Tidal Amplitude and Wave Setup in Trained and Untrained River Entrances.

Theo Moura[1], Mohammad Olfateh[1], David Callaghan[1], Peter Nielsen[1], Bob You[2] and Tom Baldock[1]

[1]School of Civil Engineering, University of Queensland, Brisbane, Australia; t.moura@uq.edu.au
[2]Coastal Science, NSW Office of Environment & Heritage, Newcastle, Australia

Abstract
Coastal entrance tailwater levels are an important parameter in the modelling of estuarine and riverine floods and water quality and risk forecasting. This report presents results from the most recent fieldwork to study wave setup for trained and untrained river entrances at Hasting Point and Pottsville on the NSW north coast. Field water level data were collected with both stilling wells and pressure transducers in Cudgera Creek at Hasting Point and at Mooball Creek of Pottsville. The absolute levels of the stilling wells and pressure transducers relative to the AHD datum were surveyed to high accuracy. Based on the field data collected, it is found that the tidal amplitude decays significantly through the river entrance, to approximately the 0.8~0.9 of the tidal amplitude outside the entrance, with negligible decay immediately upstream of the entrance. The decay in tidal amplitude primarily occurs on the ebb tide, and is associated with significant tidal head loss through and across the entrance. This cannot solely be attributed to normal friction and local losses. Total surface water levels measured inside the entrance are found to be higher than those in the ocean on the ebb tides, but lower than in the ocean on the flood tides. The mean elevation over the tide cycle indicates that the water level in the estuary is superelevated above the ocean level in some cases, particularly on the ebb tide. Further work is required to determine exactly how the tidal head loss is related to superelevation of the water levels relative to the ocean.

Keywords: Estuary entrances, tide propagation, wave setup.

1. Introduction

This paper complements a wider study of Tailwater levels and Storm surge penetration into NSW for an OEH research project on Tidal Limits and Flooding Tailwater Levels at NSW Coastal Entrances (Stage-I and II). That study has identified that significant losses in tidal amplitude occur at or within the estuary entrances for a range of trained and untrained estuaries, even those of significant width and depth (e.g. Brunswick River). Further, the report builds on a previous analysis of ocean-estuarine interaction in NSW estuaries by Nielsen [6]. The key conclusion from that study was that losses in tidal amplitude or surge amplitude in the immediate vicinity of the estuary entrance were potentially significant, were not well resolved by current models, and required further investigation.

The purpose of the present study is to conduct fieldwork at a trained and an untrained coastal entrance in order to provide higher resolution of tidal energy losses and to compare tidal amplitudes at the entrances of two types. Two river entrances closely located on the northern NSW coast, Cudgera creek in Hastings Point, and Mooball creek in Pottsville, were selected as the study sites. Two field trips were conducted; the first for 14 days in November 2011 and the last for 3 days in January 2013.

Total surface water levels were measured by a combination of pressure sensors and stilling wells installed within the creeks. Most of the field data were collected in the river mouths. The shoreline wave setup on the adjacent beach was also measured with stilling wells following the approach of Hanslow and Nielsen [3]. Water levels were measured to the AHD datum through repeated and accurate survey by engineering level and total station (Cudgera creek), or relative to Mean Sea Level (MSL) when a nearby permanent mark was not available (Mooball creek). Cross-sections of the creeks were also surveyed by total station.

2. Previous Work

To a first approximation, the effects of ocean waves on mean water levels at/inside inlets or river mouths have been estimated by using the dimensionless plot of 1D beach wave setup vs depth and the associated formula (1) suggested by Hanslow et. al. [4]- That is, a wave setup contribution corresponding to

$$\bar{\eta} = \frac{0.4H_{orms}}{1 + 10\dfrac{h_{min}}{H_{orms}}} \qquad (1)$$

where h_{min} is the minimum depth on the entrance transect, was included in estimates of water levels inside the wave breaking zone in inlets and river entrances. However, field work by Nielsen and others around 1990 and more recent observations from the Gold Coast Seaway, show no measurable (>3cm) wave contribution, where the above procedure predicts several tens of centimetres. Thus, equation (1) is not applicable in trained deep river entrances.

In order to explain the absence of measurable wave setup in the Brunswick River, Dunn [2] considered the 2DH scenario with energy- and momentum absorbing breakwaters, see photos in Nielsen [4] Section 2.3.5. This leads to

$$\frac{\partial\bar{\eta}}{\partial x} = -\frac{1}{\rho g h}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) + \frac{1}{\rho g h}(\tau_{wind} - \tau_{bed}) \tag{2}$$

where $\bar{\eta}, \rho, g, \tau, h$ and S_{xx} and S_{xy} are mean water surface elevation, density, gravity, shear stress, depth and radiation stresses in the cross-shore and longshore directions.

Dunn [2] estimated that the 2D effects (inclusion of the dS_{xy}/dy term) typically reduce the setup between a pair of rock walls by a factor two compared with the 1D beach scenario and equation (1). However, even with this reduction, the state of the art theories (and state of the art numerical Boussinesq models) still predict a significant wave setup, which is not visible in field measurements from trained river entrances, which was discussed extensively by [2]. A comprehensive review of such field measurements is given by [5].

Tanaka and Tinh [8] investigated the influence of wave setup height to sand spit evolution during extreme events at two different river mouths in Japan.Results showed a negative relation between wave setup height and average water depth at the entrance. Wave setup height was estimated from 2 to 14 % of offshore wave height for cases of average water depth at the entrance from 1.2 m to 6.5 m. Doet et al [1] found similar values for wave setup height (7 – 12 % offshore wave height) inside a lagoon with a narrow and shallow entrance.

The tidal amplitude is expected to decay from the offshore tide range through the entrance. On an open beach, the MWS and tide range distribution across the surf zone (the tidal envelope) was measured by [7]. These data show that the tidal amplitude is constant across the surf zone, until the wave run-up zone is reached, after which the amplitude variation becomes constrained by the beach face and water table oscillations around the mean shoreline position. The water table variations increase inland. Therefore, for the purposes of this report, we will assume that the nearshore tide range measured in the surf zone is equivalent to that offshore of the breakpoint.

3. Methodology and data collected

3.1 Field trip 1 - 05/11/2012-21/11/2012

Cudgera Creek - Hastings Point

Self-logging pressure transducers (model PT2X from INW) were installed inside stilling wells mounted on star posts at 5 locations, commencing at the creek entrance and finishing approximately 1km upstream (Figure 1) from the river entrance. Another pressure transducer and stilling well were installed in the outer surf zone. Four stilling wells were installed on a short transect on the beach face to measure the mean water surface (MWS) and the shoreline setup, [3]. For the ocean well and pressure sensor TB0, only few hours of measurement on 05/11/12 were obtained due to wave impact on the well leaving it unstable. Data were recorded for the full duration of the field trip for the other sensors (343 hours).

Mooball Creek - Pottsville

Self-logging pressure transducers were also installed inside stilling wells at 5 locations, commencing at the creek entrance and finishing approximately 3km upstream (Figure 2). Data were recorded for the full duration of the field trip for all sensors (327 hours). However, the well at location 1 scoured out overnight on 12/11/12 and was reinstalled on 13/11/12.

3.2 Field trip 2 - 21/01/2013-25/01/2013

Cudgera Creek - Hastings Point

Based on the field data collected in the first field trip, a more closely spaced array of self-logging pressure transducers were installed inside stilling wells at 4 locations, focused on the creek entrance, commencing at the creek entrance and finishing approximately 200m upstream (Figure 1). A more extensive transect of stilling wells was installed on the beach face to measure the mean shoreline water level and inner surf zone setup. The field data were recorded over the period of 21/01/13 to 23/01/13 for all sensors and wells (40 hours).

Mooball Creek - Pottsville

Self-logging pressure transducers were installed within stilling wells at 2 locations within the section of training walls, approximately 30-40m apart (Figure 2). An extensive transect of stilling wells was installed on the beach face to measure the mean shoreline water level and inner surf zone setup. Data were recorded over a period of 6 hours for all sensors and wells. This duration is sufficient for analysing water level gradients, but not tidal amplitudes, which were not determined at Pottsville for this field trip.

For both field trips water levels in the stilling wells were read manually approximately every 10 minutes to provide accurate reference levels for the pressure sensor records, yielding pressure sensor records giving absolute water elevations within the survey accuracy of ±1cm. This is performed by matching the water levels recorded by the pressure sensors to the absolute water levels from the manual well readings. In order to determine the water depth for standard wave setup plotting, the sand levels at the wells were also recorded at regular intervals.

The absolute levels of the top of the stilling wells were surveyed by Engineering Level and Total Station. The beach and creek seabed profile was measured at selected locations with a Total Station. The elevation of the sensor port for the pressure sensors within each well is also recorded.

The ocean tide record used was collected at Brunswick Heads breakwater and Tweed Heads breakwater and wave data used was collected by the Byron Bay wave buoy.

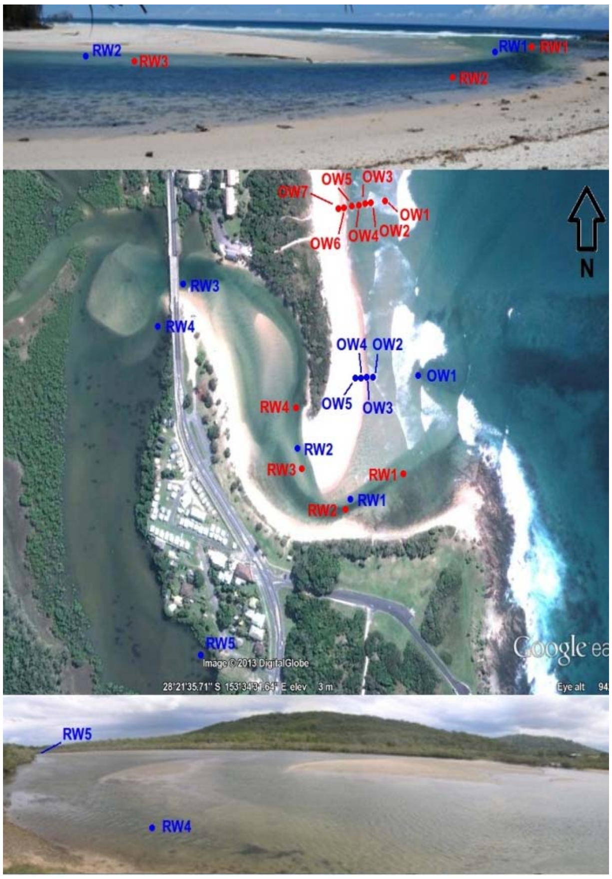

Figure 1. Instrument locations in Cudgera Creek. Numbers of pressure sensors and stilling wells. Blue: field trip 1; Red: field trip 2;

Toward the end of the field trip, forecasts for ex TC Oswald suggested that this would move south into S.E. QLD and Northern NSW over the period 25-31 January 2013. Consequently, two pressure sensors and stilling wells were reinstalled in Cudgera Creek, at location RW-4 (blue) in Figure 1. These were left in-situ to log water levels over that period, and were recovered on 02/02/13. These data cover the period of the passage of ex TC Oswald through the catchment, during which time a storm surge and large waves occurred offshore. Unfortunately, no data is available from the Byron wave buoy after 28th January. Further, the data suggest a possible malfunction after 26/1/2013. Hindcast data from WW-III shows the wave height at 1m on 25/01/13, climbing to 5m on 28/01/13, and then declining to 2m by 31/1/13.

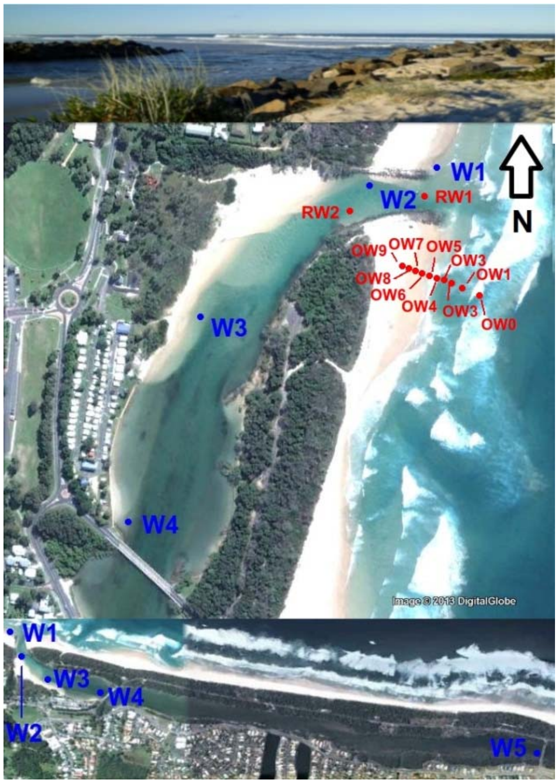

Figure 2. Instrument locations in Mooball Creek. Numbers of pressure sensors and stilling wells. Blue: filed trip 1; Red: field trip 2,

4. Analysis

4.1 Variation in Tidal Amplitude

Tidal amplitude was calculated from the variance (σ^2) of the pressure sensor record in each stilling well. For these calculations, the mean of the variance was taken over durations of 24, 72, and 120 hours, in steps of 1 hour. Tidal amplitude for the purpose of this study is defined as $A = \sqrt{2\sigma^2}$.

In Cudgera Creek, the tidal amplitude was observed to drop significantly through the creek entrance, between well 1 and well 2, with a further minor drop up to the highway bridge (well 3), thereafter, no significant losses occurred up to well 5. The reduction in tidal amplitude is greater in absolute terms during the spring tide at the end of the deployment. The amplitude ratio between ocean tide record and well 1 is consistently about 90%, with a further bigger reduction in amplitude at well 2 to about 64% following a smaller reduction further upstream to about 57%, illustrated in Figure 3.

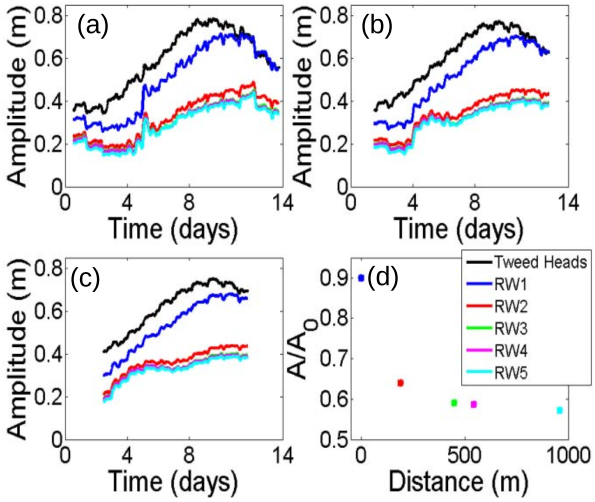

Figure 3. Tidal amplitude in Cudgera Creek calculated with centred moving windows of lengths: (a) 24 hrs. (b) 72 hrs. (c) 120 hrs. (d) Whole record, 05/11/12 - 20/11/12.

Corresponding data for Mooball creek show the same overall behaviour with a significant amplitude reduction between wells 1 and 2, and little change in amplitude progressing upstream. In fact, a slightly larger tidal amplitude is recorded at wells 3 and 4 in comparison to well 2, but this is within the instrument accuracy. Despite the difference entrance characteristics (size of the entrance and the presence of training walls), a very similar reduction in tidal amplitude occurs to that in Cudgera creek, approximately 70% between the offshore well and further upstream. No significant further amplitude decay is observed at well 5, approximately 3 km further upstream. Both entrances were shallow at the mouth, less than 1m deep.

4.2 Tidal Level and Shoreline Setup

The tidal elevation at each station in Cudgera creek for 05/11/2012-20/11/2012 shows that on the ebb tide, the tide in the river does not follow the ocean tide, becoming decoupled about halfway through the ebb tide. This effect is largest for spring tides. It is a real effect, measured in both manual readings and by the pressure sensors. The wells and pressure sensors do not become dry; the water level in the river is superelevated above the ocean because of the head loss through the entrance. This effect also leads to a lag in the flood tide in the river, i.e. until the ocean levels again exceed the river levels. This suggests that the reduction in tidal amplitude is larger on the falling tides, and particularly for spring tides. Same observation appears looking at the residuals (Figure 4), which are large on ebb tides as a result of the phase lags and head loss in the entrance, and the mean river level is also higher than the mean ocean level.

The shoreline level defined by the wells as in Figure 2, show the shoreline consistently above the tidal elevation in the creek, with maximum shoreline setup on 11/11/12 when offshore wave heights approached 4m. The shoreline level is also above the high tide level at all times. Wave setup in the river entrance is negligible compared to the shoreline setup for these wave conditions. This is discussed further later. Data for the shoreline elevation was not obtained at Mooball creek during field trip 1.

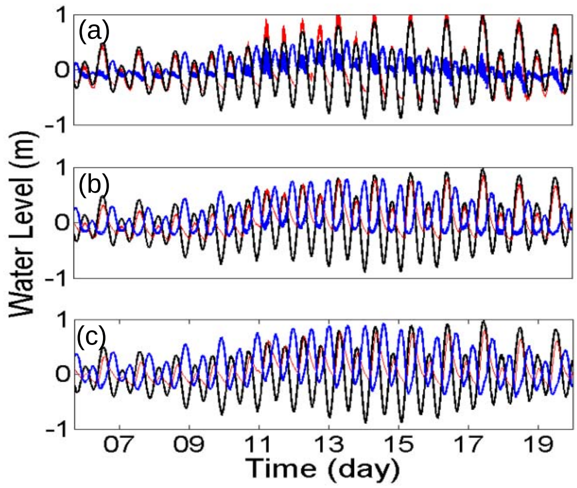

Figure 4. Tidal and residual elevations, Cudgera creek. (a) Black line - Tweed Heads tide record, red line – river well 1 and blue line – residual elevation. (b) Black line- Tweed Heads tide record, red line – river well 2 and blue line – residual elevation. (c) Black line- Tweed Heads tide record, red line – river well 5 and blue line – residual elevation.

The tidal elevation at each station in Cudgera creek for 22/01-23/01 is shown in Figure 5. The loss in tidal amplitude through the entrance was observed to be considerably smaller over this data recording period in comparison to that in November 2011. The losses that did occur appear to have again occurred predominantly on the falling tide. Note that for the January 2013 data, well 4 is equivalent to well 2 in November in terms of location within the creek. The tide range was comparable to the neap tide at the beginning of the November experiment. Again, water level superelevation in the river entrance is negligible compared to the shoreline setup for these wave conditions. The water level superelevation relative to the ocean level is compared in more detail below. A similar picture emerges for Mooball creek, albeit with a more limited data set. The shoreline elevation remains higher than the creek water levels.

The record from the two pressure sensors installed in Cudgera Creek during the passage of ex TC

Oswald show no significant rise in the high tide level even during the period of large waves, suggesting the water level superelevation in the river at high tide is negligible in comparison to the beach face setup, and with negligible fresh water influence. Again, entrance losses at low tide lead to a superelevation of the river compared to the ocean, in that the creek level remains raised above the ocean level on the ebb tide. Accurate survey data is not available for these two sensors, so the absolute level has been estimated by matching the recorded high water levels to those at the Tweed Heads tide gauge prior to the arrival of the large waves generated by ex TC Oswald.

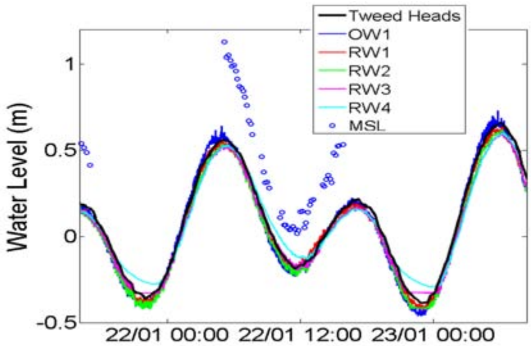

Figure 5. Tidal elevations and mean shore line level in Cudgera creek, 21/01/13-23/01/13.

5. Discussion

5.1 Setup

Setup at the river entrance of Cudgera Creek is compared to the most offshore water level recorded at each field site. Here, the setup is calculated as the elevation of the creek entrance level (RW2 in Figure 1 and Figure 6) above the offshore water level (OW1). Prior experience shows insignificant setup can be expected at OW1 based on measurements at comparable relative (h/H_{rms}) water depths on beaches. These calculations therefore assume setup at OW1 is zero. Estimates of the setup will therefore be slightly below true values, but not significantly. While there is some setup above the ocean level, equally there is set down, and both are well below the usual shoreline setup observed on an open beach. This suggests that the differences in water level simply reflect the head gradients due to the tide. However, the superelevation of the water level at low tide in the entrance is comparable to that across a beach at the same relative water depth. Note that these calculations are based on synchronous water level differentials between the two measurement locations, which are of order 50m apart in the cross-shore direction

An equivalent analysis for Mooball Creek using water level differences between RW1 and OW0 (Figure 2) is applied. In this case, a greater setup is observed than at Cudgera Creek, perhaps as a result of the shallower water depths in the entrance, and the setup is comparable to that observed on natural beaches at the same relative water depth. However, the data record does not cover a full tidal cycle.

A similar analysis is presented by [8], where wave setup height is compared against an empirical logarithm relationship between normalized setup and normalized water depth at the entrance. Unfortunately the full tidal cycle is not shown, and therefore is difficult to differentiate wave setup from head gradients due to the tide.

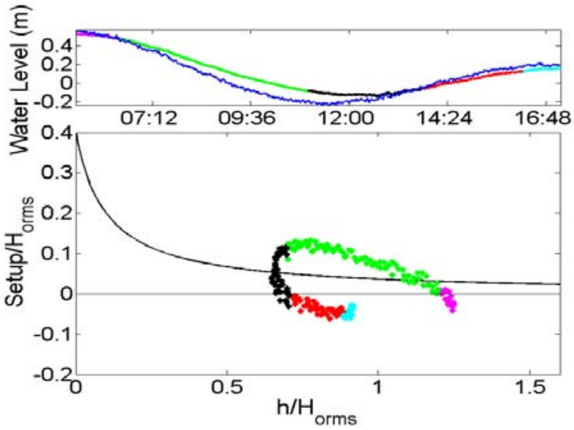

Figure 6. Setup in Cudgera Creek entrance (river well 1) versus empirical curve Nielsen [5], record from 22/01.

5.2 Head loss

Steady state modelling between wells 1 and 2 on Cudgera Creek has been undertaken to see if frictional and local losses are enough to explain the differences in water surface levels through the river mouth measured in November 2012. Bed friction was modelled using the log-law with uniform bed roughness height of $r = 0.1$ m. The high value was adapted to model rocks within this reach of Cudgera Creek. Within the sandy areas, small through to large bed forms existed and a 10 cm roughness height is acceptable as reasonable for these areas as well. Two velocity head point losses were included at the most seaward and narrowest sections. The point loss at the most seaward section was included for exit losses as the flow decelerates when exiting Cudgera Creek. The point loss at the narrowest section was included for contraction and expansion losses.

The cross-sectional survey used for modelling was obtained during the January 2013 field trip. Visually, entrance changes appeared minor between November 2012 and January 2013. However, this has not been confirmed. As our measurements do not include discharge, discharge was chosen to generate a flow velocity of 1 m/s at the narrowest section. During field measurements, it was possible to walk across Cudgera Creek at low and mid tide. Consequently, selection of 1 m/s is at the possible upper limit of velocity, with a more reasonable estimate being between 0.3 m/s and 0.5 m/s. Nevertheless, using 1 m/s yields a maximum Froude number of 0.4 at the narrowest section and water surface elevation difference between wells 1 and 2 of 0.1 m, which is well below observed differences of up to 0.25 m. Increasing the discharge to yield a Froude number of 0.6 at the narrowest section, the predicted water surface elevation difference between wells 1 and 2 then becomes 0.27 m, within the measured range. However, this flow has a velocity at the narrowest section of V = 1.5 m/s, well above visual estimates. Free surface flow is generally very difficult to walk through when the vertically averaged velocity times the local depth is greater than 0.5 m^2/s. At the narrowest section, the maximum depth at mid-tide is approximately 0.7 m, which yields a vertically averaged velocity of 0.7 m/s. Using this velocity across the entire section to estimate the discharge yields a water surface elevation difference between wells 1 and 2 of 0.07m.

These simplified estimates indicate that the measured differences in water surface levels exceed likely bed friction, exit losses and contraction and expansions losses during the November 2012 fieldwork. Nevertheless, during January 2013, where much smaller water surface level differences were measured, the measurements are consistent with frictional and point losses. If the January 2013 survey was representative of November 2012 morphology, these estimates would confirm the January 2013 measurements as frictional and point losses but the large water level differences measured in November 2012 remain unexplained. Alternatively, if the January 2013 survey was not representative of November 2012 morphology, then there is a possibility that friction and point losses could explain November 2012 measurements.

Future research on untrained entrances

The figure above, where the data points circulate anti-clockwise is a nice new perspective on the question of wave contribution to the super-elevation of estuary water levels above the ocean. The symmetry of the curve about the horizontal axis (~ zero overall superelevation) supports a conclusion of no wave contribution, like the Brunswick River data in Figure 10 of [3]. For further strengthening of this conclusion in the future it would be useful to have similar datasets from the same location, but with different wave heights, added to the same figure, and data for shallower entrances. It is also necessary to know the exact time of slack water in order to draw the full range of conclusions from such plots. This will require flow velocity measurements or measurement of flow direction.

6. Conclusion

This paper presents results from fieldwork to study the tailwater level, and water level differences between the ocean and estuary (setup), for trained and untrained estuaries on the NSW north coast. Field data were collected from stilling wells and pressure transducers, surveyed to high accuracy, in Cudgera Creek (Hastings Point) and Mooball Creek (Pottsville). The tidal amplitude decays significantly through the estuary entrance, to approximately 0.80-0.9 of the amplitude outside the entrance. Measurements indicate negligible decay immediately upstream of the entrance. The amplitude loss primarily occurs on the ebb tide, and is associated with significant head loss through and across the entrance. On the basis of numerical modelling, this head loss cannot solely be attributed to normal friction and local losses. Water levels are elevated inside the entrance in comparison to the ocean on the ebb tide. Water levels in the ocean are elevated above the entrance level on the flood tide. The mean elevation over the tide cycle indicates a superelevation of the water level in the estuary mouth. Detailed analysis of the water level gradients through the entrance suggests that this is not due to wave setup, but is due to larger head loss on the ebb tide in comparison to that during the flood tide. Further work is required to determine exactly how the head loss is related to superelevation of the water levels relative to the ocean.

7. References

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