Canadian Technical Report of
Fisheries and Aquatic Sciences 3099

2014

Tidal Analysis in Little Port Joli Basin, Kejimkujik National Park Seaside, NS: Before and After Removal of Bridge and Causeway

by

M. Dowd[1], M.C. Wong, and C. McCarthy[2]

Science Branch, Coastal Ecosystem Sciences Division
Maritimes Region, Fisheries and Oceans Canada
Bedford Institute of Oceanography
1 Challenger Drive
Dartmouth, NS B2Y 4A2

[1] Department of Mathematics and Statistics, Dalhousie University, Halifax, NS B3H 4R2
[2] Parks Canada, Kejimkujik National Park and National Historic Site of Canada, Maitland Bridge, NS B0T 1B0

Cat. No. Fs 97-6/3099E-PDF ISBN 978-1-100-24779-3 ISSN 1488-5379

Correct citation for this publication:

Dowd, M., Wong, M.C., and McCarthy, C. 2014. Tidal Analysis in Little Port Joli Basin, Kejimkujik National Park Seaside, NS: Before and After Removal of Bridge and Causeway. Can. Tech. Rep. Fish. Aquat. Sci. 3099: v + 23 p.

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ABSTRACT

Dowd, M., Wong, M.C., and McCarthy, C. 2014. Tidal Analysis in Little Port Joli Basin, Kejimkujik National Park Seaside, NS: Before and After Removal of Bridge and Causeway. Can. Tech. Rep. Fish. Aquat. Sci. 3099: v + 23 p.

A dramatic decline in the areal extent and health of seagrass (*Zostera marina*) has been observed within Kejimkujik National Park Seaside, located on the south shore of Nova Scotia. In response, Parks Canada initiated a habitat restoration program in the eastern-most lagoon system, Little Port Joli Basin. This lagoon is comprised of an inner and outer region. One aspect of the restoration was the removal of a bridge and causeway structure that severely restricted tidal flows into and out of the inner estuary, where the most severe seagrass declines were observed. The removal took place in Fall 2012. It was anticipated that removal of the bridge and causeway structure would improve tidal flushing and overall ecosystem health of the inner estuary. This report presents a physical oceanographic assessment of the tidal regime, both before and after bridge removal. Pressure sensors were deployed to measure sea level in the inner and outer lagoon, and time series analysis was used to determine the tidal regime. It was found that before the bridge and causeway removal, tides were strongly attenuated and phase lagged in the inner estuary relative to the outer lagoon, consistent with a hydraulic restriction imposed by the bridge and causeway. After its removal, the amplitude and timing of the tides was the same in the inner and outer lagoon, suggesting the bridge and causeway removal has the desired effect of fully removing the hydraulic restriction.

RÉSUMÉ

Dowd, M., Wong, M.C., and McCarthy, C. 2014. Analyse de la marée de la baie Little Port Joli Basin, parc national Kejimkujik Bord de mer, Nouvelle-Écosse: Avant et après l'enlèvement du pont et du pont-jetée. Can. Tech. Rep. Fish. Aquat. Sci. 3099: v + xx p.

Un déclin spectaculaire quant à l'étendue aréale et à la santé des phanérogames marines (*Zostera marina*) a été observé dans le parc national du Canada Kejimkujik, qui se trouve sur la côte sud de la Nouvelle-Écosse. Parcs Canada a donc lancé un programme de restauration de l'habitat dans le système de lagunage le plus à l'est (Little Port Joli Basin). Cette lagune est composée d'une zone intérieure et d'une zone extérieure. Un aspect de la restauration consistait en l'enlèvement d'une structure de pont et de pont-jetée, laquelle limitait grandement les courants de marée entrant et sortant à l'intérieur de la lagune, où les déclins les plus importants de phanérogames marines ont été observés. L'enlèvement a eu lieu à l'automne 2012. On s'attendait à ce que l'enlèvement de la structure du pont et du pont-jetée améliore le renouvellement de l'eau par les marées et la santé globale des écosystèmes à l'intérieur de la lagune. Ce rapport présente une évaluation océanographique physique du régime des marées, à la fois avant et après l'enlèvement du pont. Des capteurs de pression ont été installés pour mesurer le niveau de la mer à l'intérieur et à l'extérieur de la lagune, et une analyse de séries chronologiques a été utilisée pour déterminer le régime des marées. Il a été constaté qu'avant l'enlèvement du pont et du pont-jetée, la force des marées était fortement atténuée et la phase accusait un retard à l'intérieur de la lagune par rapport à l'extérieur de la lagune, ce qui est cohérent avec un obstacle hydraulique tels un pont et un pont-jetée. Après l'enlèvement de la structure, l'amplitude et le calendrier des marées étaient semblables pour l'intérieur et l'extérieur de la lagune, ce qui laisse croire que l'enlèvement du pont et du pont-jetée a eu l'effet désiré, soit l'enlèvement complet de l'obstacle hydraulique.

INTRODUCTION

Little Port Joli Basin is the eastern-most lagoon system of Kejimkujik National Park Seaside, located on the south shore of Nova Scotia (Figure 1). It has been the focus of various research efforts related to its ecology, some of which have been motivated by the decline of seagrass (*Zostera marina*) over the past decades (Ure et al. 2010). The Little Port Joli Basin system is comprised of two regions: an inner estuary and outer lagoon (Figure 1). These two regions have been separated by a bridge and causeway structure that were erected in the early 1900s, and modified in various ways over the years. The most recent bridge and causeway (dating from the 1960s) is shown in the BEFORE photo of Figure 2. An important feature is the very narrow opening that has significantly restricted the tidal flows in and out of the inner estuary.

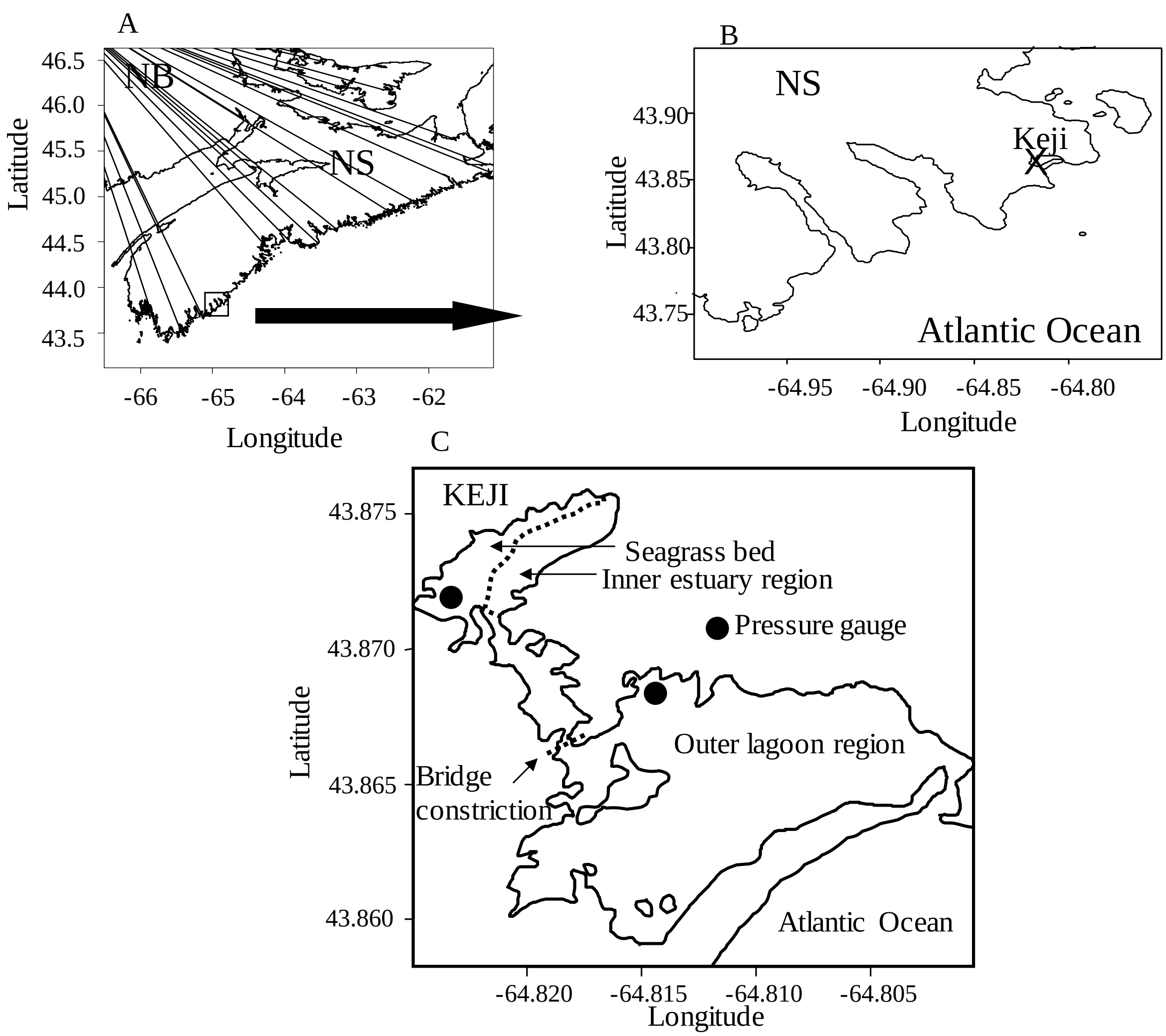


Figure 1. (A) Location of Kejimkujik (Keji) National Park Seaside on the south shore of Nova Scotia. (B) Detailed location of Little Port Joli Basin within the Keji Seaside. (C) Detailed map of Little Port Joli Basin in Keji, showing the inner estuary and outer lagoon regions, location of pressure gauges, and location of the bridge and causeway constriction.

In the presence of the bridge and causeway structure, the tidal range in the inner estuary is much smaller than the outer lagoon, and the timing of the high and low tides occurs much later in the inner estuary. This is indicative of hydraulic control by the bridge constriction. The hydrodynamics of such situations are described in detail by Stigebrandt (1980). The poorly flushed inner region has experienced severe eelgrass (*Zostera marina*) declines, losing nearly all its eelgrass (Wong et al. 2013). This is likely due in part to the weak tidal flushing and consequent elevated temperature, increased sedimentation of fine particulates, and growth of epiphytic and floating algal mats.

BEFORE removal:

AFTER removal

Figure 2. Before (top) and after (bottom) the bridge and causeway removal.

As part of a habitat restoration program, the bridge and causeway was removed during the week of October 22, 2012. The narrow constriction under the bridge was eliminated and with the causeway removed the restored channel followed the original natural shoreline (illustrated in AFTER photo of Figure 2). The result was an opening to the inner estuary with a much wider and deeper channel. Because the basin geometry is thought to now more closely resemble the pre-causeway conditions, it is anticipated that the physical oceanography of the inner basin will return to its original conditions, and other geological, chemical and biological elements will eventually follow.

The purpose of this analysis is to assess the effect of the bridge and causeway removal on one key aspect of the physical oceanography: the sea level, or tidal height. Here, we compare the tidal regime both before and after the bridge and causeway removal to determine the effectiveness of this physical oceanographic aspect of habitat restoration.

METHODS

DATA COLLECTION

Details of the bridge geometry are given in Figure 3. The tidally averaged depth below the bridge was approximately 1m. The narrow opening, along with the observed tidal rapids (a small form of reversing falls), provides evidence for hydraulic control of the flow. This led to strongly restricted tidal flushing of the inner estuary.

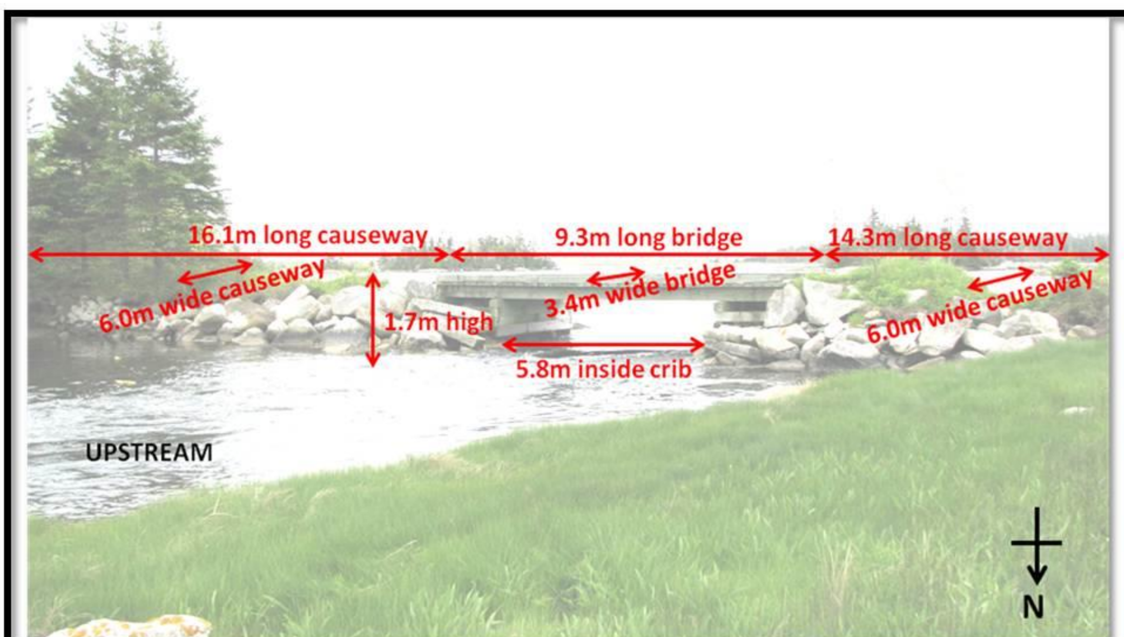


Figure 3. Detailed picture of the bridge and causeway structure with dimensions.

Underwater pressure sensors (Onset Computer Corporation) were deployed to measure the sea level (i.e., tidal height). These were located as shown in Figure 1. One pressure gauge was deployed in the outer lagoon, and one in the inner estuary (that is, inside and outside of the bridge and causeway constriction). Since the tidal height is roughly the same within both the inner estuary and outer lagoon, each pressure sensor is fairly representative of the region in which it was deployed.

Tidal height from both before and after the bridge and causeway removal was collected. The idea was to use height records from before/after removal in both the inner estuary and outer lagoon that are coincident in time. These can then be directly examined in terms of changes in the tidal magnitude and timing to assess the overall effect of bridge removal on the tidal regime.

A continuous sea level record was obtained from October 6, 2012 to December 8, 2012. These data were sampled at 15 minute intervals. This record was split into the periods before (before October 23) and after (after October 25) the bridge and causeway removal. This yielded a record length for sea level of about 44 days after bridge and causeway removal, and 19 days before the bridge and causeway removal.

Since the above tidal height record for before the bridge and causeway removal is relatively short in duration, another longer tidal height record from July to September 2010 was also examined in order to better quantify the pre-removal tidal regime. This record had pressure sensors deployed at the same locations, and comprised a 60 day record (with a 10 minute sampling interval). Note that this record was taken more than 2 years prior to bridge removal - we will remark further on this below.

DATA ANALYSES

The following pre-processing procedures were carried out. Each of the data series were truncated to ensure only the in-water period was being included. Basic quality control procedures looked for spurious spikes, and instrument errors. Since none of these were found in these records, no corrections or data infilling were needed.

Low frequency non-tidal variations in the record were then removed (these are mainly due to atmospheric pressure fluctuations that are also recorded by the pressure sensor). This was done by fitting the low frequency trend using smoothing splines, and removing this trend. The eliminated fluctuations with periods longer that about 2 days. Note that this does not affect the spring-neap cycle as it is a modulation of two closely space high frequency signals. This process yields the sea level anomalies due to tidal processes, and these data were used as the basis for the analysis.

There are 4 tidal time series records:

- Inner estuary, before bridge and causeway removal (Inner/Before)
- Outer lagoon, before bridge and causeway removal (Outer/Before)
- Inner estuary, after bridge and causeway removal (Inner/After)
- Outer lagoon, after bridge and causeway removal (Outer/After)

Our aim is to quantify the differences in the tidal regime of the lagoon system before and after the bridge and causeway removal by comparing the inner estuary and outer lagoons in terms of their tidal range and tidal timing.

Analyses of the records was undertaken using two approaches:

1. *Statistical Time Series Analysis*: The tidal height records were each subjected to spectral analysis to look at the distribution of variance (tidal energy) with respect to tidal period. To determine the relationships between the inner estuary and outer lagoon in both the before and after periods, cross-correlation and cross spectral (phase spectra) analyses were undertaken.

2. *Harmonic Analysis*: The tidal height records were subjected to a harmonic analysis that quantified the contributions of the various tidal constituents. These are summarized as amplitudes and Greenwich phases (the Greenwich phase is the tidal timing relative to Greenwich Mean Time). This was done using the U-Tide package in Matlab, with details given by Codiga (2011). For all identifiable tidal constituents (which depends largely on record length), amplitudes and their confidence interval (A and A_ci), as well as Greenwich phases and their confidence interval (g and g_ci), were obtained.

RESULTS

BEFORE BRIDGE AND CAUSEWAY REMOVAL: SUMMER 2010 RECORD

Tidal height time series from a period two years before the bridge and causeway removal are shown in Figure 4 for both the inner estuary and outer lagoon. These records show the twice-daily (semi-diurnal) tides, and exhibit a spring-neap cycle. They also indicate an asymmetry in the high and low tides in this very shallow system. An important feature of these records is the much smaller tidal range seen in the inner estuary, as compared to the outer lagoon. The magnitude and timing changes of the tides are quantified in detail later.

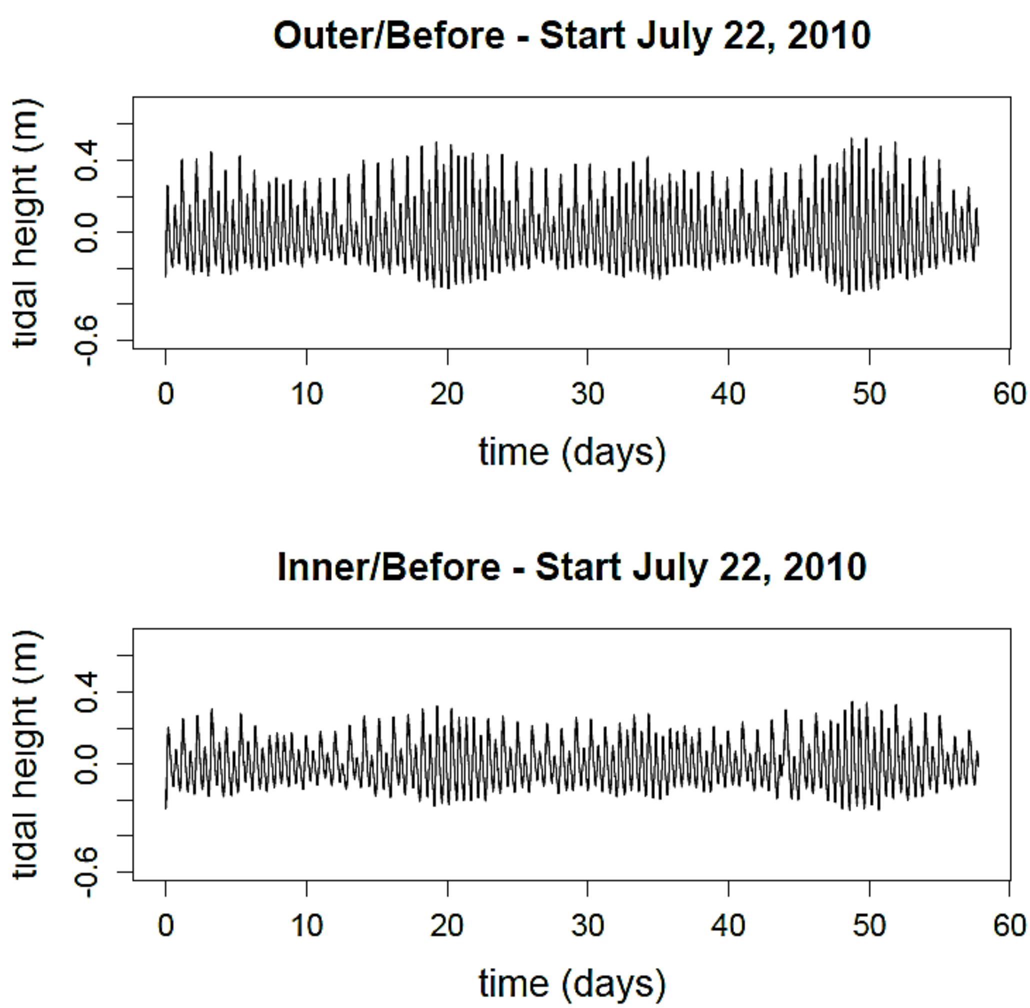


Figure 4. Tidal height (m) time series from the outer lagoon (top) and inner estuary (bottom) in summer 2010, before the bridge and causeway removal.

The power spectra of the tidal height in the inner estuary and outer lagoon are shown in the left hand panel of Figure 5. These indicate that the dominant time scale of variability is at the period of the semi-diurnal lunar tide (M2, with period 12.42 hours). There is also a smaller peak for the daily tides. Short period over-tides (nonlinear shallow water tides that give rise to the asymmetry in the tidal record) are seen at observed periods of 8.33 hours (shallow water diurnal) and 6.21 hours (M4, and the shallow water quarter diurnal constituents). It is also evident that there is substantially less tidal energy in the inner estuary as compared to the outer lagoon - in fact, the energy, or variance, is about halved in the inner estuary. The phase spectrum is shown in the right hand panel. This measures the tidal timing change between the inner estuary and outer lagoon. The phase shift here indicates that the semi-diurnal tide in the inner estuary is 1.5 hours behind the outer lagoon, while the diurnal tide is 2.26 hours behind.

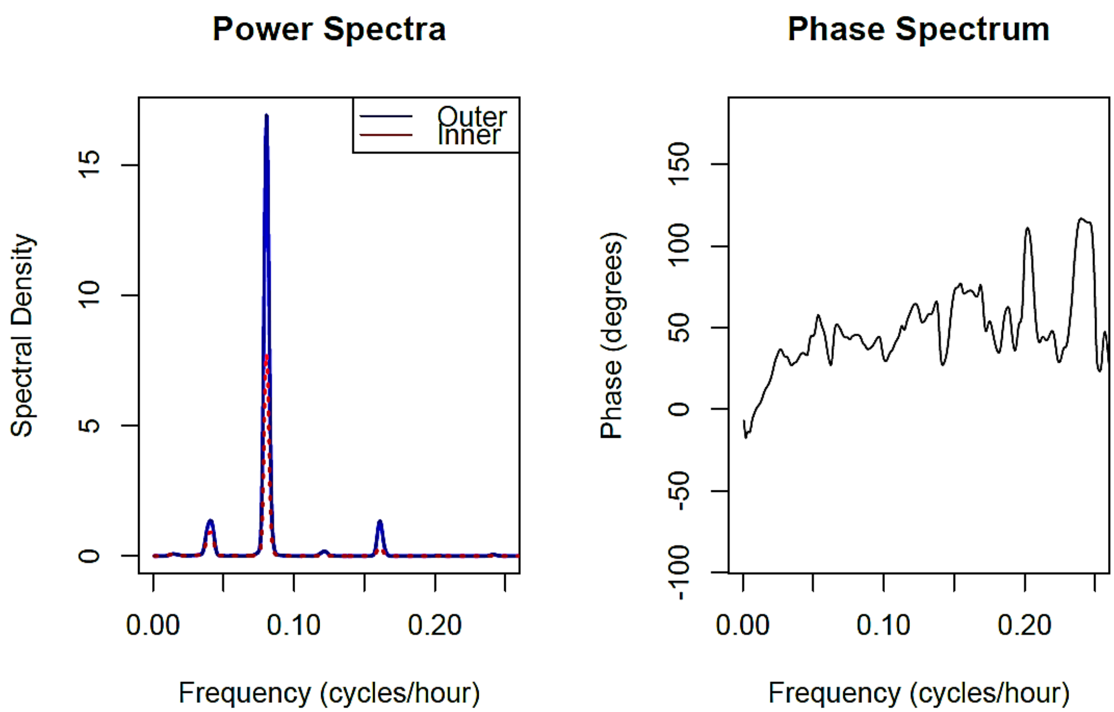


Figure 5. Power spectra (left-hand panel) of the tidal height in the inner estuary (red) and outer (blue) lagoon in summer 2010 before the bridge and causeway removal. The phase spectrum (right-hand panel) measures the tidal timing change between the inner and outer regions.

The cross-correlation for tidal height in the inner estuary and outer lagoon is shown in Figure 6. This indicates that the overall tide in the outer lagoon leads that of the inner estuary by 1.5 hours (i.e., the lag associated with the peak of the cross-correlation function).

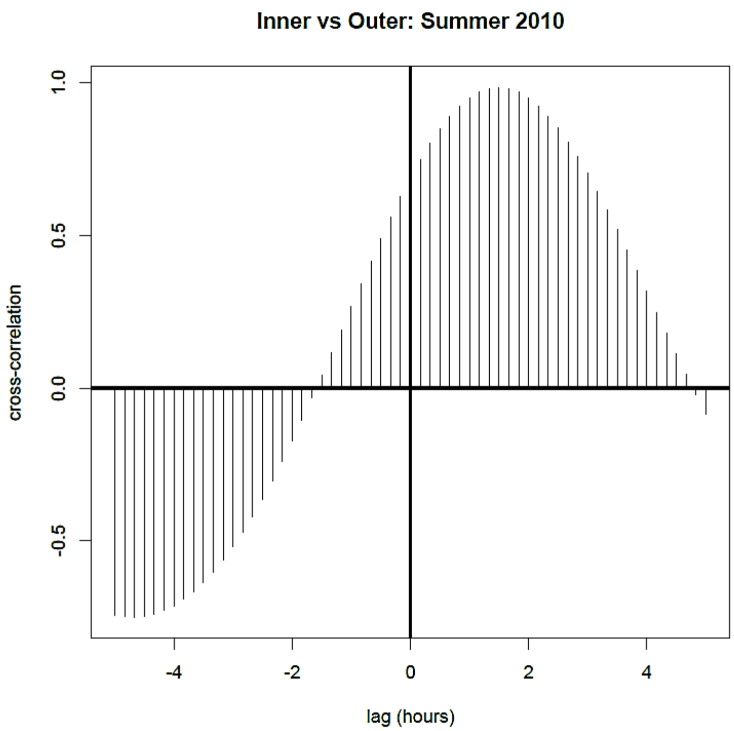


Figure 6. Cross-correlation function for tidal height between the inner estuary and outer lagoon in summer 2010 before the bridge and causeway removal.

Results from the harmonic analysis of the tidal height record of the outer lagoon are given in Table 1 (the 10 most important tidal constituents are shown, the full list of constituents is given in the Appendix Table A1):

Table 1: Harmonic analysis for the Outer Lagoon (before the bridge and causeway removal in Summer 2010). The 10 most important tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.207	0.00179	47.4	0.528
M4	0.0553	0.00108	41	1.31
K1	0.0524	0.00232	213	2.14
N2	0.0498	0.002	22.5	2.69
S2	0.0492	0.00182	88.9	2.52
O1	0.0473	0.0018	194	2.45
MN4	0.0251	0.000951	15.7	2.78
MS4	0.0222	0.00125	92.6	3.35
MK3	0.0187	0.0012	200	3.43
MO3	0.0138	0.00108	163	5.1

Results from the harmonic analysis of the record for the inner estuary are given in Table 2 (the 10 most important tidal constituents being shown, the full list of constituents is given in the Appendix A2):

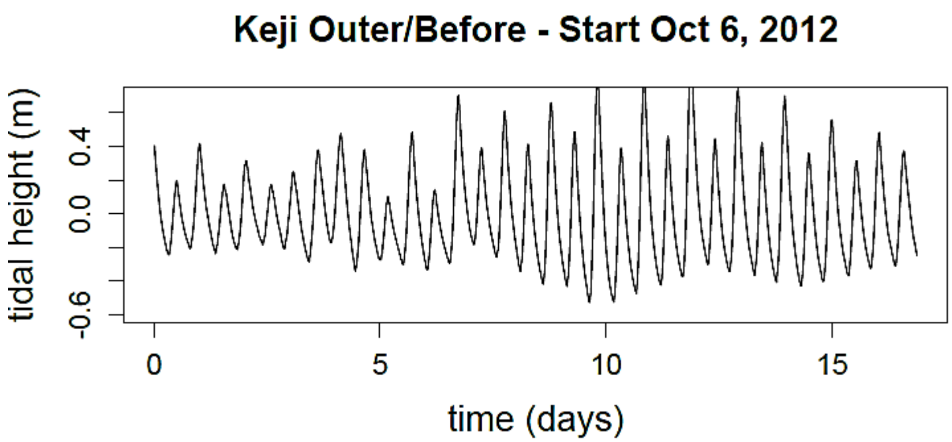
Table 2. Harmonic analysis result for the Inner Estuary (before the bridge and causeway removal in Summer 2010). The 10 most important tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.14	0.00182	93.2	0.628
K1	0.0419	0.00182	248	2.04
O1	0.0381	0.0017	223	2.28
N2	0.0335	0.00165	66.1	2.82
S2	0.032	0.00185	128	3.2
M4	0.0291	0.000951	115	1.62
MN4	0.0132	0.000903	87.1	3.51
MS4	0.0116	0.000785	159	3.71
MK3	0.0102	0.000613	267	3.65
MU2	0.00825	0.00188	38	10.9

Results from this harmonic analysis confirm the lunar semi-diurnal M2 tide is the most important constituent, and has an amplitude of 20 cm (for a tidal range of 40 cm). The solar semi-diurnal tide S2, as well as N2, are about 1/5 the amplitude of M2 (and their interaction with M2 causes the spring-neap cycle). The lunar diurnal constituents K1 and O1 are also present, along with shallow water tides (notably M4, the lunar over-tide). The main difference between the inner estuary and outer lagoon are: (i) all the constituent amplitudes are smaller in the inner estuary (e.g., M2 is 30% smaller); (ii) The non-linear shallow water tide M4 is much less important in the inner estuary; (iii) The Greenwich phases are larger indicating that the tidal timing is later in the inner estuary (and corresponds to the time shifts found via the phase spectra above).

BEFORE BRIDGE AND CAUSEWAY REMOVAL: FALL 2012 RECORD

The tidal height time series from the 17 days immediately proceeding the bridge and causeway removal are shown in the time series of Figure 7, for the inner estuary and outer lagoon. This is a relatively short record and we will not be able to resolve the tidal variability to the same extent as for the other, longer, records (which is the rationale for including the more extensive Summer 2010 record in the analysis). The time series again clearly indicates the smaller magnitude of the tides in the inner estuary relative to the outer lagoon. The other point of interest is that the magnitude of the overall tidal height range is nearly 20cm larger than the Summer 2010 record. The reason for this large variation is the changes in the geometry of the channel that connects the lagoon system to the adjacent ocean (i.e. it opened up) - this is discussed further in the Conclusions.



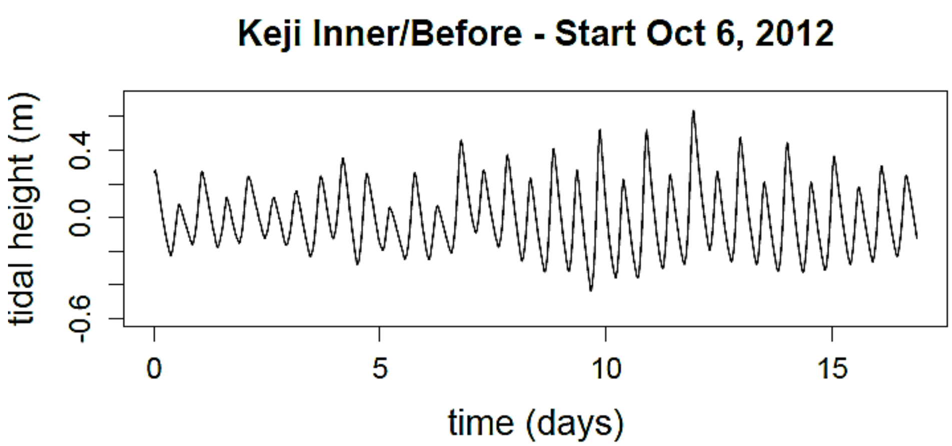


Figure 7. Tidal height time series in the outer estuary (top) and inner estuary (bottom) from Fall 2012, immediately before the bridge and causeway removal.

The power spectra of the tidal height in the inner estuary and outer lagoon are show in the left hand panel of Figure 8. A very similar pattern of variation to the Summer 2010 record is seen with diurnal, semi-diurnal and shallow water tides; the much smaller magnitude of the tidal energy in each of these same frequency bands for the inner estuary is also evident (note that the spectral peaks are broader). The phase spectrum indicates that tides in the inner estuary lag those of the outer lagoon. Specifically, for the diurnal tides the lag is 2.06 hours, and for the semidiurnal tides it is 1.52 hours.

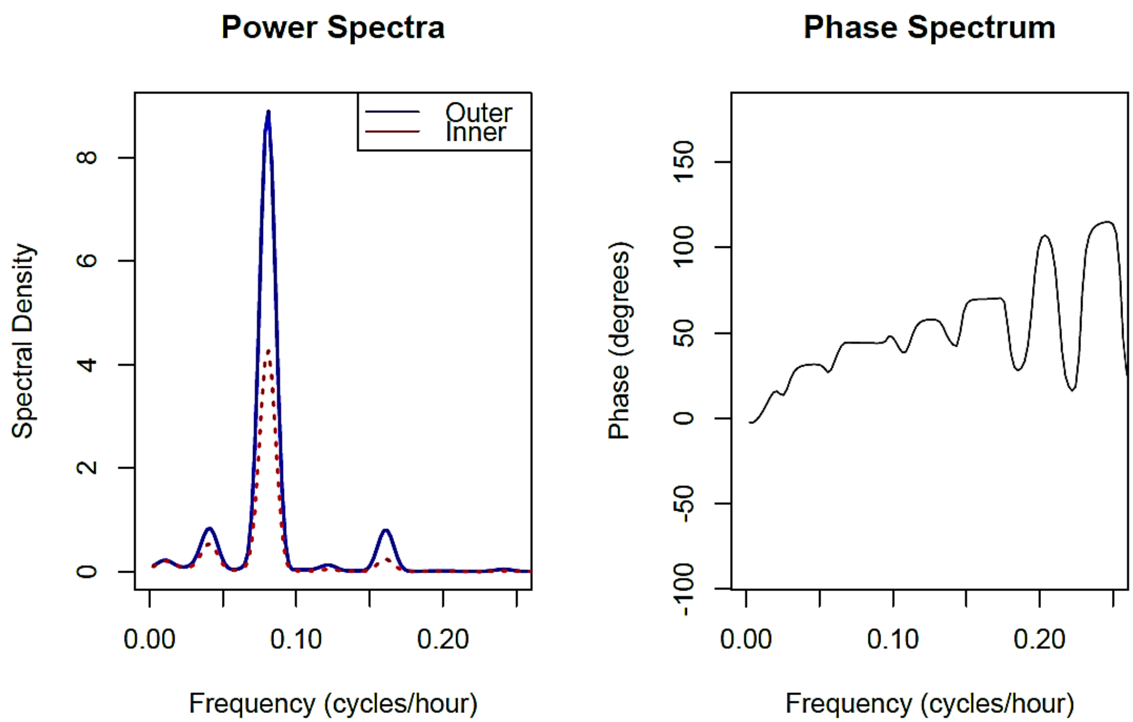


Figure 8. Power spectra (left-hand panel) of the tidal height in the inner estuary (red) and outer lagoon (blue) in Fall 2012 immediately before the bridge and causeway removal. The phase spectrum (right-hand panel) measures the tidal timing change between the inner and outer regions.

The cross-correlation for tidal height between the inner estuary and outer lagoon is shown Figure 9. As in the Summer 2010 record, it is seen that the overall tide in the inner estuary lags that of the outer lagoon is later by 1.5 hours.

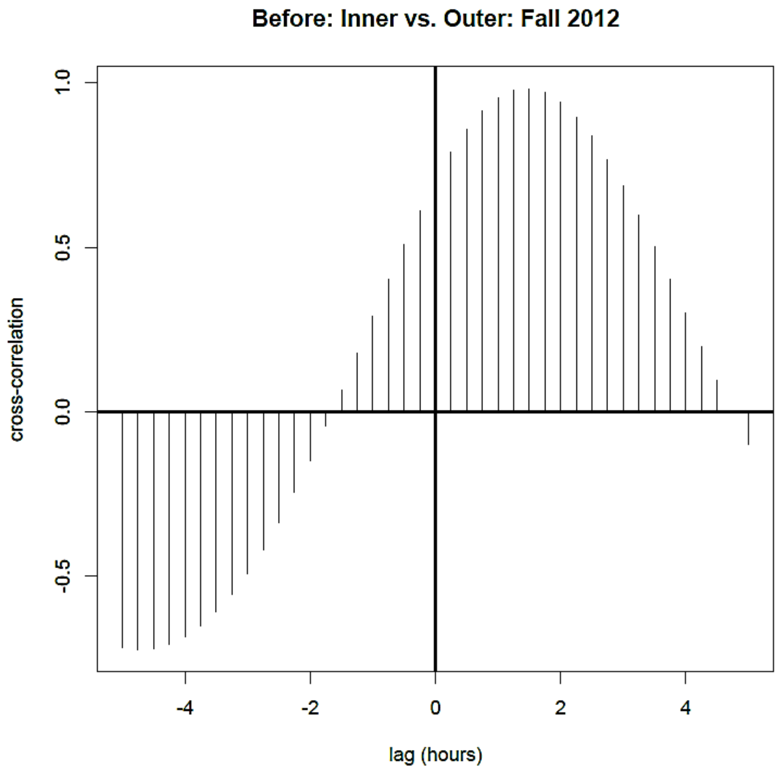


Figure 9. Cross-correlation function for tidal height between the inner estuary and outer lagoon in Fall 2012 immediately before to the bridge and causeway removal.

Results from the harmonic analysis in the Outer Lagoon are show in Table 3. Only a limited set of tidal constituents can be inferred from this relatively short record. We chose to estimate only the constituents that were deemed the most important in the later, and longer, record in Fall 2012 (see next section).

Table 3. Harmonic analysis result for the Outer Lagoon for the Fall 2012 record immediately prior to bridge removal. The tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.329	0.0103	50.3	1.62
K1	0.0926	0.00882	167	5.74
S2	0.0868	0.00975	75.8	5.88
N2	0.086	0.00868	16.4	6.39
M4	0.0852	0.0115	31.8	7.97
O1	0.0685	0.00789	228	6.83
MK3	0.0321	0.00334	168	6.8
L2	0.0283	0.00838	61.2	19.4

Results from the harmonic analysis in the Inner Estuary are given in Table 4.

Table 4. Harmonic analysis result for the Inner Estuary for the Fall 2012 record immediately prior to bridge removal. The tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.241	0.00761	86.8	1.73
K1	0.0718	0.00687	198	5.11
O1	0.0511	0.00651	251	7.44
S2	0.0505	0.00696	91.9	8.69
M4	0.0498	0.00593	101	7.34
N2	0.038	0.006	54.5	10.8
L2	0.0206	0.00735	7.5	21.2
MK3	0.0177	0.00329	229	10.5

This harmonic analysis shows results consistent with the earlier record from Summer 2010, with Greenwich phases being similar. The exception is that the tidal amplitudes are generally higher than before (see Conclusions regarding the barrier beach dynamics and outer channel), but the tidal amplitudes of all the constituents are again smaller in the inner estuary relative to the outer lagoon. Notably, the dominant M2 tide has decreased by 27%. The Greenwich phases indicate timing changes relative to the outer lagoon consistent with the phase spectra above. Again, there is clear evidence from strong hydraulic control by the bridge and causeway.

AFTER BRIDGE AND CAUSEWAY REMOVAL: FALL 2012 RECORD

Tidal height time series from the 45 days after the bridge and causeway removal are shown in Figure 10. The amplitude of the tide is similar to that of the Fall 2012 outer lagoon record immediately preceding bridge removal (previous Section). However, the most important feature here is that these tidal records in the inner estuary and outer lagoon after the bridge and causeway removal look nearly identical to one another in terms of magnitude of the tidal height.

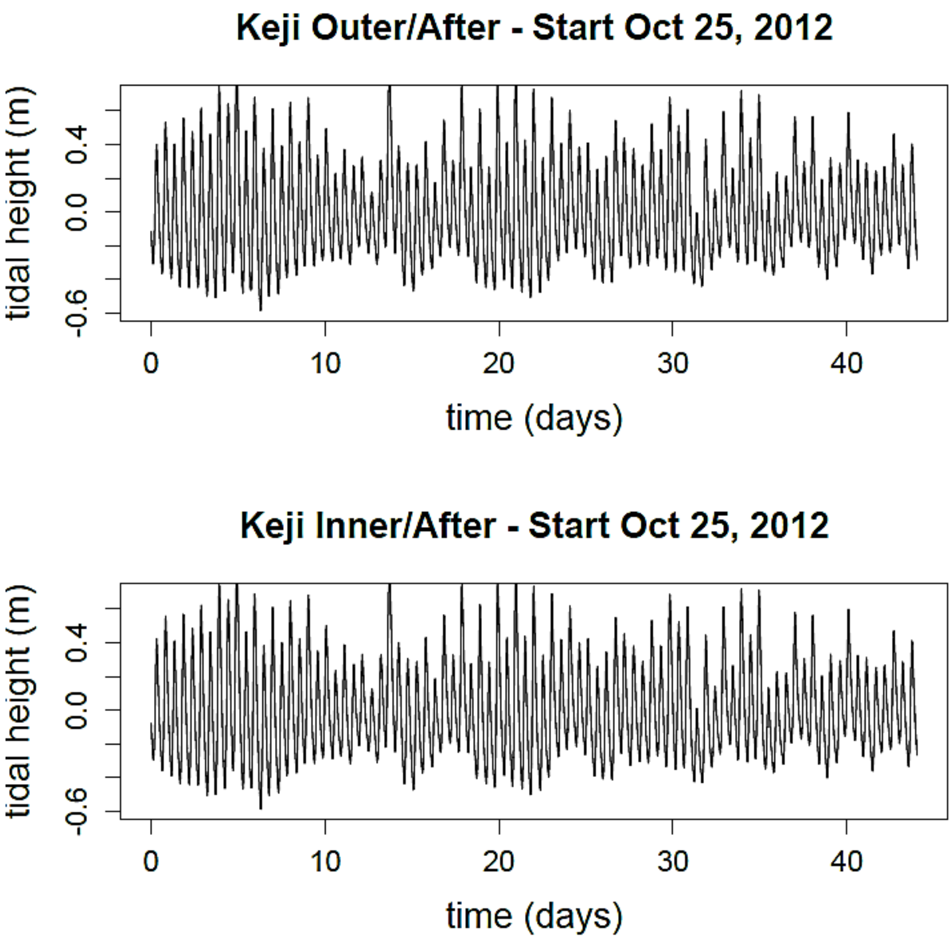


Figure 10. Tidal height (m) time series in the outer lagoon (top) and inner estuary (bottom) in Fall 2012, immediately after the bridge and causeway removal.

The power spectra of the tidal height in the inner estuary and outer lagoon are show in the left hand panel of Figure 11. These show diurnal, semidiurnal, and higher frequency shallow water tides. The main feature here that is different from the situation before the bridge and causeway removal is that the tidal regime is nearly identical in both the inner estuary and outer lagoon (the inner estuary does have a fractionally smaller energy). The phase spectra (right hand panel) indicates that the tides in the inner estuary now only slightly lag the outer lagoon; the semi-diurnal and diurnal tides in the inner estuary are 15 minutes behind the outer lagoon.

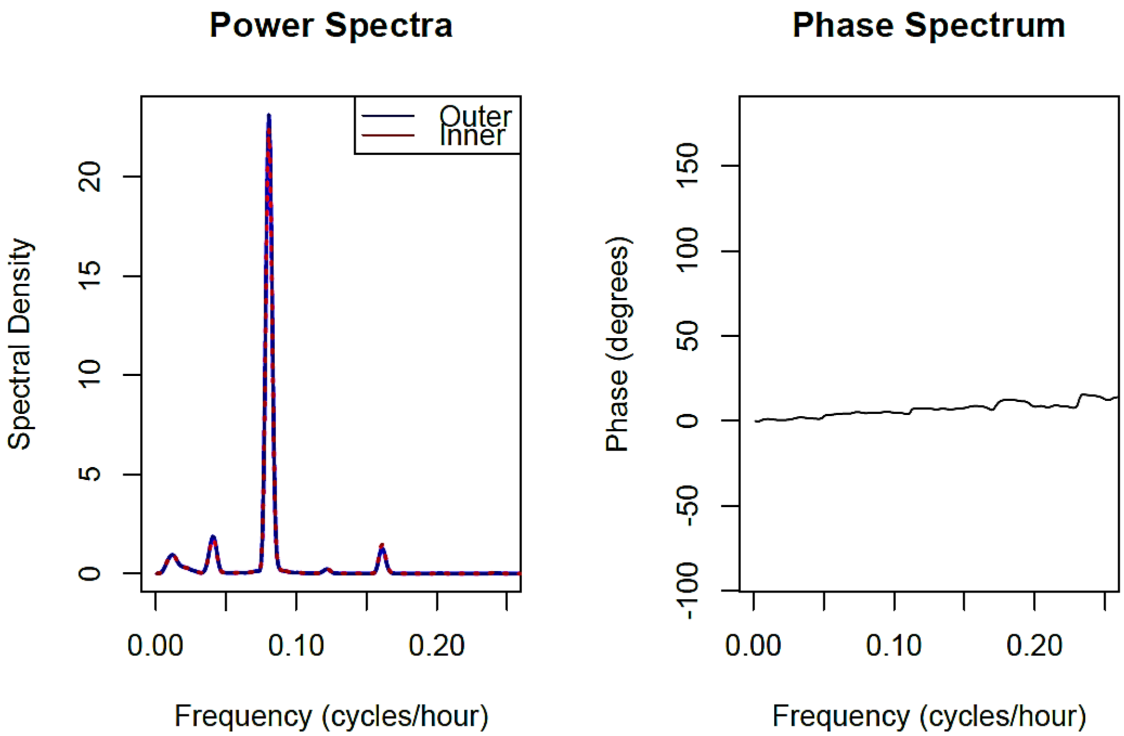


Figure 11. Power spectra (left-hand panel) of the tidal height in the inner estuary (red) and outer lagoon (blue) immediately after the bridge and causeway removal. The phase spectrum (right-hand panel) measures the tidal timing change between the inner and outer regions.

The cross-correlation for tidal height in the inner estuary and outer lagoon is shown in Figure 12. This confirms that the overall tide in the outer lagoon leads that of the inner estuary by 15 minutes (which is a single lag unit, corresponding to the sampling interval).

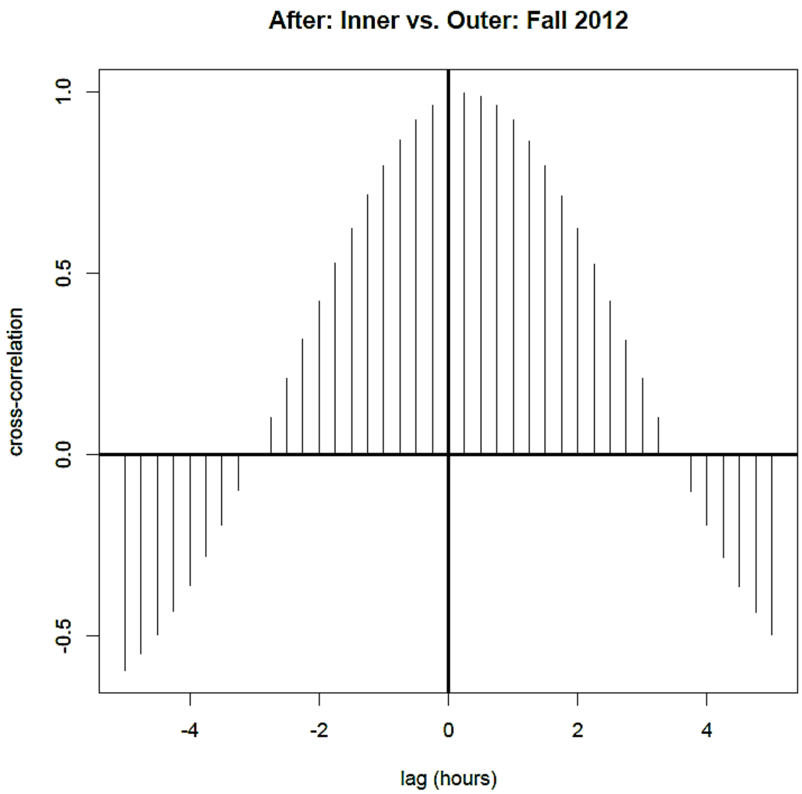


Figure 12. Cross-correlation function for tidal height between the inner estuary and outer lagoon for the Fall 2012 record immediately after the bridge and causeway removal.

Results from the harmonic analysis of the record for the outer lagoon are given in Table 5 (10 most important tidal constituents are shown, full list given in Appendix Table 3).

Table 5. Harmonic analysis result for the Outer Lagoon for the Fall 2012 record immediately after bridge removal. The tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.335	0.00786	53.2	1.59
K1	0.0963	0.00327	184	1.75
M4	0.0751	0.00186	50.1	1.47
S2	0.0709	0.00836	63	6.74
O1	0.0649	0.00256	213	2.72
N2	0.0565	0.00682	19.9	8
L2	0.0344	0.00773	30.8	14.3
MK3	0.0319	0.002	171	3.32
MS4	0.0285	0.00189	66.8	3.32
MN4	0.0283	0.00191	27.1	3.82

Results from the harmonic analysis of the record for the inner estuary are given in Table 6 (10 most important tidal constituents are shown, full list given in Appendix Table 4).

Table 6. Harmonic analysis result for the Inner Estuary for the Fall 2012 record immediately after bridge removal. The 10 most important tidal consituents (Cnstit) are given. Here, A is the amplitude in metres, A_ci is the width of its associated confidence interval, g is in phase in degrees relative to Greenwich, and g_ci is the width of its confidence interval.

Cnstit	A	A_ci	g	g_ci
M2	0.33	0.00689	60.6	1.43
K1	0.0939	0.00305	189	1.91
M4	0.0799	0.00223	65.3	1.32
S2	0.0692	0.00822	69.6	5.42
O1	0.0632	0.00302	217	2.74
N2	0.0541	0.00723	28.9	7.65
L2	0.0342	0.0077	36	12.8
MK3	0.0326	0.00178	184	3.97
MN4	0.0304	0.00174	44.7	3.78
MS4	0.0293	0.00168	80.5	3.57

The exact same tidal constituents in the same order of importance are found in both the inner estuary and outer lagoon (the only exception being a change in order for the last 2 shallow water tidal constituents). The tidal amplitude for all semidiurnal and diurnal constituents are decreased fractionally in the inner estuary, and Greenwich phases indicate the approximately 15 minute phase shift due to the time it takes for the tidal wave to propagate into the inner estuary. The tidal amplitude for the shallow water constituents are increased fractionally in the inner estuary with small phase changes, reflecting the local generation of these components due to basin geometry and friction.

This overall implication of the analysis of the sea level record is that after the bridge and causeway removal there is no evidence of hydraulic control and its associated amplitude and phase signature. The tides in the inner estuary and outer lagoon now vary almost synchronously.

SUMMARY AND CONCLUSIONS

Sea level time series were analysed from both before and after the bridge and causeway removal, which took place the week of October 22, 2012. The purpose here was to assess the effectiveness of bridge removal as part of a habitat restoration program in Little Port Joli Basin. Towards this end, we addressed the question of whether the physical oceanography has returned to its (presumed) original pre-bridge state, with consequent improvement of tidal flushing of the inner estuary.

The tidal height record from before the bridge and causeway removal indicated that the bridge structure strongly restricted water exchange and flushing of the inner estuary. Tidal amplitudes were compared from the outer lagoon and the inner estuary *before* the bridge and causeway removal, and showed that the tidal range was about 30% smaller in the inner estuary, and that the tidal timing was delayed by about 1.5 hours. The analysis of the sea level *after* the bridge and causeway removal showed that tidal range decreased by only a few percent, and timing of the tides differed by 15 minutes or less between the inner and outer regions. The tidal constituents in the inner and outer regions were, in fact, virtually identical after the bridge and causeway removal, in contrast to having a quite different makeup before removal. The situation after the bridge and causeway removal is therefore consistent with removal of hydraulic control, and about what would be expected for this type of tidal inlet as the tide propagates landward and is affected by bay geometry and bottom friction.

It was also noted that there seem to be some longer term changes in the overall tidal regime within the Little Port Joli Basin system. Comparing the two records from *before* bridge removal - that is, Summer 2010 and Fall 2012 - suggested an increase in tidal range from 2010 to 2012, and also indicated differences in the shallow water tidal constituents. Such an observation can only be explained by changes in the geometry of the outer lagoon channel and its connection to the open ocean. The outer channel also acts as a hydraulic restriction, and it appears that tidal exchange with the open ocean has become greater since 2010 due to changes in its geometry. Channel geometry is a dynamic quantity resulting from sediment transport processes associated with barrier beach dynamics, and the re-working of the sand deposits within the lagoon. Aerial photography studies confirm that the barrier beach and outer channel have significant variability over the last 80 years (Bourdeau 2010).

In conclusion, the bridge and causeway removal appears to be effective in fully removing the hydraulic control that had been imposed on the inner estuary by the bridge and causeway constriction. The sea level variations are now nearly synchronous, tidal flushing is greatly enhanced, and the expectation is that sediment, biological and chemical processes will now re-equilibrate on longer time-scales to reflect this new reality in the physical environment.

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APPENDIX: COMPLETE HARMONIC ANALYSIS RESULTS

BEFORE BRIDGE AND CAUSEWAY REMOVAL: SUMMER 2010

Table A1. Results from the harmonic analysis of the record for the Outer Lagoon. A is the amplitude in metres, g is in phase in degrees (relative to Greenwhich), and A_ci and g_ci are the associated widths of the confidence intervals.

Cnstit	A	A_ci	g	g_ci
M2	0.207	0.00179	47.4	0.528
M4	0.0553	0.00108	41	1.31
K1	0.0524	0.00232	213	2.14
N2	0.0498	0.002	22.5	2.69
S2	0.0492	0.00182	88.9	2.52
O1	0.0473	0.0018	194	2.45
MN4	0.0251	0.000951	15.7	2.78
MS4	0.0222	0.00125	92.6	3.35
MK3	0.0187	0.0012	200	3.43
MO3	0.0138	0.00108	163	5.1
L2	0.0121	0.00225	89.5	9.07
MU2	0.0115	0.00218	2.18	18.6
M6	0.0107	0.000663	47.4	3.18
Q1	0.00857	0.00185	207	11.6
M3	0.00713	0.00108	89.2	9.97
2MN6	0.00618	0.00068	20.6	5.88
2MS6	0.00595	0.000717	104	6.97
OO1	0.00498	0.00179	248	22.7
2MK5	0.00496	0.000811	196	9.9
NO1	0.00455	0.0016	210	26.4
SK3	0.00419	0.00101	252	13.7
2Q1	0.00393	0.00194	169	27.5
J1	0.0035	0.00175	163	31.9
M8	0.00322	0.000303	104	4.46
SN4	0.00276	0.00111	278	24.5
ETA2	0.00275	0.00193	105	48.4
EPS2	0.00229	0.00207	308	49
ALP1	0.00216	0.00167	300	50.2
S4	0.00183	0.00123	110	39.8
2SM6	0.00142	0.000659	121	26.7
MSF	0.0012	0.000313	101	15.5
3MK7	0.00119	0.000326	237	15.3
MM	0.000971	0.000342	173	20.2

Table A2. Results from the harmonic analysis of the record for the Inner Estuary. . A is the amplitude in metres, g is in phase in degrees (relative to Greenwhich), and A_ci and g_ci are the associated widths of the confidence intervals.

Cnstit	A	A_ci	g	g_ci
M2	0.14	0.00182	93.2	0.628
K1	0.0419	0.00182	248	2.04
O1	0.0381	0.0017	223	2.28
N2	0.0335	0.00165	66.1	2.82
S2	0.032	0.00185	128	3.2
M4	0.0291	0.000951	115	1.62
MN4	0.0132	0.000903	87.1	3.51
MS4	0.0116	0.000785	159	3.71
MK3	0.0102	0.000613	267	3.65
MU2	0.00825	0.00188	38	10.9
L2	0.00809	0.00187	143	13.1
Q1	0.00744	0.00179	237	13.9
MO3	0.00676	0.000603	219	4.07
M6	0.00505	0.000446	166	5.54
OO1	0.00397	0.00167	265	20
2Q1	0.00382	0.00171	205	22.4
NO1	0.00346	0.00188	233	27.4
M3	0.00328	0.000572	148	10.8
SK3	0.00278	0.000605	305	13.3
2MN6	0.00272	0.000436	144	8.52
2MS6	0.00267	0.000486	212	9.56
M8	0.00239	0.000203	242	4.42
J1	0.00232	0.0015	203	46.1
ETA2	0.00228	0.00153	148	50.7
ALP1	0.00224	0.0017	336	49.2
2MK5	0.00223	0.000296	318	8.08
SN4	0.00211	0.000787	24.4	24
EPS2	0.00187	0.00207	304	65
MSF	0.00167	0.000586	101	22.5
S4	0.00142	0.000811	187	37.1
3MK7	0.00128	0.000274	36	11.6
MM	0.00119	0.000547	177	28.2
UPS1	0.000898	0.00153	321	130
2SM6	0.000837	0.000408	217	31.9
2SK5	0.000553	0.000273	359	105

AFTER BRIDGE REMOVAL: NOV 2012

Table A3. Results from the harmonic analysis of the record for the Outer Lagoon. . A is the amplitude in metres, g is in phase in degrees (relative to Greenwhich), and A_ci and g_ci are the associated widths of the confidence intervals.

Cnstit	A	A_ci	g	g_ci
M2	0.335	0.00786	53.2	1.59
K1	0.0963	0.00327	184	1.75
M4	0.0751	0.00186	50.1	1.47
S2	0.0709	0.00836	63	6.74
O1	0.0649	0.00256	213	2.72
N2	0.0565	0.00682	19.9	8
L2	0.0344	0.00773	30.8	14.3
MK3	0.0319	0.002	171	3.32
MS4	0.0285	0.00189	66.8	3.32
MN4	0.0283	0.00191	27.1	3.82
ETA2	0.0213	0.00669	293	24.2
Q1	0.0192	0.00301	250	8.9
MO3	0.0186	0.00212	173	5.72
J1	0.0125	0.00278	202	16.3
MU2	0.0122	0.00686	338	34.4
M6	0.0113	0.00109	56.6	5.41
SN4	0.0112	0.00191	265	8.07
MM	0.00942	0.00268	137	16.7
MSF	0.00837	0.00298	14.9	22
2MK5	0.00716	0.00145	136	11.1
2Q1	0.00714	0.00331	230	21.4
UPS1	0.00663	0.00293	183	21.8
NO1	0.00657	0.00285	268	27
2MS6	0.00598	0.00117	84.6	10.1
2MN6	0.00596	0.00102	35.3	9.11
OO1	0.00549	0.00301	325	34.2
EPS2	0.00473	0.00657	296	87.9
SK3	0.00408	0.0017	206	25
M3	0.00408	0.002	70.9	31.5
S4	0.00372	0.00165	59.4	28.9
2SK5	0.0023	0.00125	152	34.9
ALP1	0.00228	0.00284	46	75.9
M8	0.00216	0.00033	131	9.52
2SM6	0.00121	0.001	62.5	54.7
3MK7	0.00115	0.00052	212	23.3

Table A4. Results from the harmonic analysis of the record for the Inner Estuary. A is the amplitude in metres, g is in phase in degrees (relative to Greenwhich), and A_ci and g_ci are the associated widths of the confidence intervals.

Cnstit	A	A_ci	g	g_ci
M2	0.33	0.00689	60.6	1.43
K1	0.0939	0.00305	189	1.91
M4	0.0799	0.00223	65.3	1.32
S2	0.0692	0.00822	69.6	5.42
O1	0.0632	0.00302	217	2.74
N2	0.0541	0.00723	28.9	7.65
L2	0.0342	0.0077	36	12.8
MK3	0.0326	0.00178	184	3.97
MN4	0.0304	0.00174	44.7	3.78
MS4	0.0293	0.00168	80.5	3.57
ETA2	0.0237	0.0075	298	15.9
Q1	0.0186	0.00292	256	8.8
MO3	0.0184	0.0021	186	6.52
M6	0.0164	0.00136	79.3	4.24
SN4	0.0121	0.00183	274	9.34
J1	0.012	0.00282	212	15
MU2	0.0114	0.00766	346	38.4
2MN6	0.00923	0.00124	60.3	8.94
MM	0.0091	0.00289	136	17.5
2MK5	0.00868	0.00168	163	10.8
2MS6	0.00828	0.00121	101	8.3
MSF	0.00812	0.00241	15.8	20.5
NO1	0.00694	0.00313	279	27.3
2Q1	0.00691	0.00246	233	22.8
UPS1	0.00556	0.00278	183	33.3
OO1	0.00513	0.00293	327	34.7
M3	0.00483	0.0022	85.7	27.1
S4	0.00472	0.00162	66.2	20.2
SK3	0.0046	0.00217	213	24
EPS2	0.00444	0.00673	308	116
M8	0.00407	0.000616	125	7.75
3MK7	0.00292	0.000685	208	11.2
2SK5	0.00258	0.00166	172	35.9
ALP1	0.00237	0.00269	67.2	62.5
2SM6	0.00204	0.00136	69.7	38.2