Field data were collected over a 3-year period from several tidal inlet channels within the Hunter Wetland National Park (HWNP), a coastal wetland undergoing restoration in southeastern Australia. The collected data included depth, top width, and cross-sectional area of nine channels, ranging in size from approximately 10 to 200 ha. The observations provided a novel data set characterising the evolution of tidal inlet channels. The present field data were compared with existing empirical predictions for equilibrium conditions in tidal inlets. The comparative analysis showed that most channels were in a dynamic equilibrium state, whereas channel evolution data for a youthful tidal channel suggested that it is converging to its predicted equilibrium morphology.

1 INTRODUCTION

Over the past two decades, the restoration of coastal wetlands has increased globally. The recognition of the environmental and ecological values of coastal wetlands has resulted in a shift from destruction for agriculture and development, to restoration and preservation. Many characteristics of these restored systems are governed by the stability of the inlet channels that control tidal exchange, water quality, and local flooding.

Continuously, tidal inlets to coastal wetlands and estuaries exhibit a dynamic stability, changing in response to variations in the controlling hydrodynamic forcing functions (e.g. floods, tidal exchange, sedimentary regimes) and anthropogenic perturbations (e.g. dredging, entrance training, climate change). The understanding of tidal inlet stability relies on a synthesis of process-based and theoretical approaches. Previous key studies in understanding channel geomorphology for wetland restoration sites have been undertaken in the United Kingdom [12], San Francisco Bay estuary [13], and the Columbia River estuary [2]. These studies build on earlier tidal inlet research in estuaries and coastal bays [10][3], and the hydraulic geometry of fluvial and estuarine systems [8]. Intrinsic to the description of these approaches is a concept that there is an equilibrium form of an inlet, for a given-sized upstream tidal area, and a tidal range within an estuary that is relative stable over long periods of time.

[13] surveyed a number of existing, as well as historical marshes, in San Francisco Bay and developed empirical geometry relationships of depth, width, and cross-sectional area of mature tidal channels, as functions of marsh area and tidal prism. The relationships are based on data from tidal marsh areas ranging in size from 2 to 5,700 ha. The regression relationship for cross-sectional area as a function of tidal prism, as determined by [13], is similar to the one derived by [12], however, shows less data scatter ($r^2 = 0.92$) than those developed by [12] for more heterogeneous conditions ($r^2 = 0.8$). [13] also compared channel evolution data of immature marsh systems subjected to an increased tidal prism, with the hydraulic geometry relationships of mature marsh systems, to predict and assess the equilibrium morphology of these youthful channels. However, several studies suggest that relationships derived for tidal systems in one region are not applicable in another because of variations in tidal regimes, elevation, sediment load, as well as bed and bank friction conditions [1][13][5].

The time histories of amplitude and phase of tidal constituents within estuaries present signatures that, along with established estuary stability theories, may allow for an informed assessment of the stability of an estuary and a prognosis of its future course. [9] showed that several large, apparently stable estuaries in New South Wales (NSW), which have been modified by entrance breakwaters, have been in an unstable scouring mode for decades with prognoses of centuries for them to reach new hydraulically stable regimes. Implications have included extensive erosion protection works and permanent changes to fringing ecologies, none of which had been predicted.

Our review of literature reveals no analyses combining stochastic approaches for assessing tidal inlet stability to coastal wetlands undergoing restoration, in mature-barrier, tidally-dominated estuary systems. This
multi-year project aims to determine if previously published hydraulic geometry relationships derived for mature wetlands can be applied to southeastern Australia. Here we use the relationships defined by [13] to assess and compare the current equilibrium status of tidal channels in cohesive sediments undergoing restoration within the Hunter Wetlands National Park (HWNP). Furthermore, in the absence of long-term monitoring data, can we use the time histories of tidal constituents within estuaries to predict the evolution of tidal channels in restored wetlands? To this aim, it is hoped that by monitoring these sites over the entire restoration period and beyond, we can improve the efficacy of restoration projects through a knowledge database of natural patterns and processes specific to coastal wetlands.

2 STUDY AREA

The field research for this study was undertaken in the HWNP, an internationally recognised wetland site located in the Hunter River estuary on the central coast of NSW, approximately 10 km north of Newcastle (33°S, 152°E). The Hunter River estuary has semi-diurnal tides with a mean tidal range between -0.451 to +0.547 m Australian Height Datum (AHD) [7]. The HWNP covers approximately 3000 ha, including Tomago Wetland near Tomago and Kooraingang Wetlands on Kooraingang Island (Figure 1). Floodplain topography across the HWNP ranges between -0.25 to +1.5 m AHD, with typical elevations around mean high water (MHW) to mean high water springs (MHWS).

Since the HWNP was gazetted to the Ramsar list in 1984, a multi-staged approach has been adopted to restore the coastal wetlands of the Hunter estuary. Tidal restoration works were undertaken at Tomago Wetland to rehabilitate saltmarsh habitat and provide conditions suitable to migratory wading birds. Automated gates were installed at the tidal entrances to Tomago Wetland to allow for tidal exchange, to control upstream water in the wetland and optimise tidal inundation regimes for saltmarsh habitat. Other on-ground rehabilitation works included the installation of internal control structures to direct tidal waters across the site, clearing of exotic plant species, and the construction of an internal levee across the upstream boundary of the wetland. Similar restoration works have been undertaken on Kooraingang Island [6].

3 METHODS AND DATA SET

3.1 Data Collection

The development of accurate relationships to predict changes in tidal inlet stability over time is largely dependent on adequately representing the site geometry. This research follows the methods for developing a hydraulic geometry database as outlined in [11]. Supplementary data used for this study included high resolution aerial imagery (nearmap) and an aerial laser survey (LiDAR) of the wetland in 2005 which was ground-truthed by an on-ground survey undertaken to capture key landforms and structures at a higher accuracy. LiDAR data of the study site was supplied by Industry and Investment NSW on a 2 x 2 m grid with a vertical accuracy of ±0.2 m.

Field surveys were conducted in April 2012 (Round 1), October 2014 (Round 2), and July 2015 (Round 3), to measure nine (9) representative cross-sections of the tidal inlet channels within the HWNP: six (6) channels in Tomago Wetland and three (3) in Kooraingang Wetlands. Channel surveys were undertaken using a Trimble 5800 RTK-GPS (Real-Time Kinematic Global Positioning System) with an accuracy of within ±20 mm vertically and horizontally. During each channel survey, the RTK-GPS was initially used to establish a bench mark on the channel bank. Once the bench mark was determined, a survey pole was submerged from a kayak at known intervals to measure the depth of the channel and relate the depth back to AHD. Bed elevations were recorded every 0.5 to 2 m, with closer spacing for steeper slopes. The deepest point on the cross-section was always surveyed and widths were measured relative to MHW (Figure 2). Surveyed cross-sections were interpolated to a 0.1 m grid and the area integrated below MHW. Contributing marsh area was estimated by delineating approximate upstream drainage boundaries between tidal channel systems using LiDAR elevations below MHW and measuring the area. Tidal prism (the volume of water between high and low tide) was estimated for the contributing marsh areas using GIS storage volume techniques. Channel location and hydraulic geometry data for mature marshes from the July 2015 survey are provided in Table 1. A time series of channel evolution data for Site001 is provided in Table 2. Cross-sectional profiles from each round of survey are compared in Figure 2.
Figure 1. Study Site Location in Hunter Wetlands National Park, Australia.

Table 1. Tidal Channel Hydraulic Geometry of Mature Marshes in the HWNP (July 2015).

<table>
<thead>
<tr>
<th>Location</th>
<th>Site Name</th>
<th>Thalweg Depth (m)</th>
<th>Top Width (m)</th>
<th>Channel Cross-Sectional Area (m$^2$)</th>
<th>Contributing Marsh Area at MHW$^1$ (ha)</th>
<th>Tidal Prism ($\times10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomago Wetland</td>
<td>Site002</td>
<td>1.9</td>
<td>12.3</td>
<td>17.0</td>
<td>186 (0)</td>
<td>4.091</td>
</tr>
<tr>
<td></td>
<td>Site003</td>
<td>1.2</td>
<td>20.0</td>
<td>7.8</td>
<td>19 (2)</td>
<td>0.439</td>
</tr>
<tr>
<td></td>
<td>Site004</td>
<td>1.7</td>
<td>7.1</td>
<td>5.8</td>
<td>19 (2)</td>
<td>0.439</td>
</tr>
<tr>
<td></td>
<td>Site005</td>
<td>2.0</td>
<td>10.3</td>
<td>11.0</td>
<td>206 (0+2)</td>
<td>4.530</td>
</tr>
<tr>
<td></td>
<td>Site006</td>
<td>2.3</td>
<td>12.2</td>
<td>20.0</td>
<td>206 (0+2)</td>
<td>4.530</td>
</tr>
<tr>
<td>Kooragang Island</td>
<td>Site007</td>
<td>0.5</td>
<td>8.1</td>
<td>3.3</td>
<td>71 (3)</td>
<td>0.497</td>
</tr>
<tr>
<td></td>
<td>Site008</td>
<td>1.1</td>
<td>12.3</td>
<td>11.0</td>
<td>67 (5)</td>
<td>0.509</td>
</tr>
<tr>
<td></td>
<td>Site009</td>
<td>2.6</td>
<td>22.4</td>
<td>29.9</td>
<td>14 (4)</td>
<td>0.169</td>
</tr>
</tbody>
</table>

$^1$ (Zone) for contributing marsh area calculated at MHW (Figure 1)

Table 2. Evolution of Site001 in Response to Changing Tidal Prism in the HWNP.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date (years since restoration)</th>
<th>Thalweg Depth (m)</th>
<th>Top Width (m)</th>
<th>Channel Cross-Sectional Area (m$^2$)</th>
<th>Contributing Marsh Area at MHW$^1$ (ha)</th>
<th>Tidal Prism ($\times10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site001, Tomago Wetland</td>
<td>April 2012 (5)</td>
<td>0.8</td>
<td>156</td>
<td>51.3</td>
<td>4</td>
<td>0.0155</td>
</tr>
<tr>
<td></td>
<td>October 2014 (7)</td>
<td>1.2</td>
<td>156</td>
<td>54.0</td>
<td>15</td>
<td>0.0533</td>
</tr>
<tr>
<td></td>
<td>July 2015 (8)</td>
<td>1.3</td>
<td>156</td>
<td>59.0</td>
<td>34 (1)</td>
<td>0.0922</td>
</tr>
</tbody>
</table>

$^1$ (Zone) for contributing marsh area calculated at MHW (Figure 1)
3.2 Equilibrium Hydraulic Geometry Relationships

[13] compiled a database of channel cross-sections, marsh area and tidal prism for six existing and six historic mature marshes with contributing tidal areas. These data were used to derive log-log linear regression relationships between specific channel morphology parameters, including depth, top width, and cross-sectional area, as functions of marsh area and tidal prism. The regression relationships are defined as:

\[
D_{eq} = 1.31MA^{0.202} = 0.388P^{0.176}
\]

\[
W_{eq} = 3.44MA^{0.522} = 0.147P^{0.461}
\]

\[
A_{eq} = 2.40MA^{0.772} = 0.0284P^{0.649}
\]

where, \(D_{eq}\) is channel depth (m), \(MA\) is marsh area (ha), \(P\) is tidal prism (m\(^3\)), \(W_{eq}\) is channel cross-sectional top width (m), and \(A_{eq}\) is channel cross-sectional area (m\(^2\)).

Estuaries experiencing an unstable scouring or shoaling mode will have a tidal prism, cross-sectional area and hydraulic radius that all vary with time. [13] showed that data from evolving tidal channels can be compared with predictions of equilibrium geometry to develop a better understanding of the time scale of the evolutionary trajectory of the channel. While it may be possible to use these relationships to identify that tidal inlets may be prone to such instabilities, it is not possible to predict the exact trajectory toward the stable configuration and when that may be reached.

3.3 Tidal Constituents

The time histories of amplitude and phase of tidal constituents within estuaries present a signature that may allow for an informed assessment of the stability of an estuary and prognosis of its future course. The major tidal constituents contributing to the astronomical tidal stage variation in NSW are:

- **M2** – Principle lunar semidiurnal constituent; and
- **S2** – Principle solar semidiurnal constituent.
Together, these findings suggest that a balance of dynamic process and equilibrium conditions is maintained within the estuary. The importance of this balance may be understood through the relationship between tidal prism and cross-sectional area, as described by Williams, with early work on this relationship providing the basis for later studies that considered the dynamic nature of tidal wetlands.


correlation between tidal prism and cross-sectional area, as a function of tidal prism from Table 1 rather than marsh area. Figures 3 and 4 also include data of mature marshes in the San Francisco Bay estuary (including existing and historic marshes) provided by [13], and are represented as empty (blue) diamonds. A regression analysis (in the form of $y = ax^b$) was applied to the mature marshes in the San Francisco Bay estuary and HWNP data, and is plotted as a dashed (red) line in Figures 3 and 4.

In Figure 3, the HWNP data showed a relatively weak correlation between channel dimensions and marsh area, compared to the equilibrium relationships of [13] (solid black line). The correlation between data was improved when channel dimensions were plotted as a function of tidal prism (Figure 4). The most significant data outliers were for thalweg depth and cross-sectional area of Site007 and Site008 on Kooragang Island, while all data points for Site009 showed a strong positive linear correlation to the equilibrium regression lines. Note that Site007 and Site008 are located behind structures that control upstream water levels and flow in the wetlands, whereas Site009 is open to unimpeded tidal flow from the south-arm of the Hunter River.

The strongest correlations between the San Francisco Bay and HWNP marshes were found between channel depth and channel area, as functions of tidal prism. In Figure 4, the HWNP data showed a positive correlation between tidal prism and cross-sectional area when compared to the equilibrium relationship proposed by [13]. The regression relationship (“Williams Equilibrium + HWNP Data”) ($y = 0.01087x^{0.7318}$) for cross-sectional area as a function of tidal prism is similar to [13] ($y = 0.0284x^{0.649}$), and [12] ($y = 0.02x^{0.07}$), in the only other known comparable studies. These results suggest that the hydraulic geometry relationships proposed by [13] should be applicable to the Hunter River estuary for use in design and restoration of coastal wetlands.

A strong indication of an increasing tidal prism suggests a possible unstable scouring mode at the inlets to the surveyed tidal channels, with amplitudes of the major tidal constituents that are increasing over time. The time histories of major tidal constituent amplitude and phase at Stockton Bridge since 1990 are provided in Figure 5. The data indicates an average increasing rate of change in the tidal range of around 0.42 mm/year, corresponding to an increase in tidal range of approximately 8 mm over a 19 year period. Figure 5 also shows a weak trend of decreasing tidal phase in the estuary, indicating increasing efficiency in tidal wave penetration. These conditions are likely due to significant entrance training works in the Hunter River, which have been imposed over the past century, combined with ongoing dredging programs at the river mouth and across the estuary. The implication of this dynamic downstream boundary condition is one important factor worth considering in the design of any tidal wetland restoration project. In addition to the dynamic nature of open channels, [13] showed that restoration of tidal flows to a restored site increases the downstream cross-sectional area (including top and bottom widths). The extent of the change is directly proportional to the tidal prism and the restored wetland area, with larger sites having a greater influence downstream.

4 RESULTS AND DISCUSSION

Data collected during field surveys in the HWNP have been grouped by location and are represented in Figures 3 and 4 as solid (red) circles for the Tomago Sites and solid (blue) squares for the Kooragang Island Sites. Site001 within Tomago Wetland has been excluded from Figures 3 and 4 as the data provided in Table 2 showed the site is still evolving due to changes in tidal prism since restoration works began in 2007. Site002 to Site009 are considered to be relatively mature systems as the channels existed prior to any restoration works within the HWNP, and the recent field data surveys have confirmed that the cross-sectional dimensions of the tidal channels have been largely unchanged since 2012.

Figure 3 provides channel dimensions (thalweg depth, top width, and cross-sectional area) for the mature marshes surveyed in the HWNP as provided in Table 1, plotted against marsh area, and compared to the equilibrium relationships proposed by [13]. Figure 4 shows the same data as Figure 3, but using potential tidal prism from Table 1 rather than marsh area. Figures 3 and 4 also include data of mature marshes in the San Francisco Bay estuary (including existing and historic marshes) provided by [13], and are represented as empty (blue) diamonds. A regression analysis (in the form of $y = ax^b$) was applied to the mature marshes in the San Francisco Bay estuary and HWNP data, and is plotted as a dashed (red) line in Figures 3 and 4.

In Figure 3, the HWNP data showed a relatively weak correlation between channel dimensions and marsh area, compared to the equilibrium relationships of [13] (solid black line). The correlation between data was improved when channel dimensions were plotted as a function of tidal prism (Figure 4). The most significant data outliers were for thalweg depth and cross-sectional area of Site007 and Site008 on Kooragang Island, while all data points for Site009 showed a strong positive linear correlation to the equilibrium regression lines. Note that Site007 and Site008 are located behind structures that control upstream water levels and flow in the wetlands, whereas Site009 is open to unimpeded tidal flow from the south-arm of the Hunter River.

The strongest correlations between the San Francisco Bay and HWNP marshes were found between channel depth and channel area, as functions of tidal prism. In Figure 4, the HWNP data showed a positive correlation between tidal prism and cross-sectional area when compared to the equilibrium relationship proposed by [13]. The regression relationship (“Williams Equilibrium + HWNP Data”) ($y = 0.01087x^{0.7318}$) for cross-sectional area as a function of tidal prism is similar to [13] ($y = 0.0284x^{0.649}$), and [12] ($y = 0.02x^{0.07}$), in the only other known comparable studies. These results suggest that the hydraulic geometry relationships proposed by [13] should be applicable to the Hunter River estuary for use in design and restoration of coastal wetlands.

A strong indication of an increasing tidal prism suggests a possible unstable scouring mode at the inlets to the surveyed tidal channels, with amplitudes of the major tidal constituents that are increasing over time. The time histories of major tidal constituent amplitude and phase at Stockton Bridge since 1990 are provided in Figure 5. The data indicates an average increasing rate of change in the tidal range of around 0.42 mm/year, corresponding to an increase in tidal range of approximately 8 mm over a 19 year period. Figure 5 also shows a weak trend of decreasing tidal phase in the estuary, indicating increasing efficiency in tidal wave penetration. These conditions are likely due to significant entrance training works in the Hunter River, which have been imposed over the past century, combined with ongoing dredging programs at the river mouth and across the estuary. The implication of this dynamic downstream boundary condition is one important factor worth considering in the design of any tidal wetland restoration project. In addition to the dynamic nature of open channels, [13] showed that restoration of tidal flows to a restored site increases the downstream cross-sectional area (including top and bottom widths). The extent of the change is directly proportional to the tidal prism and the restored wetland area, with larger sites having a greater influence downstream.
Figure 3. Comparison of [13] equilibrium relationships to data from the HWNP for Channel depth (top), width (middle) and area (bottom) versus Marsh Area.

Figure 4. Comparison of [13] equilibrium relationships to data from the HWNP for Channel depth (top), width (middle) and area (bottom) versus Tidal Prism.

Table 2 provides hydraulic geometry data for Site001 which is an evolving tidal channel within the HWNP. A plot of cross-sectional area versus tidal prism (Figure 6) for each cross-section in the time-series showed how the tidal channel responded to changes in tidal prism following the restoration of Tomago Wetland. Also shown in Figure 6 is the predicted cross-sectional area versus tidal prism regression lines from Figure 4. In this study, it was assumed that the updated regression line for tidal prism-entrance area, which includes data from both San Francisco Bay estuary and the HWNP, satisfactorily represented the hydraulic geometry of tidal channels surveyed within the HWNP. This general regression was subsequently used to predict the equilibrium geometry of Site001.

Figure 6 shows that the cross-sectional area at Site001 is increasing to converge on the mature marsh predicted equilibrium geometry. The exact evolutionary path is unpredictable using current methods, however, based on field data it was reasonable to assume a straight line trajectory toward the stable inlet configuration.
This method predicts that an equilibrium condition would be attained when the flow area reached approximately 200 m², a two-fold increase in flow area. By that stage, the tidal prism would be an order of magnitude larger than under the present conditions, and the corresponding marsh area would also need to increase by an order of magnitude. For this condition to occur, Tomago Wetlands would transform into a large, connected open water body, not to dissimilar to Fullerton Cove adjacent to Tomago Wetlands. At a rate of increase for the tidal range of around 0.42 mm/year, as determined by the time histories of the tidal constituents in the Hunter River estuary (Figure 6), it would take some 2,000 years for the equilibrium cross-sectional area to be reached. Although these changes are difficult to contemplate, some of these changes are already taking place onsite, and with the future implications of sea level rise due to climate change being unknown, the changes onsite could exceed our current predictions.

Figure 5. Time Histories of Major Tidal Constituent Amplitudes (Top) and Phase (Bottom) at Stockton Bridge. Data from [7].

Figure 6. Evolutionary Trajectory of Channel Cross-Sectional Area and Tidal Prism of Site001 at Tomago Wetlands.
5 CONCLUSION

This study provides empirical hydraulic geometry data collected over a 3-year period from several tidal inlet channels within the HWNP, a coastal wetland in the Hunter River estuary undergoing restoration. The field database includes channel morphology parameters (depth, width and cross-sectional area), as functions of contributing marsh area and tidal prism. Site001 within Tomago Wetlands was shown to still be evolving due to changes in tidal prism since restoration works began in 2007. Site002 to Site009 are considered to be relatively mature systems as the channels existed prior to any restoration works within the HWNP, and the recent field data surveys have confirmed that the cross-sectional dimensions of the tidal channels have been largely unchanged since 2012.

This study has found a positive correlation between channel morphology parameters and catchment-scale features of present-day mature marshes in the Hunter River and San Francisco Bay estuaries [13]. Differences in the data may be a result of variations in tidal regimes and floodplain elevations between the two estuaries. Further research is required to assess wetland size as a major hydrological factor in developing hydraulic geometry relationships for wetland restoration projects in other estuaries. Nonetheless, this study confirms the utility of hydraulic geometry for planning and designing the restoration of coastal wetlands in tidally-dominated estuaries, and general regression lines to predict equilibrium geometry of evolving sites.

An examination of the time histories of major tidal constituents in the Hunter River estuary, where entrance breakwaters have been constructed, has indicated that perturbations to entrances of large estuaries can cause changes to tidal regimes that may take centuries to stabilise. In the absence of long-term monitoring data at the HWNP, tidal constituents were used to predict a trajectory of an evolving site. It was estimated it may take some 2,000 years to reach a stable configuration, with potentially devastating consequences to existing ecosystems.

REFERENCES


