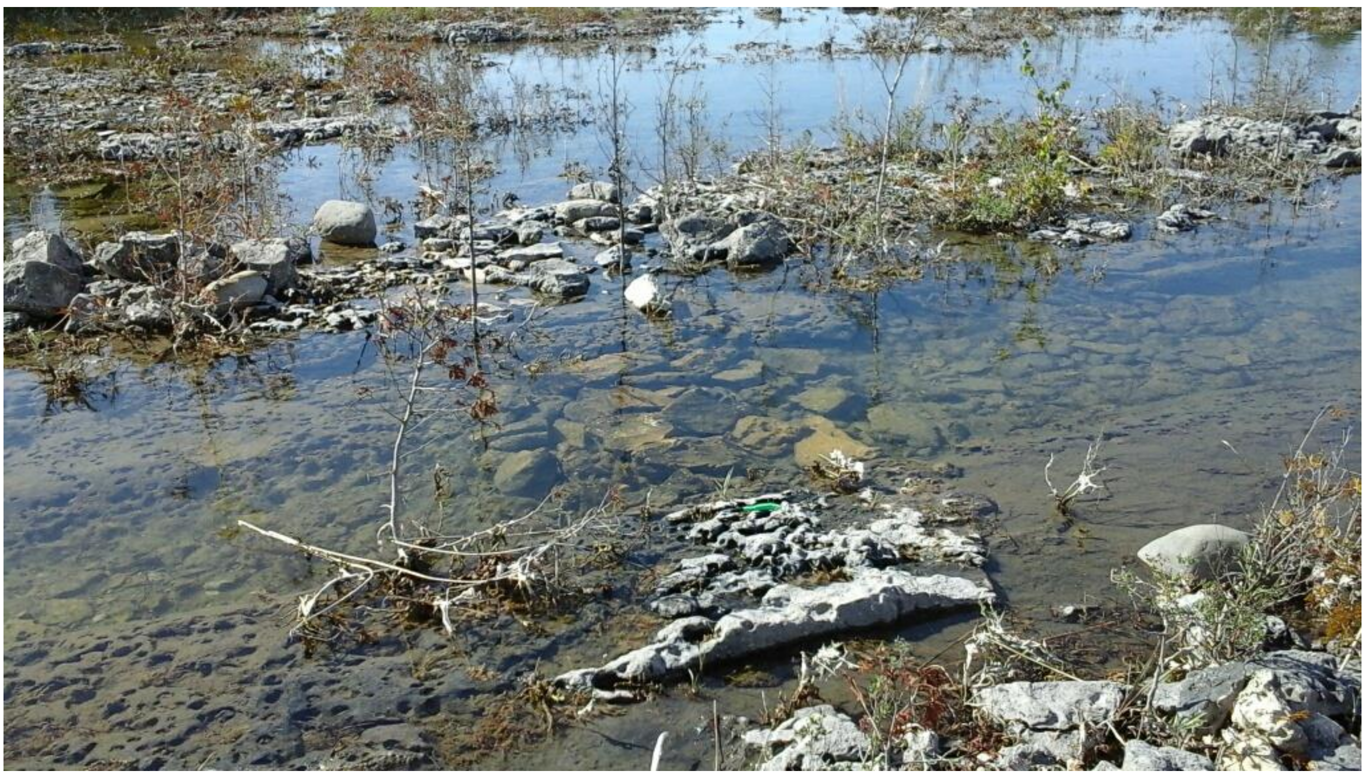
THE TIDES O' BRUCE

SEICHE RHYTHMS OF EMBAYMENTS ALONG THE WEST COAST OF THE NORTHERN SAUGEEN PENINSULA



A reversing stream, west end of Hay Bay.

BY JOHN GREENHOUSE

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SUMMARY.

Observant people who have the good fortune to live, work or play on the shoreline of the bays and harbours of the Bruce Peninsula know that these bodies of water gently oscillate, day in day out, with frequencies typically a few times per hour. Hydrodynamicists recognize these harbour oscillations as a resonance or "slosh" of water moving within the confines of a semi-confined space, and can produce mathematical models to explain why and how this occurs. Between the observers and the scientists there would seem to be nothing left to say about harbour oscillations. They exist, and we mainly know why!

There is, however, perhaps, a knowledge gap worth being filled. The observer, with a human's attention span, might recognize a 10 minute oscillation but miss the much larger 30 minute one that modulates it. The scientific explanation, drenched in mathematics, is limited to solving equations for hypothetical harbours with simple shapes and bathymetries. What seems to be missing are careful measurements to allow a detailed characterization of the oscillations in each harbour. Observations of water level variations over periods of days and weeks might at least clarify <u>what</u> happens, even if not a full understanding of how and why it happens.

This was the rational for undertaking measurements, over a 5 year period, of water level variations in at 19 embayments down the west coast of the Northern Bruce Peninsula. Readings at these were made at least once per minute, using instruments borrowed and built. Because we are dealing with oscillatory motions the characterization is best undertaken in the Fourier domain, associating each harbour with a spectrum of its motions. The results, simply stated, are:

- *i.* *Each harbour does have a unique spectral signature, and this signature is remarkably stable over time.*
- *ii.* *This spectrum is also stable in space within a harbour; that is, measurements made at multiple locations within the harbour will have the same signature.*
- *iii.* *A harbour spectrum will usually have one prominent peak that can be identified as the resonant frequency. These resonances varied from 0.8 cycles per hour (cph) at Stokes bay to 13 cph in Little Tub. These values are in reasonable agreement with simple theory based on idealized models.*
- *iv.* *Some harbour spectra exhibit more than one peak. They may be simply multiples of the dominant frequency, or they may represent harbours-within-harbours, arms of the main harbour that add their own resonance to the spectrum.*
- *v.* *Measurements made in two harbours simultaneously allow the separation of motions characteristic of the harbour from those generated in the lake outside. Generally speaking, oscillation frequencies below 1 cph are ascribed to the lake.*
- *vi.* *These measurements do not shed light on the driving mechanism for harbour oscillations, generally thought to be either low frequency waves from the lake that closely match the harbour resonance, non-linear interaction between surf at the harbour mouth and the water inside, or a combination of the two. It seems to be the*

case, however, that oscillations can continue through periods of dead calm in the lake outside, suggesting that the former mechanism may predominate.

vii. *As theory predicts, the simplest explanation for why some harbours exhibit larger oscillations than others is the ratio of their breadth to their length. The smaller this ratio, the more prominent the oscillations are likely to be.*

viii. *From time to time very large and sudden seiches sweep in from the lake, causing damage to harbour infrastructure and in some cases loss of life. These are generally ascribed to sharp pressure changes accompanying thunderstorms over the lake, resulting in a tsunami-like wave that travels with or outruns the pressure event that created it. Water levels in harbours can rise and fall very substantially in a matter of a few minutes. There is the question of how and when these lake seiches are amplified in the embayments, and whether potentially damaging harbour oscillations can be predicted. Where unusually strong oscillations were initiated simultaneously in separate harbours during our recordings, they can be assumed to originate in the lake outside. The external "trigger" sets the embayments in oscillation. Recordings made on an offshore island in 2019 suggest that these trigger events do have periodicities similar to harbour resonance periods, in the range 5 to 30 minutes.*

ix. *The Tobermory and Goderich gauges and meteorological records for three major meteotsunami events of the last decade are examined. These show that strong seiches tend to occur during the downward (decreasing) leg of a pressure cycle, shortly before the bottom of the cycle is reached. These rare events tend to be associated with "chatter" on the plot of decreasing pressure, presumably from more localized thunderstorms.*

For the future it would be useful to obtain more high resolution measurements both inside and outside these embayments of the water level and barometric pressure variations during major meteotsunamis, in order to understand how severe harbour oscillations are triggered. Since not all our coastal embayments can be instrumented all the time, having observers record the period of time between peaks of these major events would provide useful information.

INTRODUCTION

A personal background.

A few years ago I published a short paper on the Sources of Knowledge web site called “The Tobermory Tides”. It came about from visitor questions like “are there tides in the Great Lakes?”. The internet confirmed that indeed there are tides on the Great Lakes, and papers on the subject date back at least to the early 1900s. My small contribution was to explain the subject in layman’s terms, and to show that one could quite easily identify tides at the Fisheries and Oceans Canada water level gauges around the lakes through the blunt instrument of a Fourier analysis add-on to Microsoft Excel. On very languid days of early summer you could even see tides in the raw records.
Here in Tobermory the tidal range is of the order of 2 cm, slightly higher at stations like Little Current and Killarney where tidal movements are funneled through narrow channels. This was interesting, but tides of this magnitude do not disrupt shipping or damage coastal infrastructure. They are not a factor in life around the Great Lakes.

In 2010 I ran into Baptist Harbour resident Eric Goodyear at a party and found he had actually read my paper on tides. I was flattered but, more importantly, intrigued by his description of strong periodic water motions by his dock in Baptist Harbour (BH). When you throw a piece of wood into the water off his dock, it moves back and forth about 100 metres every 15-18 minutes. Although the flow was relatively gentle during my visit, Eric showed time-lapse video of very strong back and forth surges that washed shore boats and docks away. This phenomena, which we recognized as a form of seiche known as “harbour oscillation”, <u>is</u> a factor in life around the edges of the Great Lakes.

Seiches in a harbour or in a larger lake or ocean are scaled-up versions of the waves we could watch in a household water basin. Joggle the basin sharply and water will slosh back and forth, slowly dying down with time. Blow across the basin, pushing the water to one end, and it will come rushing back once the blowing stops to be reflected again and again from each end. Blowing directly down on the centre of the bowl will depress the water below, resulting in standing wave patterns radiating out from the centre when the blowing stops. These scenarios can roughly mimic the seiches produced by earthquakes, wind and localized intense high-pressure cells respectively.

A couple of summers ago I nudged my kayak into calm, shallow rocky water on the west side of Hay Bay, hoping to ease my way through to the Cape Hurd Channel and then west along the coast. The water proved too shallow even for a kayak, but I watched fascinated as a little rivulet, running through the exposed rocks blocking my way, flowed alternatively to the north east and then to the southwest. Norbert Woerns and I returned to the spot (pictured on the cover page)later in the day and timed this cycle at about 10 minutes.

Another well known continuous seiche motion can be experienced at the south end of La Ronde Harbour on Cove Island, directly north across the Cape Hurd and Devil’s Island channels from Hay Bay. The cycle time or period of oscillation is also in the range

10 to 12 minutes (Hlevca et al., 2015). These water level oscillations at Hay Bay and Baptist and La Ronde harbours are continuous, varying in size but almost always present. Local paddlers (Cavan Harpur, pers. comm.) say that when the amplitude of the oscillations in La Ronde starts to increase in otherwise calm weather it usually presages a storm approaching from the west. Variations in amplitude of the oscillations in Baptist Harbour are unpredictable and probably reflect distant as well a local sources.

Infrequently, typically once every few years, there occur very large, sudden, spectacular, short-lived and damaging seiche events. They often come "out-of-the-blue", in clear weather, sweeping onto the shore, withdrawing, then returning and repeating the cycle several times on time scales of a few minutes. They have washed people off piers and thrown freighters up onto the beach. These events get everyone's attention when they occur, but because they are infrequent we forget they can happen at any time.

Large seiches are almost always associated with strong weather disturbances somewhere over the lake, and are now often referred to as "meteotsunamis". Like earthquake tsunamis they radiate away from a source, in this case abrupt pressure changes and strong winds associated perhaps with a violent, localized thunderstorm somewhere over the lake. The seiche has outrun the storm to reach the shore where we observe it, or perhaps radiated outwards from a localized storm that has moved on a different path and will never pass over us.

These large seiches have positive effects as well. They flush wetlands and bring nutrients from the bottom nepheloid layer upwards into the water column.

First hand descriptions of these large events always describe a period between successive highs of 5 to 15 minutes. This is comparable to the natural resonance of embayments like Baptist and La Ronde Harbours, but considerably shorter than what would be expected of oscillations in the big lake basin. So how and under what circumstances do these long period lake seiches – if indeed that is what they are - excite short period harbour seiches

Science background.

There is a large body of work on Great Lake seiches, much of it highly theoretical. Hlevca et al (2015) and Rabinovich (2009) are particularly useful references, though quite mathematical in their treatments of the subject. I have borrowed extensively from these authors.

Rabinovich gives a superb overview of the topic, and is a very good starting point for anyone wanting to probe deeper than the treatment here. The work of Hlevca et al. is particularly relevant as they analyzed water level variations on two harbours in Cove Island, La Ronde and Boat Passage, and compared them to those occurring simultaneously in the lake outside. They then looked at the likely mechanisms for driving these variations, and found relatively good agreement with mathematical models. Their work will be further described below.

Goals of this project.

Most coastal property owners are aware that lake levels fluctuate regularly on scales of minutes to hours. The main goal here was to describe these fluctuations more precisely and, in doing so, to try to understand why they occur.

More specifically, the goals are:

i. to measure the characteristics of the continuous seiche activity in several bays and harbours – embayments - down the western shore of the Northern Bruce Peninsula;
ii. to determine whether these characteristics are repeatable in time; that is, will independent measurements at different times produce the same results;
iii. to determine if these characteristics are spatially consistent within the embayment in question. That is, will measurements made simultaneously at two different locations within the embayment have the same characteristics;
iv. to separate the characteristics of water movements of the lake outside from those characteristic of the embayment itself. Measurements in the lake outside are difficult with the equipment available to us; the best way to separate the two characteristics is therefore to look for those that are common to two embayments measured simultaneously. These can reasonably be taken to represent the influence of the lake, while characteristics that differ between the two locations are those of the individual harbours;
v. to compare the seiche characteristics of these embayments to what can be roughly predicted from their length, width and depth;
vi. to record the response of one or more of there harbours to a meteotsunami event, and to relate that response to the characteristics of its continuous seiche;

Regarding the last item, with very good luck we might have recorded a meteotsunami during harbour measurements but this unfortunately did not happen.

WHAT IS A **SEICHE?**

Definitions.

The standard definition of a seiche is "*a periodic oscillation of the surface of an enclosed or semi-enclosed body of water (lake,inland sea, bay, etc) caused by such phenomena as atmospheric pressure changes, winds, tidal currents, and earthquakes*" (Collins English Dictionary). The origins of the word seiche are disputed. Some say it is derived from ancient Swiss/French dialects and may have meant "to sway back and forth". Others claim it to have derived from the latin "succus" referring to the dry littoral zone exposed during one half of the seiche cycle. Whatever its origins, the word's use was promoted by Swiss hydrologist François-Alphonse Forel in 1890, who was the first to make scientific observations of the effect in Lake Geneva, Switzerland.

A more nuanced definition, this time from Wikipedia, describes a seiche as a "*standing wave in an enclosed or partially enclosed body of water. Seiches and seiche-related phenomena have been observed on lakes, reservoirs, swimming pools, bays, harbours and seas. The key requirement for formation of a seiche is that the body of water be at least partially bounded, allowing the formation of the standing wave.*"

The terms "standing wave" and "enclosed" are important. Seiches, at least in their ideal form, are not moving waves like ocean swell, but stationary waves like those which set up in a skipping rope or an organ pipe. Standing waves require that the waving medium (rope, pipe, basin, etc.) be enclosed so that the energy in the wave is reflected back and forth. Inlets and harbours are not of course fully enclosed. Energy inside the water body can leak back out into the bigger lake through an opening, so the internal movement is not a pure standing wave but a leaky version.

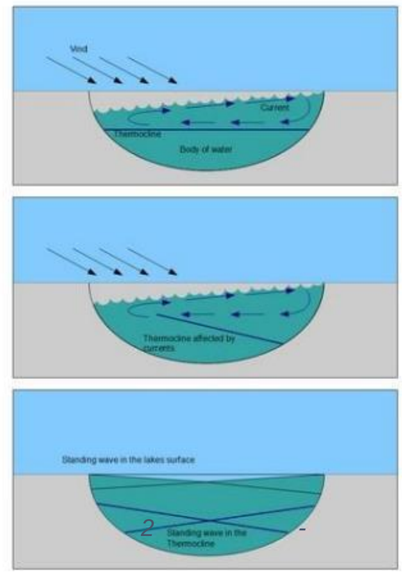

Figure 1. Seiche development under wind stress on the surface and thermocline of a basin.

Seiches co-exist in a basin with many other types of waves, from tiny capillary waves to chop, swell and tides, but they are distinctive in one key aspect. They have periods (the time between succeeding crests) of a few minutes to hours, far longer than capillary (< 1 sec), chop or swell (1-20 seconds) and far lower than the dominant 12.5 hour tidal period. With the exception of places like Baptist Harbour one has to be quite patient to see day-to-day seiche activity, perhaps by placing a stick in the sand at the water's edge at Dorcas Bay on a calm day and watching the slow advance and retreat of that edge relative to the stick over 30 minutes or more. As we will see, spectral analysis makes the detection and separation of these various wave types much simpler.

Complications.

The Great Lake basins themselves are enclosed and have continuous oscillations. The conceptual model for bays on the Northern Bruce is therefore one of a large water body connected through an opening to a small water body. Think of a bathtub connected to a basin connected to a basin (Figure 2). Each basin has its own standing wave properties; intuitively the bigger bathtub will have slower oscillations than the smaller basins. How do oscillations in the bathtub influence those in the basin? And how do you separate the bathtub and basin motions if you make measurements only in the basin?

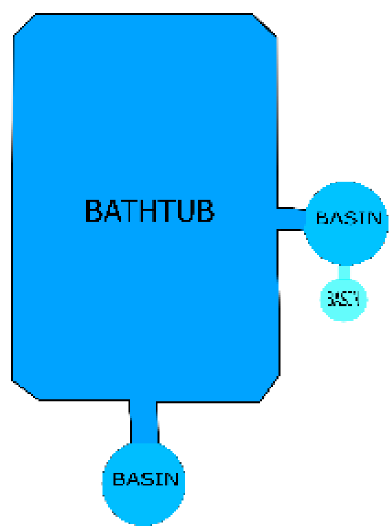

Figure 2. Bathtub/basin/basin conceptual model.

As shown schematically in Figure 2, basins may be links to smaller basins.. For example, Little Tub and Big Tub Harbours are connected to Georgian Bay via the larger basin of Tobermory bay. Oscillations in the Tubs can be expected to have components from both the bay and the lake outside

Furthermore, the lake surface is not the only surface capable of standing waves (see Figure 1). The thermocline, typically 15 to 20m below the surface, separates upper and lower regions of the lake with warmer/lighter and denser/colder water respectively. That surface can also be set into standing wave motion; think of the oil/water desktop gadgets one can buy. Most bays, with the possible exception of Big Tub Harbour, are too shallow to host a thermocline but interaction with the thermocline in the big lake beyond is a possibility.

Bays are seldom completely circular or square. As a result the standing waves set up can depend on the orientation of the disturbing force relative to the bay. Wind blowing east to west across Lake Huron can be expected to excite standing waves different from wind blowing from the north along the longer axis. Seiches will have properties that reflect the dimensions of the bay, and also its depth.

Edge waves are a final complication. These are travelling (as opposed to stationary) waves that propagate around the rim of the bay. They travel around the bay rather than across it; their properties can be expected to reflect the length and depth profile of the shoreline.

Descriptions of major seiche events on the Bruce Peninsula

Chapter 7 of Sherwood Fox's “The Bruce Beckons”, titled “The Tides o’ Bruce”, is both a wonderful summary of the seiche phenomena in general and a vivid description of a major event in Stokes Bay which he refers to as “the Great Tide”. The weather preceding the event was languorous, the air hot and stifling, what we often associate with the precursor to thunder storms. He was observing the water at a small bridge connecting the mainland to Tamarac Island across a roughly 15 metre channel, now replaced by fill and a culvert. This channel exhibited a pronounced continuous back and forth, what Fox called a “secondary seiche”, but as he watched on that day …

The straight at the bridge was beginning to boil and foam in an unusual manner. Each incoming seiche was rising higher and with more commotion than the one before, and each ebb sank lower and more noisily then the ebb that had just preceded it. The span between high water and low water was now at least a foot and was increasing with each reversal of the current which had now the volume of a stream after a thaw. Though we were standing at the summit of the island 200 yards from the turmoil the roar of it tingled in our ears. The whole scene touched every nerve within us. Even the birds were behaving oddly.

In the eerie twilight, like that of an eclipse of the sun I once saw at Rondeau on Lake Erie, the swallows ceased their skimming over the bay and retired to the rafters of the *old mill as if for the night. In separate flocks the gulls and the crows set out, each flock in his own direction, with the singleness of purpose that marks a homeward flight. The only living thing with in our ken that remained unmoved was a lone great blue Heron. There he stood like a tall grey stick lodged in the muddy bottom of the lagoon. He had the air of waiting for something worth waiting for. He was right. Doubtless having lived all his summers in this region of inlets he had known such a scene before.*

It is hard to match that eloquence, but Appendix 1 includes some first-person descriptions of major seiches observed recently in Tobermory and the west coast of the Saugeen Peninsula. Tracy Edwards describes the eerie sight of the wreck of the Sweepstakes rising out of the water as her boat sank during the withdrawal stage of a seiche in Big Tub Harbour, and with Perry Smith the simultaneous effect on Little Tub. Jack O'Shea shows a photo of his house taken from the lake bottom at the site where his dock normally floated in almost 2 metres of water, and how he had to run for the shore as the water returned. Carol Herman describes the sucking sound as water rushes out of Big Tub Harbour while she was on a December bird count. The Burtons on Baptist Harbour photograph a wall of water moving into that bay.

VERY BASIC MATHEMATICS CONCERNING SEICHES

Terms required when describing seiches.

In a scientific paper like "Seiches and Harbour Oscillations" by Alexander Rabinovitch[1] and you will be confronted with a lot of complicated mathematics. This need not deter us from a less rigorous explanation but it is a reminder that seiches and their interactions with coastal features are complicated hydrodynamic phenomena. Without that mathematics we will not get far below the surface, but some basic concepts are still helpful.

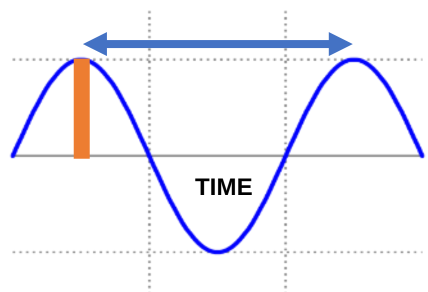

*Figure 3. A sine wave. The red line indicates amplitude and the blue double arrow the period **T**.*

Water waves are characterized by three basic parameters: amplitude, wavelength, frequency and speed of propagation.

Treating each one separately …

<ins>Amplitude</ins>: the height of the wave, in metres, as shown in orange on Figure 3.

<ins>Period</ins>: the time **T**, in seconds, between successive peaks as seen by someone standing on a dock (blue arrow, Figure 4).

<ins>Frequency</ins>: the number of times (**f**) each second the peak occurs at that dock: **f = 1/T** .

[1] See References

<u>Wavelength:</u> if instead of standing on a dock you were to look down on the wave from above, the wavelength **λ** (in metres) is the <u>distance</u> between peaks (yellow arrow, Figure 4).

Figure 4. Swell approaching shore. Arrow indicates wavelength.

<u>Speed of propagation, **V .**</u> Here we have two distinct limiting cases, deep water in which the depth is greater or equal to the wavelength λ, and shallow water in which the water depth H is less than λ/20**.**

Deep water: $\mathbf{V} = \sqrt{(g\lambda/2\pi)}$ (i)

Shallow water: $\mathbf{V} = \sqrt{gH}$ (ii)

…where g is the gravitational acceleration 9.8 m/sec^2.

The period of a seiche in an enclosed basin can be related to the time for a wave to travel from one end to the other and back again. As shown diagrammatically in Figure 5, the time for a wave to go back and forth once, travelling at velocity V, would be:

$$T = 2L/V \quad \text{(iii)}$$

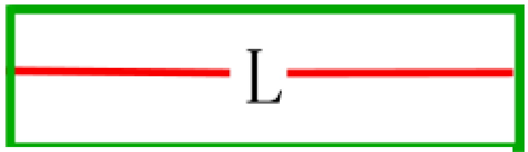

Figure 5. Closed basin, length L

However, most of the embayments we will be dealing with are open to the lake, more closely resembling Figure 6 than Figure 5. With one end open, it turns out that the period from equation (iii) is doubled so that a more reasonable estimate is obtained from equation (iv):

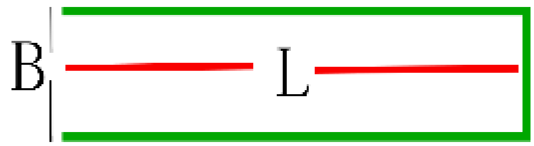

Figure 6. Open basin, harbour mouth width B.

$$T = 4L/V \quad \text{(iv)}$$

Rabinovich expands on equation (iv) by considering solutions for open basins with sloping bottoms and triangular, semi-elliptical and semi-circular cross-sections. These shapes end up replacing the factor 4 in equation (iv) with a factor k that varies between 3.3 and 5.2. Because wavelengths are much larger than depth in these shallow embayments, equation (iii) applies. Accordingly, the resonance frequency for an embayment will be (combining equations (iv) and (ii)):

$$f_0 = \sqrt{gH} / kL \quad \text{(v)}$$

Rabinovich also gives formulae for the harmonics of the fundamental frequency f_0. f_1 will have a frequency of $3f_0$, f_2 will be $5f_0$, and so on. One or more of these might possibly show up in our data.

Some simple examples of these formulae.

1. Swell. If the swells in Figure 3 have a wavelength of 50 m they could travel across a water body 50 m or greater deep at a speed of roughly 9 m/sec. If they were to encounter water depths of 5 metres (say on approaching the Huron shore) they would be slowed to about 7 m/sec, resulting in the increased amplitude observed as swell approaches a beach.
2. Meteotsunamis. If a strong and localized low pressure (e.g.thunderstorm) system were to uplift by a few centimetres and then drop western Lake Huron water over a broad area, creating a wave with wavelength much greater than the lake depth of (say) 200 metres, its speed towards our coast would be about 45 m/sec (160

km/hr). Choosing a wavelength comparable to the scale of the storm, say 30 km, this wave would have a period T=30/160 = .19 hours or 11 minutes. The speed is much faster than swell or chop can move, and the wave might outrun or leave behind the storm that caused it. As it reached the coast of the Saugeen Peninsula it would slow down, build up in amplitude, but retain its 11 minute periodicity. This is comparable to eye-witness reports of the time between successive peaks of major tsunamis (but it must be acknowledged that the 30km wavelength was deliberately chosen to make this so!)

3. Baptist Harbour (Figure 7) .If we assume an idealized Baptist Harbour to have a length L of 900 metres, and depth 3 metres, then the fundamental resonance frequency from equation 5 is (with a k of 4.4) :

   $f_0 = \sqrt{gH}\ /4.4L = 0.0013$ cycles per second or 4 cph. (vi)

   or a period T of 15 minutes which turns out to be very similar to what is actually observed.

Figure 7. Baptist Harbour. The red line indicates the length L (1100 metres) used in equation (v).

   Big Tub Harbour (Figure 8). Taking the length of Big Tub to be 830 metres and its average depth to be 10 metres we get (using equation (vi)) a frequency of 9.8 cph or a period of 6 minutes. This is in very reasonable agreement with the observed value.

So for two harbours that roughly resemble long rectangular basins of fixed depth, this simple model appears to work. Most harbours and bays do not conform to this geometry, so we can expect equation (v) to be less accurate. But the conceptual model of the seiche frequency as being related to the time for a wave to move back and forth across a simple basin is credible.

Figure 8. Big tub harbour, showing the length L used in Equation (v).

Harmonics

The richness of tone of a musical instrument like a flute or cello derives from harmonics that accompany the note being played. Harmonics are simple multiples of the root frequency. Playing the note A of 440 cps (cycles per second) on an instrument will also activate harmonics of 880 cps, 1320cps, 1760 cps, etc. , in amounts that depend on the instrument, that give the simple A the rich tone we recognize. (In high school physics these are usually demonstrated on a vibrating jump rope.) Ocean tides also have harmonics. The fundamental frequency of one high tide every 12.48 hours has smaller but observable harmonics of 6.24 hours, 3.12 hours, etc..

It is therefore possible that the fundamental periods of basin oscillation described by equations (iv) and (v) may be accompanied by harmonics having half, one third, etc. of that fundamental period. They are easier to recognize within the spectra of these recordings, of which a simple explanation is given next.

Spectra.

In the "Tobermory Tides" document the concept of the Fourier transform has been presented in the context of tidal movement and it might be useful to refer to that description. Here we use the analogy to a radio dial.

If we erected a simple radio antenna and connected it via some sort of amplifier to a set of headphones, we would hear a completely unintelligible noise[2]. The genius of a radio receiver is that it can break that noise down into a set of frequencies (think CBC FM, 98.7 megacycles per second, the Dock in Owen Sound, 92.3, etc..) each of which does make some sense to our ears.

The genius of 18th century mathematician Joseph Fourier was to show that any signal viewed as a series of data points in time can be broken down into the sum of individual frequencies (a spectrum), and he showed how to do it mathematically. In the context of our data, where measurements of water level are recorded every few seconds or minutes, the Fourier spectrum consists of a series of sine wave oscillations which when added together would return that original data. It's like the

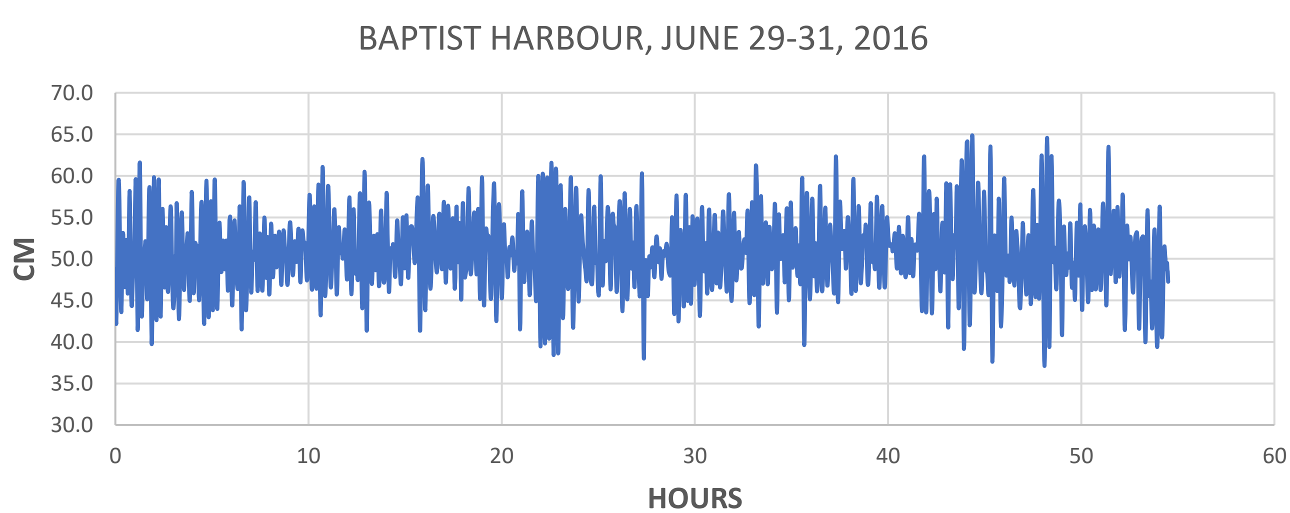

Figure 9. 50 hours of water level variations, Baptist Harbour, June 29-31, 2016

[2] Of course most of it would be out of the range of our ears – an oscilloscope would be a better option than headphones – but ignore that detail to making the point.

transformer toys of a few years ago, capable of looking like a super hero or a monster truck depending on how you twist them, basically two completely different representations of their component parts with a mechanism (or transform) for going from one to the other.

The advantage, when you are looking for oscillatory motion, is that the spectrum shows you which such motions – which frequencies – are contributing most to your data, something that might not be at all obvious from the original data.

As an example, Figure 9 shows an example of water level data measured in Baptist Harbour in June of 2016. The depth of water measured in centimetres is plotted against time measured in hours.

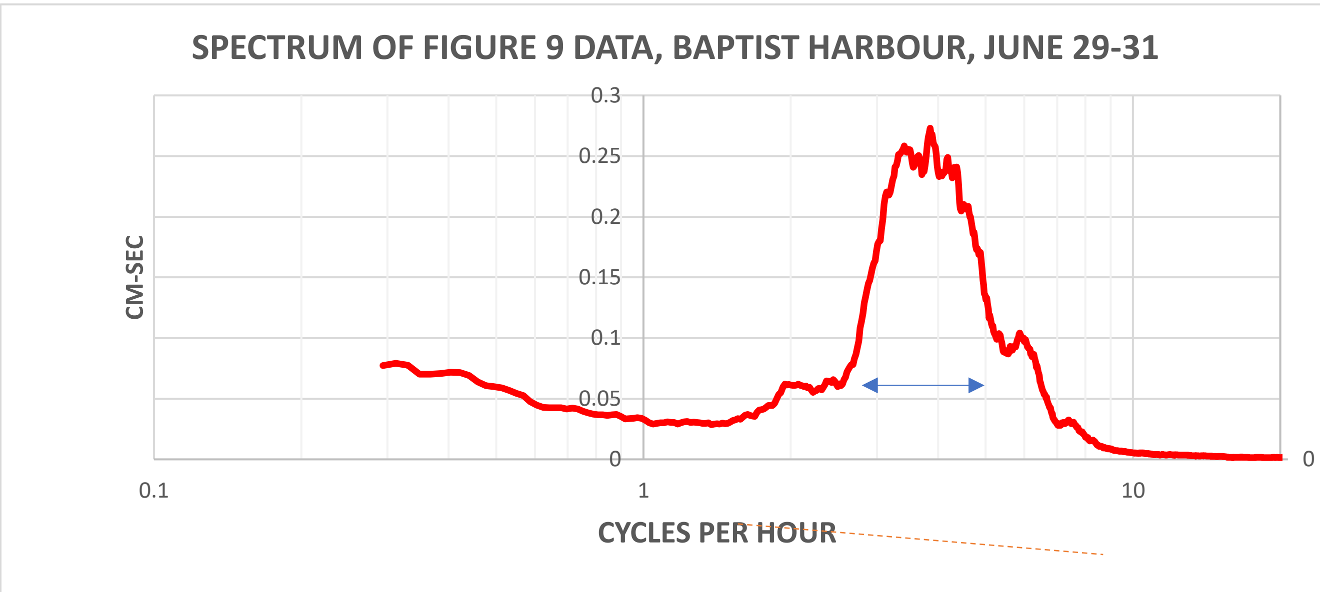

Figure 10. The Fourier spectrum of the data in Figure 9. The arrow indicates the half-width $w_{1/2}$ of the peak, the dashed line an estimate of the spectrum without the peak.

The data in Figure 9 can be Fourier transformed into the much simpler spectrum of Figure 10. The horizontal axis in Figure 10 shows the frequency, measured in cycles per hour (cph) now, and the vertical axis is a measure of how much of the variation in water level is associated with each frequency[3]. The horizontal axis uses a logarithmic scale, as is the custom with spectra, because this allows better definition of the lower frequencies than would a linear scale. In this case the transform is accomplished through an “add-on” to Microsoft EXCEL. Figure 9 and 10 contain the exact same information, just in different form.

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[3] These units are cm per frequency, or cm-sec, a measure of the contribution of each frequency to the observed water level displacement. These are ungainly units and will not be attached to the vertical axis of each spectrum from here on.

Examining these two figures, we see that in Figure 9 that the water level varies continually by 10 to 20 cm. Figure 10, apart from being a much cleaner representation of the data, shows that most of that variation takes place at frequencies tightly concentrated around f = 4 cph, or a repetition period T = ¼ hour or 15 minutes. If Baptist Harbour was a perfect oscillator, say like a pendulum, the spectrum would simply be a vertical line at f=4 cph. In practice the harbor oscillation is slightly variable, perhaps depending on factors like wind direction, but we can say that the dominant periodicity is about 15 minutes. This can easily be confirmed standing on a dock in Baptist Harbour with a stop watch to time the repetition rate of high or low water.   There is also a suggestion of a small energy peak at 6 cph.

The breadth of a spectral peak represents the variability of the repetition rate, and can be represented by its half width, $w_{1/2}$, defined as the width of the peak measured half way between its maximum value peak and its background.   There is a certain amount of subjectivity regarding the background level, but the half width of the main peak in Baptist harbor is always in the range 2-2.5 cph.

The ratio of the peak amplitude to a smoothed background (dashed line in Figure 10) is approximately 10, a measure of the signal-to-noise. This can be thought of as a measure of the quality of the peak information.

The energy in a spectrum can vary considerable from one data set to another, but the half-width and signal -to-noise ratio are relatively constant..

Oscillation amplitude/Signal-to-noise factors.

Why are seiche oscillations larger in some harbours than others? There at least two factors involved.

Harbour shape and depth. As described above, the resonant frequency (f_0) of a simple rectangular harbour depends on its length and depth. Hlevca et al. (2015) also show that the response will be larger the smaller the width of the opening channel (B) is relative to the length of the harbour.

The frequency f of the driving force, waves impinging on the harbour mouth from the lake outside. Common sense tells us that the best way to activate an oscillator like a basin of water or a mass on a spring is to drive it at its resonant frequency, $f=f_0$. So we can expect the maximum seiche amplitudes when the incoming wave energy matches the resonant

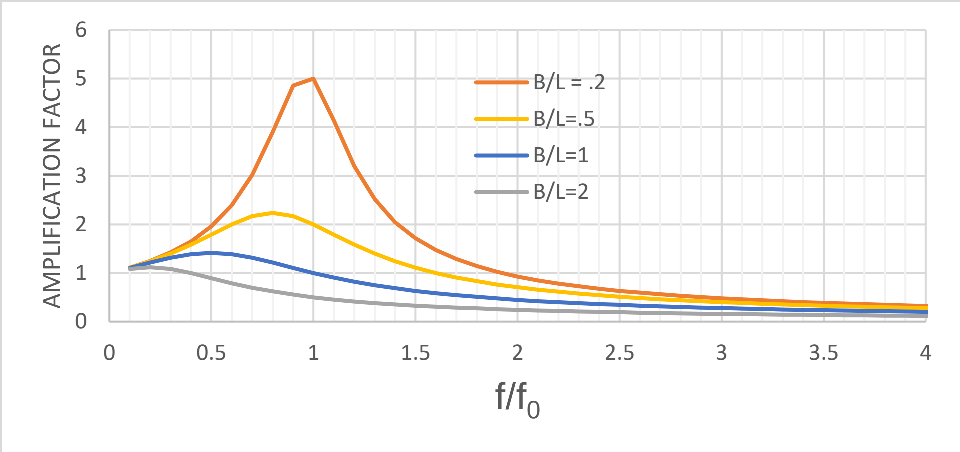


Figure 11. The amplification factor for seiches in a harbour, as a function of the ratio of the driving frequency to resonant frequency ratio (f/f_0) and the harbour mouth with B to harbour length L ratio.

frequency of the basin. Incoming waves with much lower frequency will move the water/spring at that frequency but without amplification. Waves with much higher frequency will not produce a response.

Figure 11 shows an idealized response behaviour as a function of these two ratios, based on equation (13) of Hlevca et al. The main takeaway is that smaller B/H ratios will have larger seiche amplitudes, and that excitation by incoming waves with frequencies close to the harbour resonance will also be more effective in this regard.

Figure 11 is not the whole story, however. Hlevca et.al show that higher frequency incoming energy such as swell can induce resonance within a harbour through non-linear mechanisms, and this may in fact be the dominant driver of oscillations in many harbours.

Seiche modes of Lake Huron.

Lake Huron has its own characteristic oscillations – known as “modes” - determined by its size, depth, wind direction, etc.. Schwab and Rao (1977) measured 4 seiche modes in Lake Huron; these are 0.15, 0.2, 0.304 and 0.43 cph in addition to the diurnal tide at 0.078 cph. As expected of such a large body of water, these frequencies are considerably lower than the resonant frequencies expected to be present in small harbours down our coast. From Figure 11 energy at these low frequencies would be expected to be present but largely un-amplified in the harbours. For small B/H ratios, and for the two highest Lake Huron modes, some amplification is possible.

MAKING MEASUREMENTS

Measurement Locations.

Figure 12 shows the location of all water level measurements made during this study. Each measuring site is associated with a number and details of the site are given in Table 1.

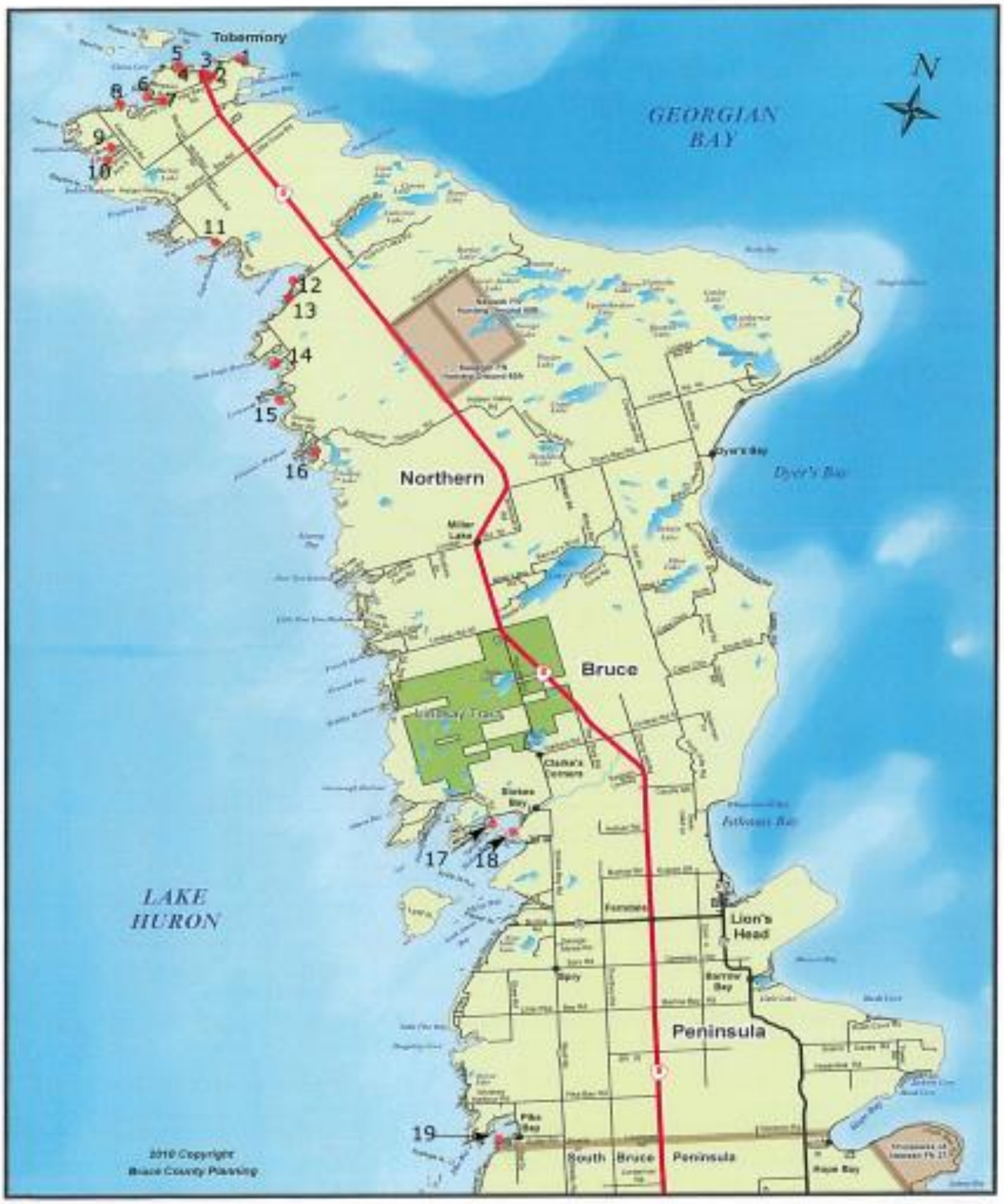
Harbour dimensions and predicted fundamental resonance frequency.

The marine charts provided by i-boating (http://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html) are used to estimate the dimensions and depth of the harbours in Table 1 and with equation (iv) their predicted resonance frequency. The results are shown in Table 2 later in this document, with the measured values from the Data Compilation section which follows for comparison.

Table 1. Location of measurement sites.

Location #	Latitude	Longtitude	Place description
1	45 15 19.61	81 39 4.1	Eversley Point, 65 Grant Watson Drive, Tobermory
2	45 15 24.68	81 39 43.03	Lees Fish Dock, Little Tub Harbour, Tobermory
3	45 15 24.18	81 46.25	Gas dock, Little Tub Harbour, Tobermory
4	45 15 22.04	81 40 27.6	Hopkins Dock, 80 Big Tub Rd, Tobermory
5	45 15 21.04	81 40 49.79	Suke Dock, 195 Big Tub Rd, Tobermory
6	45 14 23.48	81 41 20.9	Rob Davis Dock, 93 Simpson Ave, Tobermory
7	45 14 28.17	81 41 00.88	Russ Davis Dock, 47 Simpson Ave, Tobermory
8	45 14 09.25	81 41 46.24	Woerns Dock, 98 Myles Drive, Tobermory
9	45 12 56.30	81 41 52.97	Edwards Dock, 43 Bayshore Ave N, T0bermory
10	45 12 44.13	81 42 03.11	Burton Dock, 90 Bayshore Ave S, Tobermory
11	45 11 29.51	81 37 47.93	Shore, 662 Warner Bay Rd, Tobermory
12	45 11 11.05	81 34 49.30	Shore, 168 Dorcas Bay Rd, Tobermory
13	45 10 43.16	81 34 52.78	Dock, 278 Dorcas Bay Rd, Tobermory
14	45 09 05.02	81 34 58.81	Public Access, Harbour Circle, Tobermory
15	45 09 05.22	81 34 35.3	Dock, Howard Bowman Drive, Tobermory
16	45 07 20.81	81 32 39.36	Public Dock, Johnson's Harbour
17	44 59 33.61	81 23 05.26	Government Dock, Stokes Bay
18	44 59 34.55	81 22 20.22	Dock, Heron Point Campground
19	44 52 14.68	81 19 26.16	Dock, By The Bay Resort, Pike Bay

Figure 12. Map of the Northern Bruce Peninsula showing the location of the measuring stations. Numbers are referred to in Table 1.



Measuring Instruments.

Variations in water level at these sites were made using three main types of instruments: temperature changes as a thermistor is alternately submerged and exposed, ultrasonic measurement of the distance to the water surface from a fixed transmitter/receiver above that surface; and measurements of pressure changes by a detector placed on the lake floor.

In all cases readings were made at least once a minute. The devices were placed in sheltered locations to minimize the effects of chop on the lake surface which, occurring at much shorter time scales, can distort the spectrum.

Thermistors.

The earliest measurements in Baptist Harbour consisted of temperature readings made at the mean water surface. DS18B20 thermistors (~$5, Figure 13) were used in conjunction an Arduino UNO microcomputer (~$30). Several DS18B20s can be connected to a single wire and individually addressed. This capability, combined with some very basic C programs, can sample, transmit and/or store the thermistor data. As the water level rose and fell, the seiche frequency was determined via exposing and submerging the thermistor. In practice as many as 4 thermistors were sampled, one just above, one just below, one in the middle of the water column and one on the bottom. To minimize the effects of wave action the thermistor string was placed in a tube open at top and bottom. Crude, but reasonably effective in this strong seiche environment, this technique was soon abandoned.

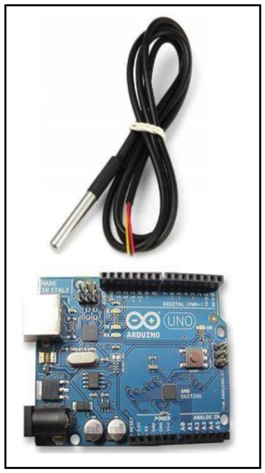


Figure 13. Waterproof thermistor with Arduino UNO micro-computer.

Ultrasonic measurements.

To measure movement of the water surface more directly, small ultrasonic distance detectors were combined with the Arduino and an onboard sd card. Again, to minimize the effects of waves, the measurements were made in a 4inch ABS pipe (Figure 15). End caps with small holes were attached top and bottom and the lower one third of the pipe was filled with fine gravel. The HC-SR04 detectors (Figure 14) cost about $5, have a range between 2 and 200 cm with an accuracy of .5 cm. With power from small 6 volt rechargeable batteries the device can make measurements of the distance to the water surface once every few seconds for about a week.

In practice this arrangement worked well most of the time, but small misalignment of the detector beam

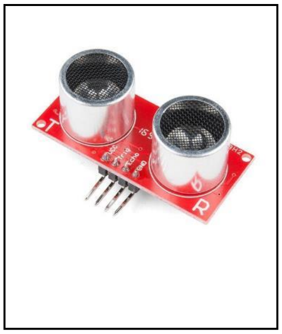


Figure 14.The HCSRO4 ultrasonic detector.

could lead to multiple reflections which would give random errors. The detectors are cheap but some worked better than others. The concept is workable, but a wider tube and a more robust ultrasonic detector would have improved the operation.

Pressure measurements.

Fathom Five National Park lent two Onset Hobo U-20 water pressure detectors (Figure 16) to this project, and these were used for most of the measurements described here. The U-20 has a depth range of 0 to 4 metres, and a resolution of .5% depth, typically 0.5 cm in the depth range we operated. They are powered by internal batteries that seemed to last indefinitely, and the onboard data logger can store almost 2 weeks of pressure data at 30 second intervals, half that if temperature is also recorded.

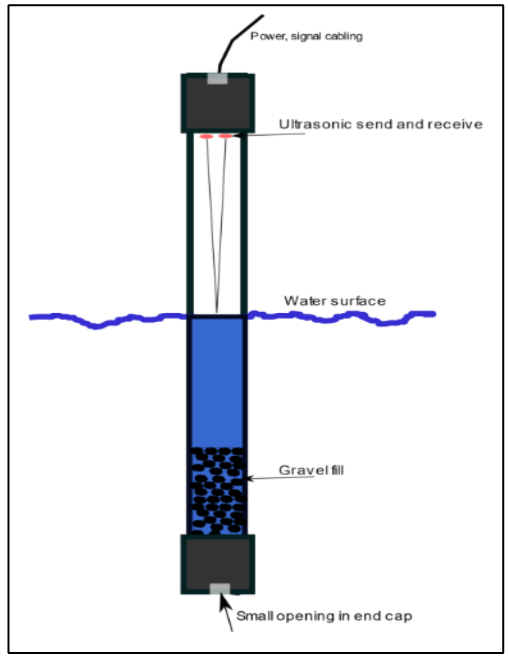


Figure 15. Ultrasonic detector mounted above water level in 4" tube . Gravel calms wave action.

To accurately measure water depth from pressure measurements the lake-bottom U-20 installed would record both temperature and pressure, and be run in conjunction with a U-20 on the surface to record the changes in atmospheric surface pressure that contribute to the bottom pressure measurement. Since our goal was measurement of <u>variations</u> in water level, not water level itself, the absolute accuracy of the depth was not important. Moreover, since the time scale of seiche-related variations range from minutes to a few hours, the largely daily variation in temperature was not considered important enough to limit the length of time (by half) that the unit U-20 could be left on the bottom. For atmospheric pressure the hourly readings provided by Environment and Natural Resources Canada was considered adequate, but again the time scale of these pressure variations is for the most part much longer than those we are interested in. Based on these assumptions, and because our interest lay in comparing the water level variations between sites, the pair of U-20s were deployed simultaneously in different locations measuring pressure only.[4]

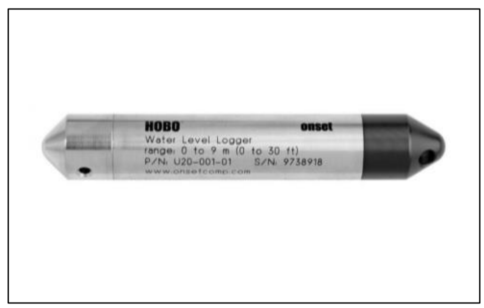


Figure 16. Onset Hobo U-20 water pressure and temperature logger.

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[4] More recently I have experimented with using the tube of Figure 15 with a pair of Adafruit BME 280 pressure, temperature and humidity sensor. One is placed in the tube to measure air pressure and the other outside to measure atmospheric pressure. The difference between the two readings is a measure of the water height. This measurement has proved remarkably stable in a test environment but has not been implemented in the lake.

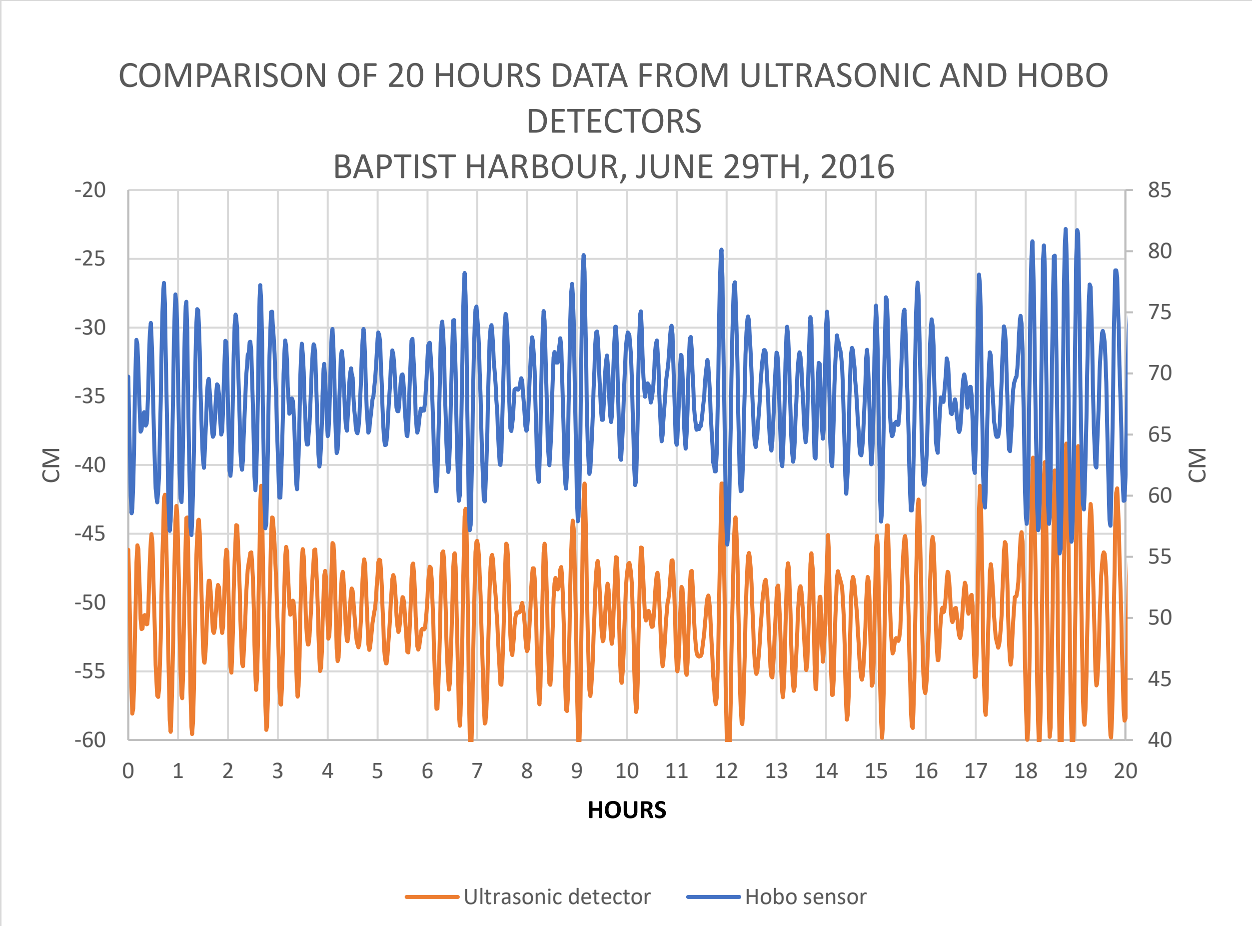

Figure 17. Twenty hours recording of water level variations at Baptist Harbour, comparing the Hobo and ultrasonic detectors. Distance to water measured by the ultrasonic detector is on the left hand axis, depth of water above the Hobo is on the right hand axis.

Comparison of pressure and ultrasonic detectors at Baptist Harbour.

Figure 17 shows 20 hours of water level variations measured in Baptist Harbour in 2016 using both the Hobo and ultrasonic detectors. The Hobo measures the height of water above the bottom sensor, whereas the ultrasonic unit records the distance to the surface of the water below the detector. For comparison the ultrasonic measurements have been inverted. The water level variations measured by the Hobo are slightly larger in amplitude than the simultaneous ultrasonic variations, possibly the result of not taking temperature into account in the former. Since our interest is in the time scale of the variations, not their amplitudes, this slight discrepancy is not a factor.

Water level gauges, meteorological data. In addition to these instruments we have access to water level measurements at several gauges around the lakes operated by Fisheries and Oceans Canada and NOAA in the US. Tobermory and

Goderich are the most useful for our purposes, and in some cases gauges in Thessalon, Little Current, Parry Sound, Midland, Collingwood and Alpena, Michigan, gauges have been consulted for comparison. The Canadian gauges take readings every 3 minutes, and they can be downloaded as .csv files from http://www.medssdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/list-listeeng.asp?user=isdm-gdsi&region=CA&tst=1.
The Hobo instruments require atmospheric pressure data to properly convert their readings to water depth. These data are available for download as hourly readings from Environment and Natural Resources Canada at:
http://climate.weather.gc.ca/climate_data/hourly_data_e.html

DATA COMPILATION

In this section the spectra of the 19 locations in Figure 12 and the gauges at Tobermory and Goderich are displayed, with comments. These spectra have been smoothed sufficiently to remove unwanted noise while leaving the significant peaks clearly visible. Unless otherwise specified, the spectra have been confirmed from two or more independent records of water level variation.

The gauges: Tobermory and Goderich Harbour.

Sampling every three minutes limits the spectra of these gauge site to frequencies lower than 10cph. The calculated resonant frequency of the Tobermory Harbour falls above that threshold, and we cannot expect to see it on these records. Figure 18 shows two spectra each for Goderich and Tobermory gauges, all transformed from a full month's data recorded in September 2017 and April 2018.

Note the consistency of the spectra at each gauge, and this can be further confirmed by Fourier transforming almost any time interval at these gauges. Note also that the peak energies vary between the two sites. This is hardly surprising since the two gauges are 173 km apart and Tobermory is influenced by Georgian Bay. Three of the normal modes are quite well matched at the Tobermory gauge, but only the 0.15 cph mode at Goderich. The Goderich spectrum peak at 4.4 cph matches the model value very well[5].

[5] I have resisted the urge to choose lengths, depths and k factors to produce resonances that match the data but, that said, the model is a very simplified version of the actual harbour and matches this close simply fortunate.

The peaks in the vicinity of 1 cph, though slightly offset at the two gauges, are fairly ubiquitous on our records and, like the normal modes, may be characteristic of the lake in this area. There is pronounced energy in the vicinity of 1.6 to 2 cph at the Tobermory gauge. As will be discussed below in the discussion of Locations 1, 2 and 3, this might be

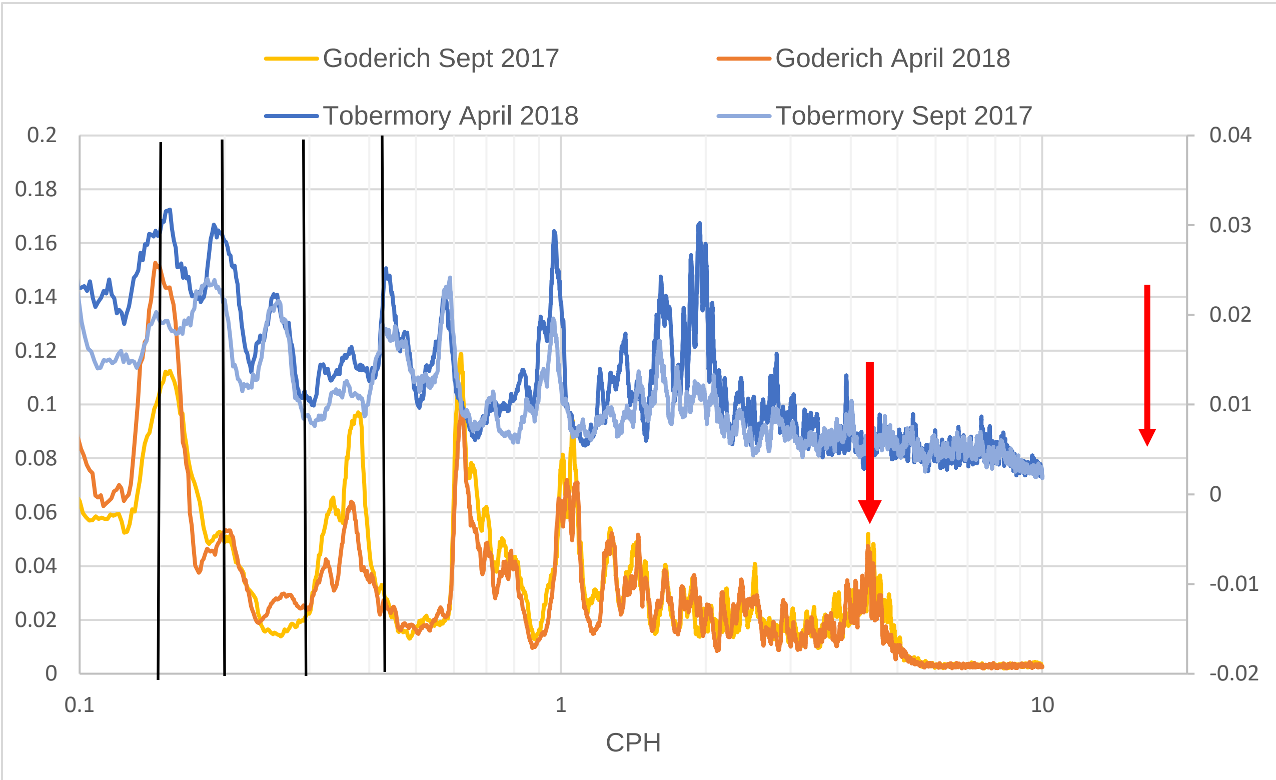

Figure 18. Spectra of two separate months of water level variation data at the Goderich and Tobermory gauges. The black lines represent the Lake Huron normal mode frequencies. The heavy red arrow shows the modeled resonance frequency for Goderich Harbor (Table 2) and the lighter arrow the same for Tobermory Harbor.

associated with resonance of the larger bay separating the Tobermory harbours from the lake proper.

Location 1, Eversley Point.

Located along the north coast (Figure 19) of the peninsula, this site is alone in <u>not</u> being within an embayment that would be expected to have characteristic oscillations. Like Tobermory Harbour, Eversley Point is located on the Georgian Bay side and its spectra may not be typical of Lake Huron to the west.

Figure 19. Location of Eversley Point (#1) with respect to Little Tub Harbour.

In Figure 20 the spectrum of 115 hours of recording is compared with that obtained simultaneously at the Tobermory gauge. The three peaks at 0.55, .98 and 1.46 cph, being common to the two sites, are taken to be characteristic of this area of Georgian Bay. The normal mode peak at 0.43 cph is not present here (as in the data of Figure 18)

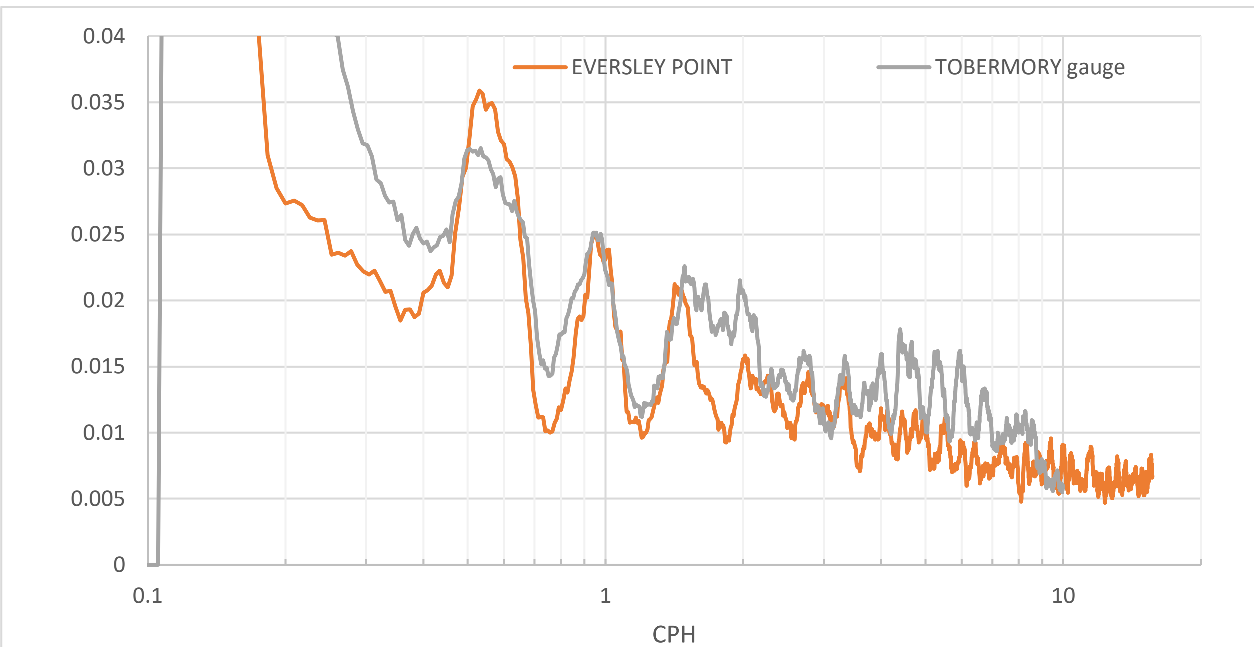

Figure 20. Spectra at Eversley Point compared with simultaneous recording at Tobermory gauge. The vertical blue line indicates the 5th oscillation mode of Lake Huron, 0.43CPH (Schwab and Rao, 1977).

but the peaks at 0.55, 0.98 and 1.46 cph match pretty closely the counterparts in Figure 18. As they are common to both the Tobermory gauge and Eversley point they can be identified as properties of the lake, at least locally. The Tobermory gauge has energy spread over the 1.5 to 2 cph range that is not matched at Eversley point and, as stated above, might represent resonances within the larger Tobermory Bay outside the two harbours.

Locations 2 and 3: Little Tub Harbour.

Figure 22 shows spectra recorded by two Hobos in Little Tub Harbour (Figure 21) over 10 days in November 2016, using a 0.5 minute sampling interval. The Tobermory gauge spectrum for the same period is shown for comparison.

The two Hobos situated on either side of the Harbour at Lees dock and the gas dock have identical spectra, confirming that the motions are harbor wide, not localized. The simultaneous Tobermory gauge spectrum confirms the presence of the three prominent frequencies of Figure 22, near .50, .93 and 1.45 cph as in Figures 18. Again there is a broad peak between 1.5 and 2.0 cph.

Figure 21. Locations #2 and #4 on either side of Little Tub Harbour.

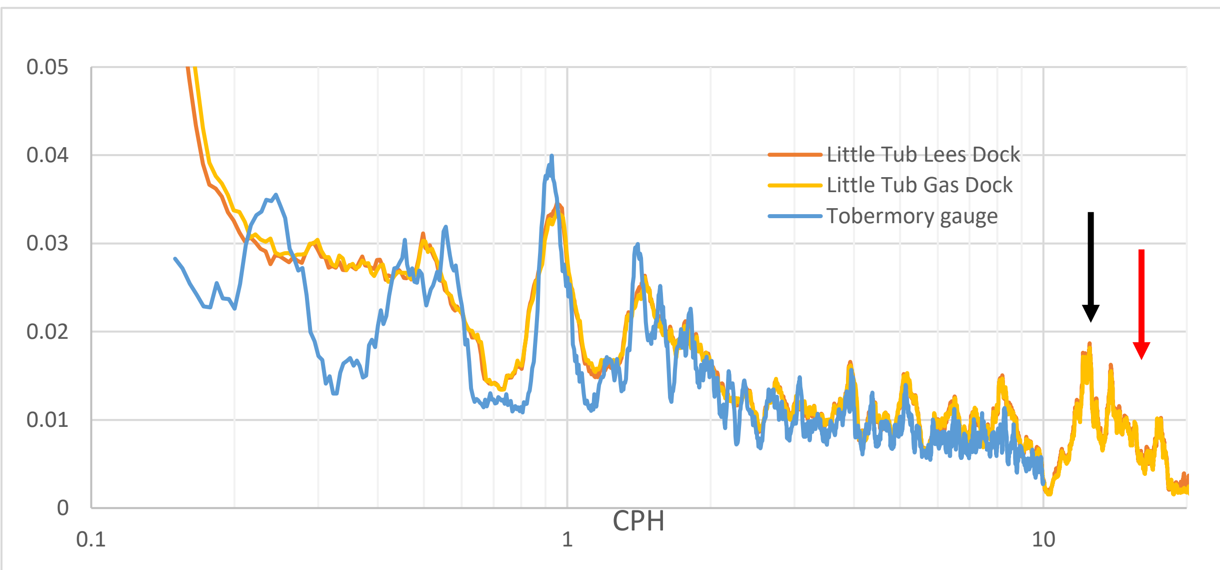

Figure 22. Spectra for Hobo stations on either side of Little Tub Harbour, November 2-10, 2016, together with that of the Tobermory gauge. The black arrow indicates the presumed resonance peak, the red arrow the model estimate.

The Tobermory gauge spectrum, clearly similar to those of the two Hobos in general, is different in minor detail. One reason for this is the lower sampling rate of the gauge (3 minutes compared with 30 seconds) which results in higher frequency energy being folded back into the lower part of the spectrum (termed "aliasing"). Atmospheric pressure effects have not been subtracted from the Hobo data, but these are almost certainly very minor on time scales below 4 hours. Finally, the mechanism of measurement is different for the two data sets, but we are not familiar enough with details of the gauge construction to comment on that.

The spectral peak which is thought to represent the resonant frequency of Little Tub harbour is centred on 13 cph (period of 4.5 minutes), reasonably close to the predicted value of 17 cph. This peak cannot be detected with the 3 minute sampling at the gauge.

Locations 4 and 5, Big Tub Harbour (Figure 23).

Figure 23. Locations 4 and 5, Big Tub Harbour

Figure 24 shows 10 hours of representative data recorded at locations 4 and 5 on either side of Big Tub Harbour. The records from the Tobermory gauge is shown for comparison. The two Big Tub records (offset for clarity) are obviously very similar in shape (0.96 correlation); the record at the Suke dock has larger amplitude than at Hopkins which probably reflects the shallowing of the harbour at the Suke site. These oscillations are completely different from those at the gauge just around the point. A count shows there are between 9 and 10 complete oscillations per hour in Big Tub, a period of 5-6 minutes. Figure 25 shows the spectra for the two Big Tub sites. The most prominent peak is at 10 cph with a less prominent one at 8 cph. The 10 cph peak is very close to the predicted resonance. Note the triplet of peaks at .53 and .98 and (though less pronounced) 1.45 cph are present here as well. There is also a suggestion of the broad peak between 1.5 and 2 cph seen in Little Tub. A study in Big Tub by Flood (2016) found a broader spectral peak centred on 4.1 minutes compared to our well-defined 6 minute period. The cause of this difference is not clear; we have not had a chance to evaluate their data.

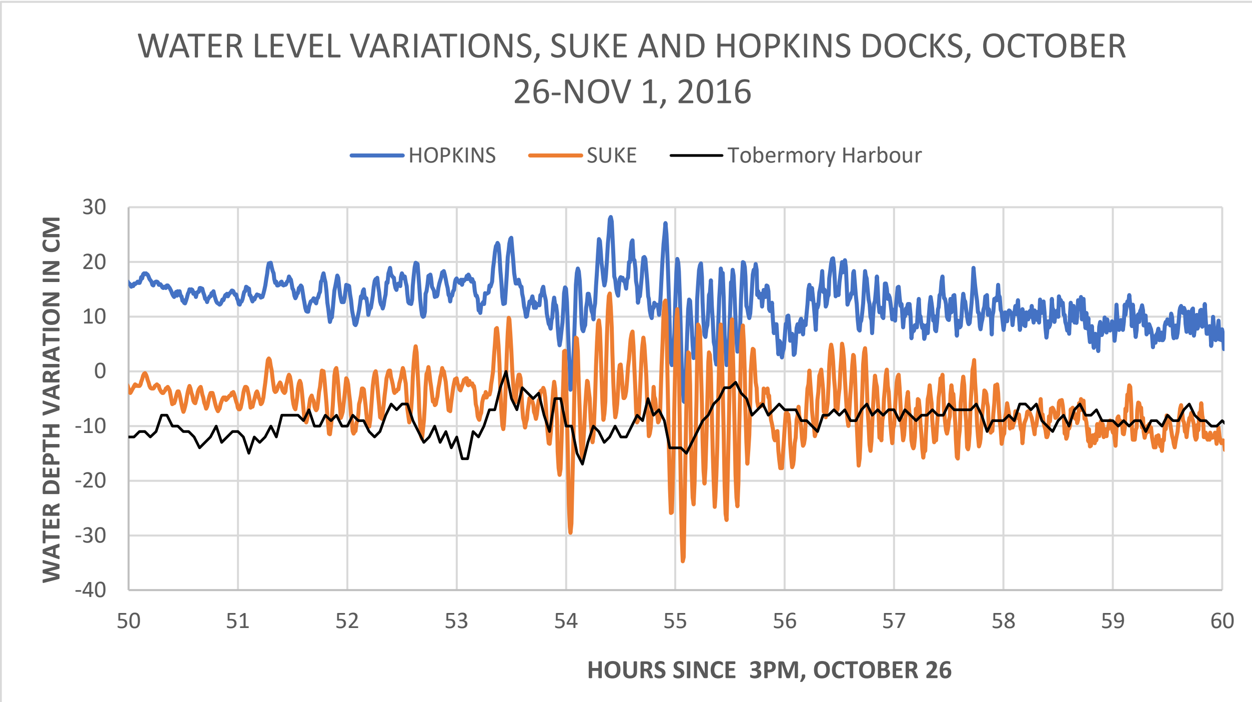

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Figure 24. Ten hours of water level variations recorded at Hopkins and Suke docks on either side of Big Tub Harbour. The recording at the Tobermory gauge is shown for comparison.

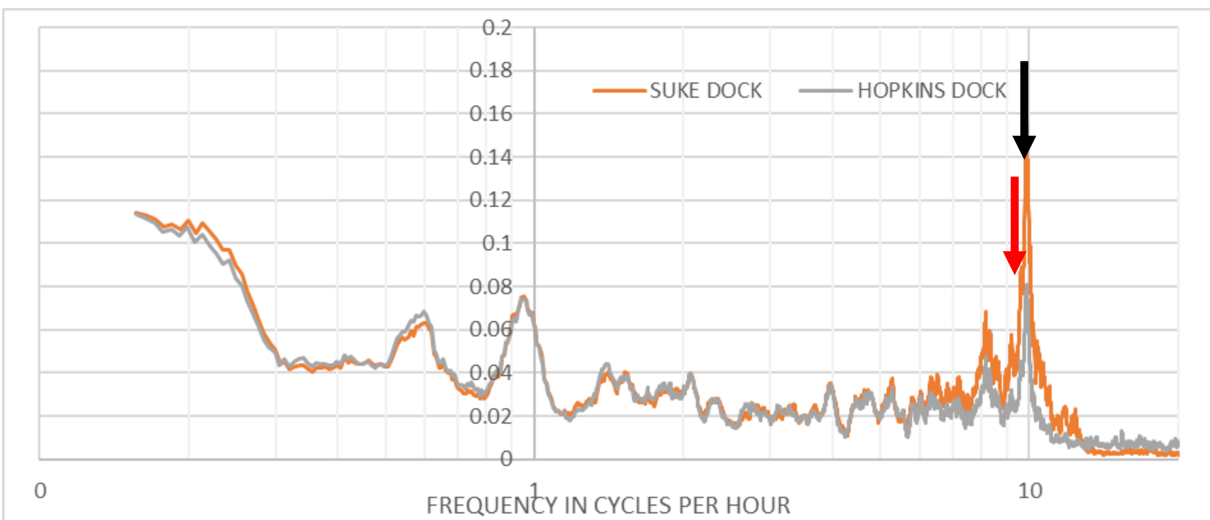

Figure 25. Spectra for the recordings at Suke and Hopkins docks, Big Tub Harbour, October 6-Nov 1, 2016. Red and black arrows indicate the predicted and observed resonance frequencies. Units of the vertical scale are cm-secs.

Locations 6,7 and 8, Hay Bay.

Figure 26. Hay Bay, showing locations 6 (Rob Davis Dock), 7 (Russ Davis Dock) and 8 (Woerns Dock)

Figure 26 shows the locations of three measuring locations on Hay Bay and Figure 27 the spectra of water level variations recorded at these sites. The Woerns and Rob Davis dock data were recorded simultaneously over one time period, the Russ Davis and Rob Davis dock data at a different time period.

Note that the two spectra at the Davis dock, measured at different times, are very similar in shape. Comparing the three sites we note that the spectral shapes are also very similar, but the amplitude increases as one goes farther into the bay. Presumably this reflects the width and perhaps average depth of the bay at each location. There are prominent peaks in all four spectra centred on 2.3 and a lesser peak centred at 4.4 cph (24 and 13.5 minute periods). The predicted resonance frequencies are in reasonable agreement with these two prominent peaks.

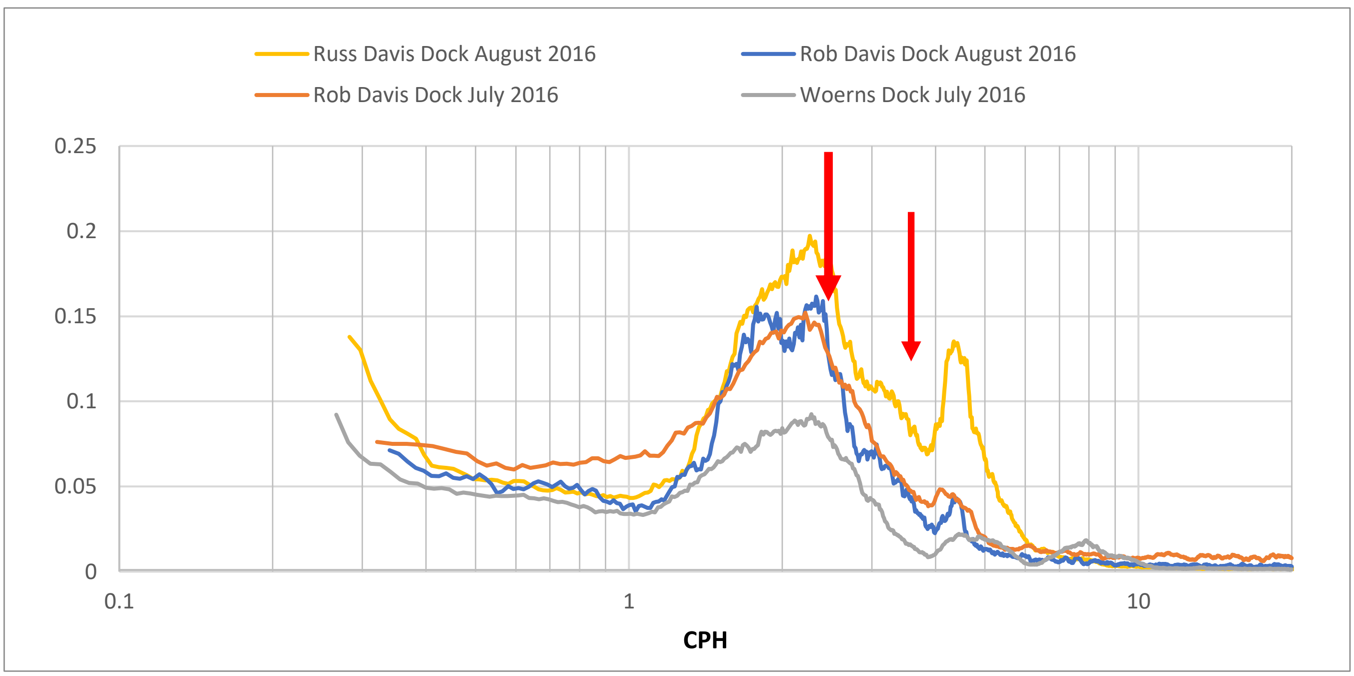

Figure 27. Spectra for locations 6 (Rob Davis) ,7 (Russ Davis) and 8 (Woerns) in Hay Bay. Thick and narrow red arrows indicate predicted resonances for the bay as a whole and the narrow extension where #7 is located.

The narrow peak at 4.4 cph, while present on all four spectra, is greatly amplified in the narrow extension of the bay where #7 is located. This frequency is reasonably close to the value predicted for the extension itself; however, it may be that the 4.4

cph is actually a multiple of 2.3 cph which is amplified because of the geometry of the extension.

These peak frequencies are unique to Hay Bay and we therefore assume they are developed by that particular bathymetry. Woerns dock is very close to the point described in the Forward (see also cover photo) where a tiny stream was observed to reverse every 8-12 minutes. This may explain the very small peak at 8 cph in Figure 26 at that location.

Locations 9 and 10, Baptist Harbour (Figure 28).

Locations 9 and 10 are in the middle and the mouth of Baptist Harbour respectively. Five hours of simultaneously recorded data are shown in Figure 29. The two records are very similar, but the amplitude of the water level variations are highest at Edwards dock in the middle of the inlet where the water is shallower and the width narrower.

Figure 28. Locations 9 and 10 Baptist Harbour.

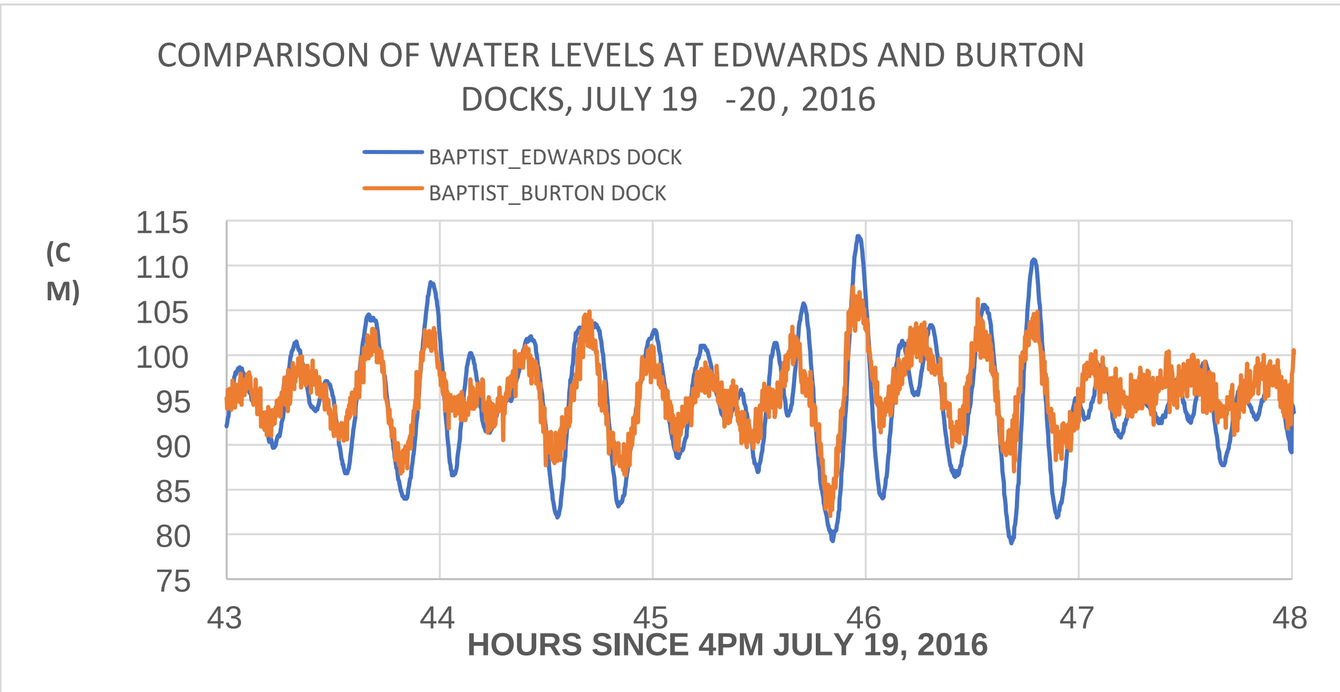

Figure 29. Five hours of water level variations at Edwards and Burton docks, Baptist Harbour

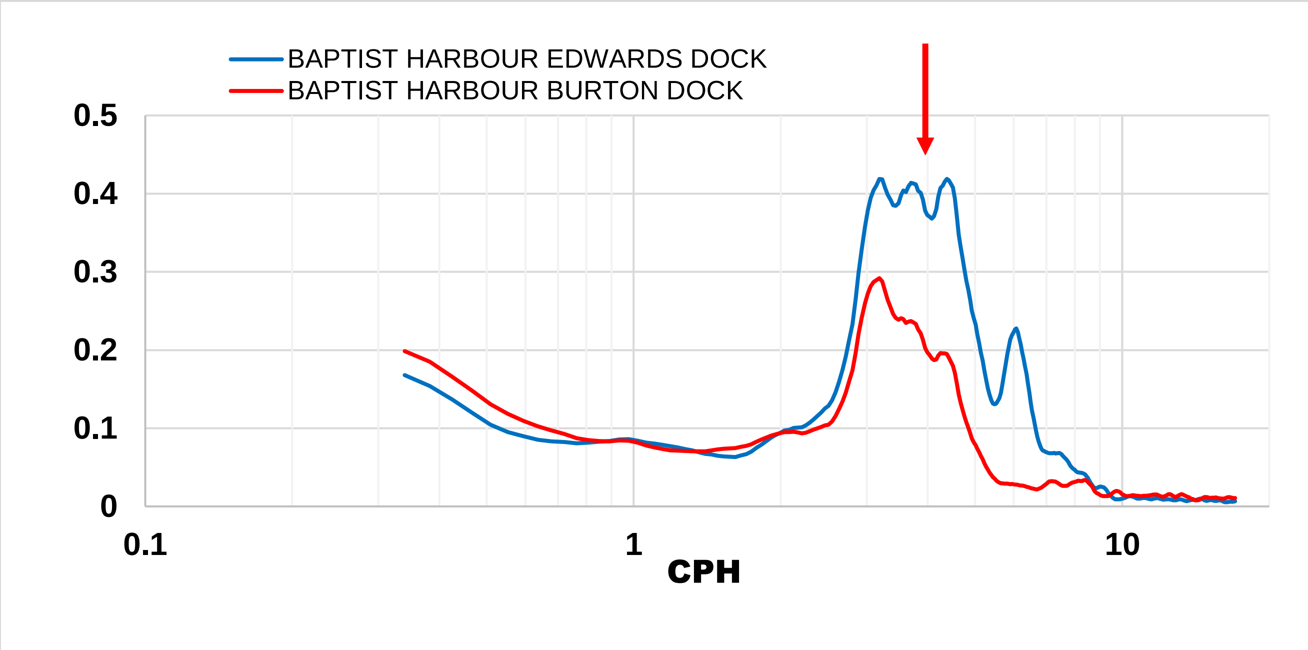

Figure 30. Spectra recorded at Edwards and Burton docks, Baptist Harbour, July 19-20, 2016. The red arrow indicates the predicted resonance frequency for this harbour.

In Figure 30, the Edwards dock spectrum is very similar to the Figure 10 version. The amplitude of the spectrum at Burton's dock is smaller, as expected, and that spectrum lacks the 6 cph secondary peak.

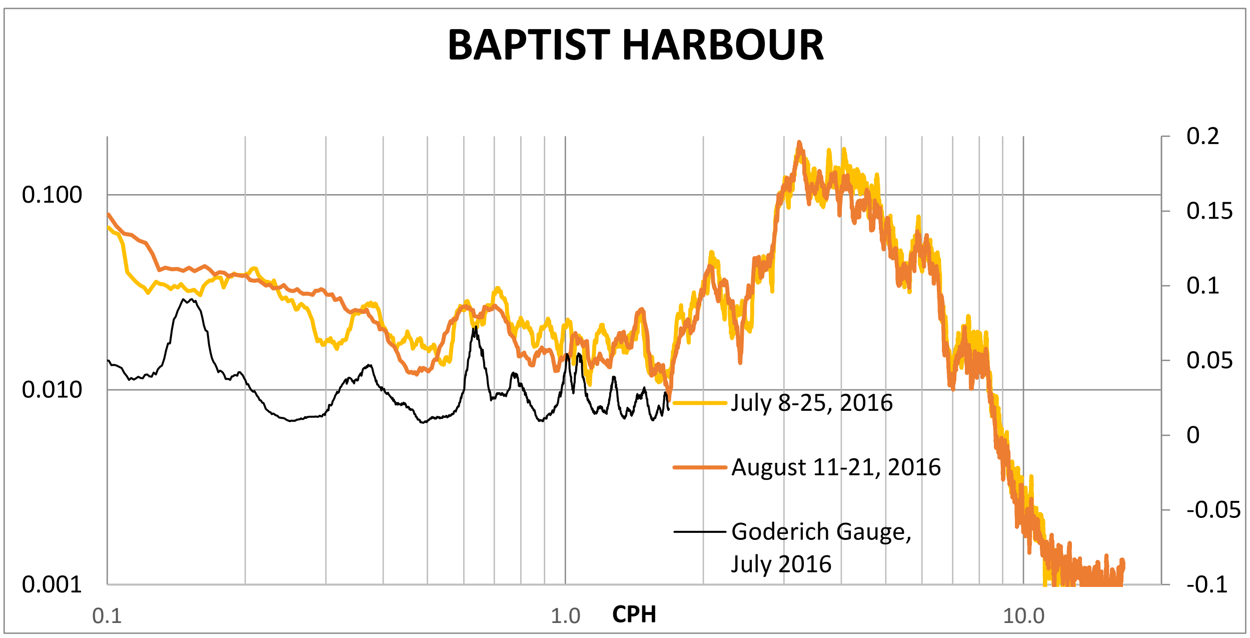

Figure 31. The spectra for two multi-day records of water level variations at the Edwards Dock. The low frequency spectra for Goderich gauge is shown for comparison. A log-log scale is employed to show detail of the low frequency sections.

The spectra of Figure 30 have been heavily smoothed to show the main features. To illustrate the finer structure of the spectrum at Baptist Harbour, and to show its stability with time, Figure 31 shows the very lightly smoothed spectra of two long segments of data (10 and 17 days) from the Edwards dock location. Because the size of the resonance peak tends to dwarf the lower frequency structure a log-log scale is used.

The similarity of the completely independent spectra is remarkable, not just in the overall shape but in the fine structure as well. Two well defined smaller peaks at 2 and 6 cph now straddle the main 4 cph resonance. The low frequency spectra (below 1cph) are also reasonably consistent, and show some similarity to that of the Goderich gauge 170 km to the south. There was less similarity with the Tobermory gauge.

Figure 32. Location of the Warner Bay (11), Dorcas Bay (12) and Ligeti Inlet (13) measurements.

Locations 11, 12. Warner Bay, Dorcas Bay and Ligeti Inlet (Figure 32).

Simultaneous data were obtained from Hobo sensors in shallow water off properties in Warner and Dorcas Bays during several days in September, 2016. A 20 hour record of water levels at these two sites is shown in Figure 33. Of particular interest in this record is the burst of activity between 25

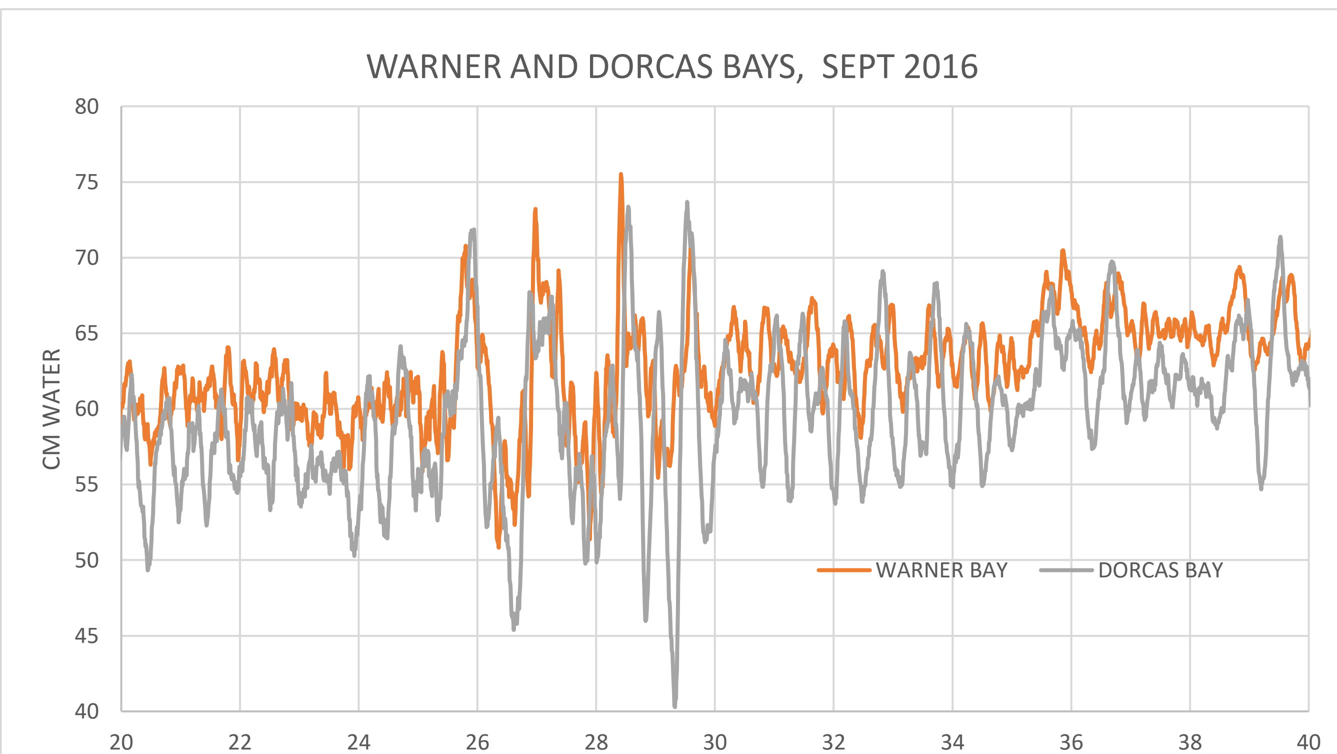

Figure 33.Twenty hours of water level variations measured in Warner and Dorcas Bays, September 2016.

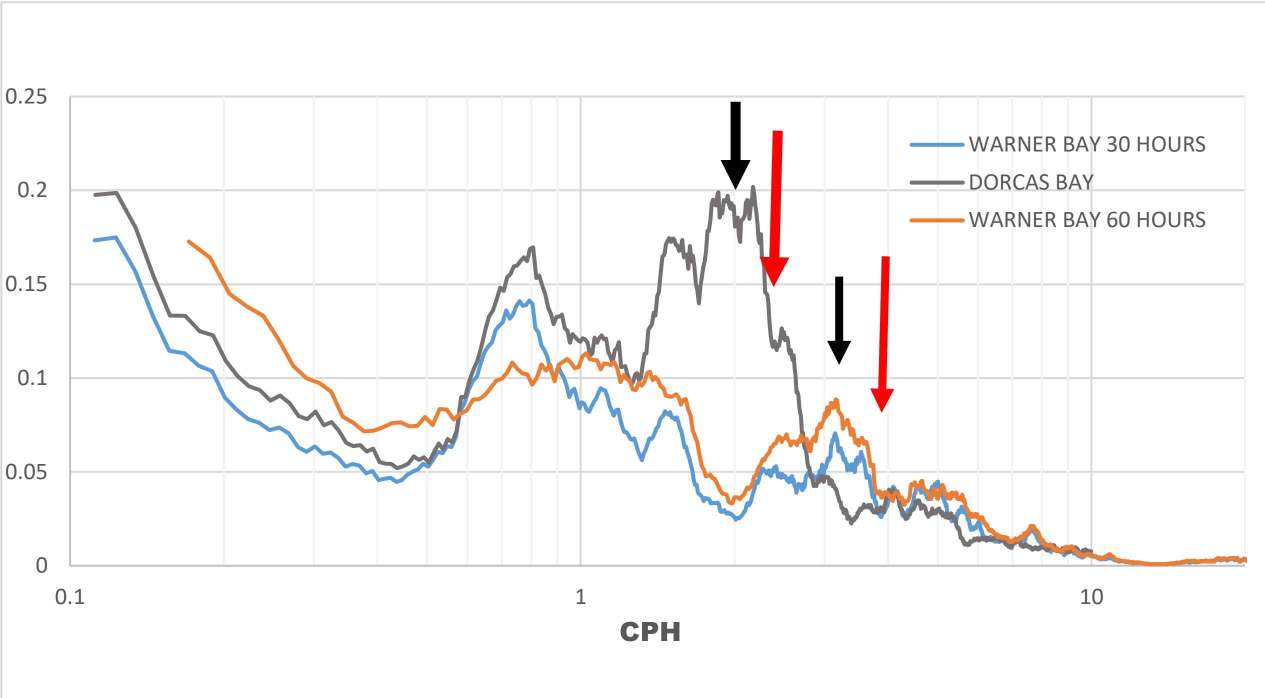

Figure 34. Spectra of the water level variations in Figure 32. The 30 hour Warner Bay record includes the strong event between 25 and 30 hours in Figure 32; the 60 hour Warner Bay spectra does not. Red and black arrows indicate the predicted and interpreted resonant frequencies, the thicker arrows for Dorcas Bay and the thinner for Warner.

and 30 hours which produces a series of 4 peaks <u>on both records</u> spaced on average by 70 minutes (0.87 cph). The fact that they disrupt both harbours, and appear unrelated to what we estimate to be their natural resonance, suggests they originate from motions in the lake outside.

Figure 34 shows the spectra of these two records, with a second Warner Bay spectrum that does not contain the activity between 25 and 30 hours. The prominent peak at 0.82 cph is common to both spectra and we suggest reflects energy from outside the harbours. Beyond that there is a prominent peak at 2 cph at the Dorcas Bay site but very little sign of energy near 6 cph which would match the roughly 10 minute variation in water levels that bathers can watch at the Singing Sands shore. The Warner Bay spectrum is suprisingly featureless beyond 1 cph but there is a weak peak centred on 3 cph.

The Ligeti Inlet spectrum is compared to Dorcas bay's in Figure 35. This small narrow inlet displays its own fundamental frequency of 3.8 cph in addition to the broad peak associated with Dorcas Bay to which it is attached.

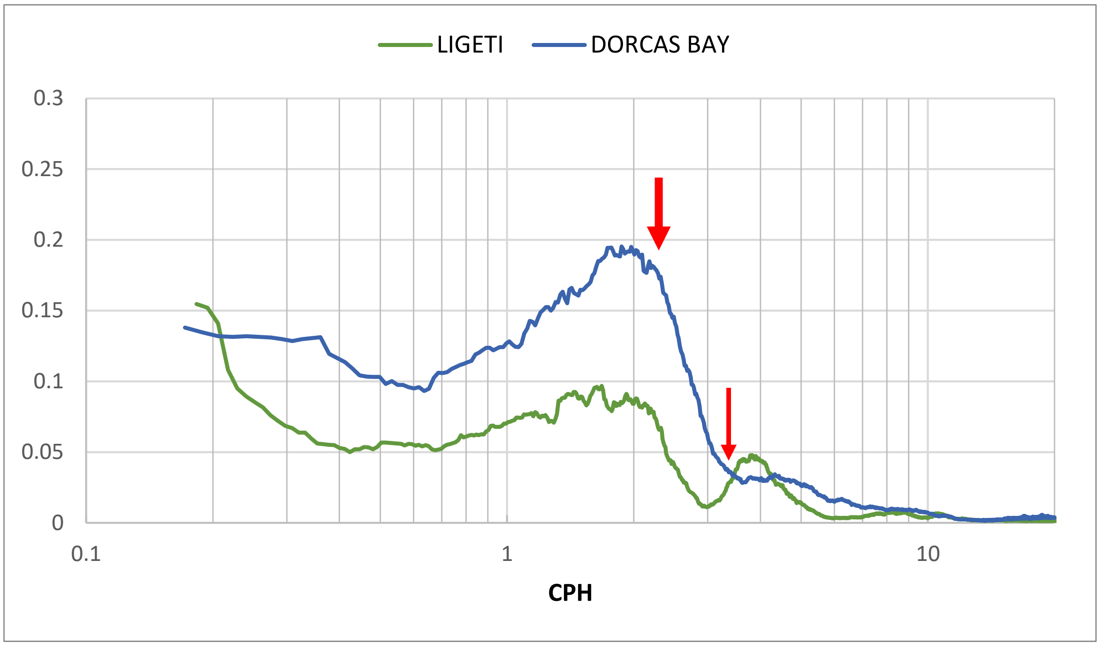

Figure 35. Spectra for Dorcas Bay and Ligeti Inlet for the period August 9-13, 2016. The thick and thin arrows represent the estimated resonance frequency of Dorcas Bay and Ligeti Inlet respectively.

Locations 14 and 15, Harbour Circle and Little Eagle Harbour.

These two locations were occupied in different years, the Harbour Circle site at a public dock in Little Eagle Harbour on a private dock on Howard Bauman Drive (Figure 36). In Figure two separate spectra are shown for Little Eagle Harbour, and one for Harbour Circle. The relative amplitudes are not meaningful as they were all three recorded over different time periods. Red arrows estimate the resonant frequencies of the two sites. The spectral peaks are basically the same for the two sites, suggesting that they are part of a larger oscillation pattern within the bay as a whole. It is also possible that the higher frequency peak (~6 cph) is just a harmonic of the lower one (3.2 cph), and not associated with a specific branch of the three-branch harbour.

Figure 36. Locations of Harbour Circle (14) and Little Eagle Harbour (15) measurement sites.

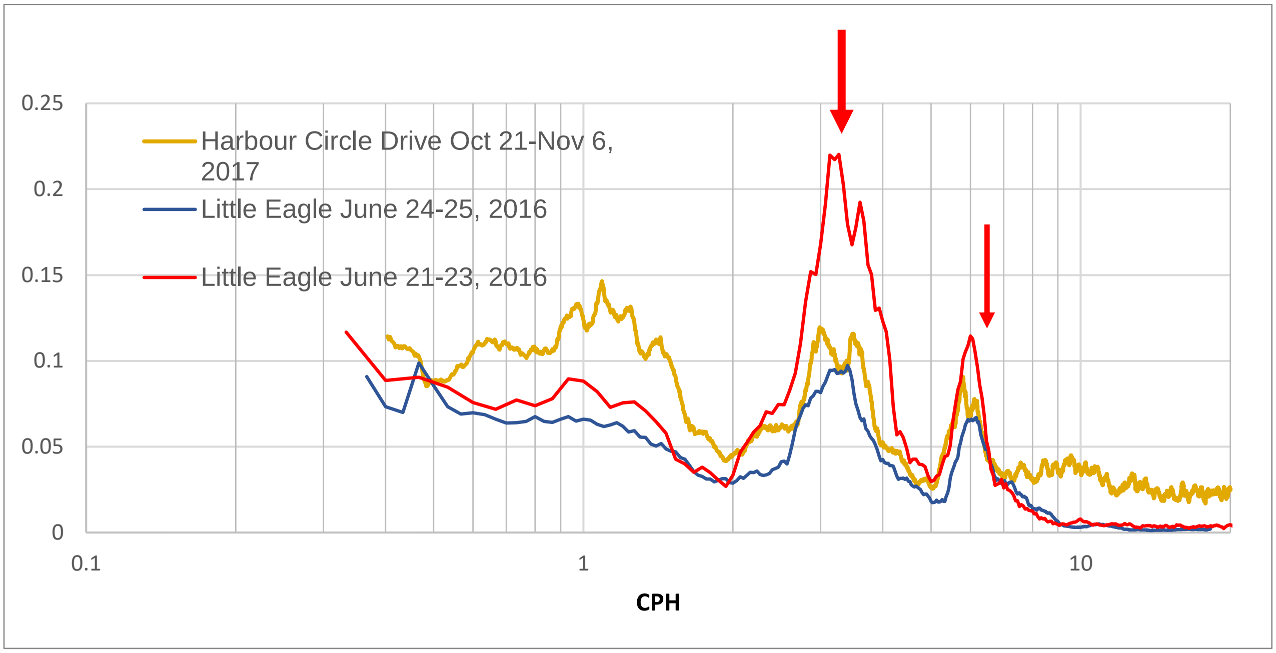

Figure 37. Spectra at Little Eagle Harbour for June 21-23 and June 23-25, 2016, compared with that of Harbour Circle Drive. The thick red arrow indicates the predicted resonance for Harbour Circle, the thin for Little Eagle Harbour

Johnsons Harbour (#16).

Water level variations were recorded by a Hobo located off the public dock as shown in Figure . The recordings here coincided with measurements being made at the foot of Harbour Circle Drive (location 14, previous section). A 20 hour section of the 240 hour recordings is shown in Figure 39. These records exhibit no clear strong periodicities but they are unusual in that they exhibit a strong event between 144 and 145 hours which changes the water level over 50 cm in 20 minutes at Harbour Circle Drive. The record at Tobermory gauge, also shown, records a 15 cm variation over the same period. Note that the sampling rate in Tobermory, 3 minutes, is one third of that at the other two sites and therefore may not record the full range of water level variation. We return to this event in the section on meteotsunamis below.

Figure 38. Location 16, Johnson's Harbour.

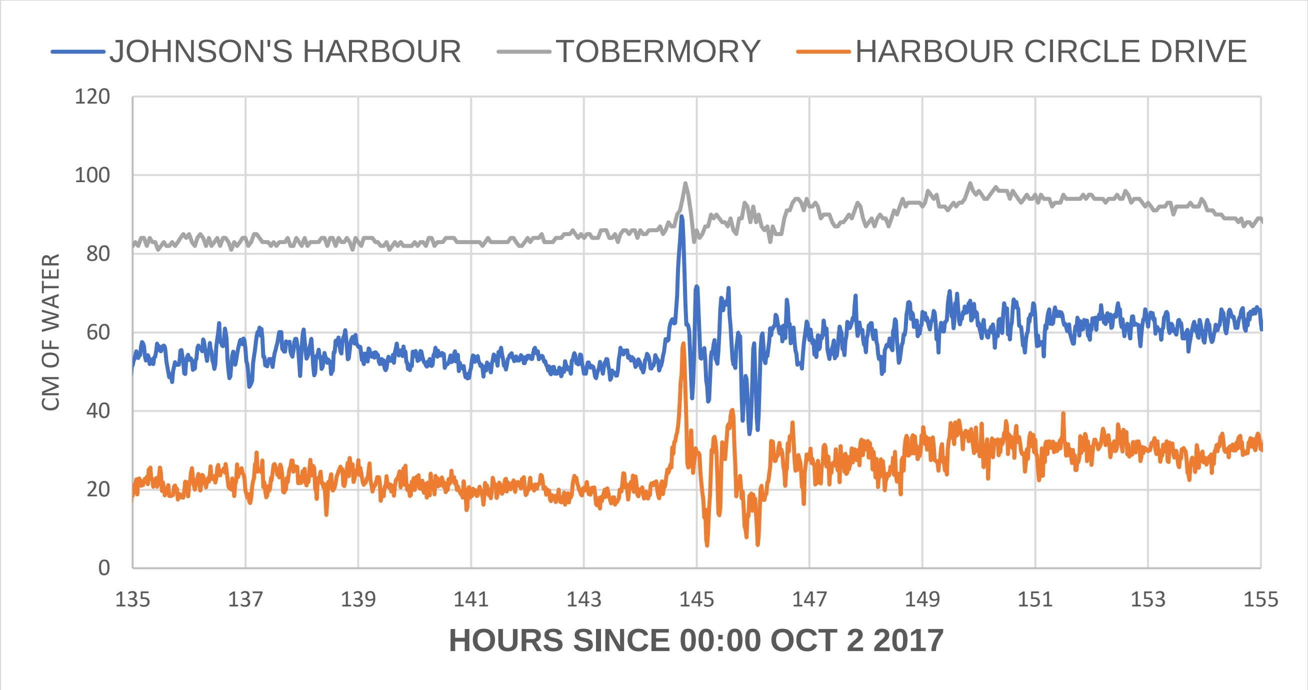

Figure 39. A 20 hour section of the 240 hour record at Johnsons Harbour and Harbour Circle Drive, with the Tobermory gauge record for comparison.

The spectra for the full 240 hour Harbour Circle and Johnson's Harbour records are shown in Figure 40. The records below 1.5 cph are basically identical, suggesting these relate to movements of the lake outside. The predicted resonance frequency for Harbour Circle is reasonably close to the observed peak at 3 cph, as is the 8.2 cph prediction for Johnson's harbour. However, Johnson's Harbour also has a strong peak at 2.9 cph which certainly

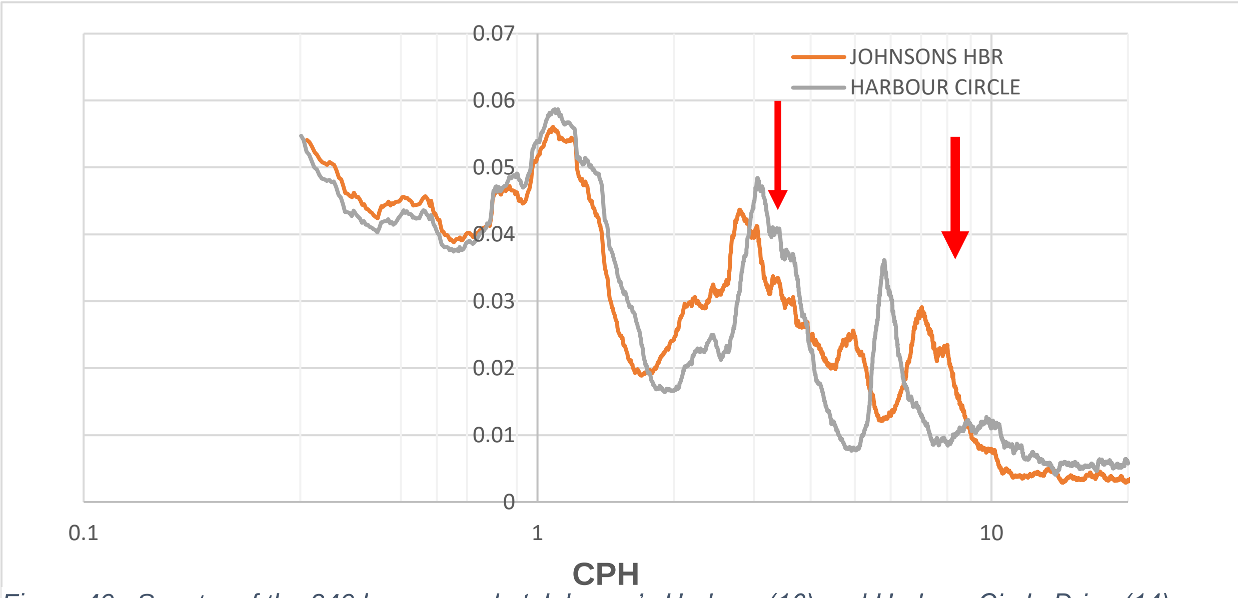

Figure 40. Spectra of the 240 hour record at Johnson's Harbour (16) and Harbour Circle Drive (14) October 2-12, 2017. The thick red arrow indicates the estimated resonance frequency for Johnson's Harbour, the thinner arrow for Harbour Circle inlet.

does not fit the prediction. One possibility is that this is a resonance within the shallow bay at the end of the harbour where the measurement was made.

Stokes Bay (17, 18)

This large bay where the "great tide" Sherwood Fox so eloquently described in the 1940s is basically rectangular. Simultaneous measurements were made at the two locations shown in Figure 41. A section of those records is given in Figure 42, and their spectra in Figure 43. It is readily seen that the two Stokes Bay records are very similar, very sinusoidal, and quite different from what was recorded down the coast in Goderich. Their spectra are almost identical. The predicted resonance frequency is very close to what is observed, probably helped by the fact that this harbour is so rectangular and has a simple depth profile.

Figure 41. Location of Stokes Bay measurements, Government Dock (17) and Heron Point Lodge (18).

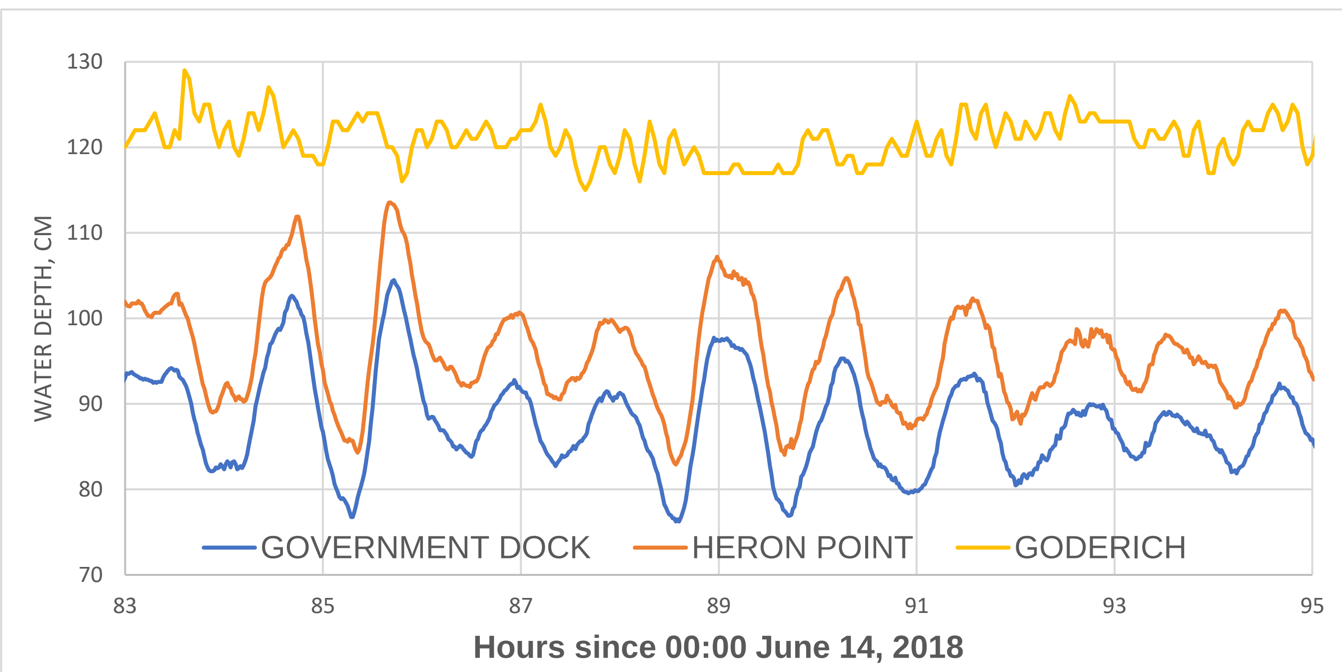

Figure 42. Water level variations recorded at the government dock and Heron Point Lodge, Stokes Bay, June, 2018. The record for Goderich is also shown.

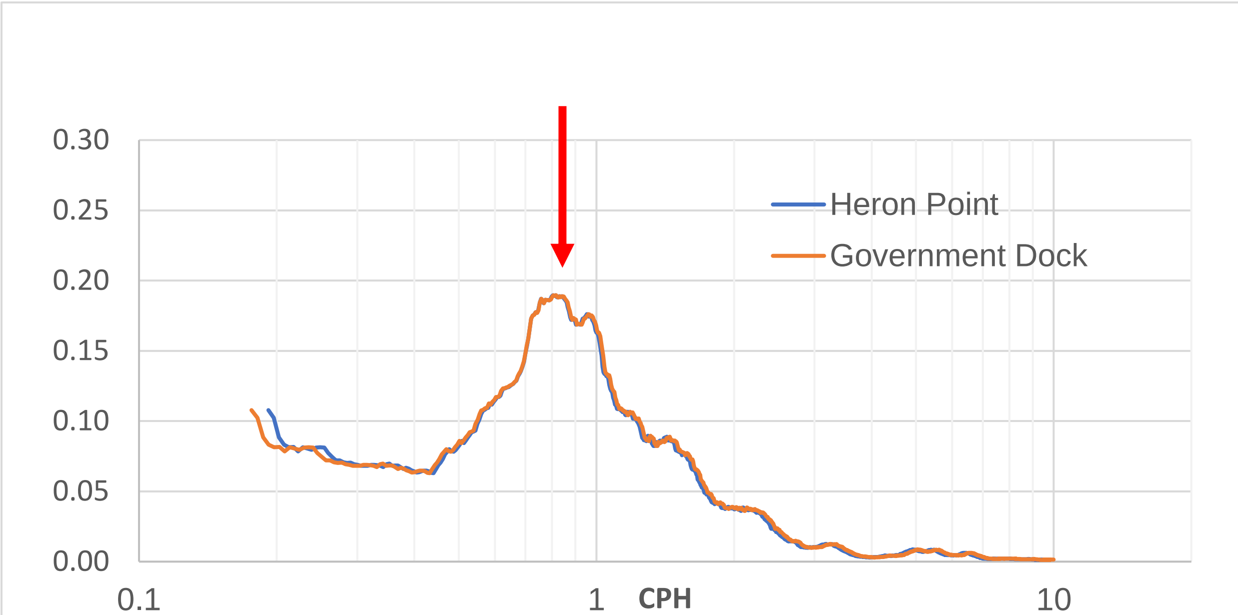

Figure 43. The spectra of water level variations recorded at the Heron Point and Government Dock locations in Stokes Bay.

Pike Bay (18, Figure 44)

Figure 45 shows a section of the 300 hour simultaneous recordings at Pike Bay (18) and Stokes Bay (19). The oscillations in this particular section of a much longer record are prominent, and slightly different between the sites.

Figure 46 compares the spectra of 12 days of measurements at these two sites and at the Goderich gauge. Stokes Bay and Pike Bay have prominent peaks centred on 0.82 and 1.2 cph respectively which have no counterparts at Goderich.

Figure 44. Pike Bay location (19).

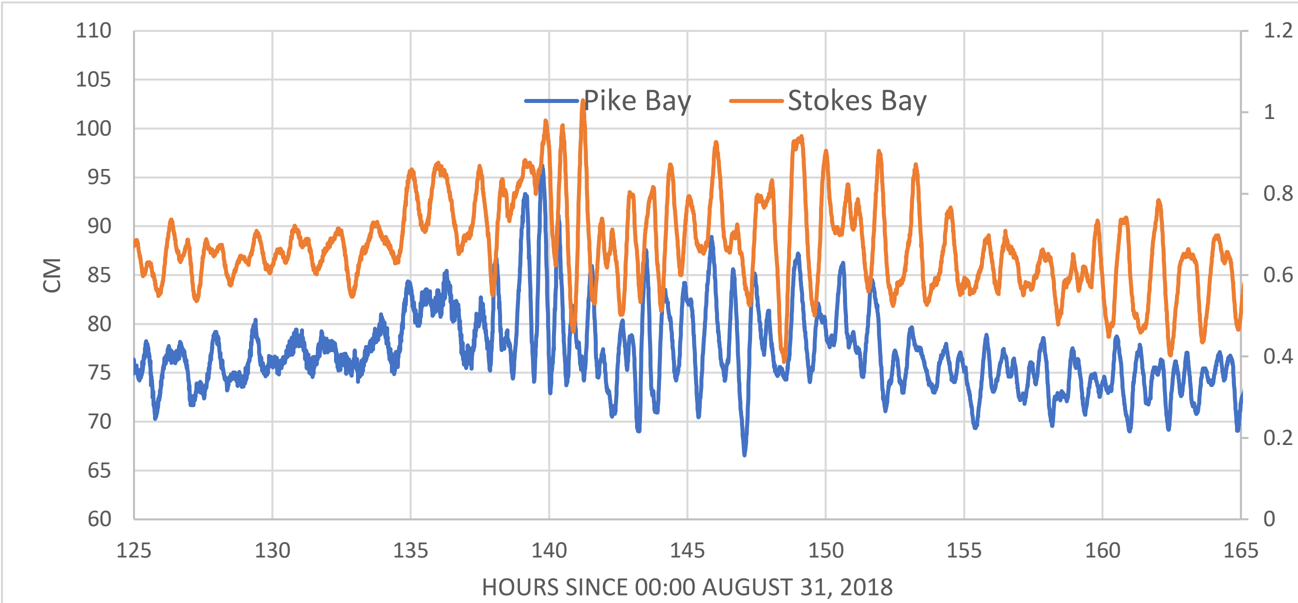

Figure 45. A 40 hour segment of the recordings at Stokes and Pike Bays, August 31-Sept 11, 2016.

These two data sets make a good case for the separation of basin modes from lake modes by observing simultaneously in nearby basins. Making measurements out in the lake itself is logistically difficult; however, making simultaneous measurements in two or different harbours is straightforward. As we have seen in several of the comparisons above, the low frequency section of the spectra tend to be similar

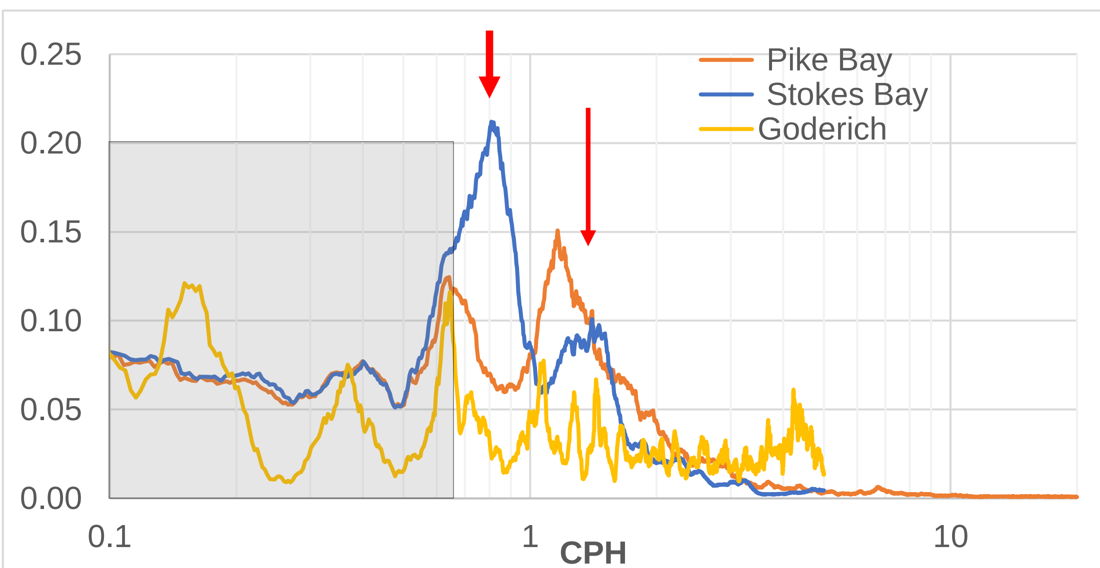

Figure 46. Spectra of 12 days of water level variations at Pike Bay, Stokes Bay and Goderich gauge, August 31-Sept 12, 2018. The shaded area is taken shows the area of the spectrum common to both Pike Bay and Stokes Bay, suggested to represent influences from the lake outside. Thick arrow indicates estimated resonance frequency for Stokes Bay, thinner arrow for Pike Bay

between basins; this part of the spectrum can be considered as a property of the lake. Where the spectra differ the spectra can be considered characteristic of the basins themselves. Put another way, spectral peaks that are common to each harbour probably originate in the lake outside.

Below about .65 cph (shaded area) in Figure 46 there is a good measure of agreement, particularly between the Stokes and Pike Bay spectra. The peak at 0.65 cph at Pike Bay is also present at Stokes Bay but occurs on the flank of the larger peak at 0.82 cph, and so this frequency can reasonably be inferred to be common and external. The Goderich record below 0.65 cph is very similar to that shown earlier (Figure 17) and has similarities with the Stokes and Pike Bay spectra in that region.

SUMMARY OF THE HARBOUR RESONANCE DATA

Table 2 brings together the theoretical and measured resonant frequency estimates for the studied sites. L, B and H in columns 1, 2 AND 3 represent the length, breadth (at the mouth) and average depth of the bay respectively. The choice of H is obviously suspect given the irregular bathymetry, and there is a strong temptation to use it to predict a resonant frequency f_0 close to what is observed!

The ratio B/L in column 4 is a measure of the narrowness of a bay. Theory suggests that harbour resonance should be stronger the narrower the opening is compared to the length of a bay, and this is generally born out by comparison with the signal-to-noise

ratio S/N (column 8), which is a measure of how strong the resonance spectral peak is compared to background.

The factor k (column 5) comes from equation (v) based on the formulation by Rabinovich (2009) to take account of the shape of the bays. In practice it has very little influence one way or the other here.

The predicted fundamental or Helmholtz frequency in column 6 is again computed using equation (v). The centre of the dominant spectral peak f_0 observed at each site is listed in column 7 and estimates of that peak’s signal-to-noise and half width are listed in columns 8 mand 9.

Where pronounced secondary (f1) or tertiary (f2) peaks are observed in the spectrum they are recorded in columns 10 and 11.

As noted earlier the frequency spectra for Harbour Circle and little Eagle harbours (Figure 36) are very similar and the calculated resonances of the two locations suggest that the f_0 for Harbour Circle is the lower frequency observed peak and the higher frequency peak is the f_0 for Little Eagle Harbour. Accordingly the lower frequency peak is attributed to Harbour Circle, the higher one to Little Eagle, but the reasoning here is suspect!

Table 2. A summary of the predicted and observed resonance frequencies at the measuring locations. See text for explanation of the columns.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11
						PREDICTED			OBSERVED		
	L	B	H			FUNDAMENTAL	CENTRE	S/N	$w_{1/2}$		
HARBOUR	**LENGTH**	**WIDTH**	**DEPTH**	**B/L**	**k**	**RESONANCE**	f_0	at f_0	f_0	f_1	f_2
	m	m	m			cph	cph		cph	cph	cph
BAPTIST HARBOUR	890	160	2.00	0.18	5.00	3.6	3.8	6	2	6.00	
BIG TUB	830	110	10.00	0.13	4.40	9.8	10	8	0.5	10.00	
DORCAS BAY	2110	1320	4.00	0.63	4.40	2.4	2.1	3	1.1	4.40	
GODERICH	1500	180	6.00	0.12	4.40	4.2	4.3	3	0.5		
HARBOUR CIRCLE	550	60	0.50	0.11	4.40	3.3	3.2	3	1	6.00	
HAY BAY	1030	490	1.00	0.48	4.40	2.5	2.3	3	1.4	4.40	8
HAY BAY EXT	480	80	0.50	0.17	4.40	3.8	2.3	5	1.4	4.40	8
JOHNSON'S HARBOUR	870	280	4.00	0.32	4.40	5.9	2.8	2	1	4.70	7.5
LA RONDE	510	60	1.50	0.12	4.40	6.2	5.3	6	1		
LIGETTI INLET	930	150	2.00	0.16	5.20	3.3	2.1	6	1.4	3.80	
LITTLE EAGLE	548	169	2.00	0.31	4.40	6.6	6.1	2	1	3.1	
LITTLE TUB	330	65	4.00	0.20	4.50	15.2	13	8	3.7	6.21	1.4
PIKE BAY	1830	600	1.00	0.33	4.40	1.4	1.2	3	0.9	0.30	
STOKES BAY	5360	1680	3.00	0.31	4.40	0.8	0.82	5	0.3	1.37	
WARNER BAY	1540	610	5.00	0.40	4.40	3.7	1.1	2	1	3.20	

METEOTSUNAMI EVENTS.

No major seiches occurred during the periods we were recording with our own (as opposed to the gauge) instruments. Eye witness reports (see Appendix 1) tend to be very vague about the time between successive highs or lows but they always suggest something on the order of a 5-10 minute period. Because the gauges sample only every three minutes they are not the most reliable recorders of these events. Here we look at some eye-witness reports of major seiches around the Bruce.

Baptist Harbor "bore", April 11, 2011.

This remarkable photo of a tidal-bore-like wave moving up Baptist Harbour would seem to be evidence of a fairly sudden onset seiche. Unfortunately we have no information as to whether this was a one-time event, or one of a series of such waves. It was part of a disturbance in the harbour that sent the Burtons running for their camera. Atmospheric records show that this occurred at the bottom of one of a series a low pressure events that track through this area every few days, but neither the pressure gradient nor the wind speeds stand out as unusual.

Figure 47. Wave moves up Baptist harbour, April 11, 2011. Photo by Bernadette Burton.

June 8, 2011.

Figure 48 shows the Tobermory gauge record bracketing the period that Tracy Edwards and Perry Smith describe in Appendix 1. This was a major event in both Tobermory Harbours, with eye-witness reported rises and falls of several feet. Before hour 10:00 on the 8th, and after hour 15:00 (hour 39) on the 9th the water level variations can be described as normal. Beginning about 12:00 on the 8th the lake becomes agitated and this continues right through to noon the following day.

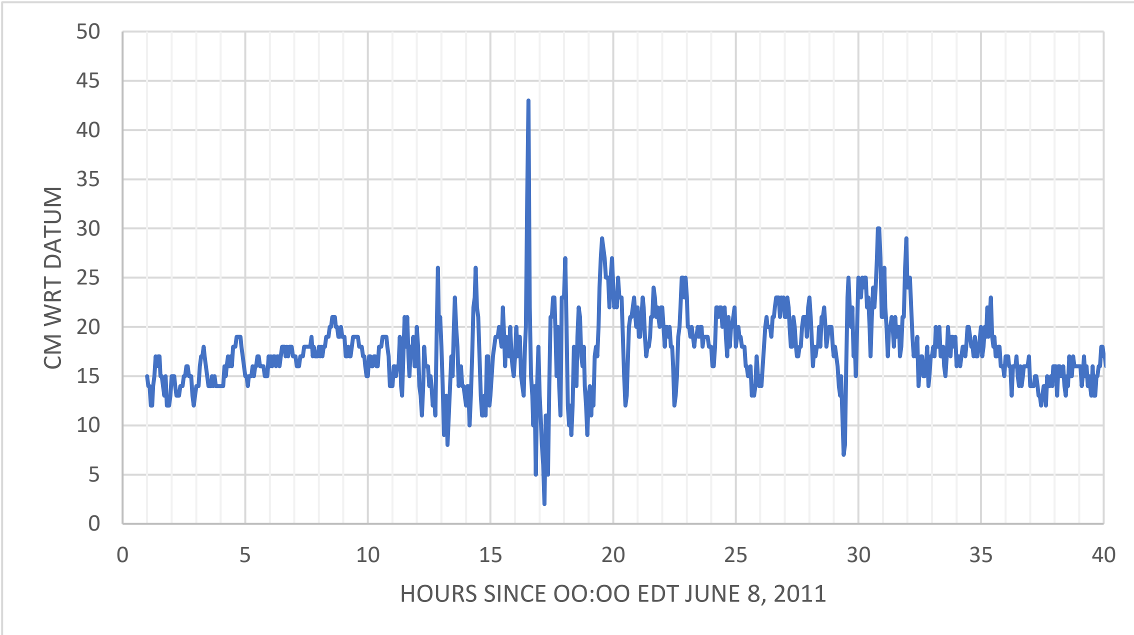

Figure 48. A 40 hour segment of the Tobermory gauge record beginning 00:00 EDT, June 8, 2011

The period of intense oscillations reported by Tracy and Perry began at roughly 16:00 and continued through about 19:00. Tracy and Perry are a bit uncertain of the time of the very dramatic events in the harbours but almost certain they did not begin before 16:00. However, Tracy's divers recorded unusually high currents on the bottom well before that. Between 12:30 and 15:00 there are a series of 3 very even cycles of roughly 40 minutes each which can be associated perhaps with these bottom currents.

The large event begins to develop at 16:24 (4:24PM) and reaches its peak between 9 and 12 minutes later. The lowest point is reached at 5:12 later although there may be smaller and shorter oscillations between the peak and the trough. The water level has gone through a 40 cm range in no more than 30 minutes. It is important to note that witnesses reported much larger variations than 40 cm, and the most likely reason for that (other than a human tendency to exaggerate) is that the 3 minute sampling at the gauge is unable to resolve the large and short lived swings in water level. This in turn is consistent with the idea that the major swings may occur at the 12 cph frequency the spectra of Figure 21 suggest. The dominant frequencies on the June 8-9, 2011 gauge record are consistent with the spectra of Figure 21, but of course do not reach the 12 cph frequency.

One picture of this major seiche that emerges at the Tobermory gauge for June 8-9, 2011, and can be inferred from the eye witness accounts, is of a disturbance which sets the harbours into motion several hours before the major seiche. At some point, either due to the arrival of a sharp pulse from outside or by random constructive interference of wave trains within the harbours, a large resonance oscillation is triggered there which dies away after three cycles over 20-30 minutes. The original disturbance continues on for another 15 hours, but no more major harbour oscillations occur.

August 2, 2015.

A massive storm with a cloud front shaped like a huge roll travelled across southern Ontario on this day, accompanied by thunderstorms, tornados and strong seiches in Goderich and Lions Head amongst many other places. In Tobermory Harbor the general confusion caused by the winds was such that no one seems to have noticed a seiche, but the record of Figure 49 shows that an event with amplitudes of 10 to 20 cm began sharply at 12:00 PM coincident with a sharp drop in pressure as the cloud

Figure 49. The "roll cloud" of August 2, 2015. Photo by Alden Greenhouse

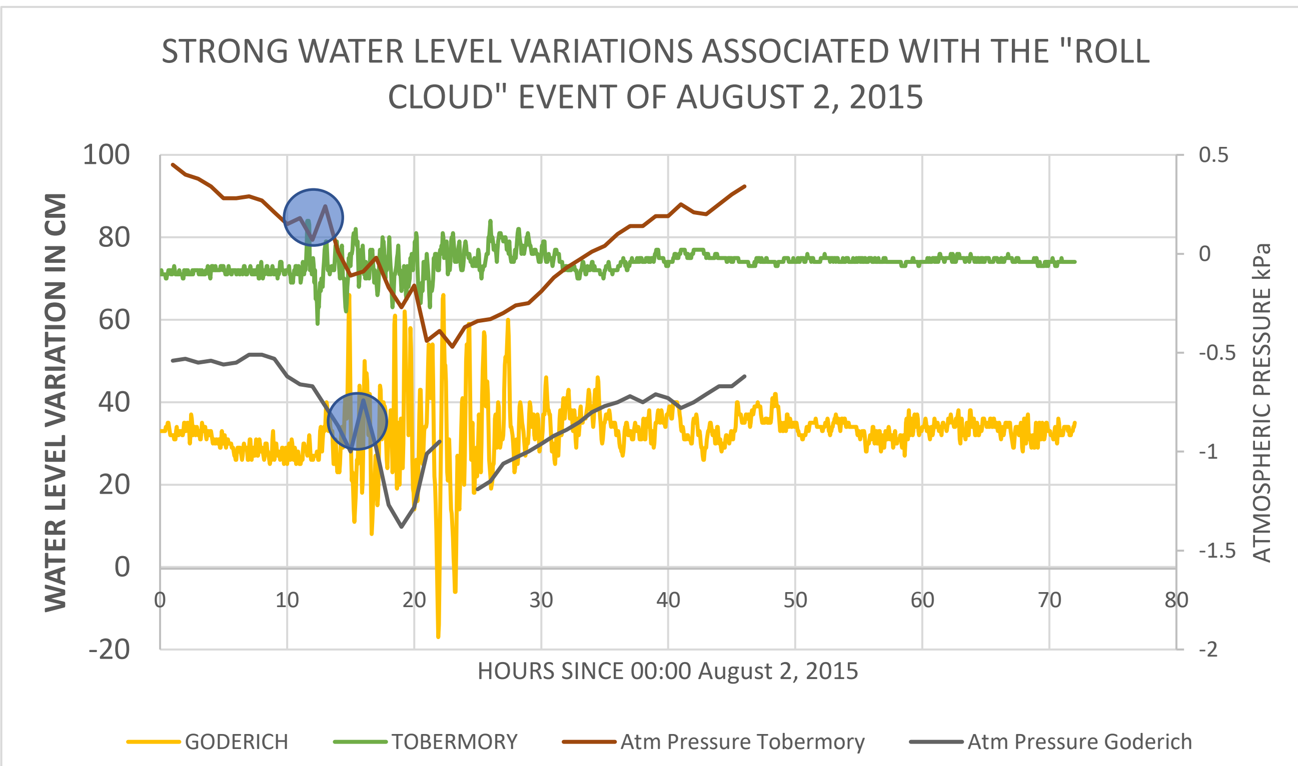

Figure 50. Water levels and atmospheric pressure variation associated with the "roll cloud" of August 2, 2015. Both data sets have been offset for purposes of display. The circled "couplet" in atmospheric pressure appears to accompany the onset of seiche activity

arrived. At Goderich the same event arrives at 1:00PM again coincident with the same "down-up" couplet or chatter during the downward limb of a pressure cycle.

The onset is sharp. At Goderich the water level rises 26 cm in 6 minutes then drops 45 cm in the next 24 minutes. Thereafter its spectra closely resembles Figure 18, with large oscillations of about an hour's period and smaller ones at about 15 minutes. We are suggesting that the former are generated outside the harbour in the lake, the latter represent the harbour resonance.

At Tobermory the initial onset is 12 cm in 9 minutes; thereafter the spectral signature is very similar to that shown in Figure 18.

The overall picture is of an energetic seiche that arrives with a major storm. There is no "out-of-the-blue" factor here. Once again the largest swings in water level in the ensuing few hours appear almost at random within the train of arrivals, possibly the result of constructive interference within the oscillating harbour, but there is no one extremely large seiche event.

Sept 4, 2018.

The near simultaneous arrival of a train of oscillations in Stokes Bay and Pike Bay (Figure 45) at about 3:36 PM on August 4th shows that this is a regional effect; it appears to be associated with the passage of a low pressure system; the lowest pressure occurs at 135 hours and rises by 1kPa over the next 25 hours, a substantial but not unusual pressure gradient. The increased energy does not therefore seem to arrive with a particular storm front, suggesting that it comes from waves incident on the coast. There is no sharp onset; rather the effect on each harbour is to amplify the natural resonance frequencies over a 25 hour period. The location of the maximum rise/fall within that train of oscillations again seems to be somewhat random, and may be best explained as constructive interference.

October 8, 2017.

Figure 39 above shows a sharp onset and short burst of oscillatory energy at Harbour Circle Drive (#14) and Johnson's Harbour (#16)in the early morning of October 8, 2017. The onset takes place over roughly 6 minutes, sampled every minute, and occurs almost simultaneously at the two harbours and the Tobermory gauge. The records revert to their characteristic oscillations following the sharp onset.

Figure 51 below shows an expanded 100 hour view of that record, together with the Goderich gauge and the hourly wind speed and atmospheric pressure readings at Tobermory.The hourly atmospheric data reveal no sharp discontinuities coincident with the water level rise but this is to expected given the different sampling rates. As with the September 2018 example above, the event occurs right at the bottom of a pressure cycle. Of interest also is the fact that the event arrives at Goderich slightly earlier and with an opposite polarity!

It is tempting to attribute these events to a wave-like arrival, perhaps similar to the one shown in the Appendix at Baptist Harbour. On the other hand,it is hard to explain the near simultaneous arrival of this event at the two harbours and the Tobermory gauge spread over 50 km as the result of a wave radiating from a storm event over the lake. Once again we are left with clues, but no real solution.

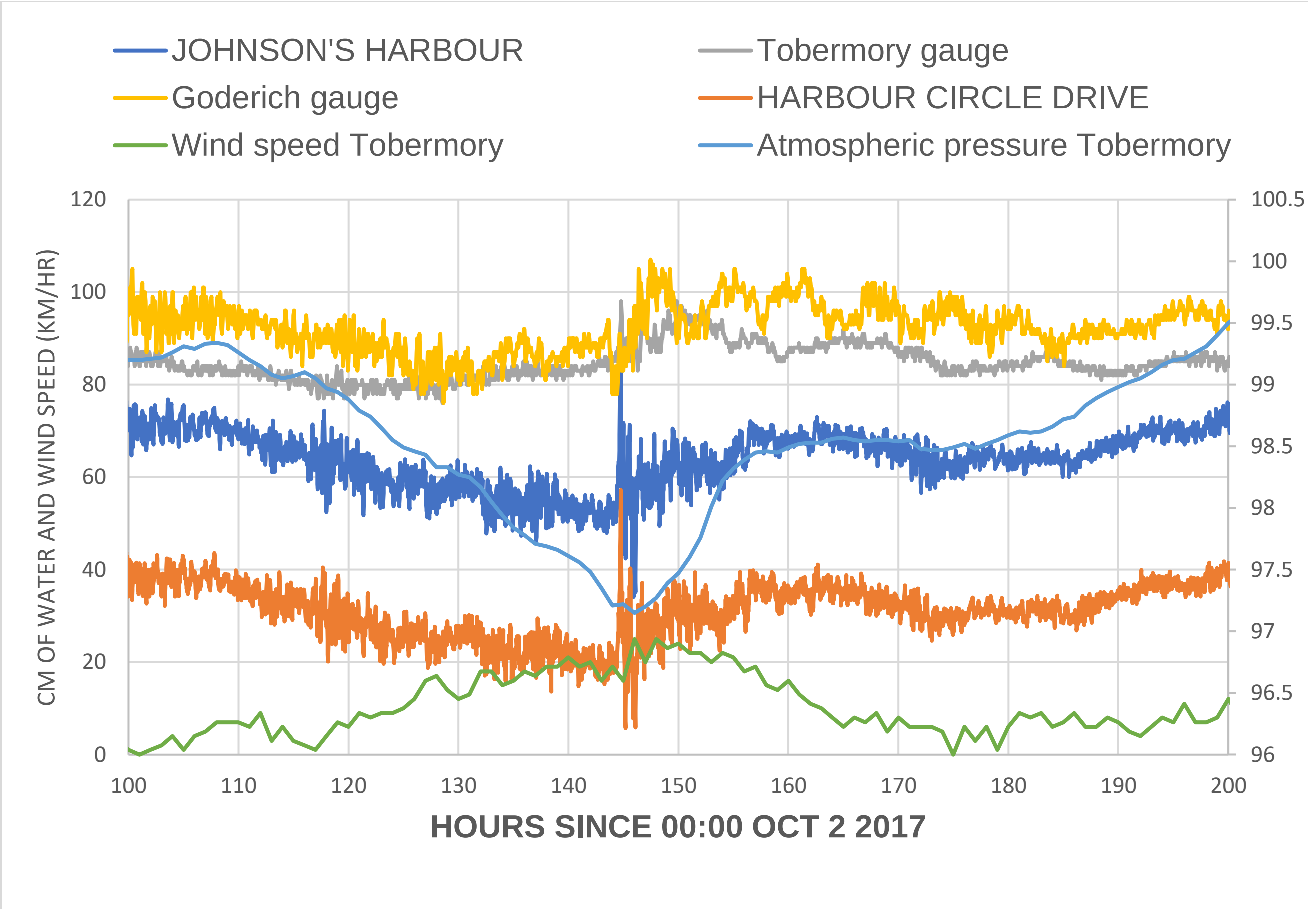

Figure 51. An expanded view of Figure 39 showing 100 hours of data at the Johnson's harbour and Harbour Circle sites as well as the gauge records from Tobermory and Goderich and the wind speed and atmospheric pressure (kPa) at Tobermory.

What is missing in discussions of these large events are simultaneous measurements at 30-60 second intervals, both in two or more harbours and outside. Atmospheric pressure should probably also be measured at the same interval. Because large events may happen only once or twice a year this involves data collection over months or even years, but this approach might yield a better description of the incoming energy from the lake and the responses of the harbours to that energy.

July-Oct, 2019, June-July 2020.

The two Parks Canada Hobo transducers were deployed in Baptist Harbour and in a small bay on the east side of Devils Island (Figure 52). The goal was to intercept a seiche impinging on the coastline from the west at an offshore location and in a resonant harbour, on the assumption that the former could be seen as driving force for the latter.

No major events were intercepted but two minor were. One of these was clearly associated with a coincident thunderstorm, while the other was "out of the blue" as it were. In 2020 a major meteotsunami event was intercepted by this network. This is the topic of a separate article on the SOK website.

Figure 52. Three station SOK network, 2019 and 2020

CONCLUSIONS.

This study has tried to find a middle ground between the shoreline observer who sees waterline oscillations as a part of the beauty of everyday life on the Bruce, and the academics who see in them the beauty of hydrodynamics. The layman, with a basic knowledge of software like Microsoft EXCEL and a $600 (but hopefully borrowed) Hobo or similar pressure transducer with built-in data logger, can explore this middle ground in their own harbour, quantifying these water movements for fun if not profit.

Harbour Oscillations.

Our experience here suggests the following.

i. Each harbour does have a unique spectral signature, and this signature is remarkably stable over time. The amplitudes of the motion will vary from day to day, but the shape of the spectrum is remarkably stable with time.

ii. This spectrum is also stable in space within a harbour; that is, measurements made at multiple locations within the harbour will have the same signature. Again the amplitude of the spectrum will vary with location, but the shape stays constant.

iii. A harbour spectrum will usually have one prominent and broad peak whose apex can be identified as the resonant frequency. These resonances varied from 0.8 cph at Stokes bay to 13 cph in Little Tub. The resonant peaks are not sharp spectral lines as can be observed with tidal motions. If one measures successive cycles of water level rise and fall, say at Dorcas Bay, the time for each cycle will probably vary over a small range. These are not perfect oscillators; the driving forces of wind and pressure are not constant like the motions of the moon. There is however, a well defined centre to these spectral peaks, defining a dominant frequency.

iv. These peak frequencies are in reasonable agreement with simple theory based on idealized models mimicking the shape and bathymetry of the harbour. As theory predicts, the simplest explanation for why some harbours exhibit larger oscillations than others is the ratio of their breadth to their length. The smaller this ratio, the more prominent the oscillations are likely to be.

v. Some harbour spectra exhibit more than one peak. They may be simply multiples of the dominant frequency, or they may represent harbours-within-harbours, arms of the main harbour that add their own resonance to the spectrum. The broad indentation containing the Harbour Circle and Little Eagle measurement sites may be an example of this.

vi. The fact that the observed peaks are reasonably modeled by simple harbour models lends support to the claim that these are indeed properties of the harbour in question, and not the result of outside factors. This conclusion has been buttressed by taking measurements in two harbours simultaneously.

Water level variations common to both harbours are ascribed to the lake outside; where their spectra differ, it must reflect local influence.

vii. Water level oscillations arising from the lake outside tend to have frequencies below 1cph. However the largest harbour in this study, Stokes Bay, had a resonance of 0.8 cph within this frequency range.

viii. These measurements do not shed light on the driving mechanism for harbour oscillations, generally thought to be either low frequency waves from the lake that closely match the harbour resonance, non-linear interaction between surf at the harbour mouth and the water inside, or a combination of the two. It is noteworthy, however, that harbour oscillations are observed to continue through periods of dead calm in the lake outside, suggesting that the former mechanism may predominate.

Large seiche events.

Physics and common sense both (and Figure 11) tell us that the best way to make an oscillator oscillate is to drive it at its resonant frequency. For Baptist Harbour, the ideal “driver” would be a wave incident from the west with a period of 15 minutes

Because the normal seiche modes of Lake Huron have much lower periods a lake-wide seiche is not ideal as the source of large harbour oscillations, at Baptist Harbour or any other sites instrumented here.

Meteotsunami events can have quite localized sources (such as a thunderstorm cell) and as Example 2 in Section 3 above demonstrates these could generate waves with frequencies comparable to the resonant frequencies of local harbours. Another possibility is the arrival of a sharp pulse – a wall of water as it were – like the wave shown in the Burton’s photograph in the Appendix. A pulse contains a wide range of frequencies, and so might also trigger a large harbour event. Unfortunately we were unable to find in the literature measurements of large events in the lake proper that would give clues as to properties of the incident energy as it approaches the shore.

No major seiches occurred during the recordings for this project. Nevertheless we examined two cases where unusually strong oscillations were initiated simultaneously in separate harbours during our recordings. In these examples it does appear that the onset of the harbour oscillation in each case is very sharp, suggesting that the incoming energy is of a frequency comparable to the harbour resonance. Without measurements in the lake outside this is, however, just conjecture.

There are records for major seiche events at DFO gauges in harbours like Tobermory and Goderich around the lake but the 3 minute sampling frequency is not ideal for events with short periodicities. Nevertheless we examined the gauge records and meteorological records for three major meteotsunami events of the last decade. We noted that they all occurred on the descending limb of the pressure cycle, shortly before the minimum was reached. Increased water level variation activity appears to start at about the same time at widely separated gauges. The onset of activity occurs in some cases hours before the major events are recorded in harbours[6], suggesting that there is perhaps a random constructive interference involved.

Once again the missing information is a record of major events both inside the harbours and in the lake outside.

FUTURE WORK

Other harbours along the Bruce Peninsula shoreline.

There are many other bays and harbours along the east and west coast of the peninsula where these measurements could be made. A week's recording at one or preferably two sites within the bay would be sufficient to determine a resonant frequency. Ideally two separate bays on the same coast would be measured simultaneously in order to separate local and external influences.

Even at a 30 second recording interval the data can be "aliased" by chop on the surface. Quiet locations in the lee of piers, or manufactured using stand-pipes, are required.

Long term monitoring for major seiches.

More interesting, but more logistically difficult, would be to carry out long-term monitoring in one or more harbours and at a site in the lake outside, with the goal of capturing major seiche events. This could lead to a better understanding of the link between the two.

Outside the harbours, finding a suitably calm area can be difficult. One option would be a small pond connected on the exposed coast but buffered from wave action. Several candidates can be identified on Google Earth. Failing that the lee of an island might do.

The Hobo pressure sensors used in this study can record pressure alone at 1 minute intervals for about 13 days. Ideally, to eliminate diurnal temperature effects, temperature would be measured as well, reducing the on-bottom time to less than a week. If the recording interval were 30 seconds the limit would be about 3 days for both measurements. Even at 13 days there are considerable logistics involved in servicing three or four instruments.

Continuous recording in Baptist Harbour and Little Eagle Harbour, with a third site on the exposed coast in the lee of an island in-between, might make a viable project. Weekly dumping of the data to a databank would be feasible over the summer months, subject to battery limitations. Ideally a fourth instrument would record atmospheric pressure at the same interval. [7]

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[6] These of course depend on the availability of an observer – the largest amplitudes could occur when no one is looking, at night for example.

[7] As indicated in the previous section, such a network was setup in 2019 nd is reported on elsewhere on this website.

ACKNOWLEDGEMENTS.

I thank the many property owners who allowed me access to their shoreline for this project. They include: the Tobermory Harbor master's office, Barney Hopkins and Ralph Suke in Big Tub, Rob Davis and Norbert Woerns in Hay Bay, the Tony and Tracy Edwards and Don and Bernadette Burton in Baptist Harbour; John Vince in Warner Bay; Ivy Pollock in Dorcas Bay; the management of the Heron Point campground in Stokes Bay and By The Bay resort in Pike Bay.

Carol Herman, Tracy Edwards, Jack O'Shea, Perry Smith. Michael Butler and Alan Bobo were generous with their time in allowing me to record their reminiscences or see videos of seiche events.

Fathom Five Marine Park lent me the two Hobo pressure sensors used in most of the work. Park staff, Cavan Harpur and Scott Parker in particular, allowed me to bend their ear from time to time. I also greatly benefited from talks some years ago with Bogdan Hlevca, who with Scott Parker and Mathew Wells wrote the seminal paper on Cove Island seiches referenced below.

I also acknowledge that there is much that I do not understand about seiches, and some of the opinions given and mechanisms proposed here may turn out to be wide of the mark. I apologize in advance if I have misled!

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APPENDIX. EYE WITNESS REPORTS OF MAJOR SEICHE EVENTS.

Transcript of a description by Carol Herman of a seiche in Big Tub Harbour, Tobermory, on December 16. 2015.

I was at the foot of Big Tub taking part in the Christmas Bird Count. About 4 of us had walked over to the water's edge at about 3:45 PM when I asked everyone to be quiet for a minute. I heard this big swishing noise like somebody pulled the plug on a bathtub. All of a sudden I noticed the water rushing out – I mean rushing out – tipping docks on both sides of the harbor over on their sides. At least 3 ft of water went out and I could feel the ground, it was very soft. It must have been 2 minutes later when the water started coming back. It went out again and back 3 times, the water depth variation decreasing each time. You could hear the water rushing. There was no "wall"of water coming in initially – at least we didn't see the initial inflow if in fact there was one. Tom Williamson went to get his camera but he didn't get back in time to film it.

Comment. The graph below shows that this event took place on a falling pressure, possibly characterized (as in Figure 49) with a short reversal "couplet" in the pressure. Between 15:36 and 15:48 the water at the gauge drops by 17 cm, based on readings every 3 minutes. Higher resolution barometric pressure data would be useful here.

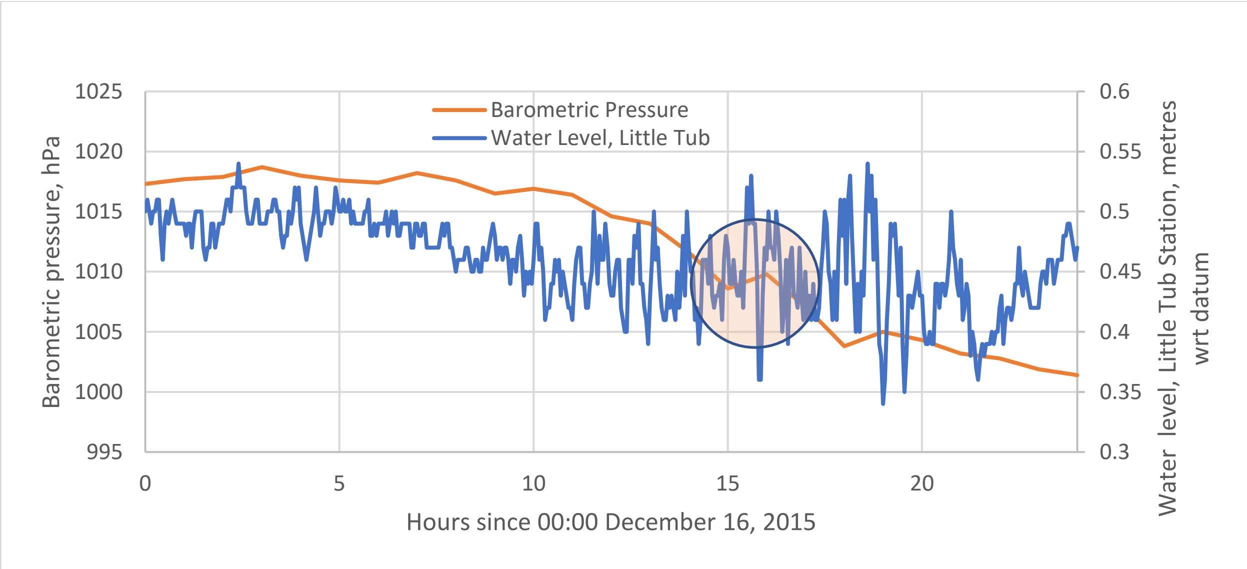


Figure A1. Tobermory gauge and atmospheric pressure for December 16, 2015.

Transcript of a recording by Tracy Edwards, skipper of the dive boat Bruce Isles, June 8, 2011. See also Figure 49.

A description of the seiche of June 8, 2011, in Big Tub Harbour. Tracy Edwards was captaining the Bruce Isles. These recollections were recorded on December 16, 2016. Understandably, details such as times are difficult to recall after 5 years.

On June 8, 2011, I was captaining the Bruce Isles with a group divers. At or shortly after 4PM we arrived on the Sweepstakes in Big Tub Harbour. There was a bad storm at the time, with heavy rain, lightning and thunder , and I had to hold the divers back for 30 or 40 minutes before letting them in the water. Diving can take place in the rain, but not with lightning in the area.

When the lightning had seemed to stop I let the divers go in the water. A typical dive on that wreck takes 45 minutes . There was more thunder during their dive but the sun did come back out before they emerged.

When the first group of divers came back, perhaps around 5:30-5:45, they reported that there was a strong westerly current below making it really difficult to get back to the boat.. As I diver myself I found this hard to believe. I might have told them "your crazy, there are no currents here".

When the next group came up they also commented on the currents. In hindsight I seem to recall that the boat was oriented north/south parallel to the wreck at some point during all this, whereas we are usually oriented north/south along the axis of the harbor depending on the wind. You almost never find the boat aligned across the harbor. This would perhaps currents changing direction but that did not occur to me at the time

The third group came up and they also commented on the currents. Typically the divers emerge over a span of 15 minutes. I began paying more attention to their observations. I pulled up the ladder getting ready to leave, and went to the bow to untie the boat from the buoy. Shortly thereafter the dive shop phoned. As I answered the phone I looked out the boat's window and saw that the yacht Spindrift at the head of the harbor (west of my boat)had rolled over on its side and was grounded on the

As I looked around harbor I noticed other boats rolling on their side and sitting in the mud. I was in 35 ft of water so not concerned about the Bruce Isles but I then noticed that the windlass of the Sweepstakes appeared to be rising out of the water. By now it was sunny, with no wind. Then the rail and finally the deck and emerged. This was a time of very low lake levels – we routinely had to tell divers not to stand standing on the windlass or rail. Still, the water level drop I observed must have been 5-ft.

I was describing all this to Lynn Graham on the phone. She said it sounded like a seiche, a word I had never heard before. Assuming the divers had fought an east-to-west current which would have raised water levels, the flow must now have reversed.

I was about to put the boat in gear to begin our return to our dock at Little Tub, when I realized I was already half way up the harbor towards the Coast Guard station. From noticing the tilted Spindrift to this point perhaps 5 minutes had elapsed. Clearly something weird was going on.

Once past the Coast Guard Station I didn't notice anything unusual, but as we pulled into Big Tub I noticed that we were going faster than we normal. As would be the case with a strong west wind I had to put the alternately put motor in and out of gear to reduce speed while maintaining the ability to steer. Going past the Municipal Dock I could now actually see the current in the water. I warned the customers to sit down and hold onto something as the docking might be tricky. Some of the guys from G and S saw me rushing in and grabbed the lines as we approached.

I got my divers and their gear off the boat, and then the water started to drop. Soon the Joseph Simon, the Lark and the Dawn Light were on the bottom,with the Joseph Simon actually lying on its side. At the previous low the G and S staff had been forced to loosen the lines. They said the water had earlier come up so high that they had taken 2 by 4s to hold their boats off, concerned that they might roll over the wall and onto the dock.

The tender of the Dawn Light was also on the bottom where it apparently got stuck; when the water returned the tender and its outboard stayed on the bottom. They later pulled it off the bottom with the dock crane.

I observed at least one more high/low cycle of water level after that but the severity continually decreased.

Some other signs of the seiche. Larry Graham's ramp to the floating dock had been forced up during the high water and had stuck in that position forming a large "V" between the dock and the harbor wall. Larry was called and he took a sledgehammer to bang it back in place. The municipal dock had become completely unhooked; it sat on fixed vertical pins 3-4 ft tall so the water must have risen high enough to clear these.

Perry Smith's observations on the seiche of June 8, 2011

Transcribed from a conversation in August 2, 2017. Perry ran G and S dive store and was in Little Tub at the time of the June 8 seiche.

In the late afternoon of June 8, 2011, I saw the water come in raising the lake level by 4 or 5 ft and all of a sudden go out so we ran to the boats to cut the lines. Observed two cycles of about 5 minutes each. Came up over the dock by a foot or so into the parking lot.

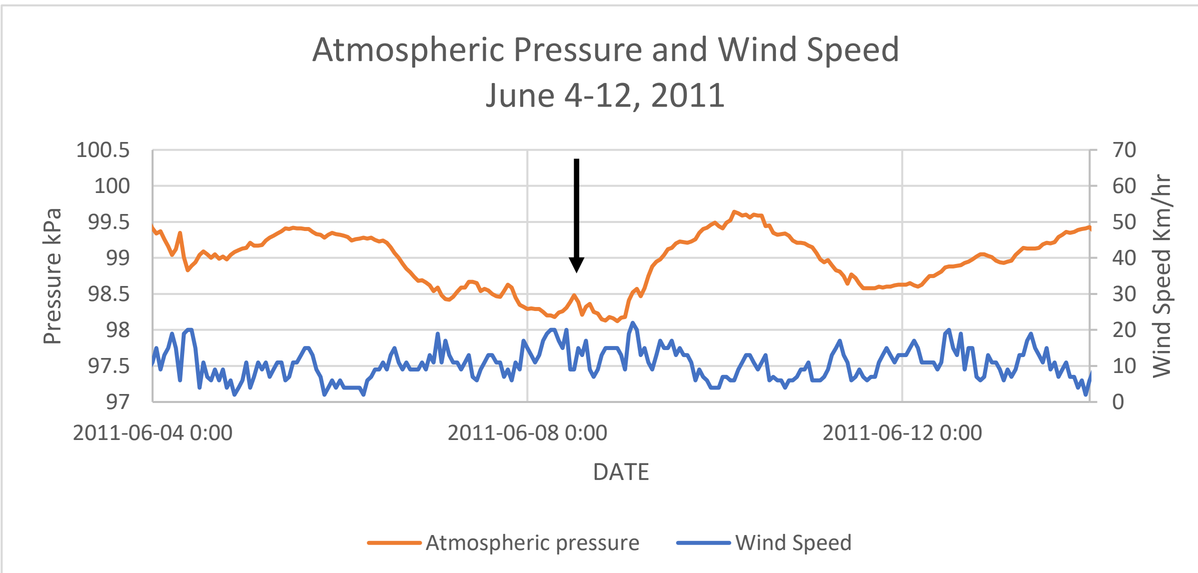
I remember as a kid we were here in the fall, my Dad and I. Percy and Shirley ran Craigies gas station. Shirley was out pumping gas when the water came right up to the steps of the shop. Ron Peacocks truck was parked by the boat ramp and the seiche flooded it. After the water had backed off we drove down to Lee's dock and off Lee's dock about 25 ft out there was a whirlpool.

I have seen two perhaps three of that size in my life.

COMMENT.

Figure A2 shows that the June 8 seiche again occurs at base of a trough in the pressure cycle. Once again there is a small pressure rise/fall pressure couplet associated the onset, but otherwise nothing in particular draws attention to this event. For further discussion see Figure 49.

Figure A2. Atmospheric pressure and wind speed at Tobermory during June 6-13, 2011. The arrow indicates 4PM on the 8th.



Seiche of February, 2016, at Dorcas Bay described by Jack O'Shea

Here are some photos of the micro tsunami...the shot back to our cottage is 100 yards off shore water is generally 7 or more feet deep. By the time I took this picture I had to run back to shore to avoid a swim back in. At the 50 yard mark on my run back water was already over my boots..

Figure A3. View of house from the lake bottom. Jack O'Shea to be photographing from a point normally covered with 7 ft of water.

Figure A4. Grounded ice floe as the water leaves Dorcas Bay

Figure A5. The water starts returning

This all happened in February 2016 calm sunny day, around 4PM.Water came and went three times each time taking less than 15 minutes. I have a short video of the rushing water.

COMMENT.

Jack was understandably uncertain of the exact day in February, except he thought it occurred near the end of the month. From an examination of the water level and meteorological data it probably took place at 2PM on February 29 (see Figure A6). The key indicators are (i) the event takes place at the base of a pressure trough in conjunction with a “couplet” and (ii) a sharp increase in the pressure gradient . This is accompanied by a small but sharp water level rise at Tobermory and a larger one at Goderich.

Despite the sharp pressure gradient Jack describes the weather as “calm, sunny”. The radar record (Figure

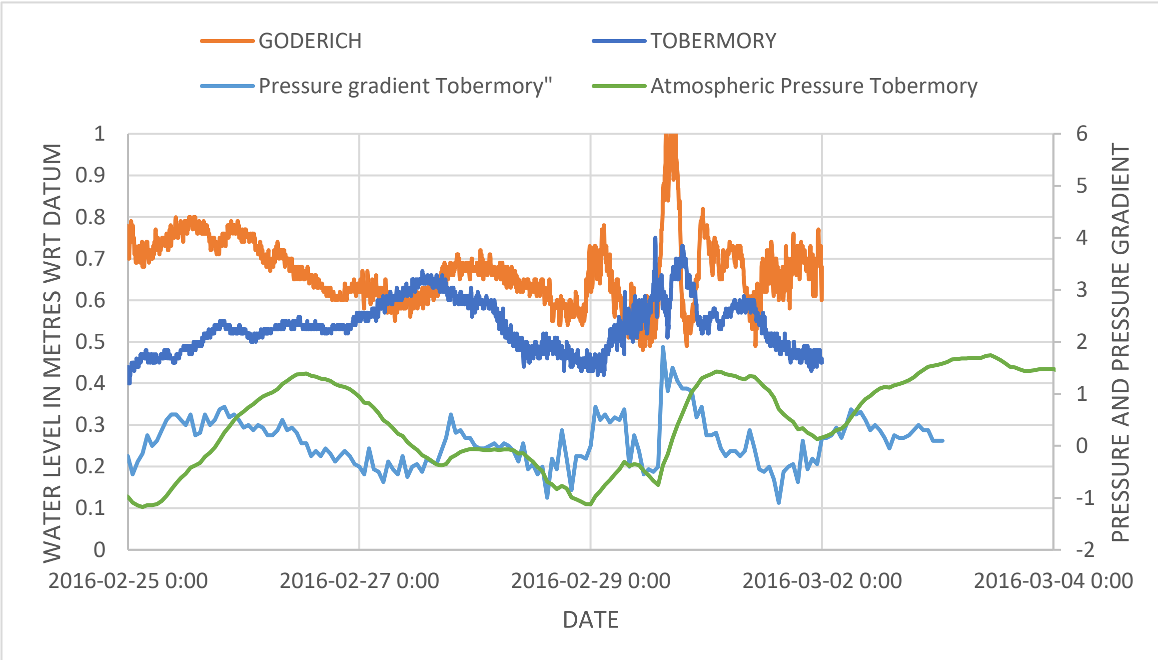


Figure A6. The black arrow designates 2PM EST, February 29, 2016.

A7) however shows that a rain front had passed through heading southeast about an hour earlier. That direction would impinge directly on a Jack’s shore. Perhaps the wave followed the rain front?

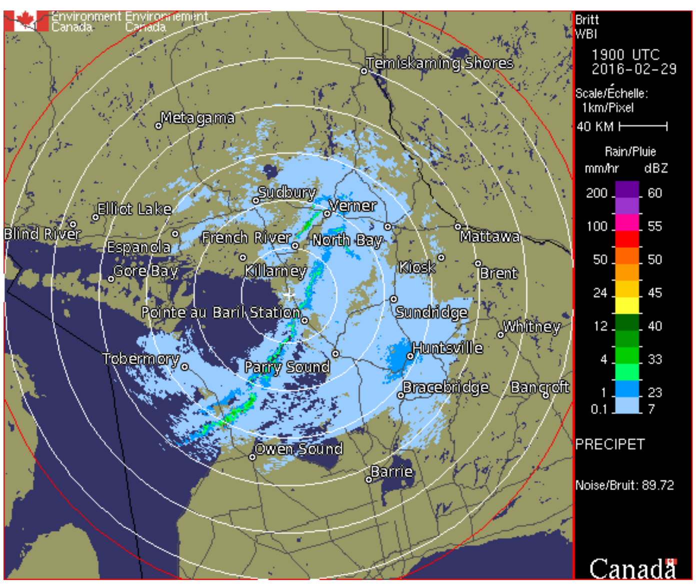


Figure A7. The radar weather at 2PM EST, Feb 29, 2019.

May, 2019.

Michael Butler who lives on Corisande Bay has provided some of the best eye-witness description of seiches occurring on two separate days, complete with video and time lapse photography. On May 9 time lapse video shows 1 cycle of roughly 28 minutes, and Michael estimates he watched 3 cycles of the seiche over an 80 minute period. The following day large oscillations continued; time lapse photography which shows three successive peaks separated from each other by 14 minutes.

Time lapse imagery of these two events can be found at:

May 9: https://mail.google.com/mail/u/0/#inbox/WhctKJVRJCkNJrhjqgNqRnjQSznQfXdJHmrGNrGgJXsBFzHhMRcFtffNfqxFlqtDclHFjDQ?projector=1

May 10: https://share.icloud.com/photos/0cmoZLFV8Oi5UktShPvxC1qig#Home

Readings are 2 minutes apart. On May 19, at 8PM, a very large seiche struck both Baptist harbour and Corisande Bay, and on the 23rd another less powerful event was observed at Corisande. Video, courtesy of Martha Allen and Michael Butler, can be seen as follows.

May 19: https://youtu.be/OCli1MQvzc8

May 23:https://youtu.be/Qx6QLr4FD4A

Figure 53 compares water level records at Tobermory, Goderich and Alpena Michigan for most of the month of May 2019. Atmospheric pressure for Tobermory is superimposed, as are the time of the May 9, May 19 and May 23 events referred to above.

As seen previously in Figure 49 and Figure 51, all three events in Figure 53 occur on the downward slope of the pressure cycle, typically shortly before the lowest pressure point is reached. These seiches are again accompanied by some high frequency chatter on the descending pressure slope. In Figure 53 the seiches all occur in the latter stages of a 20-40 hour depression of the water level. Not shown in the Figure is the fact that the wind was primarily from the east and northeast during these depressions.

Tobermory and Goderich are 176 km apart on the eastern shore of Lake Huron. Alpena is 126 km across the lake from Tobermory. A closer look at the records from May 9 (Figure) nevertheless shows a remarkably similar chain of events. There is no sharp onset but rather a long train of oscillations, beginning at roughly the same time at all three stations. The time of the maximum displacement[8] within the train varies from station to station, a constructive interference within the train that is perhaps random.

[8] Note the strong 2 hour resonance at Alpena, consistent with the size and depth of the bay.

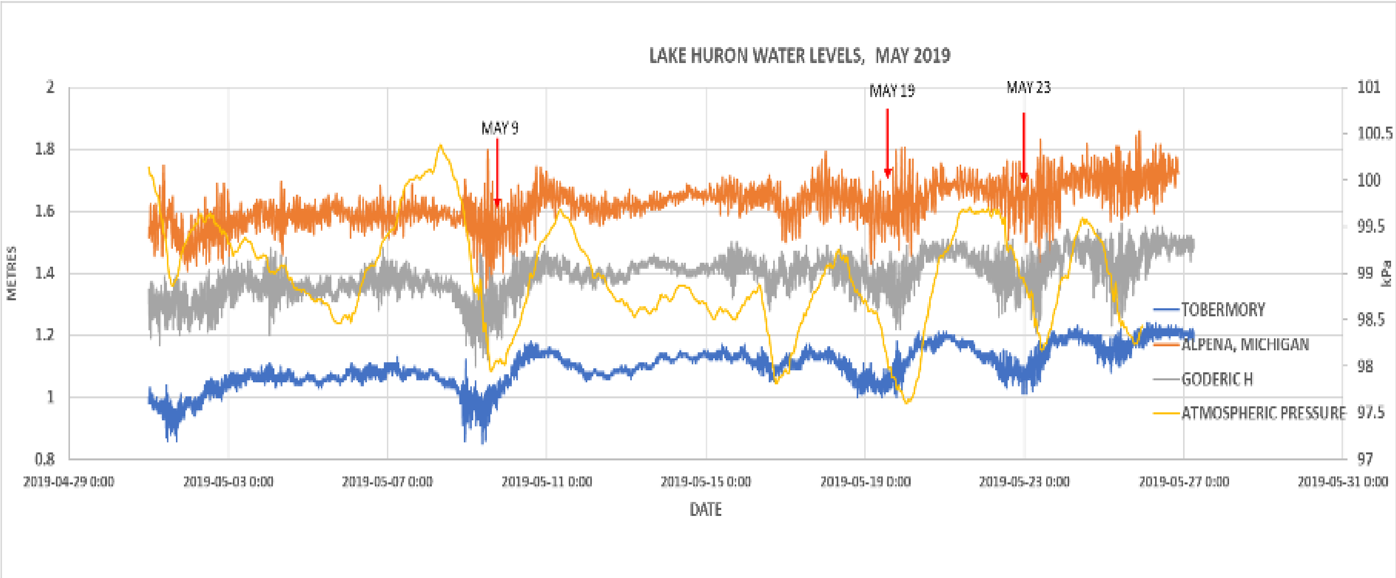


Figure 53. Water level records for Tobermory, Goderich and Alpena Michigan for the month of May, 2019. The traces have been offset for clarity.The atmospheric pressure at Tobermory is shown in yellow. The seiche times noted by observers at Corsande Bay and Baptist Harbour are indicated by the red arrows.

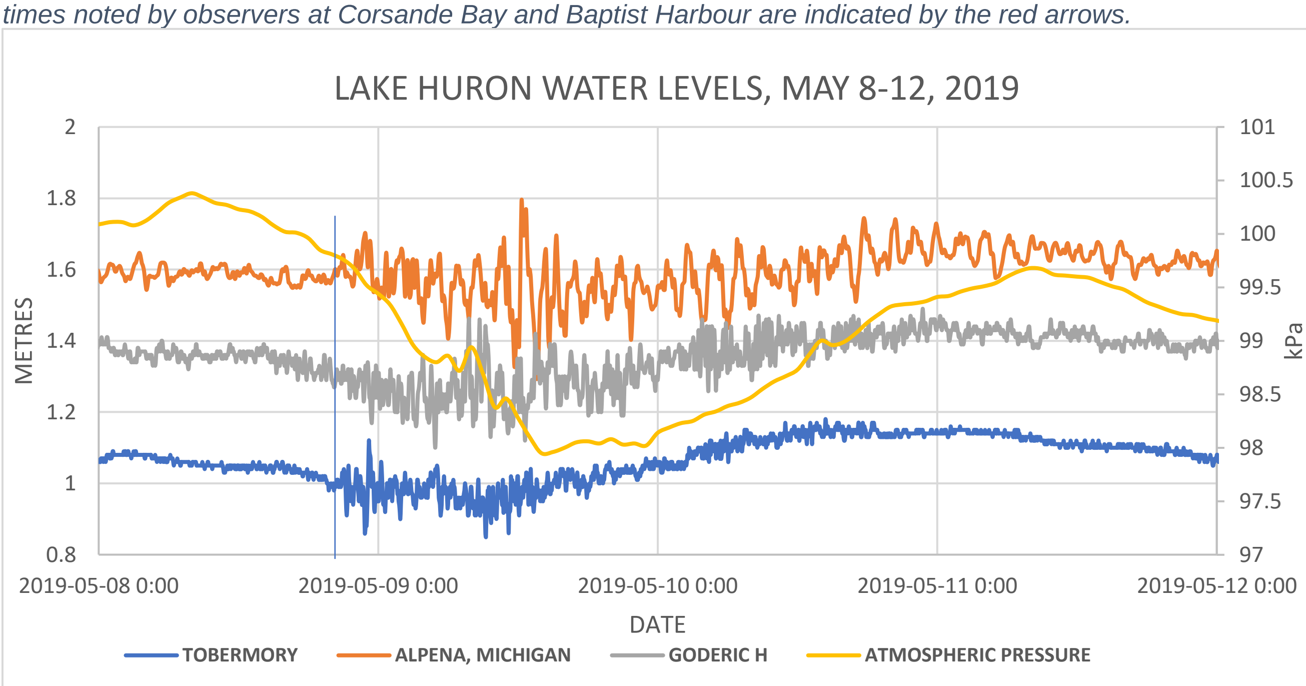


Figure A9. Closer look at the seiche of May 9. Vertical line approximates the start of seiche activity at all three sites, 22:00 on May 8. Atmospheric pressure is measured at Tobermory.