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Timescales of inlet morphodynamic forced by tides and waves

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The time scale at which an inlet responds to changes of wave height, freshwater inflow or sediment supply is called the morphological timescale, T_{morph}. To determine the morphological time scale, one usually analyses survey data of the inlet throat area or the volume of flood/ebb tidal deltas, but such data are costly and therefore rare. This paper analyses tidal records using a 24.5 hour moving window approach to find T_{morph} and provides relationships between T_{morph} and the external forcing from waves and tides for different coastal inlets in New South Wales, Australia. Response to extreme changes in forcing depends strongly on bay/inlet size; from small inlets which open and close several times every year to larger systems where the effect of even the most severe weather events is not- or is barely measurable via changes to the inlets hydraulic performance. Outcome can be used in coastal inlet management without extensive river flow and bathymetry data.

[Keywords: 24.5 hour moving window, Harmonic analysis, New South Wales inlets]

Introduction

An inlet system and its elements have a morphological equilibrium state for its normal hydrodynamic condition of waves, tides or river flow. However, this equilibrium is dynamic with the morphology varying whenever unusual freshwater flows or waves occur. Thus, inlets generally display a degree of transient behaviour in response to changes to the forcing. This behaviour can be measured, either directly via topographical surveys or indirectly via the inlets influence on the estuary tides. The difference between the actual state and the equilibrium, during transience is usually expressed as an exponentially decaying function ~ $e^{-t/T_{\mathrm{morph}}}$ as seen in Fig. 1b.

T_{morph} varies from days to weeks for the small Avoca Lake, NSW, AU[1] in closure events to months for seasonally closing inlets such as Thuan An, Tu Hien lagoons on the Central coast of Vietnam[2]. The recovery time ranges from 25 days for Arahama coast to 75 days for Akaiko coast along Miyagi prefecture, Japan, after the March 2011 Tsunami with a wave height of 20 m, depending on sediment supply[3]. T_{morph} can also be extremely long as O‟Connor *et al*.[4] estimated for the Welsh River Usk responding to barrage construction, which will reduce the tidal range from 12 m to 4 m. They suggested T_{morph} =180 years.

To determine the morphological time scale, one usually analyses data from a field survey or a physical model of, for example, the inlet throat area *A* or the volume of flood/ebb tidal delta. Such data are however scarce because of the significant time and costs involved. An alternative approach is to use numerical models, which are however often unreliable due to uncertainties in translating physical phenomena into mathematical terms. In this paper, we analyse tidal records using a 24.5 h moving window approach, which has been introduced and successfully applied in[1,5,6], to find T_{morph} for a number of inlets in NSW, AU for flood, storm surge or closure events. Relationships between T_{morph} from several closure events and the external forcing from waves and tides, combined in the dimensionless, relative wave dominance is presented for small Intermittently Closed and Opened Lakes and Lagoons (ICOLLs). The applicability of the method to derive T_{morph} for larger system is also discussed and final conclusions are drawn in the last section.

Materials and Methods

The method of tidal analysis using a 24.5 hour moving window is developed to resolve the highly transient hydro- and morpho-dynamics during storm and/or flood events, which usually last for 3 days or less. This method is a modification of earlier work[7] in which a longer window was used and five tidal components were considered.

The present method is based on the derivation of water-level statistics and hydraulic response functions from a 24.5 h moving window as shown in Fig. 1a. Time series of moving averages $\overline{\eta_{24.5}}(t)$ of water level and corresponding standard deviations $Stdv_{24.5}$(t) are generated as in Fig. 1a. After de-trending water levels by removing $\overline{\eta_{24.5}}(t)$ from tidal records, least-square harmonic analysis is utilized to extract amplitudes and phases of diurnal (24.5 h) and semi-diurnal (12.25 h) components every hour based on the surrounding (centered) 24.5 h period. The gain G (t), whichis the ratio of bay- to ocean tidal amplitude (a_B/a_O), and the phase lag $\varphi(t)$ of bay tides compared to ocean tides for each component are computed. Time series of the hydraulic response function F_j, j=1,2 with 1 for diurnal and 2 for semi-diurnal can be presented in the complex plane as $F_j = G_j e^{-i\varphi_j}$.

a)

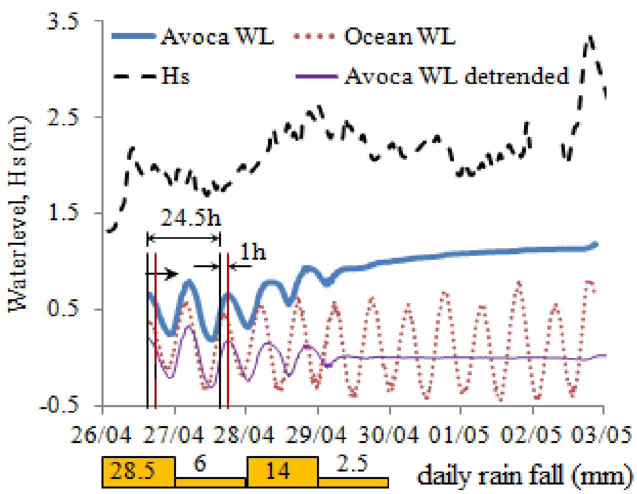

Fig. 1a—Avoca water levels, ocean tides, H_s at Sydney and daily rain fall at Kincumber during Closure Event 3 from 26/04/2011 to 03/05/2011, sketch of the 24.5 h moving window concept.

b)

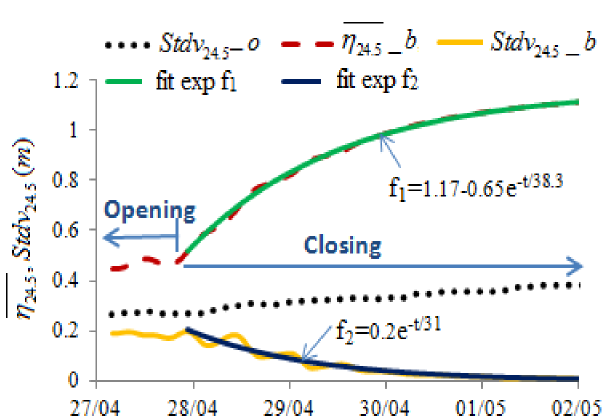

Fig. 1b—$\overline{\eta_{24.5}}(t)$ of bay tides, $Stdv_{24.5}(t)$ of ocean and bay, with fitting curves of $\overline{\eta_{24.5}}(t)$ & $Stdv_{24.5}(t)$ for the bay during Closure Event 3 at Avoca. Notation "o" for ocean and "b" for bay.

Morphological time scales can then be obtained by optimising curve fits, usually involving exp[$-t/T_{morph}$], to $\overline{\eta_{24.5}}(t)$, $Stdv_{24.5}(t)$ or G_1, G_2 as in (1), (2) and (3) below, cf.[1,5,6] and the next section. The starting time for closing processes in (1) and (2) is considered to be when the $\overline{\eta_{24.5}}(t)$-line starts rising and $Stdv_{24.5}(t)$ or $G_j(t)$ start reducing. The ending time for the closing process is when $Stdv_{24.5}(t)$ vanishes as shown in Fig. 1b. For flood or surge events, it is convenient to fit gain of primary component in the form of (3), showing the recovery time scale of the system after an event (Fig. 4).

$$\overline{\eta_{24.5}}(t) = \eta_{finish} + [\eta_{start} - \eta_{finish}]\, e^{-(t-t_{start})/T_{morph}} \quad \text{… (1)}$$

$$Stdv_{24.5}(t) = Stdv_{start}\, e^{(t-t_{start})/T_{morph}} \quad \text{… (2)}$$

$$G_j(t) = G_{finish} + \left[G_{start} - G_{finish}\right] e^{-(t-t_{start})/T_{morph}} \quad \text{… (3)}$$

Morphodynamic analysis from this new tide-based method is more reliable than process based numerical models, and more economical than analysis from topographical surveys (which are usually not available).

Results and Discussion

The application of the 24.5 h moving window method in determining T_{morph} is presented in three categories of events, viz.,

1 Closure events for small tidal inlets of NSW;
2 Flood event in a medium sized system (Brunswick River, NSW); and
3 Surge events in a large system (Thyborøen Inlet, Denmark).

Analysis of inlet closure events

The closure event from 26/3 to 3/05/2011 at Avoca

Lake is an illustration of using this method for inlet closure. Details were presented in[1,5]. Fig. 1a shows available data of the event and demonstration of the 24.5 h moving window method. The bay surface area, A_b for Avoca Lake, NSW is, ca 0.63 km^2, which is 5% of its catchment area[8,9]. The typical response of Avoca Lake to the average ocean tidal range of 1m is around 0.2 m with mean lagoon water elevation of 0.4 m above MSL. Long shore sediment transport is limited due to its location in the embayed Avoca Beach, which is only 1.5 km long. The entrance berm is regularly opened by local authorities, when the lagoon level reaches 2.1 m[9].

Fig. 1b shows $\overline{\eta_{24.5}(t)}$ and $Stdv_{24.5}(t)$ for the bay tides, with their exponential fitting curves. This case is typical for inlet closing starting during neap tides under average wave conditions ($\overline{H_s}$ = 2.2 m) and without significant rainfall. T_{morph}= 38 h is obtained from $\overline{\eta_{24.5}(t)}$ and T_{morph}= 31 h is obtained from $Stdv_{24.5}(t)$.

Similarly, the method is applied for several ICOLLs in NSW Australia. Inlets with bay area A_b<0.7 km^2 show closing process with a neat exponential decay. This seems logical because the smaller lagoons have short closing period compared to the duration of wave events so that the relative wave dominance $\frac{\sqrt{gH_s^5}}{\hat{Q}_{pot}}$ remains fairly constant throughout the closing process. Table 1 summarizes T_{morph} for 13 closure events of 7 inlets as well as external forces (average significant wave height $\overline{H_s}$ and average ocean tidal range $\overline{R_{to}}$ during closing process).

Harmonic analysis of the de-trended water levels for most closure events shows that subordinate diurnal response variability is stronger than that of the primary semi-diurnal. G_2 starts responding to closure processes earlier than G_1. The response function $F_2(t)$ the of primary component is stable for all events. Thus, it can be trusted to determine the dynamic equilibrium of the inlet and the period during which the inlet remains in such condition before moving to a new equilibrium. In contrast, $F_1(t)$ varies abruptly, tracing a lot of loops, and even becoming a rotating vector, switching between lags and leads (cf. Fig. 7, 8 and 9 in[1]) causing difficulty in interpretation and explanation, especially when an event occurs.

T_{morph} is normally determined as the average of T_{morph} from $Stdv(t)$ and from $G_2(t)$. These are more specifically associated with the inlet closing process than T_{morph} derived by fitting $\overline{\eta_{24.5}(t)}$, which may continue varying after closure due to rainwater inflow. Some cases have only one option of T_{morph} due to other sources not being suitable for exponential curve fitting or not reflecting inlet morphology change.

The „driving forces" can be represented through a dimensionless number, which shows the relative wave strength to the tide, $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$. Previously, tidal strength, which keepsinlets open, has been quantified by

Table 1—Summary of external forces and T_{morph} for 13 closure events

No	Inlet Name & event	Time event	A_b	$\overline{H_s}$	$\overline{R_{to}}$	$\sqrt{gH^5}$	$\hat{Q}_{tide,pot}$	$\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$	T_{morph} Average	T_{morph} from $\overline{\eta_{24.5}}$	T_{morph} from *Stdv*	T_{morph} From G_2
			km^2	m	m	m^3/s	m^3/s	[-]	h	h	h	h
1	Avoca 1	9/7 - 3/8/10	0.63	1.6	0.98	10.1	43.4	0.23	78.5		77	80
2	Avoca 2	5/11 - 28/11/10	0.63	1.4	0.77	7.3	34.1	0.21	89.0	86	92	
3	Avoca 3	26/4 - 3/5/11	0.63	2.23	0.76	23.2	33.6	0.69	34.7	38.3	31	
4	Avoca 5	24/4-30/4/08	0.63	1.9	0.51	15.6	22.6	0.69	45.7		50.3	41.1
5	Wamberal	29/4 - 3/5/11	0.6	2.2	0.78	22.5	32.9	0.68	39			39
6	Werri 1	7/11 - 19/11/09	0.14	1.25	0.77	5.5	7.6	0.72	25			25
7	Werri 2	1/04 - 13/05/10	0.14	1.4	1	7.3	9.8	0.74	54			54
8	Dee Why 1	17/3 - 16/4/12	0.24	1.3	0.6	6.0	10.1	0.60	26.5		31	22
9	Dee Why 2	18/4 - 28/5/12	0.24	2	1	17.7	16.9	1.05	36		30	42
10	Terrigal 1	18/1 - 5/2/11	0.52	1.6	0.6	10.1	21.9	0.46	45.4		47.2	43.6
11	Terrigal 2	13/3-24/3/12	0.52	1.6	0.92	10.1	33.6	0.30	120		120	
12	Cockrone	21/6-25/6/08	0.33	1.8	0.85	13.6	19.7	0.69	62		65	59
13	Back lagoon	14/12-18/12/10	0.36	0.94	0.61	2.7	15.4	0.17	99.2		99.2	

the tidal prism P as in classical A~P-relationship[10,11]. P is an obvious choice perhaps, but not an entirely satisfactory one. That is, for a given P, semi-diurnal tides drive twice as large peak discharge $\hat{Q}_{tide}$ and generate twice as large velocities through the inlet compared to diurnal tides, therefore, the tidal period or angular frequency $\omega_{\text{tide}}=2\pi/T_{\text{tide}}$ is important. In this paper, the strength of the tides as morphology drivers is presented in terms of the peak discharge

$$\hat{Q}_{\text{tide}} = \omega_{\text{tide}} a A_b \qquad \ldots (4)$$

where the tidal amplitude a may be the actual amplitude in the bay a_{B} or the amplitude in the ocean a_{O}. Using a_{O} gives the potential peak tidal discharge, which is an external parameter with respect to inlet morphology

$$\hat{Q}_{\text{tide,pot}} = w_{\text{tide}} a_{\text{O}} A_{\text{B}} = \frac{p}{T_{\text{tide}}} R_{\text{tO}} A_{\text{B}} \qquad \ldots (5)$$

To compare peak tidal discharge with waves" strength, which is the main force closing inlet, as inlet morphology drivers, the simplest dimensionless ratio is perhaps $\frac{\sqrt{gH^5}}{\hat{Q}_{\text{tide,pot}}}$. This compares the sediment transporting capacity of the waves as per the CERC formula for littoral drift to $\hat{Q}_{\text{tide,pot}}$.

In Table 1, 0.94 m < $\overline{H_s}$ < 2.3 m and 0.5 m< $\overline{R_{\text{to}}}$ <1 m. This results in $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$ ranging from 0.17 (Back Lagoon) to 1.05 (Dee Why event 2). Correspondingly T_{morph} ranges from 25 h to 120 h.

The relationship between $T_{\text{morph}}/T_{\text{tide}}$ and $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$ is presented in Fig. 2 and Equation (6). T_{tide} for these inlets is 12.25h corresponding to semi-diurnal is primary components. Although the correlation is modest, R^2=0.62, there is a clear trend of T_{morph} decreasing with increasing $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$.

$$T_{morph} = 2.58\left(\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}\right)^{-0.69} T_{tide} \quad \text{[h]} \qquad .. (6)$$

Analysis of recovery after a major flood

Apart from closure events, the 24.5 h moving window was also used to analyse tidal records during a major flood event in the Brunswick River (NSW, AU) in May 2009 (Fig. 3), cf.[6] for detail. This is a medium sized system with catchment area ca 200 km^2, estuary surface area 3.3 km^2 and spring tidal prism 1.94 x 10^{6}m^3[12]. The entrance is trained by break waters about 300 m long. There is a shallow bar fronting the breakwaters, which was expected to wash out during major floods[13].

Available data for the storm is shown in Fig. 3. During the storm, the highest tidal anomaly was 0.84 m observed 12 hours before a peak water level of 1.62 m at the at Brunswick Heads tide gauge (BHTG) (Fig. 3c, d). The highest H_s during this event was 6.5 m, and H_s> 5 m lasted for 3 days (Fig. 3a) with 12 s-13s wave period compared to the normal conditions: H_s= 1.5-2 m and T= 8-10 s. High waves coinciding with intensive rainfall of nearly 200 mm (Fig. 3b) occurred on the same day of peak tidal anomalies and peak BHTG water levels.

Hourly values of $\overline{\eta_{24.5}}(t)$ and $Stdv_{24.5}$(t) are analysed for the ocean and the Brunswick River. Both $\overline{\eta_{24.5\_R}}(t)$ and $Stdv_{\_R}(t)$ (subscript R denotes river), do not show exponential trends approaching asymptotes. Therefore they cannot easily be used for determination of T_{morph}.

$G_2(t)$ shows that the dominant tidal component gets reduced during the peak fresh-water discharge and recovers more or less exponentially back to the pre-storm equilibrium **(**Fig. 4). The reasons are

1 rise of mean water level causing the surface area A_{B} to increase, and/or

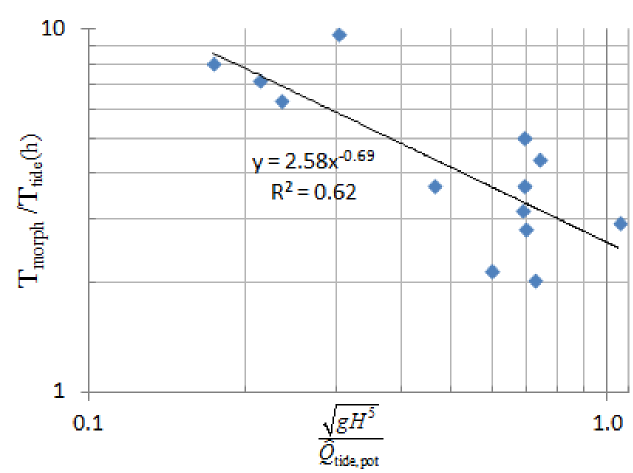

Fig. 2—$T_{\text{morph}}/T_{\text{tide}}$ vs $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$ for 13 closure events at 7 small (A_{b}<0.7 km^2) inlets in NSW.

2 (b) Increased river flow impeding tidal response via the non-linear friction.

The increasing trend of G_2 at peak water level (Fig. 4) is similar to the tidal analysis of[7]) for Lake Conjola. However, they found that the phase lag at that time decreased, while the phase lag at the Brunswick River entrance increased. This means no clear evidence of enlarged entrance, due to scouring; by the large flow Q_f leading to more hydraulic efficiency during the Brunswick event.

Response functions of both tidal components show clear equilibrium states corresponding to tight orbits, around (G_2, φ_2) = (0.91, 6°) and (G_1, φ_1) = (1.1, 20°) under normal conditions (Fig. 5). Similar pattern of running out of equilibrium during the storm and then returning to the equilibrium point is observed for both F_1 and F_2 but at different scales and manner. F_2 makes a small loop during the storm when the system floods with a large Q_f and also when it recovers. The modest size of the loop shows that the Brunswick entrance does not really change much, even under such a severe event.

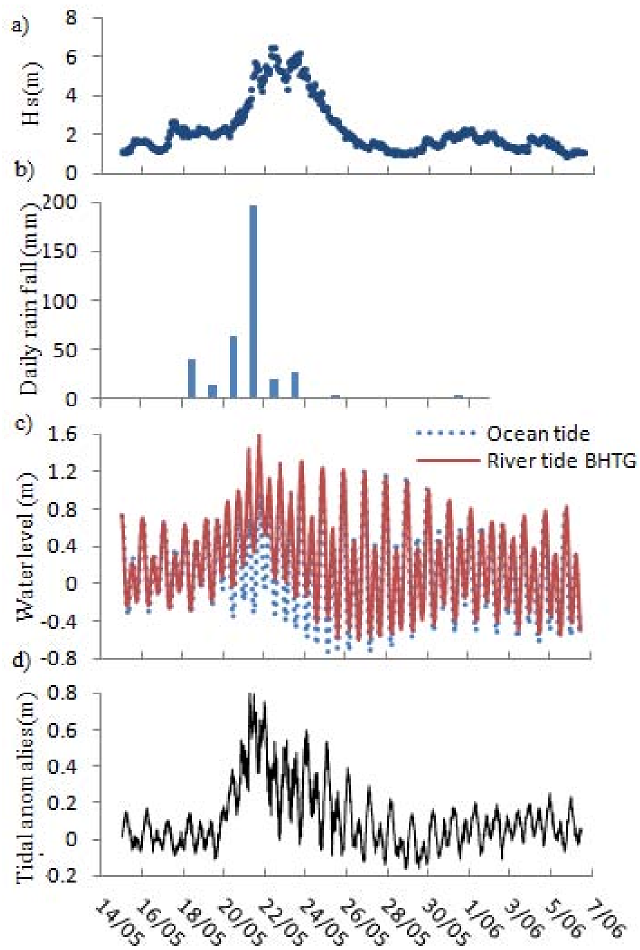

Fig. 3—Available data at the BHTG from 15/5 to 6/6/2009 a) significant wave height H_s, b) Daily rain fall (mm) at Myocum c) ocean water levels $\eta_o(t)$ and tidal levels at the BHTG □$_r(t)$, d) tidal anomalies.

The time scale obtained by fitting G_2 during the recovery process is around 76 hours from the trend line equations in Fig. 4. This may be a hydraulic (rather than morphodynamic) time scale as in the influence of Q_f on F_1, F_2 via the non-linear friction term rather than reflecting significant morphological change.

Tidal efficiency changes due to storm surges

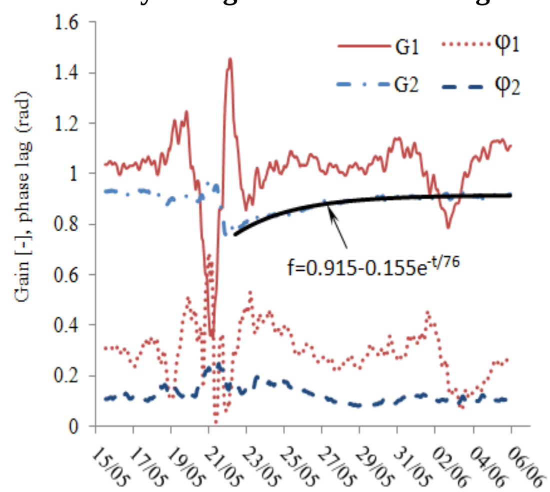

Fig. 4—Gains and phase lags of the two tidal components obtained with a 24.5 hour moving window on de-trended water levels together with fitting exponential function for G_2 to obtain T_{morph}=76 h (flood event at Brunswick River).

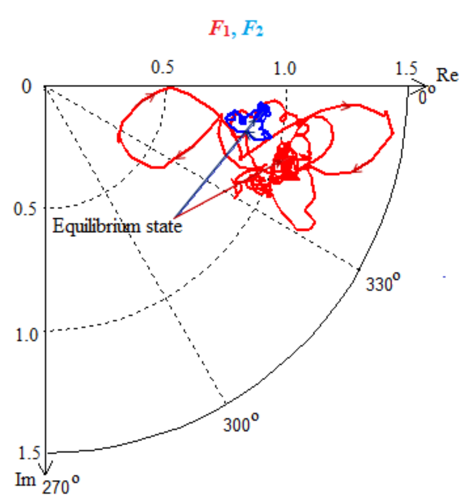

Fig. 5—The track of diurnal constituent F_1 (red) and dominant constituent F_2 (blue) in complex plane for flood event in May 2009 at Brunswick River.

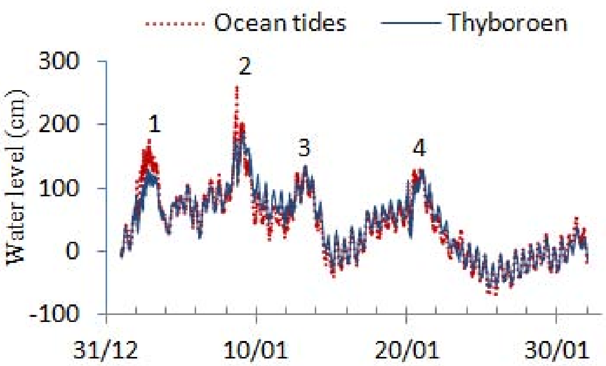

Fig. 6—Water levels in the North Sea (Ocean tides) and Thyborøn inlet station. (Data courtesy of the Danish Coastal Authorities). During January 2005, 4 storm surge events penetrated nearly full peak height through Thyborøen.

In the previous section it was found that changes to the tidal response in the Brunswick River inlet during a major flood event were due to different hydraulic parameters (Q_f and A_b) rather than due to morphological change e.g. scour of the entrance bar.

Thyborøen inlet in Denmark, which has been steadily opening and becoming more hydraulically efficient[14] over a number of years experiences a different kind of major flushing events, which might be the cause of the long-term opening. That is, while the Limfjord system has a small catchment compared to its surface area and therefore does not flood due to rain fall. It experiences large high water events (1.5 m to 2 m above MSL, see Fig. 6) driven by storm surges in the North Sea. Following similar analysis, we look for evidence of lasting hydraulic efficiency gain due to the strong outflow which follows these high water level events.

The data in Fig. 6 show that these surges, with periods of 3 to 5 days, penetrate with full peak height (surge 2, 3, 4).

Fig. 7 shows the gain G_2 and phase lag φ_2 of the primary component and $\overline{\eta_{24.5}(t)}$ by 24.5 hour moving window. During surge events 1, 2, 3 following the flushing event i.e., the steep drops in $\overline{\eta_{24.5}(t)}$, G_2 increases and φ_2 reduces. This indicates that the inlet scours out due to the significant outflow resulting in increased hydraulic efficiency. During surge event 4 drainage process (22-24/01), the non-linear friction term reduces G_2 and increases φ_2. After that, from 24-26/01 the increase of hydraulic efficiency takes place. This was supported by measured entrance cross section as presented in[14]. However there is no evidence of a long-term increase of the hydraulic efficiency. Therefore, it is difficult to determine T_{morph} in this case.

Conclusions

It has been demonstrated that morphodynamic and hydraulic parameters can be obtained from analysing tidal records using the 24.5 h moving window method for closure events and extreme events as flood/storm surge.

Morphological time scales, T_{morph}, can be obtained from $\overline{\eta_{24.5}(t)}$, $Stdv_{24.5}$(t) or gain of primary component, depending on which parameter shows exponential curve for fitting reflecting inlet morphology change. T_{morph} determined for 13 closore events are mostly obtained from $Stdv(t)$ and $G_2(t)$ and range between 25 h and 120 h. The result of inlet morphodynamic analysis from this new method is more reliable than that from process based numerical models, and more economical than analysis from topographical surveys, which is usually not available.

Application of this new method for several closure events (with bay area A_b<0.7 km^2) in NSW show a clear trend of $T_{\text{morph, close}}$ decreasing with increasing dimensionless relative wave strength $\frac{\sqrt{gH^5}}{\hat{Q}_{tide,pot}}$, Eq (6). This relation can be used to estimate closing time scale for small inlet systems corresponding external forces of waves and tides. It will help researchers and local authorities better in management coastal inlets.

However, for large, partly regulated inlet systems trained by breakwaters, the morphology change is usually not significant enough, compared to the cross section, to be measurable via the tidal records. Hence the T_{morph} determined by the method for the larger systems, e.g.. Brunswick River is just hydraulic timescale T_{hyd} but not T_{morph}. However, the method is an effective way to analyse surge or flood events for large systems to investigate the occurrence of change in hydraulic efficiency.

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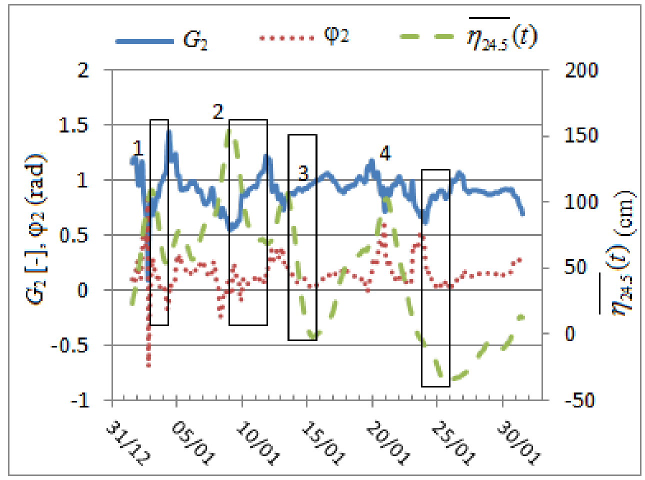

Fig. 7—Gain and phase lag of primary component *G*2, *φ*2 and $\overline{\eta_{24.5}}(t)$ by 24.5 h moving window at Thyborøen station.

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