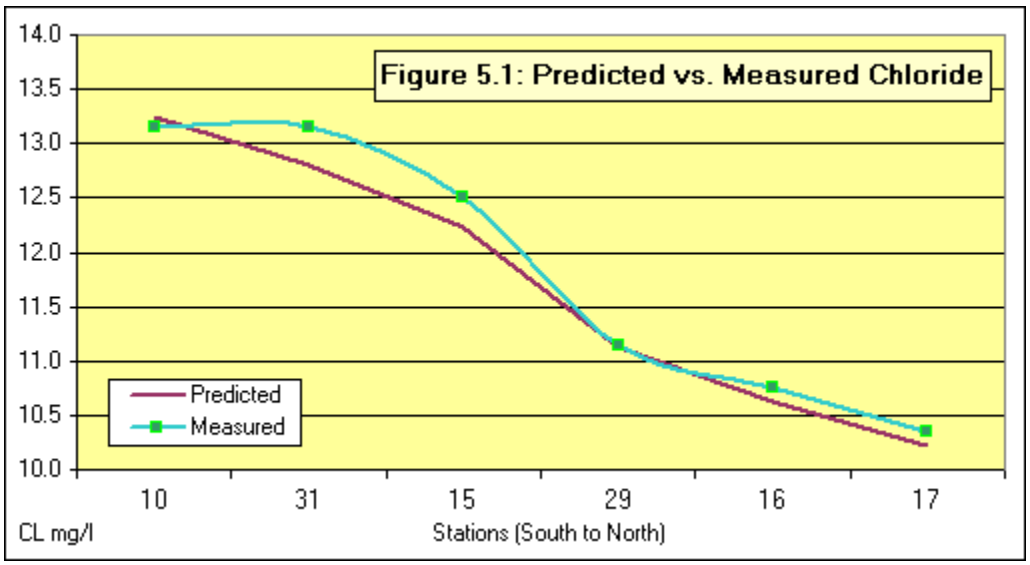

Figure 5.1: Predicted vs. Measured Chloride

The model predictions of chloride at Stations #31, #15, #16 and #17 slightly underestimate the measured average values at these locations. At stations #10 and #29 predicted and measured values are nearly identical. Overall the agreement in shape and magnitude of predicted chloride with measured chloride concentrations is very reasonable.

5.4 Simulations of Proposed Modifications

For simulations of modifications there were only two changes required in the set-up of the model. The first change was the simulated removal of causeway. Second, for both proposed modifications of middle section removed and complete removal, river discharge at the Gut was

assumed to be to be 11% of the total inflow to Missisquoi Bay instead of 22% that was assumed for conditions with the causeway in place. This choice was based on the ratio of cross-sectional area of the Gut compared to the total cross-sectional area of the open section of Carry Bay Causeway with the middle section removed and the Gut, 11%. For removal of causeway greater than the middle section, the cross-sectional area at the causeway would exceed the cross-sectional area at the Alburg Bridge (about equal to the area with the middle section removed) so 11% was also used for total causeway removed simulations.

In the application of the model, both chloride and total phosphorous are treated in a similar fashion. The major difference is related to the values selected to represent chloride or total phosphorous at the boundaries. For chloride main lake concentrations are greater than inflow to Missisquoi Bay, whereas for phosphorous main lake concentrations are less.

The results are displayed in several formats: (1) chloride concentrations versus distance along a transect from Pelots Bay to Stony Point; (2) selected plan view maps of the chloride distribution; (3) total phosphorous concentration versus distance and difference in total phosphorous concentration versus distance; and, (4) plan view maps of the difference in total phosphorous concentrations. Differences in total phosphorous concentrations were computed by subtracting the simulated concentration of predictions with causeway in-place from simulated concentrations of partial or complete removal.

5.4.1 Chloride Concentrations

Chloride concentrations are displayed in Figure 5.2. The curve representing causeway in place is exactly the same line as that shown in the calibration section above. In this figure, predicted chloride concentrations are compared with predicted chloride concentrations for partial and complete removal of the causeway. The magnitudes of the concentrations and the differences between simulations are both of interest. The range for chloride in the simulation is from 14.2 mg/l representing 100% lake water at the Isle La Motte boundary to 10.2 mg/l representing 100% river water. A concentration of 12.2 mg/l represents 50% river water and 50% lake water. An increase in modeled chloride of 0.5 mg/l represents and average increase in lake water of 12.5%. The largest increases in modeled chloride concentrations occurred east of the causeway in Carry Bay. Impacts of causeway removal determined by average change in chloride concentrations are evident past the Alburg Bridge.

Model values in Figure 5.2 represent monthly average concentrations based on simulated conditions in July. Changes in August were lower due to a prolonged period of high river in flow that had nearly 100% river water as far south as Station #15 and for a short time at the causeway. On the other hand, river inflow in September was lower on average than in July and concentrations of chloride were higher. July average calculations represent reasonable expectations of changes in chloride concentrations and corresponding ratios of lake and river water over an extended period of time.

The differences in chloride concentrations between causeway in place and middle section removed were calculated for each hour. At Station #15 where the average increase in chloride was about 0.4 mg/l, the concentration differences were often greater that 1.0 mg/l. Specifically, from a plot of concentration differences (in place minus middle section removed) there were 13 peaks on 13 different days in the month of July at Station #15 when the concentration difference was greater than 1.0 mg/l; five of these peaks were greater that 1.5 mg/l; and two of these peaks were greater that 2.0 mg/l. At Station #29, the concentration difference (in place minus middle section removed) exceeded 1.0 mg/l on four days, and on two of these days it was

greater than 1.5 mg/l. Even at Station #16 differences exceeded 1.0 on two days in July. At Station #17 the highest difference between scenarios was about 0.03 mg/l, indicating that little main lake water reaches this far north. At Station #5 in La Motte Passage the average change was less than 0.1 mg/l decrease (more river water) in chloride.

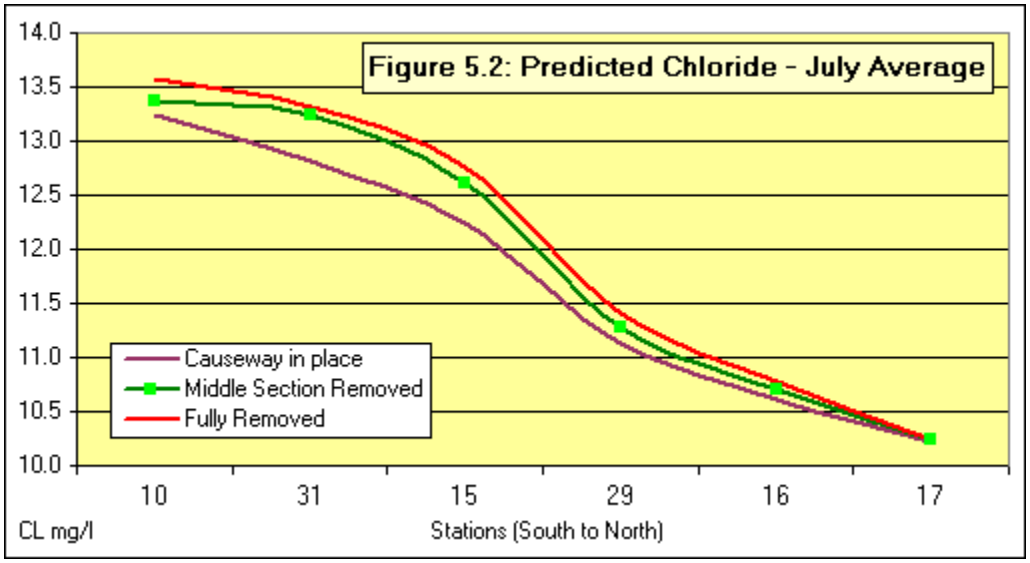

Figure 5.2: Predicted Chloride – July Average

Simulated modifications in the causeway sometimes resulted less chloride at the same time and location compared with simulations of causeway in place, indicating more river water. These decreases in chloride concentrations reduced the monthly average concentration. For example, greater simulated inflows to Carry Bay due to causeway removal were often followed by greater outflows. If river water was transported further south in the simulation of one of the proposed modifications it may have resulted in more simulated river water at that location and time compared with the causeway in place simulation.

Also, 11 % more river water was simulated flowing through the study area for the proposed modification scenarios. Increased net flow would reduce the amount of dilution water entering Carry Bay.

5.4.2 Chloride Distributions

Chloride distributions were selected to illustrate changes during summer conditions. Figure 5.10 is called typical summer and Figure 5.11 is called late summer. Both of these illustrations are at a phase corresponding to the fall of the thermocline and the inflow of hypolimnion water to Carry Bay. Figure 5.10 represent river discharges of about 450-500 cfs and Figure 5.11 is for river inflows about 300 to 350 cfs. The 12-year median river discharge for July is about 500 cfs and towards the late summer it approaches 200 -300 cfs, see Figure 4.1. These figures illustrate the point made in the previous paragraphs; the changes observed on an hourly basis between causeways in place and partially or completely removed could far exceed average monthly values. For example, in the distribution plot for causeway in place notice that chloride concentrations are <11 mg/l west of Macomb Bay. At the same location and time for middle section removed and fully removed chloride predictions are now <13.0 mg/l, representing a 50% increase in lake water.

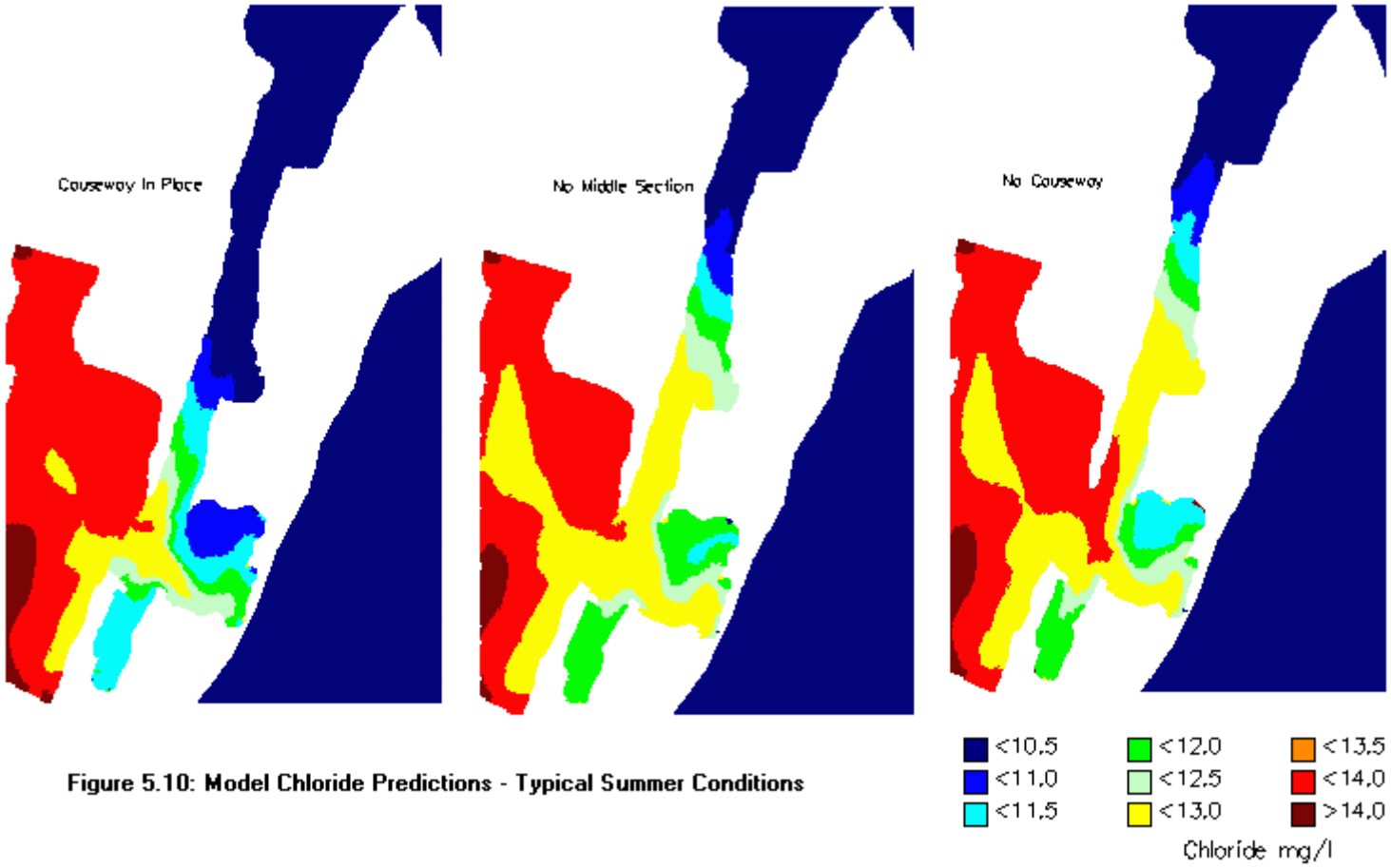

Figure 5.10: Model Chloride Predictions – Typical Summer Conditions

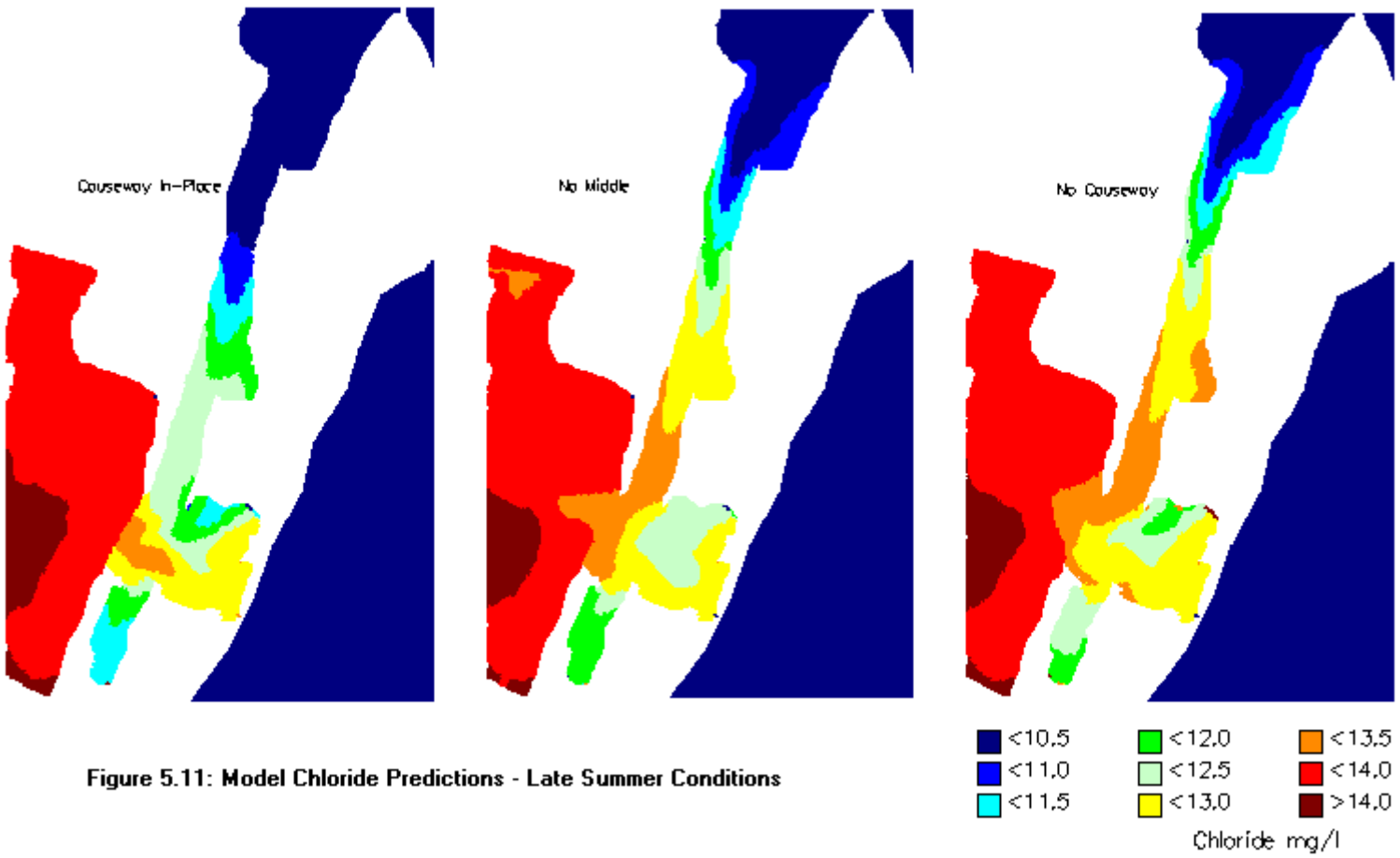

Figure 5.11: Model Chloride Predictions – Late Summer Conditions

5.4.3 Phosphorous Concentrations Versus Distance

Phosphorous predictions are illustrated in Figure 5.20 using mean simulated values for July. This curve represents essentially the same result as that obtained for chloride in Figure 5.2 with the river now representing the highest value and the lake water the lowest. A scale representing percent main lake water is added on the right hand axis.

Phosphorous is modeled as though it were a conservative substance in the water column. Processes such as settling, re-suspension, and chemical and biological interactions are not included in this prediction. The curve in Figure 5.20 has the same shape as the curve representing chloride in Figure 4.21 because that is the basis for the model calibration.

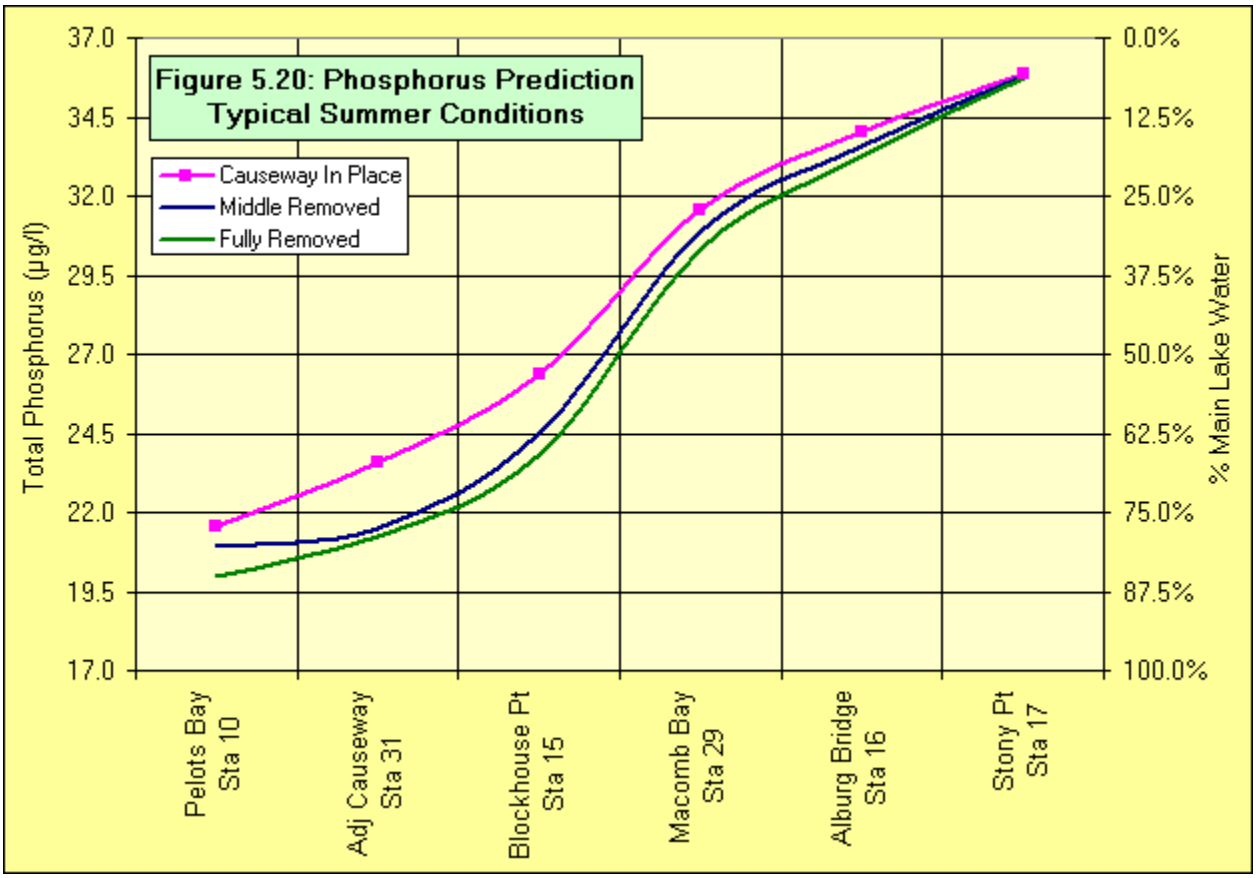

Figure 5.20: Phosphorus Prediction – July 2003 Average

More importantly for this analysis is the difference in phosphorous concentrations since the difference is due to a change in dilution characteristics due to causeway removal. The processes not simulated, e.g., settling, re-suspension, and chemical and biological interactions, will have similar effects on phosphorous with the causeway in place and without the causeway and tend to be self-canceling. For this reason while the prediction of phosphorous may not be in agreement with observations, the difference in concentration is considered to be a good indicator of impacts due to causeway removal. Difference in total phosphorous concentrations are illustrated in Figure 5.21 and tabulated in Figure 5.22. These results illustrate monthly average changes for July 2003 simulations.

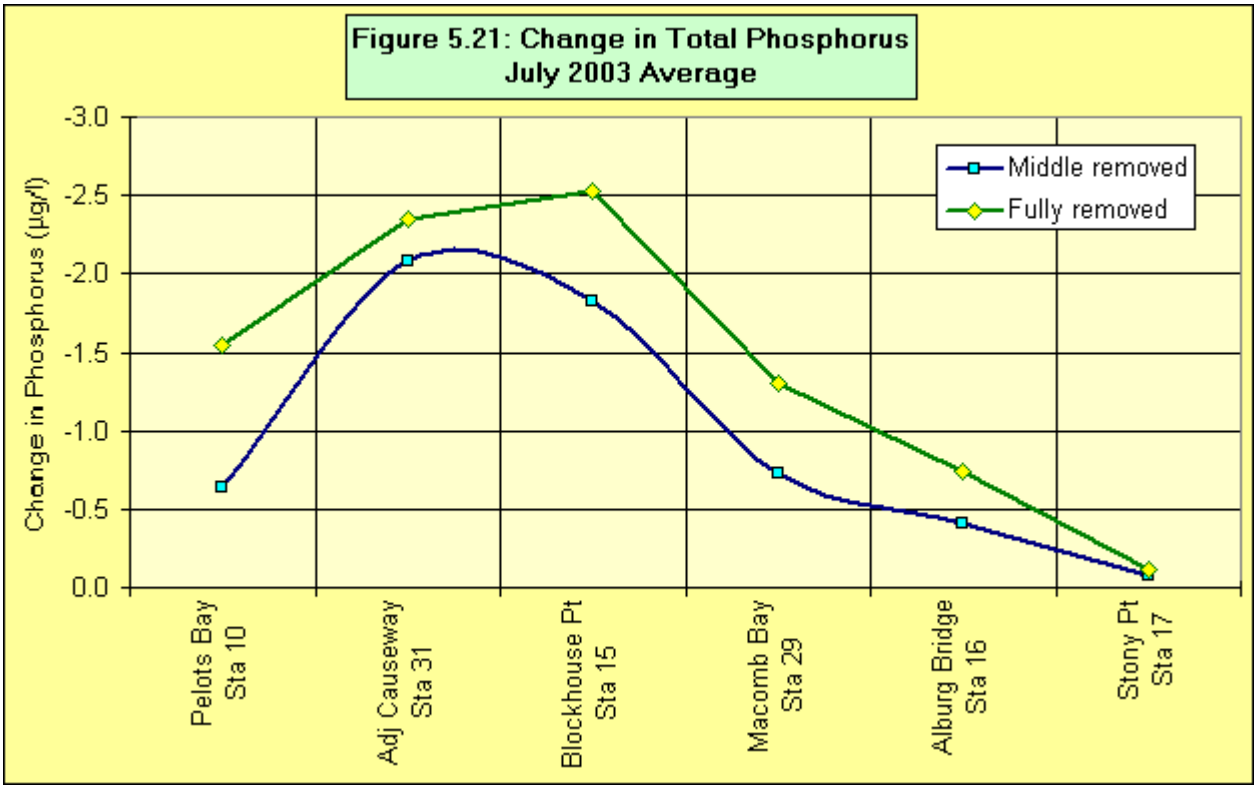

Figure 5.21: Change in Phosphorus Prediction – July 2003 Average

	Causeway In Place	Middle Section Removed			Causeway Fully Removed		
Station/Location	**Conc. (µg/l)**	**Conc. (µg/l)**	**Conc. reduction**	**Percent reduction**	**Conc. (µg/l)**	**Conc. reduction**	**Percent reduction**
10 Pelots Bay	21.55	20.91	0.64	3.0%	20.00	1.55	7.2%
31 East of Causeway	23.60	21.51	2.09	8.8%	21.25	2.35	10.0%
15 Blockhouse Point	26.34	24.51	1.83	6.9%	23.81	2.52	9.6%
29 Macomb Bay	31.59	30.85	0.73	2.3%	30.28	1.30	4.1%
16 Alburg Bridge	34.01	33.60	0.41	1.2%	33.27	0.74	2.2%
17 Stony Point	35.88	35.81	0.07	0.2%	35.76	0.12	0.3%

Figure 5.22 – Table of Change in Phosphorus – July 2003 Average

5.4.4 Distributions of Difference in Total Phosphorous

The following five figures illustrate the distribution of difference in total phosphorous between the two simulated scenarios (partial and complete causeway removal) and the simulation of causeway in place.

In Figure 5.30 notice that on the left hand side of the page predictions are displayed for middle section of the causeway removed minus causeway in place and, on the right hand side, is a display for complete causeway removal minus causeway in place, both at the same time. The display illustrates conditions at one instant in time on the date indicated. The first day (Day 1) represents a simulated condition on July 19, 2003; Day 2, July 20; Day 3, July 21; Day 4, July 22; and Day 5, July 23.

The colors depict an area where the concentration change is within a described range. A negative number associated with a color indicates that the predicted phosphorous concentration difference is less than the simulated concentration of present conditions. For, example if a value of <-0.5 µg/l ("<" means less than) is indicated for a certain color (say yellow) and the next lower range is <-1.0 µg/l, this indicates that the area described by the color yellow is between 0.5 and 1.0 µg/l lower in total phosphorous concentration with the causeway removed. Similarly, a positive number associated with a color indicates that the predicted phosphorous concentration difference is greater than the simulated concentration of present conditions. For example, the color red represents an area that is greater that 0.0 µg/l but less than 0.5 µg/l higher in total phosphorous concentration for the proposed scenario.

At first, quickly scan each of the five figures concentrating on the "dark blue" area. This color represents a total phosphorous change of <-3.0 µg/l. Day 1 (Figure 5.30) this area (or patch) is just east of the causeway and on the following day (Day 2, Figure 5.31) this patch is further north in the Alburg Passage. This simulated movement is due to the inflow of main lake water into Carry Bay associated with the fall of the thermocline and the northern surface current in La Motte Passage. Using an analogy of tidal motion, this could be considered a "flood phase." On Day 3 (Figure 5.32) a smaller "blue" area is observed toward the southern end of Alburg Passage; and on Day 4 (Figure 5.33) the "blue" area has disappeared entirely. Conditions illustrated on Days 3 and 4 are associated with the rise of the thermocline and the southern surface current in La Motte Passage. Again, using an analogy of tidal motion, this could be considered an "ebb phase." To illustrate the complete cycle Day 5 is included (Figure 5.34). The "blue" patch has returned illustrating main fresh main lake water has again entered Carry Bay.

At the same time, both lower and higher total phosphorous concentrations are predicted. Also, at a location, the concentration difference could indicate a decrease in concentration one day followed by an increase on the next day. For example, the blue area on Day 3 indicates a predicted decrease of more than 3 µg/l just east of the causeway; on Day 4, in this same area, an increase in total phosphorous of between 0.5 µg/l and 1.0 µg/l is predicted. These swings from lower to higher differences result in the monthly averages listed in Figure 5.22.

The contour interval in these plots is 0.5 µg/l. To better evaluate the change in phosphorous concentration west of the causeway, plots were created with a contour interval of 0.1 µg/l (these plots are not included in this report). The increase in total phosphorous concentration for both no middle section and total removal of the causeway for most of La Motte Passage is between 0.0 µg/l and 0.2 µg/l, with large areas between 0.0 µg/l and 0.1 µg/l.

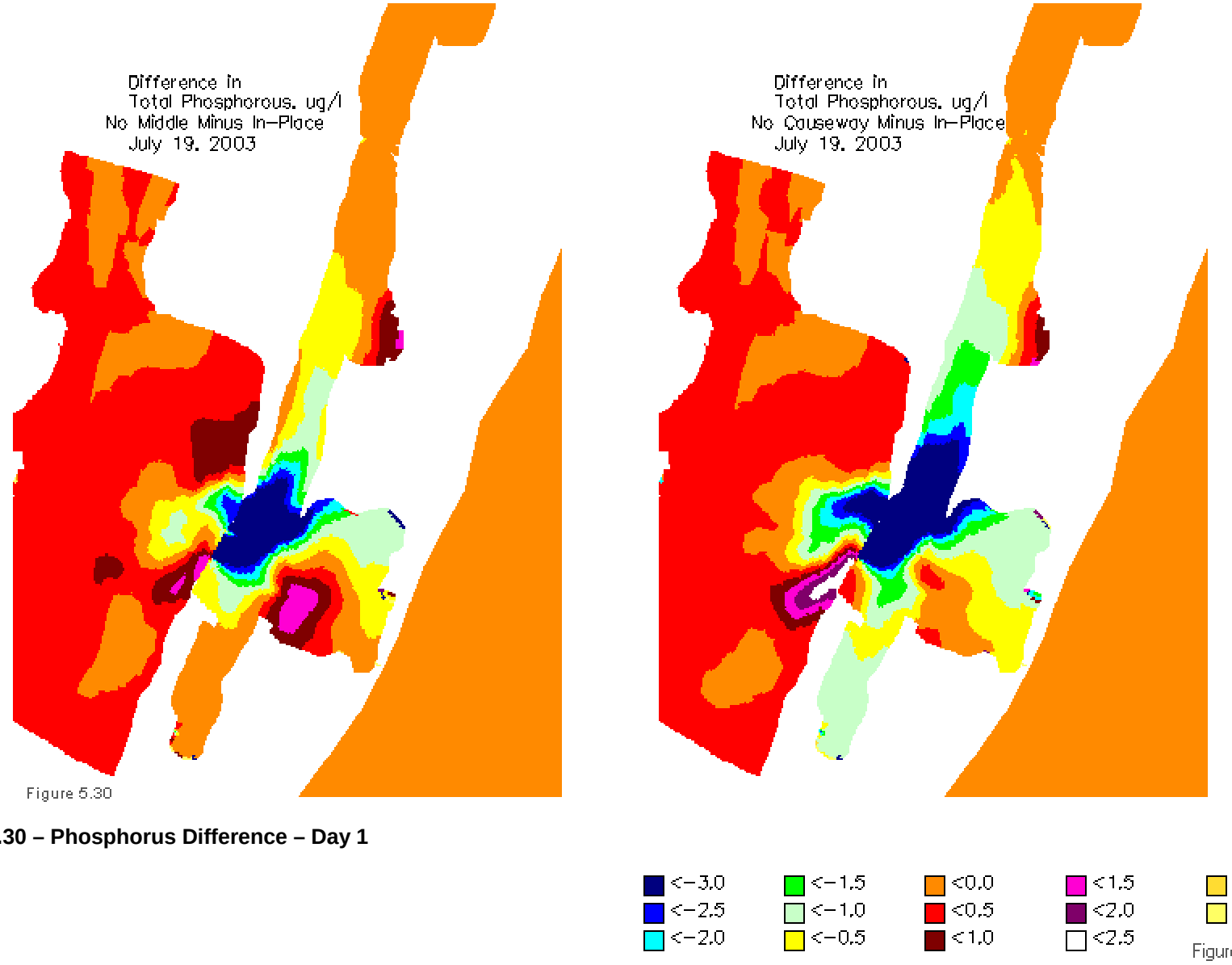

Figure 5.30 – Phosphorus Difference – Day 1

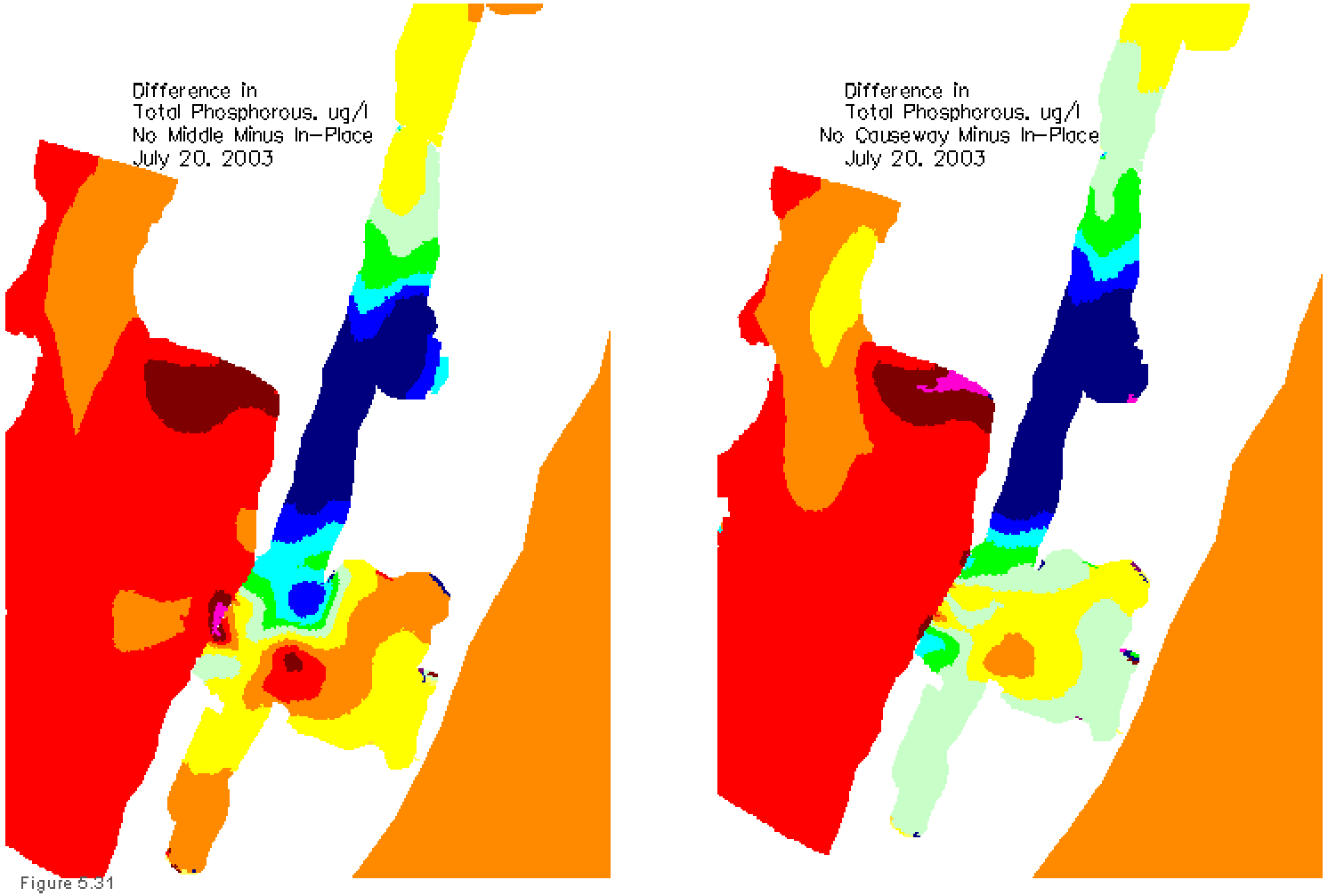

Figure 5.31 – Phosphorus Difference – Day 2

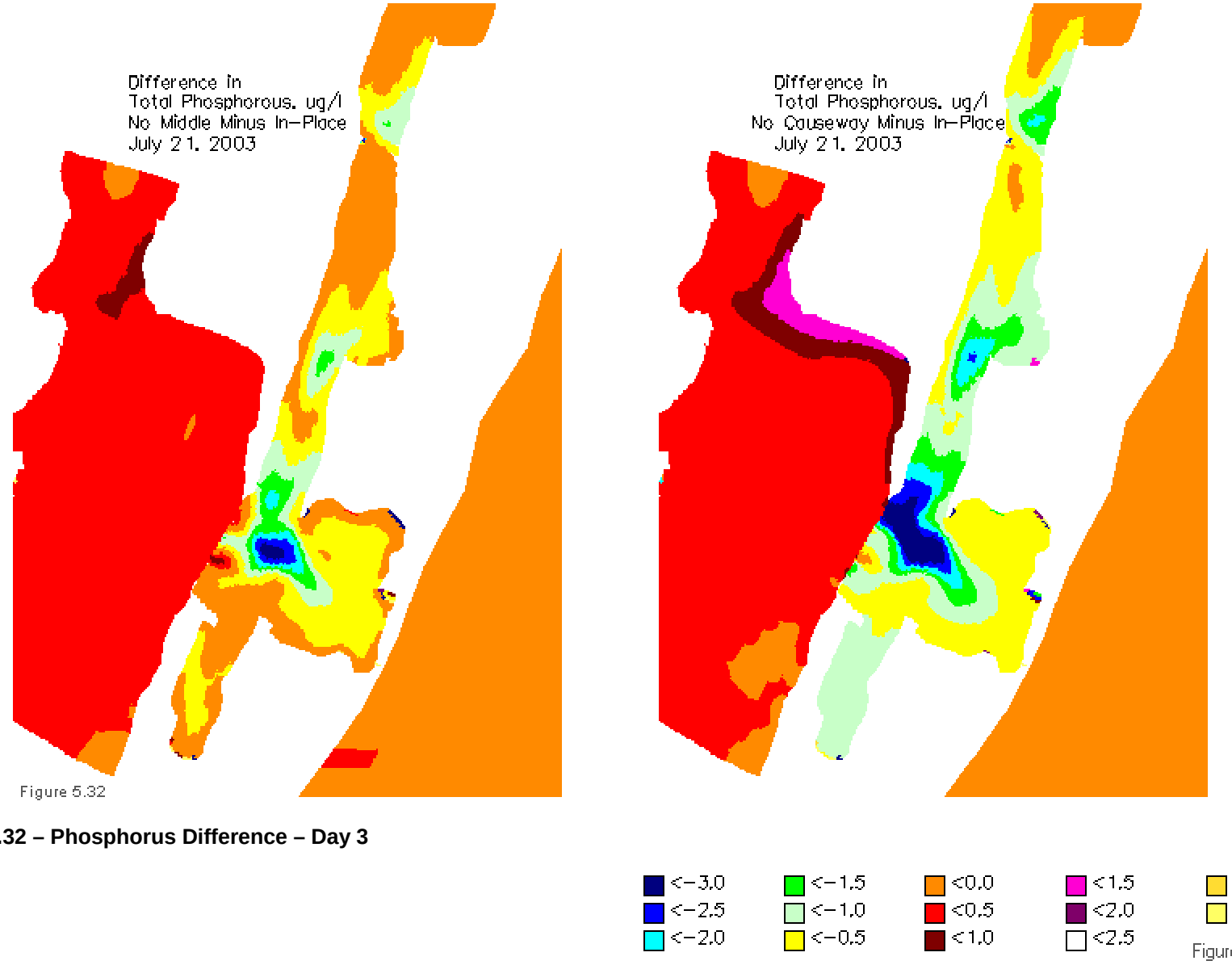

Figure 5.32 – Phosphorus Difference – Day 3

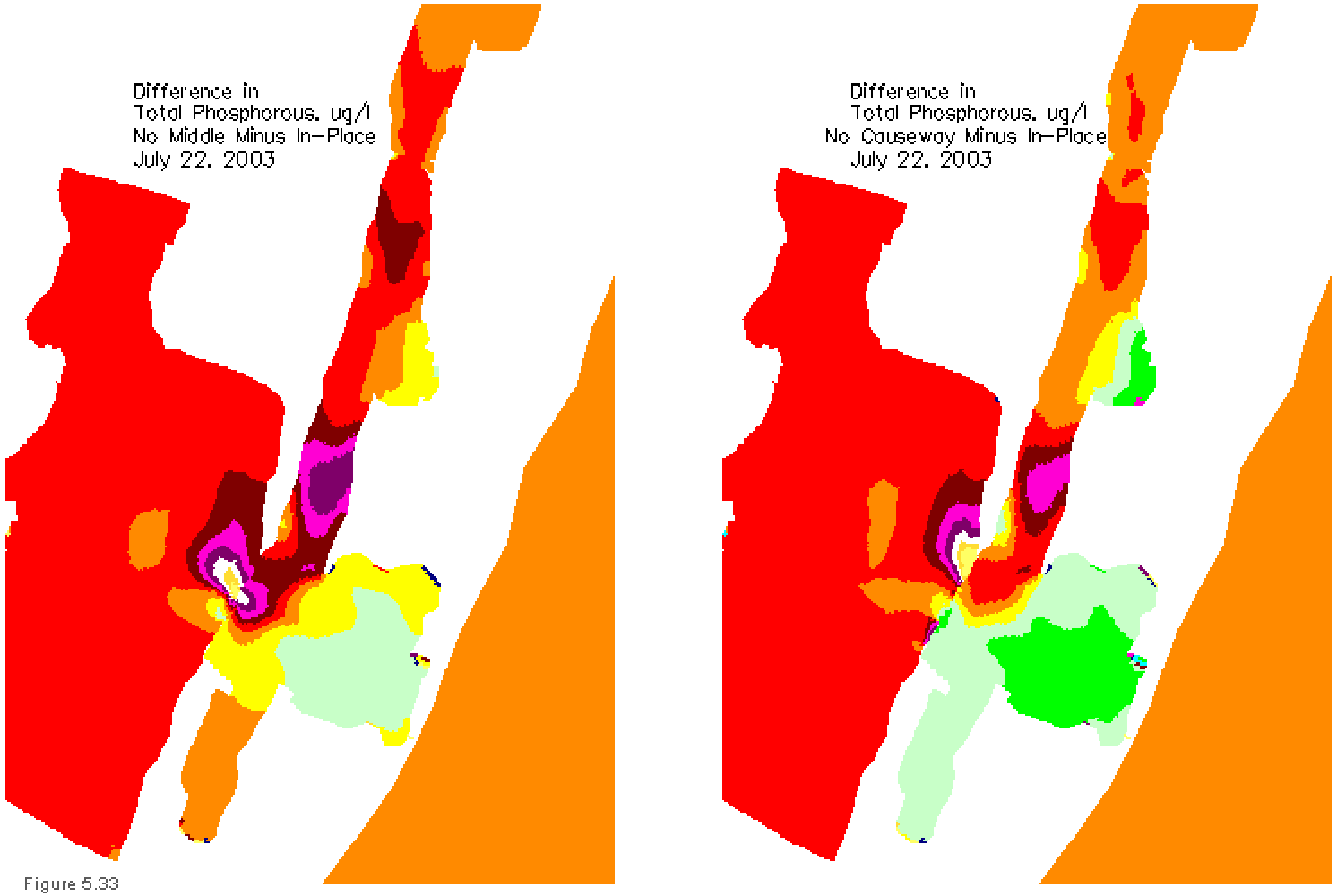

Figure 5.33 – Phosphorus Difference – Day 4

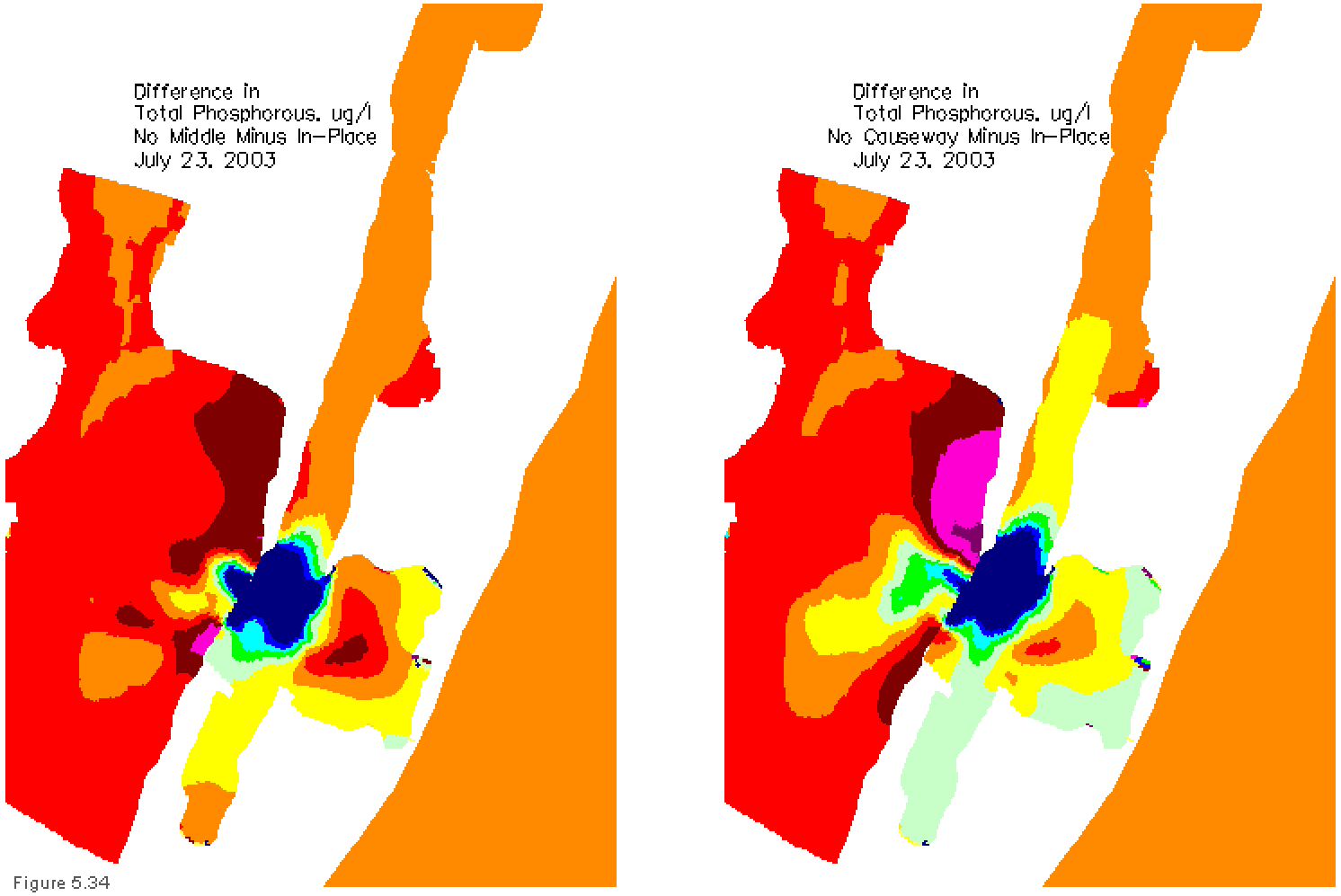

Figure 5.34 – Phosphorus Difference – Day 5

6.0 WAVE ANALYSIS

Wind generated shallow water waves were simulated using SWAN, an acronym for Simulating Waves near shore. SWAN was developed at Delft University of Technology and integrated into the Delft Hydraulics suite of models. Information on SWAN is found at http://fluidmechanics.tudelft.nl.

Wave heights in Carry Bay were simulated for the present situation with the causeway in place and for the proposed modification of complete removal of the causeway. Wave heights at locations corresponding to Station #31 and #12 were obtained from plan view maps of wave height predictions throughout all of Carry Bay. Three wind directions were simulated: 300, 195, and 0 degrees true north. Of these three directions wind from 300 degrees showed the most change. This was expected since wind from 300 degrees is perpendicular to the alignment of the causeway, whereas wind from 195 and 0 degrees align with the causeway.

Results are presented for three wind speeds of 10, 20 and 30 miles per hour (4.5, 9 and 13.5 meters per second). At Station #31 predicted wave heights at these three wind speeds were 0, 0.17 and 0.21 meters with the causeway in place. At Station #31 predicted wave heights with the causeway removed increase to 0.13, 0.27 and 0.42 meters.

At Station #12 predicted wave heights with the causeway in place were 0.1, 0.22, and 0.34 meters at wind speeds of 4.5, 9, and 13.5 meters per second, respectively. Predicted wave heights at Station #12 with the causeway removed were 0.13, 0.29, and 0.44 meters.

It appears that the largest increase in wave height with causeway removal would occur just east of the causeway in the area that is now sheltered from a west wind. Increase in wave heights are predicted to range from 0.1 meters at 4.5 m/sec to 0.2 meters at 13.5 m/sec (a tenth of a meter is about 4 inches).

These predicted changes in wave heights for a west wind (300 degrees true) are due to the change in distance that wind blows over the water surface uninterrupted, which is called fetch. From Holcomb Point, Isle La Motte to Carry Bay Causeway the fetch is 1.6 miles. At present the fetch from the causeway to Station #31 is about 1800 feet. With the causeway removed the fetch from Holcomb Point to Station #31 would be 1.6 miles. Similarly, the fetch from the causeway to Station #12 with the causeway in place is about one mile. With the causeway removed the fetch to Station #12 from Holcomb Point would be 2.6 miles.

7.0 SUMMARY OF RESULTS AND CONCLUSIONS

7.1 Survey Results

Field surveys conducted during this investigation have made two contributions toward further understanding of the complex hydrodynamics in Lake Champlain. The first contribution provides additional information on the causes of current reversals at passages in the Carry Bay Causeway; the second contribution provides both direct and indirect evidence that extends the northern location in Lake Champlain of known impacts of the internal seiche.

7.1.1 Currents at the Carry Bay Causeway

River flows into Missisquoi Bay and the Northeast Arm eventually enter the main lake via passages at the Carry Bay Causeway, the Gut and the Sandbar Causeway. Consequently, the expected direction of flow at the Carry Bay Causeway is from east to west, i.e., out of Carry Bay. However, currents at the Carry Bay Causeway are observed to flow both out of and into Carry Bay. The cause of currents and current reversals at the passages in the Carry Bay Causeway have been the subject of only one previous investigation conducted twenty-six years ago (Myer, 1977)[21]. Myer described current reversals at the Carry Bay passages to be a result of wind forces and surface seiche induced elevation differences between the main lake and the Northeast Arm. In this study, evidence for wind induced current reversals was obtained but no evidence was obtained that suggested surface seiche phenomena contributed to current reversals; however, during this investigation an additional mechanism that results in current reversals at the Carry Bay passages was discovered; the internal seiche in the main lake.

Current reversals and the transport of main lake warm surface water (epilimnion water) into Carry Bay were measured on four occasions corresponding with a rapid fall of the thermocline in the main lake. The fall of the thermocline and the transport of upper layer epilimnion water north in La Motte Passage are characteristics of the internal seiche. On one occasion cool bottom water (hypolimnion water) was also observed to enter Carry Bay as a density driven bottom current. This event was observed when the thermocline was within 10 feet of the water surface in La Motte Passage. The rise of the thermocline this close to the water surface occurred when surface water was transported south and cool bottom water was transported north into La Motte Passage, characteristic movements of the internal seiche.

The significance of current reversals from westerly to easterly, i.e., into Carry Bay, is that large amounts of main lake water are transported into Carry Bay during these events. Main lake water dilutes water of lesser water quality in Carry Bay that is transported south mainly from Missisquoi Bay.

Current reversals due to the internal seiche appear to be periodic, about every four days, as long as river discharge is not too high. For river discharge above a certain amount even the momentum of the currents caused by the internal seiche will not penetrate into Carry Bay. Model results indicate that river discharge necessary to inhibit internal seiche induced inflow to Carry Bay may be about 2,000 to 2,500 cfs (cubic feet per second), but this has not been

---

[21] Myer, G. E., 1977. “Currents of Northern Lake Champlain.” Department of Earth Sciences, State University of New York. Proceedings of the 1977- Fourth Annual Lake Champlain Basin Environmental Conference.

confirmed with field measurements and depends on individual seiche characteristics, which are highly variable.

Wind influence on current reversals at the causeway takes on a role as river discharge decreases. For low river discharge direct wind effects, indirect wind effects, and the internal seiche contribute to current reversals. Additional field surveys would be necessary to determine at just what river discharge wind events by themselves could cause current reversals. At this point it appears that river discharge needs to be as low as 200 to 300 cfs for wind effects by themselves to cause current reversals.

7.1.2 Main Lake Internal Seiche

Previous studies documented that the internal seiche in the main lake has an impact as far north as Point Au Roche. During this investigation internal seiche impacts were observed near Point Au Roche and further north into La Motte Passage and Carry Bay. Although it has not been confirmed with field measurements, there is no reason to believe that internal seiche impacts would not be observed as far north as the outlet of Lake Champlain.

7.2 Model Results

Model simulations of Carry Bay Causeway removal (partial or complete) indicate hydrodynamic and water quality changes affecting La Motte Passage, Carry Bay, Alburg Passage, Northeast Arm, and the Gut. All these areas are adjacent to each other and a physical change, such as modification of a causeway, in one of these areas affects hydrodynamics and water quality conditions in the other areas.

7.2.1 Re-distribution of Phosphorous Originating from Missisquoi Bay

Based on changes in cross-sectional areas of causeway openings, the proposed removal of the middle section of the Carry Bay Causeway, or its complete removal, may have a significant impact on the distribution of net flow and mass of phosphorous from Missisquoi Bay to the Northeast Arm and Alburg Passage.

The ratio of cross-sectional area of the Gut (at the drawbridge), to the total cross-sectional area of Carry Bay passages, the Gut, and the passage at Sandbar is about 28%. This ratio of cross-sectional areas may indicate that with the Carry Bay Causeway in place, 28% of the total discharge from Missisquoi Bay and the Northeast Arm leaves via the Gut. In this report, based in part on additional information[22], not 28%, but 22% of the total inflow to Missisquoi Bay was assumed to leave via the Gut. The remaining 78% was allowed to distribute freely between the passages at Carry Bay and the passage at Sandbar. Simulations indicated that nearly all 78% of the total inflow to Missisquoi Bay left the model area via Carry Bay.

With the middle section removed, the cross-sectional area at the Gut would be 11% of the total cross-sectional area of passages at the Gut, Carry Bay and Sandbar. For causeway removal in excess of the middle section, the cross-sectional area at the Alburg Bridge would be less than the cross-sectional area at the causeway, so the ratios of cross-sectional areas were not further affected. Therefore, in the simulation of the middle section removed and complete removal, the

---

[22] Perry, B., 1995. “Estimational Flow volumes between the Northeast Arm and main body of Lake Champlain, Vermont.” Department of Geology, Middlebury College, Middlebury, Vermont.

net flow through the Gut was decreased to 11% from 22% of Missisquoi Bay inflow.[23] Consequently, in model simulations of middle section removed and complete removal, net flow through Carry Bay passages increased from 78% to nearly 89% of the total Missisquoi Bay simulated inflow.

Due to these changes in net flow, the net mass loading of phosphorous to Alburg Passage and Carry Bay may increase by 14% and the net mass loading of phosphorous to the Northeast Arm from Missisquoi Bay may decrease by 50%. The impact of these possible changes on total phosphorous concentrations and overall phosphorous loading to the Northeast Arm is outside of the present scope of work.

The possible reduction of mass load to the Northeast Arm (NEA) due to Carry Bay Causeway removal could have a significant impact on water quality in the entire NEA and should be investigated further. At this time the VT DEC and NY DEC schematization[24] of Lake Champlain requires that all phosphorous loads from Missisquoi Bay enter the NEA segment. A schematization that better represents actual conditions would include two segments to replace the present single NEA segment: (1) a NEA segment with exchange with the main lake via the Gut and with Mallets Bay via Sandbar, and (2) a segment representing Alburg Passage, Carry Bay and Pelots Bay with exchange with the main lake via the passages at Carry Bay Causeway. With this suggested schematization changes in the expected re-distribution of mass of phosphorous due to causeway modification on phosphorous concentrations, and changes in TMDL on phosphorous concentrations, could be better evaluated for the Northeast Arm, St. Albans Bay (already a separate segment), and the proposed new segment (Alburg Passage, Carry Bay and Pelots Bay).

7.2.2 Phosphorous Concentrations

Model results indicate that even with an increase in mass loading of phosphorous to Alburg Passage, average total phosphorous concentrations would decrease in Alburg Passage, Carry Bay, and Pelots Bay. This decrease in concentration is due to an increase in lake water transported into these regions with partial or complete removal of the causeway. An increase in average total phosphorous concentration would occur in La Motte Passage with the expected change in mass loading.

Partial or complete removal of the causeway would increase the amount of main lake water in Carry Bay. On a monthly average basis the increase at the lower portion of the Alburg Passage, Carry Bay, and Pelots Bay would be about 7% to10%. This would result in a decrease in average total phosphorous concentration of about 1.6 to 2.5 µg/l.

Because of the dynamics of the main lake's internal seiche the flow of main lake water into Carry Bay and lower Alburg Passage would momentarily increase by 25% (as many as ten

---

[23] The simulated decrease of 50% in net flow through the Gut (22% to 11%) does not necessarily indicate that the exchange rate through the Gut would double. The internal seiche in the main lake most likely provides transport of main lake water into the area of the Gut, which would affect the rate of exchange; however, at this time, there is no direct evidence that supports this hypothesis.

[24] Schematization refers to a representation of Lake Champlain into segments. At this time Lake Champlain is divided into thirteen segments for phosphorous management purposes. These thirteen segments were selected, in part, based on a water quality model of Lake Champlain described in "A phosphorous budget, model, and load reduction strategy for Lake Champlain, Lake Champlain Diagnostic-Feasibility Study Final Report, 1997" by VT DEC and NY DEC.

times were simulated in July 2003) and even a few times by 50% (3 times were simulated in July 2003). These increased main lake flows would result in a decrease in total phosphorous concentration of about 5 µg/l (25% increase in lake water) to 10 µg/l (50% increase in lake water).

Typically, with causeway removal, larger inflows of main lake water were followed by larger outflows. When this occurred relatively undiluted water (higher in total phosphorous concentration) is transported further south. Consequently, the difference between phosphorous predictions with causeway removal and causeway in place indicated an increase in phosphorous concentration at a specific location. These events did not result in as many nor did they have the same magnitudes as when lake water entered Carry Bay. For example, predictions in July 2003 for Carry Bay and lower Alburg Passage indicate six events when the concentration increase exceeded 2.5 µg/l (12.5% increase in river water) and of these, one event exceeded 5 µg/l (25% increase in river water).

These events, when large amounts of lake water would be transported north in the Alburg Passage followed by south transport, are highly variable and dependent on the dynamics of the internal seiche and the amount of river water entering the Alburg Passage.

7.2.3 Comparison of Causeway Removal Scenarios

The model simulations indicate that removal of the middle section (1053 feet) would cause a significant change in the amount of lake water in Carry Bay, Pelots Bay, and the Alburg Passage. Removal of the remaining 2,300 feet of causeway would cause an additional increase in lake water in these same areas, but not in proportion to the amount of causeway removed. It appears that removal of causeway in excess of the middle section would shift the flow restricting area to Alburg Bridge as the cross-sectional area there would be about equal to the cross-sectional area at Carry Bay Causeway with the middle section removed; therefore, any impact on the NEA would be similar for partial and complete removal of the Carry Bay Causeway.

Acknowledgements

BINKERD ENVIRONMENTAL wishes to thank several people at the Vermont Agency of Natural Resources: Jeffrey Wennberg, Commissioner, Department of Environmental Conservation; Wally McLean, Director, Water Quality Division, and Eric Smeltzer, State Limnologist. Also, we thank Pete Stangel, Aquatic Biologist, and Nava Tabak for their assistance with the July field surveys.

Members of the Northern Lake Champlain Restoration Committee were instrumental in obtaining the funding for this project; they were involved in the consultant selection process, and participated in many aspects of the field program. We wish to thank Larry Dupont, Kenneth Bassett, and John Lambert.

Also, we would like to thank Bret Kernoff for use of his facilities at North Hero Marina.

Special Acknowledgement

William D. Symmes made innumerable contributions to this project from the very start. He was unselfish in his efforts and postponed other engagements of his own to work with me at making this project a success. Bill is the graphic designer, data manager, and mathematician that gave this report its special identity.

◄ End ►