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Canadian Science Advisory Secretariat
Newfoundland and Labrador Region
Science Advisory Report 2016/039

STATE OF KNOWLEDGE OF THE OCEANOGRAPHY AND WATER EXCHANGE ON THE SOUTH COAST OF NEWFOUNDLAND TO SUPPORT THE DEVELOPMENT OF BAY MANAGEMENT AREAS FOR FINFISH AQUACULTURE

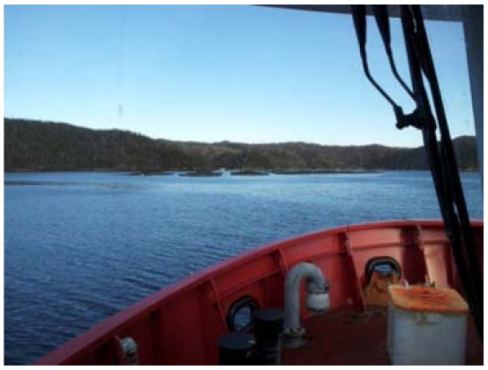

Figure 1: Aquaculture fish cages seen from the Canadian Coast Guard Ship (CCGS) Vladykov bridge.

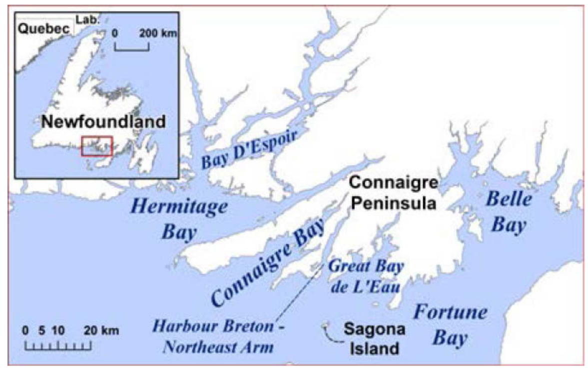

Figure 2: Map of the Coast of Bays area of the south coast of Newfoundland where finfish aquaculture activities occur.

Context:

The expansion of aquaculture operations in the Coast of Bays, an area of the south coast of Newfoundland, presents a challenge to departments and agencies responsible for regulating the industry. The regulation requires a better understanding of the environment where the aquaculture takes place. The Coast of Bays is a harsh environment exposed to severe storms with cold water temperature and strong stratification. Knowledge of the oceanographic conditions of the area is limited. A proper characterization of these conditions is necessary to ensure the design of comprehensive management strategies to support the sustainable development of aquaculture in Newfoundland and Labrador.

Research efforts have been undertaken by Fisheries and Oceans Canada (DFO), Newfoundland and Labrador Region, to carry out coastal oceanographic studies in the Coast of Bays area in order to help in the development of scientifically-based Bay Management Areas (BMAs) to support optimal fish health management. The studies consisted of the collection of in-situ oceanographic data and the development of a coastal water circulation model, based on the Finite Volume Community Ocean Model (FVCOM) to help understand the physical characteristics of the ocean in the area and map potential zones of influence associated with aquaculture activities.

The information is expected to serve as a knowledge base for regulatory decisions and procedures associated with site selection, licensing, production planning, and sustainable site management of the industry.

This Science Advisory Report is from the March 25-26, 2015 Regional Peer Review on the State of the knowledge of the oceanography and water exchange on the South coast of Newfoundland to support the development of Bay Management Areas for Finfish Aquaculture. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

Geography, Hydrology, Bathymetry and Oceanography in the Coast of Bays

- The Coast of Bays can be divided in three geographically distinct regions:
  - Bay d'Espoir: a long and narrow fjord subject to large runoff with an annual mean of ~252 m^3/s;
  - Belle Bay: a deep and wide bay subject to significant runoff (~71 m^3/s); and
  - Connaigre Peninsula: a shallower region more exposed to the open ocean and subject to a small runoff (~10 m^3/s).
- Surface wind conditions in the Coast of Bays present significant seasonal as well as spatial variability. Offshore west-northwest/northeast prevailing winds are strong (median speed of 35-45 km/h) in winter/spring while southwest prevailing winds are much weaker (median speed of 20-30 km/h) in summer.
- The tides are mainly semi-diurnal with small diurnal constituents. Tidal ranges in the whole region of interest are small (of the order of 2 m, large tides) and, consequently, associated water flushing time of the bays is large. Flushing time is significantly smaller within the Connaigre Peninsula region, ~30 days, than in both Bay d'Espoir and Belle Bay regions, ~60-70 days.
- The whole Coast of Bays area is characterized by a strong heating and cooling seasonal cycle with annual sea-surface temperature amplitude of approximately 7^{o}C. This seasonal amplitude of surface temperatures is large in comparison to the conditions seen in British Columbia but comparable to some regions in Nova Scotia where similar finfish aquaculture operations are currently taking place.

Water Column Structure and Seasonality

- Bay d'Espoir is a two-to-three layered system from spring to fall, Belle Bay is a two-layered system from spring to summer (and likely up the late fall or early winter) while the Connaigre Penninsula region is a two-to–three layered system from spring to fall, depending on local deep water intrusion below 150 m depth.
- Due to a much larger freshwater runoff, a stronger and shallower stratification is present in the Bay d'Espoir region than in Belle Bay and the Connaigre Peninsula regions. Belle Bay presents, nevertheless, an important stratification within the depth range used by the finfish aquaculture industry (0-20 m) while the Connaigre Peninsula was found to be more vertically homogeneous within that same depth range. Surface pycnocline depths were found to be as shallow as 3-3.5 m in the upper part of Bay d'Espoir, from 3-16 m in Belle Bay and generally around 20-40 m in the Connaigre Peninsula region.
- The surface water of the Coast of Bays area was found to be generally oxygen rich (i.e., >10 mg/l in spring), although some areas such as the upper part of the Bay d'Espoir consistently showed lower concentrations in both spring and fall surveys. At depth, dissolved oxygen concentration decreased significantly in the deeper part of Bay d'Espoir and the Connaigre Peninsula subject to the intrusion of the deep Mid Slope Water (MSW). In Belle Bay, a notable decrease in dissolved oxygen concentration was found in the deeper parts of the bay; likely due to the isolation of those deep inner basins.
- While short-term (order of hours to weeks) variations in the temperature, salinity and dissolved oxygen of the water column were noted, the dataset was insufficient for

determining the spatial and temporal extent of those features; precluding a good understanding of the associated dynamics. Upwelling/downwelling and internal waves were proposed as possible mechanisms explaining some of the variations observed.

Water Currents

- The median current speed observed in the Coast of Bays area ranged between 2-14 cm/s. The maximum observed current speed at each station was 5 to 10 times larger than its median speed.
- Low median speeds are generally found in sheltered coves and high median speeds in areas around sills and within narrow channels.
- Subsurface currents measured near aquaculture sites in the Coast of Bays area show that 50% of the stations have median current speeds of 4-6 cm/s in the upper 20 m.
- The tidal contribution to the variance of the sea level is 84% while the tidal contribution to the variance of the currents is generally less than 10% except in the upper Bay d’Espoir where the contribution is generally around 25%. Thus, a significant part of the current variability is not attributed to the tides.

The Development of a Circulation Model for the Coast of Bays and its Application to Bay Management Areas

- A Finite Volume Community Ocean Model (FVCOM) was implemented to investigate the circulation in the Coast of Bays area. The model was run in a three dimensional barotropic configuration (i.e., homogeneous water column structure) with two driving forces: tidal forcing at the open boundary and constant and quasi-uniform wind at the surface.
- The analysis of the sea level from the model showed that tidal sea surface elevation variation was well reproduced by the model with error less than 2 cm for the major constituents.
- The zones of influence defined by particle movement are variable and can reach maximum distances of 47 km in one day as observed in Bay d’Espoir.
- The regions with potential exchange of water within 24 hours can be grouped as:
    - Bay d’Espoir and Hermitage Bay;
    - Belle Bay (as a whole); and
    - Northeast Arm – Connaigre Bay.
- The model is at an early calibration stage and does not yet represent the complexity of the dynamics of the study area.

BACKGROUND

Following the global growth of aquaculture activities, salmonid aquaculture production in Newfoundland and Labrador has undergone an increase from 4,991 t in 2005 to 22,196 t in 2013 with more growth expected in the future. Salmonid production is entirely located in the Coast of Bays, an area of the south coast of the island.

Such growth will come with various challenges including fish health issues, limitations in the availability of suitable sites, and environmental as well as economic considerations. Measures have been taken to minimize the effects of these issues; for example, reducing the risk and spread of disease and parasites has been addressed by carrying out coordinated activities in designated aquaculture production zones defined as Farm Management Areas (FMAs) in Scotland (CoGP Management Group 2015), Barrios in Chile (Clément 2013), Single Bay Management in Ireland (Jackson 2011), and Bay Management Areas (BMAs) in New Brunswick and Newfoundland and Labrador (Chang et al. 2007, DFA 2014). The development of these production zones depends on the understanding of numerous factors including the biology of pathogens and that of the host, and their interaction with the physical environment.

In Newfoundland and Labrador, the provincial Department of Fisheries and Aquaculture together with the finfish industry implemented a BMA policy to better manage the growth and ensure sustainability of aquaculture activity in the Coast of Bays. However, scientific basis for defining BMAs is limited as there is little understanding of the oceanography of the area.

The need to study and describe the oceanographic environment and the water exchange led to the development of an oceanographic research project. The research investigated various aspects of the oceanography of the area including:

- Physical characteristics (dimensions with regards to its geography, hydrology, and oceanography);
- Seawater structure and variability (spatial and temporal);
- Vertical current structure and spatial variability; and
- Water circulation to help estimate zones of influence associated with aquaculture activities as well as to define areas with potential for water exchange.

Fisheries and Oceans Canada (DFO) is responsible for regulating the aquaculture industry in order to protect fish and fish habitat and ensure sustainable aquaculture. The information is expected to serve as a knowledge base for regulatory decisions and procedures associated with site selection and licensing, production planning, and for sustainable site management of the industry.

ASSESSMENT

Geography, Hydrology, Bathymetry and Oceanography

No comprehensive overview of the physical environment of the Coast of Bays area has been conducted since the 1980s (e.g., MSRL 1980, Yurick and Vanstone 1983, and BDE-DA 1984); furthermore little information has been published on aquaculture development in Belle Bay and the Connaigre Peninsula. The objective of this research was to provide up-to-date, comprehensive, baseline data and a physical description of the area of interest. Five bays were considered for detailed analyses:

1. Bay d'Espoir;
2. Belle Bay;
3. Connaigre Bay;
4. Harbour Breton - Northeast Arm; and
5. Great Bay de l'Eau.

For each bay, a number of parameters related to the geography, hydrography, oceanography and climate of the area were assessed. Some metrics were also extended to the greater Hermitage Bay and Fortune Bay areas.

The coastline shape and bathymetry of the area of interest is very complex with deep basins, shallow sills and numerous side bays and inlets. Bay d'Espoir consists of two main arms with numerous smaller features. It is characterized by deep basins (up to 790 m depth) and numerous shallow and steep sills (26 m to 298 m). In total, 10 basins and 11 sills were identified in the Hermitage Bay – Bay d'Espoir region (Figure 3). Belle Bay is a large and deep bay (up to 606 m depth) connected to the ocean via the fjord-like embayment of Fortune Bay. Belle Bay features two deep channels separated by a large and shallow central bank and numerous side bays and inlets, separated from the main body of water by sills. In total, 13 basins and 16 sills were identified in the Belle Bay region (Figure 4). Located between Hermitage Bay (to the west) and Fortune Bay (to the East) are two fairly large and open bays, Connaigre Bay to the west and Great Bay de l'Eau to the east, and a narrow inlet, Harbour Breton – Northeast Arm between the two bays. Together, these bays form the southern coast of the Connaigre Peninsula and while notably shallower overall, the bathymetry is also complex with a total of 13 basins and 17 sills identified (Figure 5).

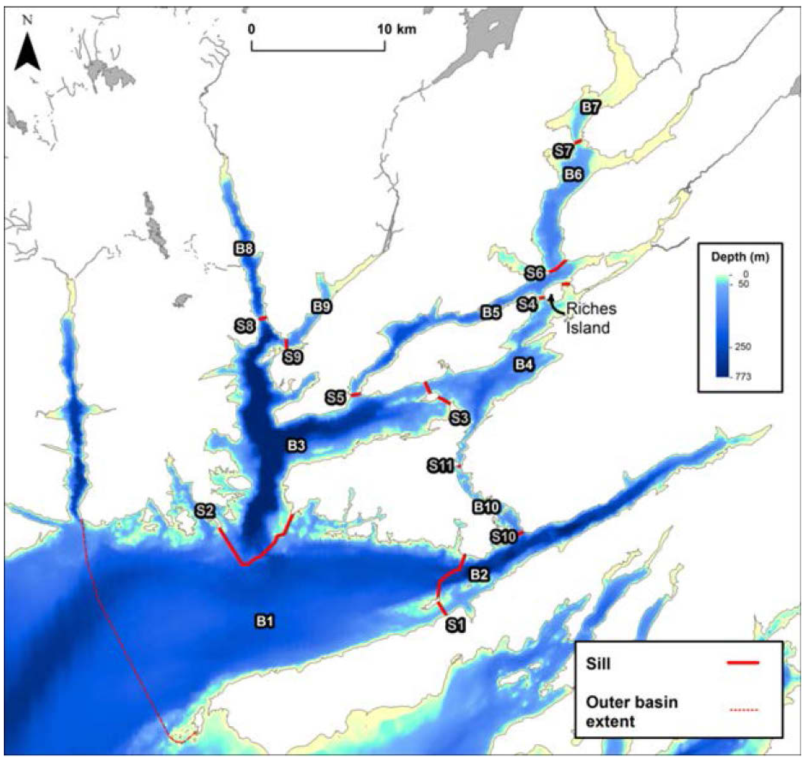

Figure 3: Bay d'Espoir basins (B) and sills (S).

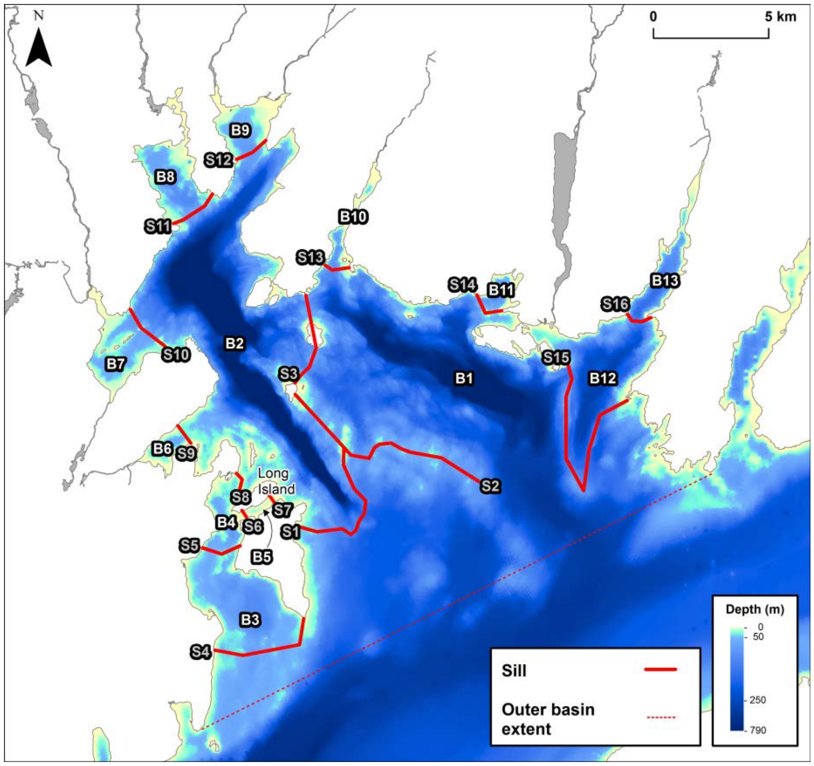

Figure 4: Belle Bay basins (B) and sills (S).

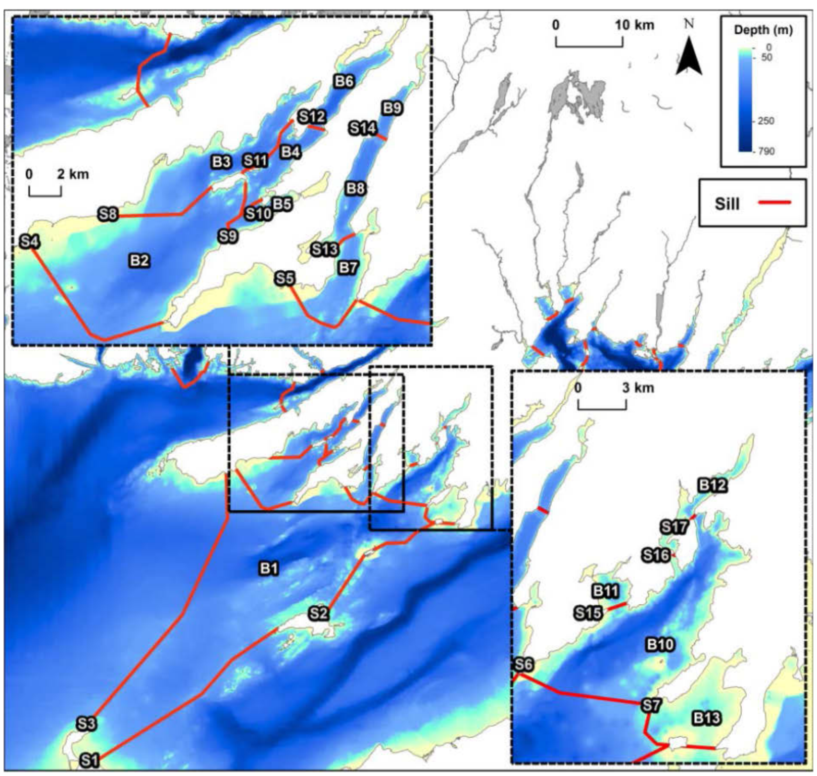

Figure 5: Connaigre Peninsula basin (B) and Sills (S).

River discharge estimates were calculated based on Environment Canada data of rivers flow available for the study area and on a watershed analysis done using the Natural Resources Canada's topographic and hydrographic data. Annual average freshwater input to each of the bays differs significantly, from ~252 m^3/s in Bay d'Espoir to ~1.4 m^3/s in Harbour Breton – Northeast Arm (about 10 m^3/s for the whole Connaigre Peninsula region). Annual average freshwater input to Belle Bay was estimated to be about 71 m^3/s, comparable to the total input from elsewhere in Fortune Bay at about 83 m^3/s. The mean annual input to Hermitage Bay other than from Bay d'Espoir was found to be small at about 21 m^3/s. For the Coast of Bays area as a whole, a total yearly average of freshwater input of about 437 m^3/s was found, corresponding to an area of about 1,055 km^2 in equivalent buoyancy input by heating at the peak summer rate using a simple scaling relationship (Simpson and Sharple, 2012; equation 2.14 p.36). If this freshwater input were to be evenly distributed over an area to match the effect of peak summer heating on buoyancy input, this area would be 1,055 km^2 (Figure 6). This area is notably larger than the combined area of the five bays studied (about 814 km^2) and indicates the importance, if not the dominance, of the freshwater input influence to the physical properties of these bays (stratification and dynamics).

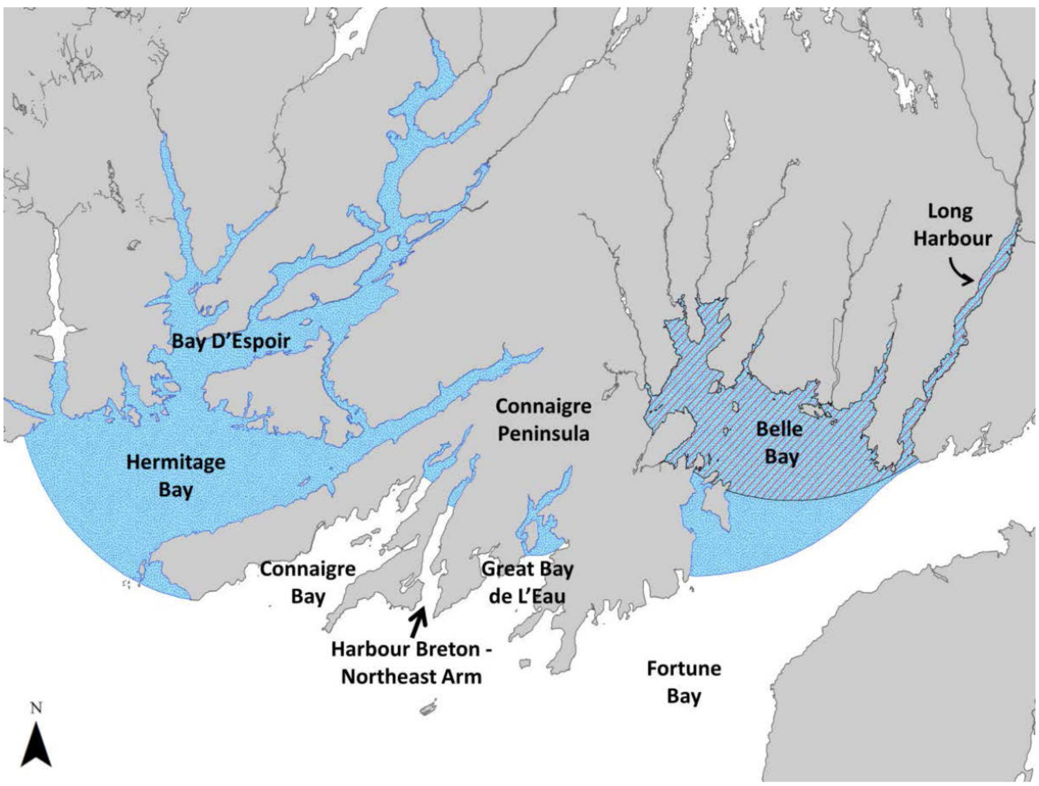

Figure 6: Estimated area (in blue) of freshwater influence (dominance) on water stratification in the Coast of Bays based on buoyancy input. The red hatched polygon represents the area corresponding to the runoff directly received by Belle Bay and the nearby Long-Harbour estuary. The remaining area corresponds to the runoff received from elsewhere in Fortune Bay

The seasonality of the wind conditions in the Coast of Bays was assessed using data from an automated weather station maintained by Environment Canada and located just offshore from the Connaigre Penninsula, on Sagona Island (Figure 2). The analysis showed that the study area is subject to two distinct wind regimes: strong winds (35-45 km/h median speed) predominantly from the north quadrant (west-northwest to northeast) in winter and weaker winds

(20-30 km/h median speed) and predominantly from the southwest in summer. During the other seasons, wind direction is more random and wind speed is transitory: increasing in fall and decreasing in spring (Figure 7). Persistence analysis performed on the wind measured at Sagona Island between 1994 and 2013 shows that the maximum duration of wind speed above 36 km/h (10 m/s) was 157 h. The average number of events with wind speed above 36 km/h for a period longer than 12 hours is about 74/year. For a wind speed above 54 km/h (15 m/s), the maximum duration was 103 h (Dec. 2010) and the average number of events for a period longer than 12 hours is about 25/year. In addition to this seasonal variability, the wind climate in the study area was shown to be also strongly affected by the local topography which can funnel the wind and increase its magnitude further or act as a barrier (Currie et al. 2013).

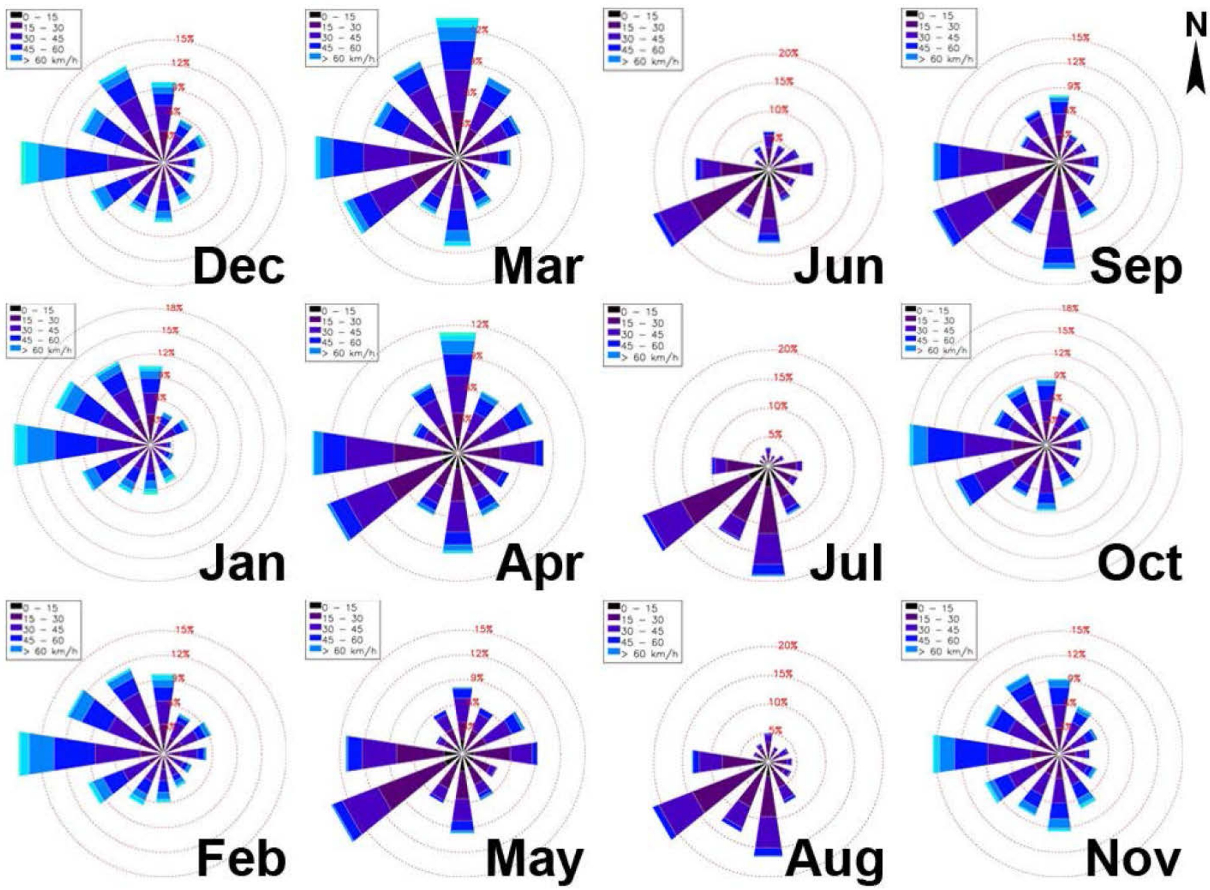

Figure 7: Wind climate (wind speed and direction) from 1994 to 2013 in the Coast of Bays from Environment Canada weather station on Sagona Island.

Tidal analysis was performed on sea level data available from the Canadian Hydrographic Service (CHS) for the study area. The data were from five stations; for each station a tidal analysis was used to derive a 19-year prediction from which mean and large tidal ranges and associated water levels (Mean High Water Level [MHWL] and High Water Level [HWL]) were calculated. Tidal ranges in the Coast of Bays are small, with a maximum of 2.18 m, predicted at Belleoram (Belle Bay). Tidal ranges increase by about 12% from the west to the east of the study area (from the mouth of Bay d'Espoir to Belle Bay). They also increase slightly from the mouth to the head of Bay d'Espoir by about 9%, the latter likely due to geometrical constriction of the fjord. Tides are largely semi-diurnal with little contribution from diurnal components.

Flushing time of the bays was estimated using the tidal prism method and assuming complete mixing during a tidal cycle (as used and described by Gregory et al. 1983). Due to the great depth of the bays and the small tidal ranges in the area, the flushing times estimated were quite large, ranging from about 66-67 days in Bay d'Espoir and Belle Bay to about 27-29 days in the Connaigre Peninsula region (27 days in Harbour Breton-Northeast Arm, 29 days in Connaigre Bay). If mixing were incomplete which is likely, the flushing times would be longer than estimated. In addition, flushing time can be greatly affected by other forcing mechanisms such as freshwater inflow or wind; these processes could significantly reduce or increase the flushing time.

Archived water temperature data from different sources were compiled to examine the annual variability of the temperature within the upper 0-20 m. The data were grouped in three regions based on their geographic characteristics:

1. Hermitage Bay – Bay d'Espoir;
2. Fortune Bay – Belle Bay; and
3. The Connaigre Peninsula (which includes Connaigre Bay, Harbour Breton – Northeast Arm and Great Bay de l'Eau).

Monthly statistics were estimated (monthly mean and standard deviation as well as daily minimum and maximum) and annual cycles were calculated using a least-square minimization harmonic analysis procedure (as described by Akenhead 1987, and Craig and Colbourne 2004). Overall, monthly averaged temperatures vary from about 0.5-1^{o}C in February-March to about 12.5-13.5^{o}C in August with a standard deviation of the order of 0.5-1^{o}C and 2-3^{o}C, respectively (Figures 8-10). Moreover, the results indicate a large range of temperature during the warmer seasons in the upper 0-20 m, suggesting a relatively shallow thermocline and/or significant short-term variability (e.g., upwelling/downwelling). This is pronounced in the Hermitage Bay - Bay d'Espoir region, less obvious in the Fortune Bay-Belle Bay, and further diminished in the Connaigre Peninsula region. The sea-surface (0-5 m) temperature amplitude was found to be about 7^{o}C in the study area, which is large in comparison to the conditions seen in British Columbia (3-4^{o}C) but comparable to some regions in Nova Scotia where similar finfish aquaculture operations are currently taking place (Brewer-Dalton et al. 2014). Using the results of the harmonic analysis, vertical mixing rate was estimated and found to be the lowest (0.5×10^{-4} m^2s^{-1}) in the Hermitage Bay-Bay d'Espoir region and the highest (1.3×10^{-4} m^2s^{-1}) in the Connaigre Peninsula region, further indicating stronger surface stratification in the former region.

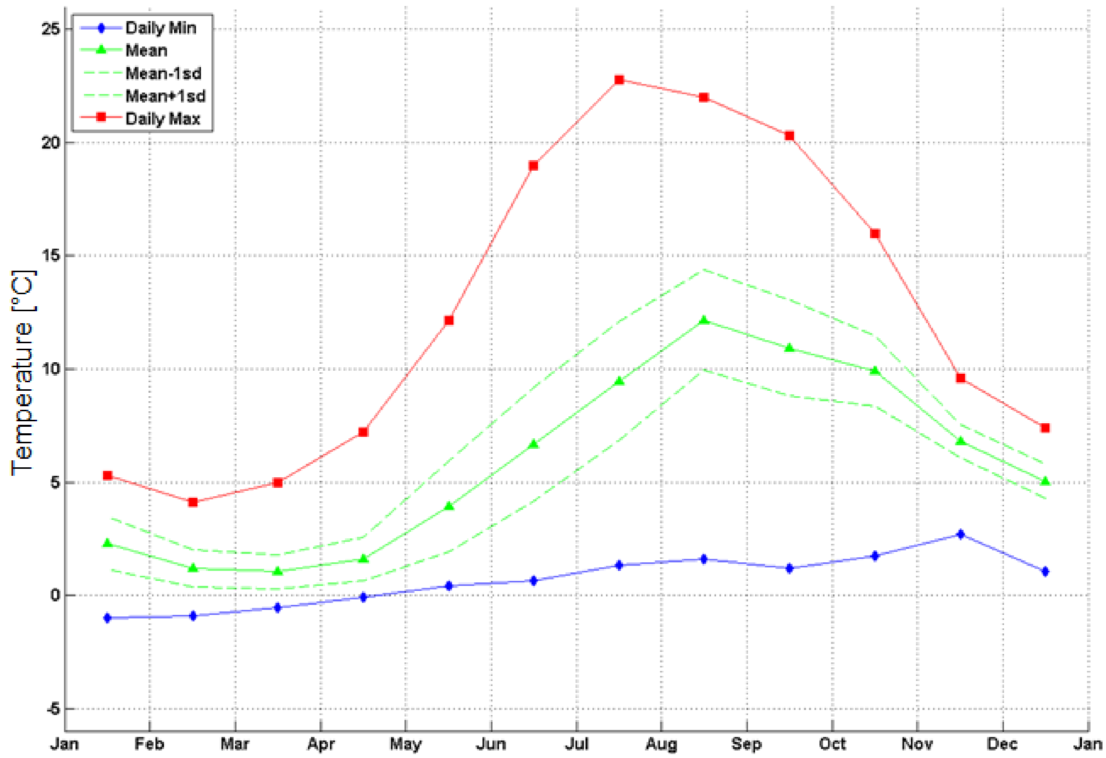

Figure 8: Hermitage Bay-Bay d'Espoir 0-20 m monthly temperature statistics. "sd"= standard deviation.

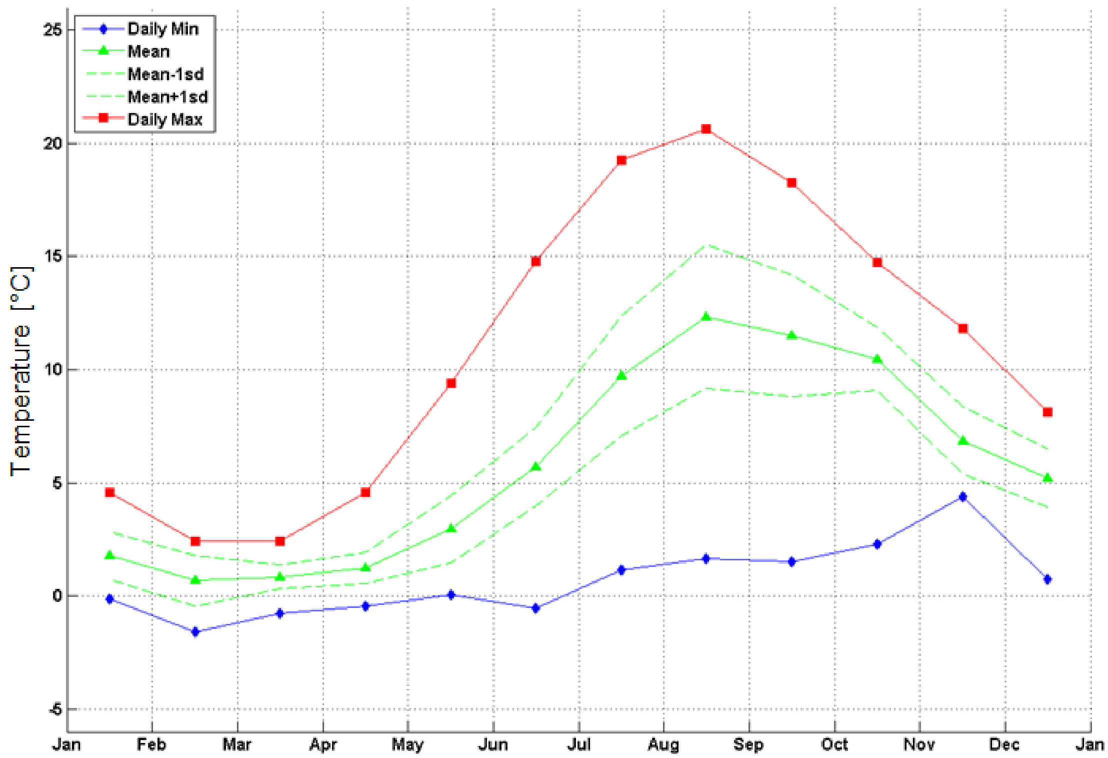

Figure 9: Fortune Bay-Belle Bay 0-20 m monthly temperature statistics. "sd"= standard deviation.

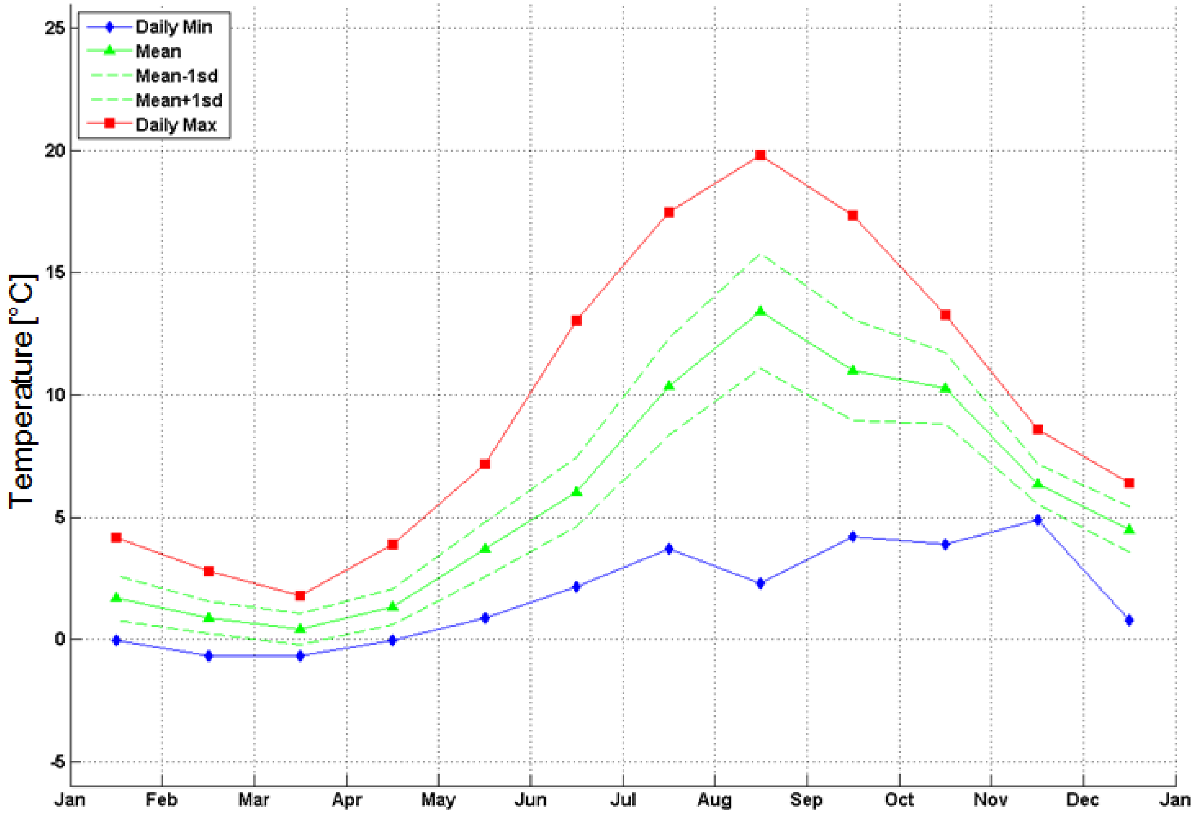

Figure 10: Connaigre Peninsula 0-20 m monthly temperature statistics. "sd"= standard deviation.

Water Column Structure and Seasonality

An oceanographic monitoring program took place between the years of 2009 and 2013 which included the collection of a number of Conductivity, Temperature and Depth (CTD) profiles within the study area. In total, 760 profiles were collected at 276 stations (Figure 11).

The objectives of this work were to:

- Provide an updated and more comprehensive description of the vertical and horizontal hydrographic structure, highlighting its spatial and temporal variability;
- Identify and enhance the understanding of the areas of water exchange and mixing; and
- Provide data and information to initialize and verify a coastal water circulation numerical model currently being implemented.

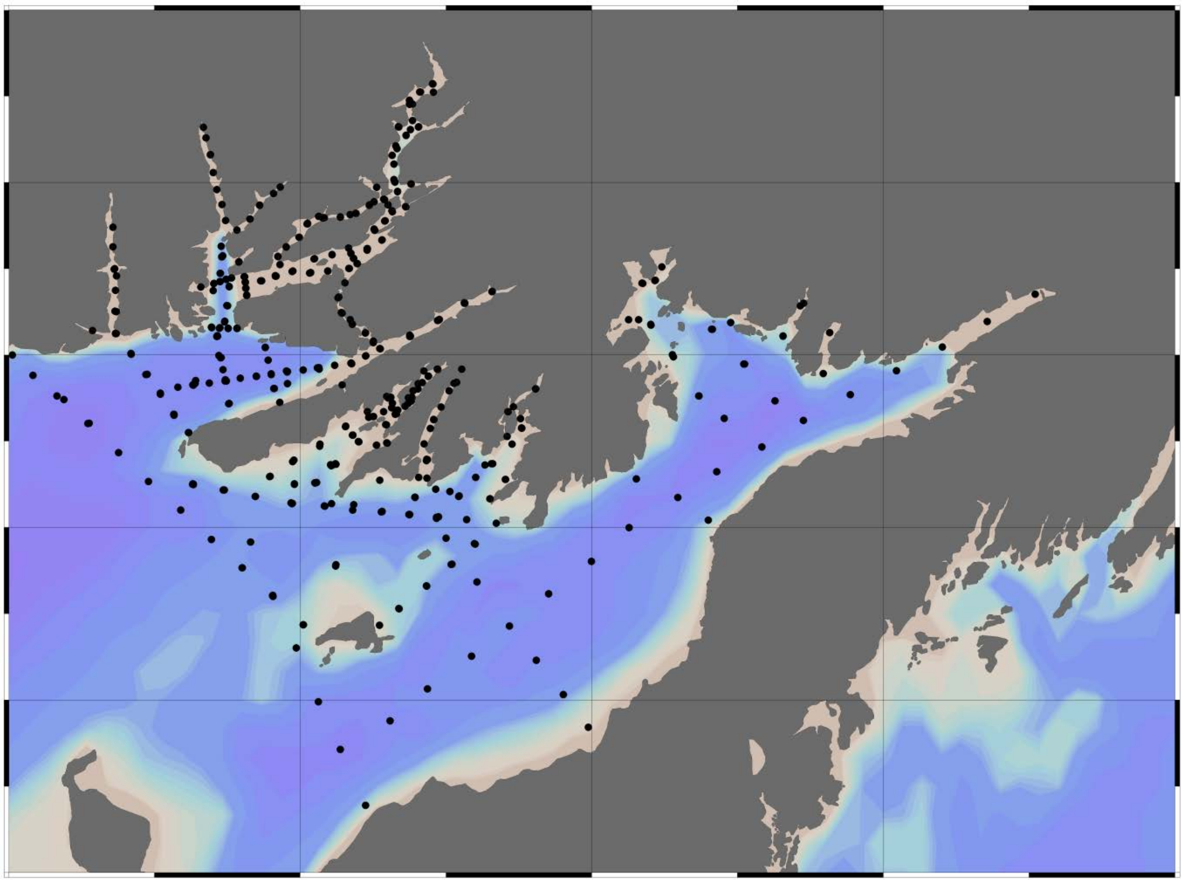

Figure 11: Station locations for the 2009-13 CTD data collection program. Shades of blue denote depth ranges and black dots CTD stations (more detail on the bathymetry is given in Figures 3-5).

The survey revealed important spatial and temporal variation in the water structure. In Bay d'Espoir, large freshwater discharge at the head of the fjord results in the presence of a sharp and shallow pycnocline for most of the year. At depth, the fjord is subject to the intrusion of both a Cold Intermediate Layer (CIL, defined here as bounded by the 2^{o}C isotherm) and a warm and saline deep water layer (MSW) from the Hermitage Channel; the latter only partially flowing into the fjord due to blockage from inner sills. As a result, the vertical structure of Bay d'Espoir is essentially a two-layered (in the inner parts) or three-layered (in the outer parts) structure from spring to fall, consistent with the earlier description given by Richard and Hay (1984). An example of the vertical structure within Bay d'Espoir is shown in Figure 12. The near-surface halocline (and thus, pycnocline) depth in the upper part of the Bay d'Espoir was consistently around 3-3.5 m, in agreement with the previous studies (e.g., MSRL 1980). In Hermitage Bay, the pycnocline was as shallow as 6 m and as deep as 22 m, varying with the season and year of the survey.

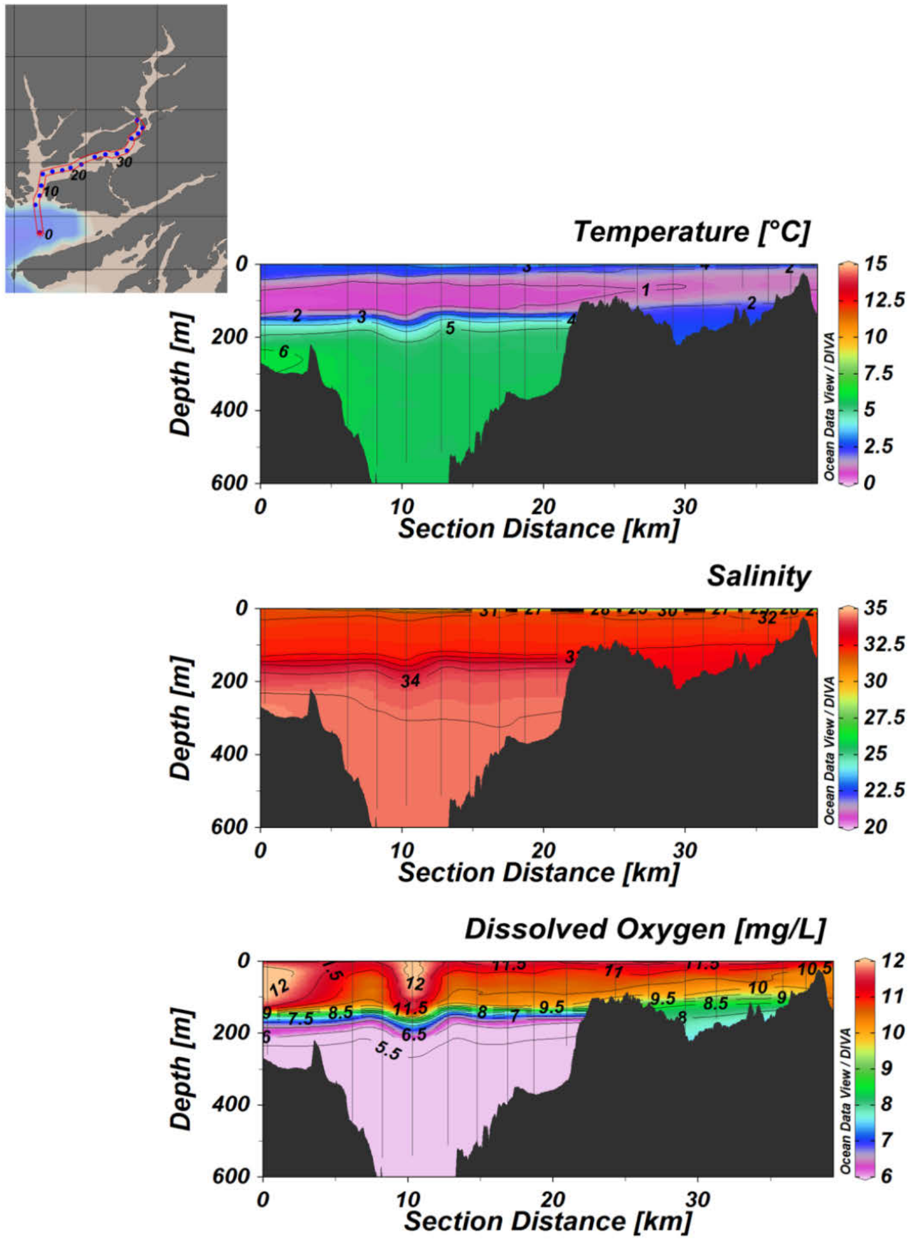

Figure 12: Bay d'Espoir water column vertical structure; spring 2010 (top panel shows survey area).

In Fortune Bay, where the freshwater discharge amount is much less than in Bay d'Espoir but still significant, a fairly strong seasonal pycnocline forms near the surface from spring to summer, particularly in Belle Bay which receives most of the discharge. Bounded by a series of sills and islands on its offshore boundaries, Fortune Bay receives a limited influx of MSW from the Hermitage Channel (ending in Hermitage Bay) and is characterized by a seasonal deep-water renewal from modified Labrador Current Water in summer and modified MSW in winter as described in Hay and De Young (1989). Thus, from spring to summer (and most likely up the late fall or early winter), when the seasonal surface layer is present, the Fortune Bay-Belle Bay region is, for the most part, characterized by a two-layered water structure. An example of the vertical structure within Belle Bay is shown in Figure 13. The pycnocline depths observed ranged from 6-16 m and 3-7 m, depending on the location (shallower towards the head) and the season (deeper in spring than in early summer).

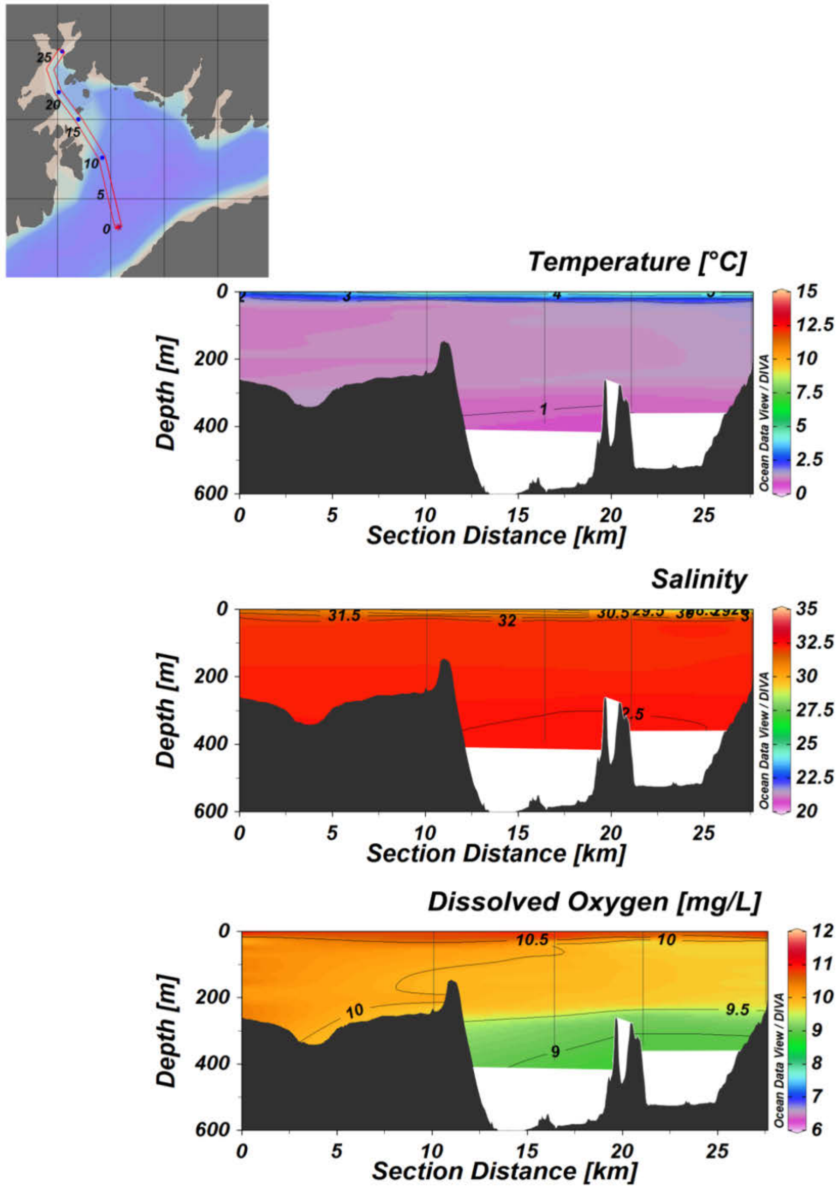

Figure 13: Belle Bay water column vertical structure; spring 2011 (top panel shows survey area).

In contrast to the other two regions, the Connaigre Peninsula does not receive a significant amount of freshwater discharge and, as a result, the near-surface water of this region is more oceanic and more vertically mixed. At depth, the CIL is widespread and down to the near-bottom. MSW is, however, well present in the deep offshore basin located within and just outside Great Bay de l'Eau. The MSW mixture was also consistently found in the inner basins of Connaigre Bay and Harbour Breton-Northeast Arm in spring, disappearing in fall. The Connaigre Peninsula region is a two-layered system from spring to fall, with some three-layered structure areas. An example of the vertical structure within the Connaigre Peninsula region is shown in Figure 14. The pycnocline depths observed were generally found in the 20-40 m depth range in the Connaigre Peninsula, although they were shallower at times, such as in Harbour Breton – Northeast Arm in July, 2010 (about 3 m) and in the upper part of Connaigre Bay in July, 2012 (about 6 m).

Lower concentrations and percent saturations of dissolved oxygen (DO) were consistently found in the upper parts of Bay d’Espoir. As suggested by Richard and Hay (1984), isolation by winter ice may have caused some of the lower values observed in spring (e.g., June, 2009 and April-May, 2010), but the conditions seen late in the summer (September, 2009 and September, 2012) are more difficult to explain. Hypoxic conditions (i.e., DO<6 mg/L) in surface waters (0-20 m) as reported in Burt et al. (2012) within fish cages were not observed in the surveyed areas in Belle Bay. These two diverging observations indicates that weak flow conditions (leading to a low flushing rate) rather than low regional DO concentration would be responsible for the hypoxic events observed within the fish cages. Overall, high DO concentration (>10 mg/L in spring, >8-9 mg/L in fall) and saturation (>=100% in spring, >80-90% in fall) were found in the surface and sub-surface (CIL) layers within the entire study area. At depth, lower DO concentrations were found in the deep basins of Bay d’Espoir, Belle Bay and the Connaigre Peninsula, indicating either intrusion of oxygen poor MSW (in Bay d’Espoir and the Connaigre Peninsula) or poor deep water renewal (Belle Bay).

Upwelling features were seen in all three regions during the 2009-13 surveys. All upwelling events seem to indicate wind forcing from the northwest, inducing Ekman transport of the surface layer to the southwest, as described by Hay and De Young (1989) for a two-layered system in winter. Our data suggests that a similar mechanism occurs in spring-summer, in a two or three-layered system. Large supersaturated DO volumes were found in both Hermitage Bay and in the deep outer basin of Bay d’Espoir associated with large vertical displacement of the deep pycnocline depth. While the vertical displacement of the pycnocline is thought to be caused by internal oscillations and the super-saturation is thought to be due to oxygen production during a phytoplankton bloom, the origin of the hypothesized short-lived “burst” in primary production is unclear since no large vertical mixing associated with the displacement was apparent. In addition, since the CTD profiles indicating those features were observed one to two days apart, the role of Lagrangian (advection of spatial features) or Eulerian (local temporal variability) processes could not be determined. In Fortune Bay, notable temperatures and salinity variations were seen along the axis of the Bay in May, 2011. Here again, the distinction between the temporal and spatial aspects could not be made due to the sampling limitation. Possible mechanisms that could be at the origin of this feature include upwelling, internal seiche and/or coastal trapped waves.

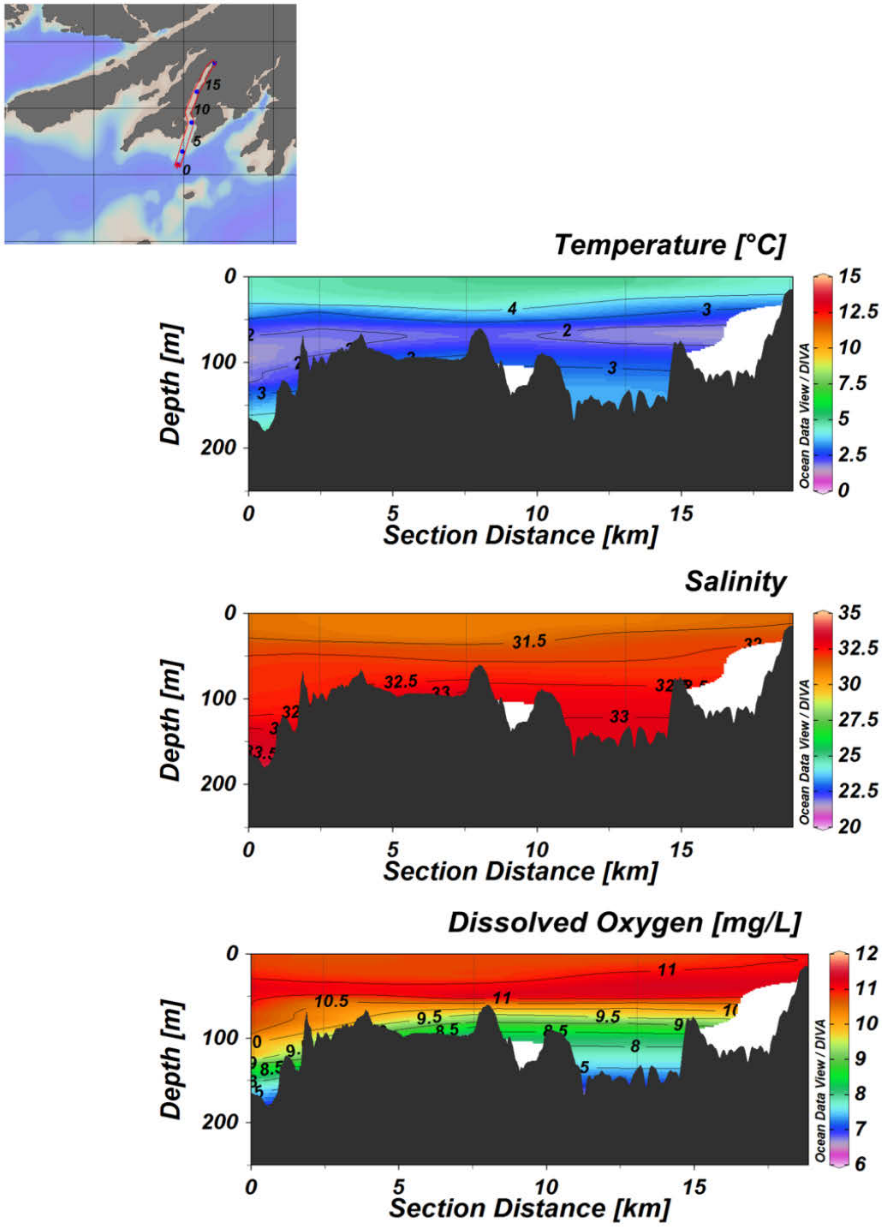

Figure 14: Connaigre Peninsula water column vertical structure; spring 2012.

Water Currents

Bottom mounted upward-looking Acoustic Doppler Current Profilers (ADCPs) were used, between 2009 and 2013, to measure ocean currents in the Coast of Bays area. The analysis of the currents was performed on two layers of the water column. The layers were the upper 0-20 m and the layer below 20 m depth. The analysis showed that the median current speed ranges between 2 and 14 cm/s. The currents within the surface layer were generally faster than the currents at depths (Figure 15). The currents showed temporal as well as spatial variability. Maximum current speed observed in the area was as high as 90 cm/s; in general, the maximum observed speed at each station was 5 to 10 times larger than its median speed.

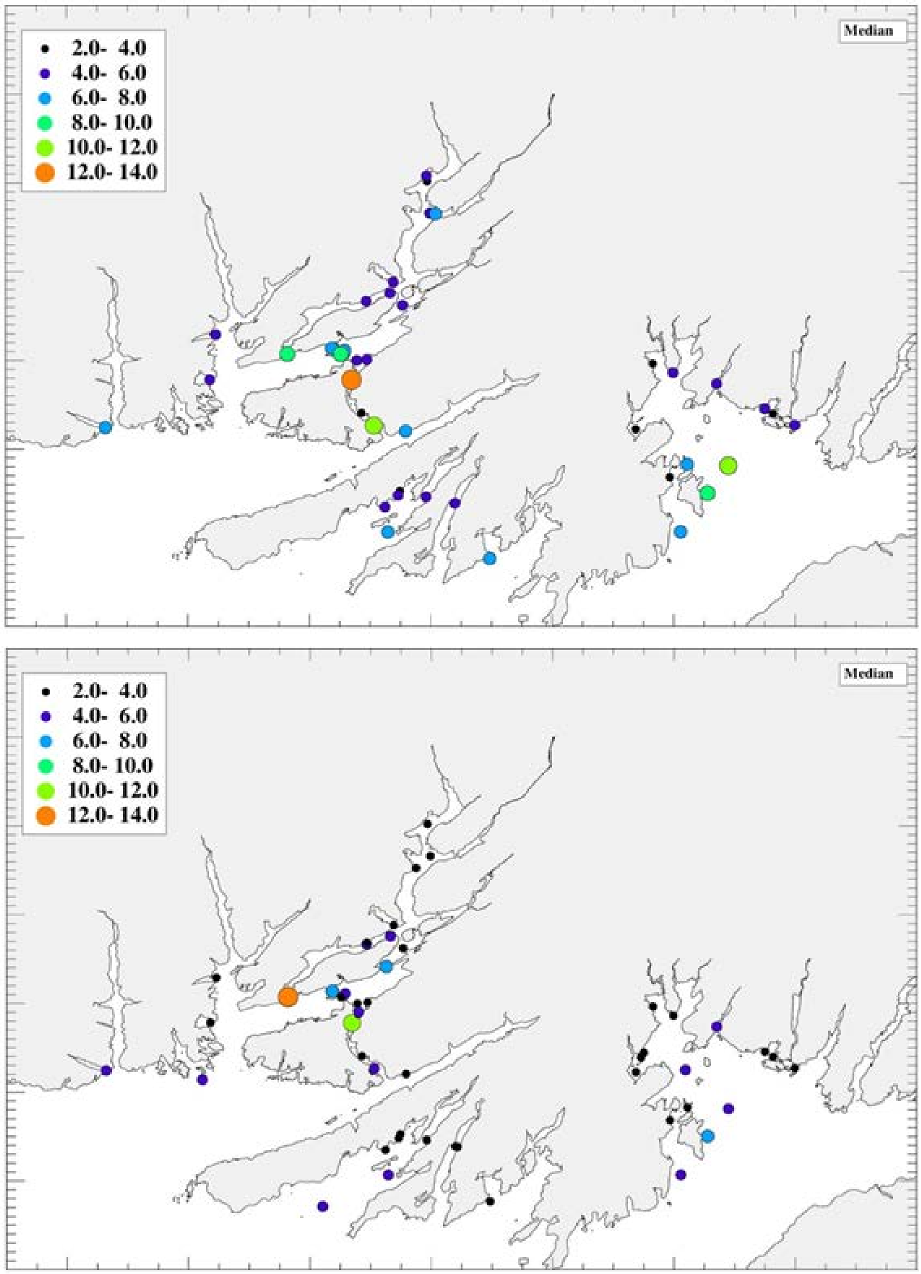

Figure 15: Median speed [cm/s] in the upper layer, 0-20 m depth (top panel), and lower layer, below 20 m depth (bottom panel), for the Coast of Bays area.

Differences were found in the statistics of the current speed among bays but also within the same bay. Fifty percent of the current measurements taken at a distance less than 1 km from aquaculture sites in the Coast of Bays area showed median speed of 4-6 cm/s in the upper 0-20 m depth. This translates to particles reaching a distance of 1 km within approximately five to seven hours assuming currents of a constant direction during that period.

The analysis of the sea level measured by the ADCP showed that, on average, tides explain 84% of the sea level variance. A slightly higher contribution was observed in the Bay d'Espoir region, followed by the Connaigre Peninsula region, then the Belle Bay region. However, the analysis showed that a significant part of the current variability is not attributed to the tides. Differences were found among bays with the region towards the head of Bay d'Espoir showing a higher tidal contribution than the other bays, generally around 25% for the former and less than 10% for the latter. In addition, the upper layer showed lower tidal contribution than the lower layer indicating the presence and importance of other forcings in driving the near surface ocean circulation.

The Development of a Circulation Model for the Coast of Bays Area and its Application to Bay Management Areas

In order to study the transport of particles to and from aquaculture sites and to estimate zones of influence associated with aquaculture activities as well as the potential for water exchange between regions, water circulation was studied through observations and a numerical model. The observations consisted of surface and subsurface drifters used to follow the movement of the surface layer and of current profilers, ADCP used to measure currents in the whole water column. For the numerical model, FVCOM was implemented to simulate the nearshore water circulation in the region.

The zones of influence were estimated as the area covered by the trajectory of particles or drifters released in the water computed from the measured and modeled water currents. The potential for water exchange between regions was assessed as the combination of various overlapping zones of influence.

The drifter experiments provided current information for the surface layer 0-10 m depth. The experiments ran from 3 to 62 hours. For safety reasons, the experiments were limited by ocean states. Therefore the experiments occurred during low to moderate wind conditions. The distance covered by the drifters depended on the region and on the forcings that drove the circulation during the experiment period; it varied between 0.7 and 52 km with a maximum distance of 47 km in one day.

The ADCP measured ocean currents 5 m from the seafloor to 5-10 m below the surface. The ADCP measured currents for a period of one to six months. The median estimated distances covered by particles calculated using the currents measured at a depth of 7.5 m ranged from approximately 1-16 km within a 24-hour period. When considering the maximum distance for the 24-hour period, the distance a particle could move increased to 3.5-32 km. The particles were assumed to have equal probability to move in any direction around the ADCP station for these calculations.

The circulation model was forced with tides at the offshore boundary and with temporally constant and spatially quasi-uniform, wind field at the surface. The wind field was characterized by a high wind speed of 72 km/h and varying wind direction to consider funneling effects due to complex topography in the region. In addition, reduction of wind speed behind mountains due to barrier effects was also applied. Two modelling scenarios were considered: a wind forcing from the southwest and a wind forcing from the northeast for one day. The model was run in a barotropic mode, i.e. uniform temperature and salinity for the entire area.

For validation purposes, the sea level measured by the ADCP pressure sensor and the corresponding sea level computed by the model were compared. The tidal sea surface elevation was well reproduced by the model with error less than 2 cm for the major tidal constituent. Considering the tides account for an average of 84% of the sea level variation in the area, the present model can be used to predict a large part of the variability of the sea surface elevation. Note that at times, storm surges can be important in the sea surface height variability in the region.

The currents predicted by the circulation model were used to force a particle tracking model which computed the transport of particles, within 0-5 m depth, released from different locations of the study area. Figure 16 illustrates the distance between the point of release and the location of the particles after 12-hours of simulation for the two wind forcing scenarios. The distance covered by particles following the computed currents was found to vary depending on the release location and the wind forcing direction. The maximum computed distance was 22 km in 24 hours.

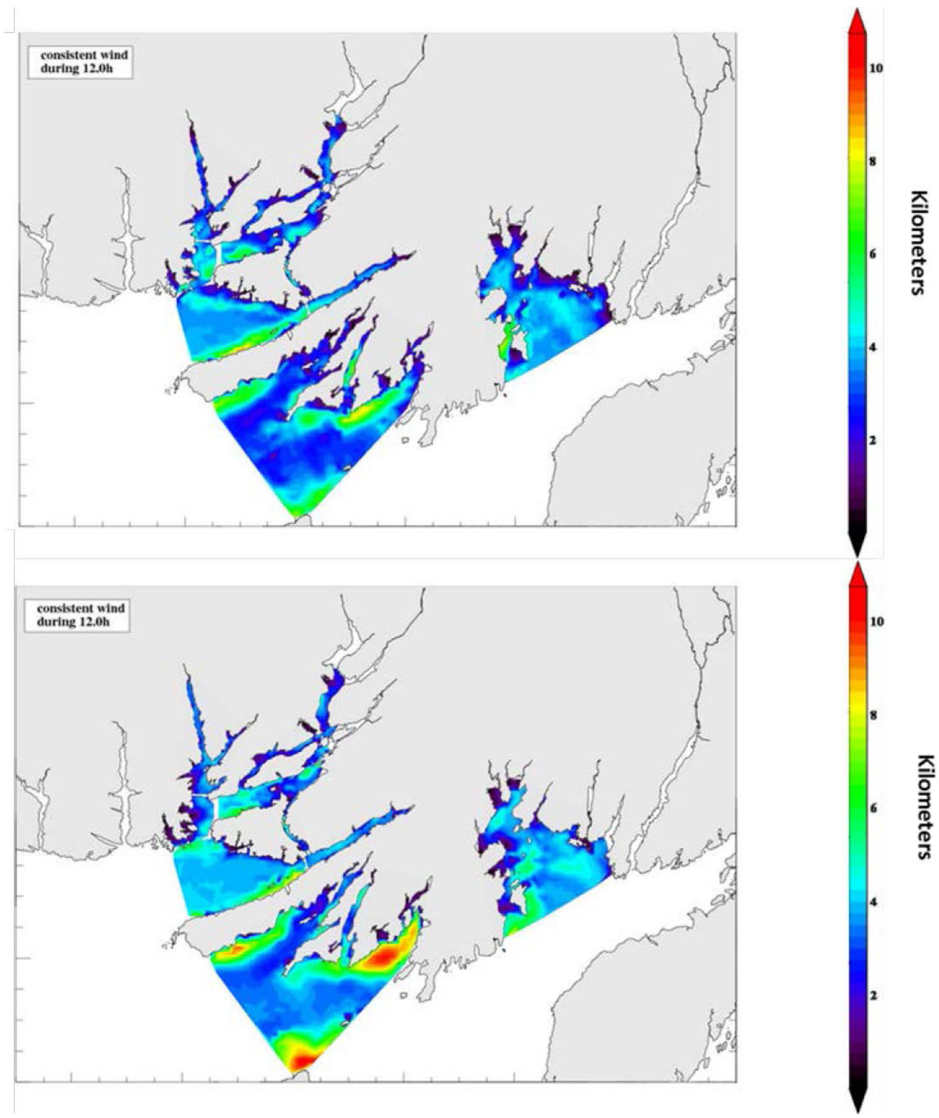

Figure 16: Displacement distance [km] for particles released at locations within the domain of interest. Upper panel shows case with wind forcing coming from the southwest and lower panel for wind coming from the northeast. Color at each location represents the displacement distance of particles released at that location.

Sources of Uncertainty

Some regions of the study area (Great Bay de l'Eau, part of Connaigre Bay and Belle Bay, in particular) are under-sampled with respect to the bathymetry, resulting in cruder approximations of the metrics.

Of the fourteen main rivers identified in the area of interest, only discharge information from four rivers could be used for a regional analysis. Estimates of the discharge from the other rivers were attempted using these data resulting in possible underestimation given the southward increase in precipitation gradient in the area as described in the Water Resources Atlas of Newfoundland (Department of Environment and Lands 1992).

Wind climatology was computed using one permanent weather station with close to 20 years of data. The station is located off-shore to the south of the Connaigre Penninsula and there are uncertainties in generalizing the analysis to the whole region. Other atmospheric variables required to compute heat flux were not available for long term analysis but will be of importance in order to assess the role of heat exchange between the ocean and the atmosphere on the water circulation in the region.

Estimates of flushing time were solely based on tidal volume (prism); thus flushing time might be significantly overestimated or underestimated due to the freshwater discharge and/or to the effect of the wind that had previously been identified as a strong physical forcing agent in the area (Ratsimandresy et al. 2012; De Young 1983, and Hay and De Young 1989).

The temperature climatology was calculated based on a limited amount of data resulting in a possible spatial and seasonal bias; in particular, data related to winter months. The analysis could be enhanced using additional sources of data such as (but not limited to) Sea Surface Temperature (SST) acquired by satellites/remote sensing techniques.

With regard to the water structure, sampling limitations prevented the distinction between temporal and spatial physical processes resulting in difficulty explaining the mechanisms that resulted in the observed short-term variation in temperature, salinity, and dissolved oxygen. The dataset is also too short and limited with respect to its temporal resolution (paucity of observations in summer and winter) to allow a good understanding of seasonal and inter-annual variations.

In terms of ocean currents information, generalization to annual conditions should be done with caution given that the measurements were carried out for periods ranging from one to six months but rarely occurred during winter. In addition, inherent limitations of the ADCP measurements to provide information at the surface resulted in current conditions available only from the sub-surface to the depth of the ADCP. Currents at near-surface (i.e., 0-5 m depth) are expected to be larger than those measured within the sub-surface and different methods of measurements would be needed to collect data at the surface.

The development of the circulation model consisted of various stages starting with a simplified water structure and forcing field. The runs did not take into account physical processes such as seasonal and spatial variability of temperature, salinity, and realistic wind as observed in the region. Freshwater runoff was not considered.

When computing the zones of influence using currents measured by ADCP, Progressive Vector Diagrams (PVD) were applied which assumed that the currents were spatially uniform. Particles released at the location of the ADCP were also assumed to have equal probability to move in any direction around the ADCP. This provides a crude approximation of the true particle trajectories as the ocean currents in the region of interest vary spatially. Consideration of the current direction will allow the generation of connectivity map with the possibility of performing probability and risk analysis.

For the zones of influence computed using the output of the circulation model combined with a particle tracking model, near-surface currents were computed in a barotropic mode. In this mode currents are independent of depth and the whole water column tends to move with the same speed. Strong wind forcing fields were necessary to produce circulation with surface currents having the same speed as the observed currents. Observation showed significant horizontal and vertical variations of temperature and salinity, and such variations require the model to be configured in baroclinic mode. In a baroclinic mode, the currents will change with depth and zones of influence associated with the water circulation would vary accordingly.

CONCLUSIONS AND ADVICE

In-situ data (from various sources including CTD, ADCP, weather stations, and drifter experiments) and the results of a circulation model were analyzed to characterize the oceanographic conditions in the Coast of Bays, an area of the south coast of the island of Newfoundland. The results show important spatial (hundreds of meters to bay scale) and temporal (days to seasonal scale) variability of the oceanography of the area as well as variability in the surface wind (speed and direction). Different regions were identified based on properties that differentiate them from the surrounding area. The analysis of the surface layer, where aquaculture activity occurs, and the sub-surface to bottom layer show differences and variability in the physical properties. The changes in the physical and dynamical properties of the water in the study area are the result of a combination of various forcings including atmospheric, tidal, freshwater runoff, density driven inflows and bathymetric characteristics. However, the quantification of the role of each forcing still requires further research. Nevertheless, the present analyses provide the most up to date understanding of the oceanography in the Coast of Bays area since the 1980s. This includes:

- A detailed description of the bathymetry;
- An analysis of freshwater discharge using the most up to date hydrological and topographical data;
- An update on the wind climate;
- A comprehensive analysis of tidal elevation and vertically averaged currents;
- A first estimate of flushing time for each of the main bays in the study area based on the tidal prism method;
- A temperature climatology of the upper 20 m of the water column including first estimates of vertical mixing rates;
- A description of the vertical and horizontal water structures including an identification of interannual, seasonal (spring and fall), and short term variability and associated processes;
- A statistical analysis of the ocean current regimes;
- The implementation of a coastal circulation model simulating tides and wind induced currents under uniform water structure conditions; and
- An estimation of zones of influence associated with particle movement within the surface layer and evaluation of potential exchange of water within the bays.

From a BMA point of view, the Coast of Bays area can be divided in various regions based on different criteria:

1. The first division, related to the geographic properties of the area, is based on the presence of basins and sills (Figure 17). The sills reduce the exchange of deep water from one region to another thus limiting, for example, deep water renewal and possible movement of waste from aquaculture sites as they reach deeper layers.

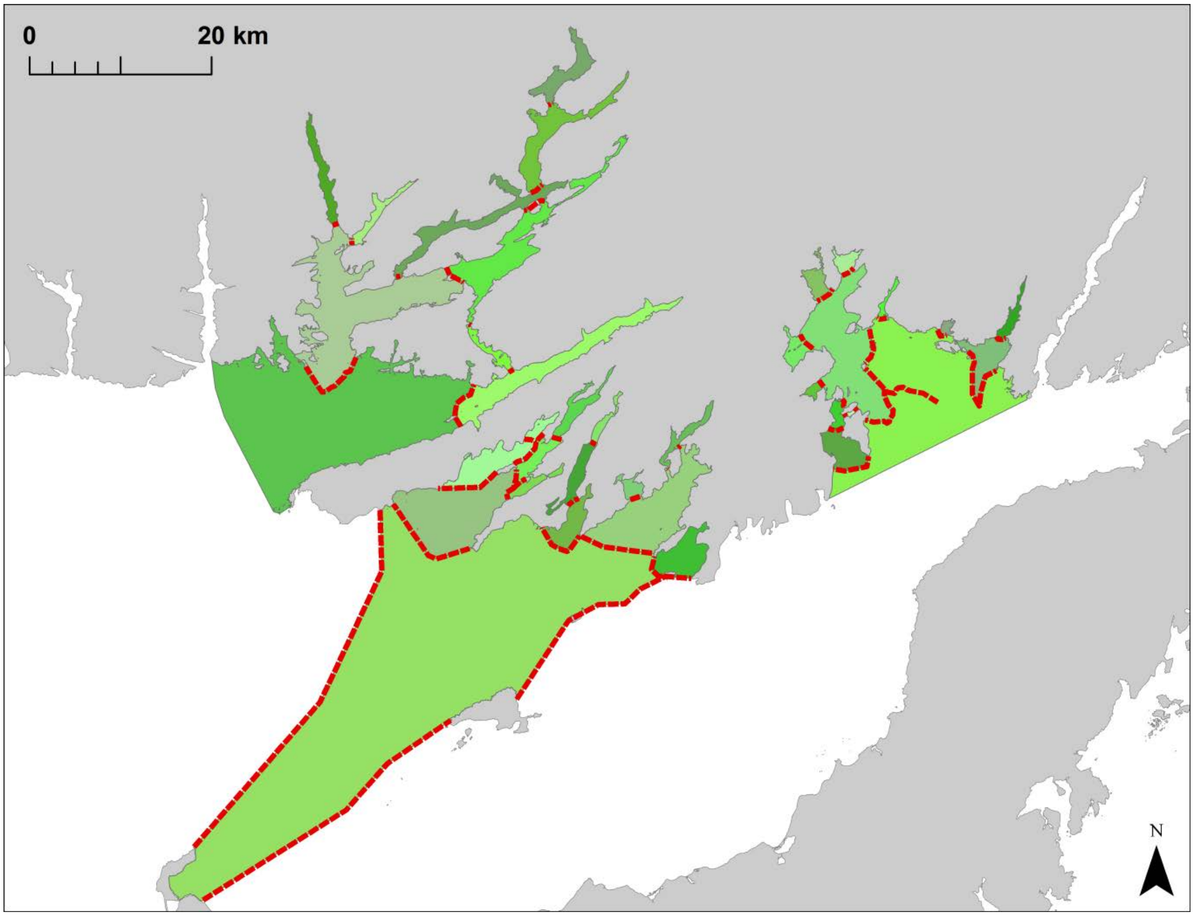

Figure 17: Basins (green areas) and sills (red lines) in the Coast of Bays area. Shades of green only represent different basins.

2. Another division can be defined as hydrographic zones based on temperature, salinity, dissolved oxygen, and mixing characteristics (Figure 18).

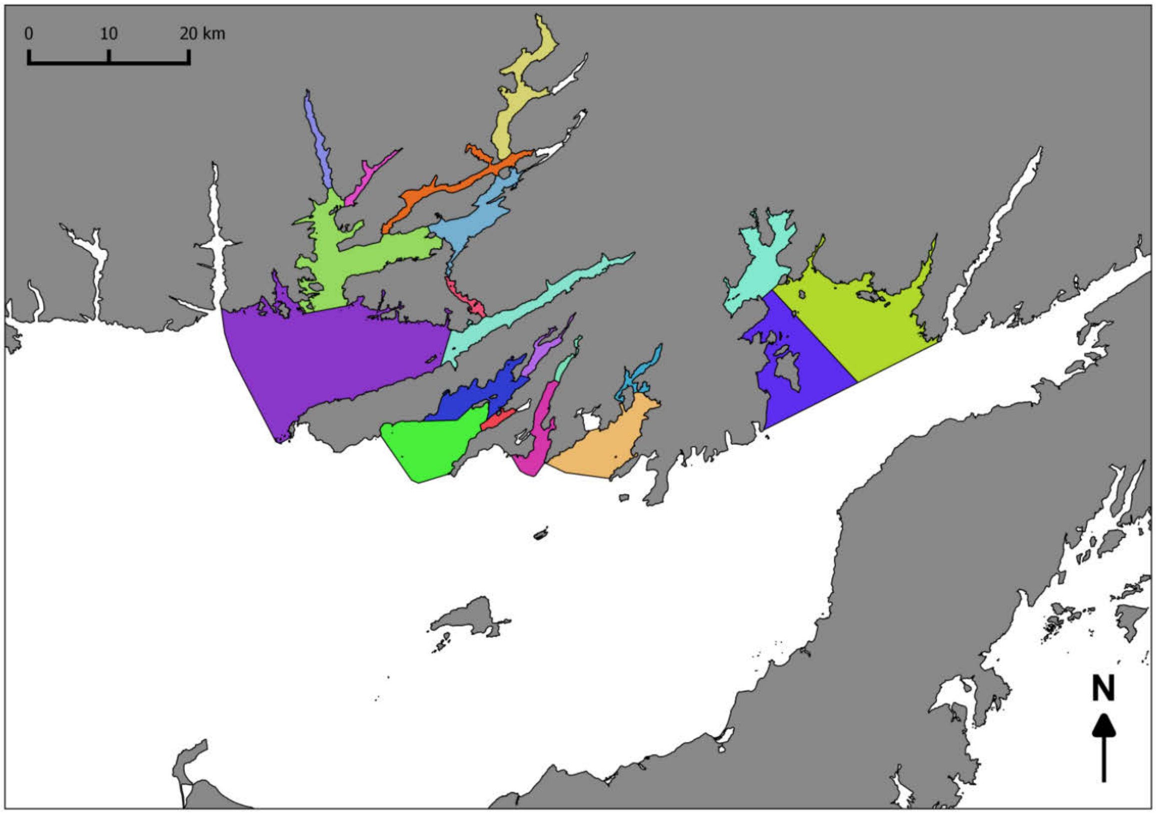

Figure 18: Map of the regions in the Coast of Bays area showing specific oceanographic criteria. Each colour represents a hydrographic region.

3. A division related to the potential for water exchange can also be defined based on the dispersion of particles at the sea surface (Figure 19). The combination of various overlapping zones of influence was used to assess the potential for water exchange between regions.

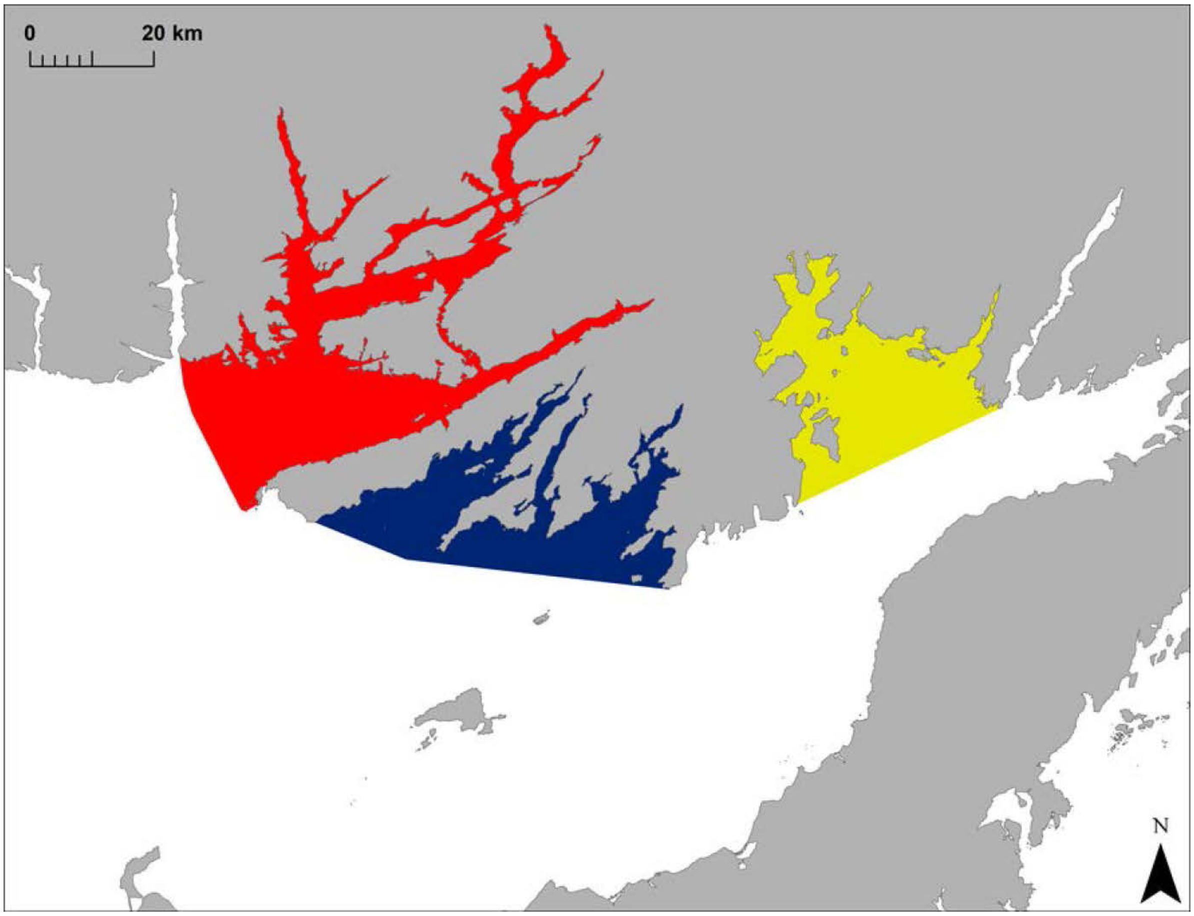

Figure 19: Regions in the Coast of Bays showing potential for water exchange. Each colour represents a region.

OTHER CONSIDERATIONS

The delineation of BMAs requires input from a number of sources (regulators, industry, etc.). The information brought to this meeting is one among many inputs that will require integration for the support of BMAs.

SOURCES OF INFORMATION

This Science Advisory Report is from the March 25-26, 2015 Regional Peer Review on the State of the knowledge of the oceanography and water exchange on the South coast of Newfoundland to support the development of Bay Management Areas for Finfish Aquaculture. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Akenhead, S.A. 1987. Temperature and Salinity off Newfoundland: Station 27 Annual Cycle and Residuals. NAFO SCR Doc 87/66.

BDE DA (Bay d'Espoir Development Association). 1984. Salmonid Aquaculture in Bay d'Espoir – a Development Plan. Vol. 3: 133 p.

Brewer-Dalton, K. (ed), F.H. Page, P. Chandler, and A. Ratsimandresy. 2015. Oceanographic conditions of salmon farming areas with attention to those factors that may influence the biology and ecology of sea lice, Lepeophtherius salmonis and Caligus spp., and their control. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/048. vi + 47 p.

Burt, K., D. Hamoutene, G. Mabrouk, C. Lang, T. Puestow, D. Drover, R. Losier, and F. Page. 2012. Environmental Conditions and Occurrence of Hypoxia within Production Cages of Atlantic Salmon on the South Coast of Newfoundland. Aquaculture Research. 43: 607-620.

Chang, B.D., F.H. Page, R.J. Losier, P. Lawton, R. Singh, and D.A. Greenberg. 2007. Evaluation of Bay Management Area Scenarios for the Southwestern New Brunswick Salmon Aquaculture Industry. Aquaculture Collaborative Research and Development Program Final Project Report. Can Tech Rep Fish Aquat. Sci. 2722:1-69.

Clément. 2013. Ecosystem approach and interactions of aquaculture activities in southern Chile. In L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez, eds. Site selection and carrying capacities for inland and coastal aquaculture, pp. 271–278. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 December 2010. Stirling, the United Kingdom of Great Britain and Northern Ireland. FAO Fisheries and Aquaculture Proceedings No. 21. Rome, FAO. 282 pp.

CoGP (Code of Good Practice) Management Group. 2015. A Code of Good Practice for Scottish Finfish Aquaculture. (accessed 30 April, 2015).

Craig, J.D.C. and E.B. Colbourne. 2004. Temperature Variability in the Coastal Waters of Eastern Newfoundland. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/004.

Currie, J.J., P. Goulet, A.W. Ratsimandresy. 2013. Wind Conditions in a Fjord-like Bay and Predictions of Wind Speed Using Neighboring Stations Employing Neural Network Models. J. Appl. Meteor. Climatol. 53: 1525–1537.

DFA (Department of Fisheries and Aquaculture), Government of Newfoundland and Labrador. 2014. Newfoundland and Labrador Sustainable Aquaculture Strategy 2014. (accessed 2 March, 2015).

De Young, B. 1983. Deep Water Exchange in Fortune Bay, Newfoundland. Thesis (M.Sc.) Memorial University of Newfoundland.

Department of Environment and Lands, Government of Newfoundland and Labrador. 1992. Water Resources Atlas of Newfoundland. Water Resources Division.

Gregory, D., B. Petrie, F. Jordan and P. Langille. 1993. Oceanographic, geographic and hydrological parameters of Scotia-Fundy and southern Gulf of St. Lawrence inlets. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 143: viii + 248 pp.

Hay, A.E. and B. De Young. 1989. An Oceanographic Flip-Flop: Deep Water Exchange in Fortune Bay, Newfoundland. Journal of Geophysical Research, 94: 843-853.

Jackson, D. 2011. Ireland: The Development of Sea Lice Management Methods. In Salmon Lice: an Integrated Approach to Understanding Parasite Abundance And Distribution. Edited by Jones S, Beamish R. Wiley-Blackwell. Oxford. pp. 177-204.

MSRL (Marine Science Research Laboratory). 1980. Bay d'Espoir Aquaculture Feasibility Study. Coastal and Estuarine Pen Rearing Sites. Vol. II, Section 10: 1–37 p.

Ratsimandresy, A.W., Page, F., Mabrouk, G., Losier, R., Drover, D., Ings, D., and McCurdy, P. 2012. Aquaculture Drifter Programme: Progress Update 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/127. vi + 41 p.

Richard J. M. and Hay A. E. 1984. The physical oceanography of Bay d'Espoir, Newfoundland. Institute of Cold Ocean Sciences. Memorial University of Newfoundland. 30 p.

Simpson J.H., and J. Sharple. 2012. Introduction to the Physical and Biological Oceanography of Shelf Seas. Cambridge University Press. 424 p.

Yurick, D. B. and M. C. Vanstone. 1983. A Biological and Oceanographic Study of the Baie d'Espoir Region, Newfoundland. Vol. 1. Final Report to Parks Canada, Department of the Environment, Ottawa. Parks Canada Ref. No. C1632/82-54.

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