Wave-dominated tidal inlet systems:

Opening and closure of intermittently open natural inlets
Cover photo: Aerial photo Lake Conjola open inlet entrance state source: NSWPublicWorks (2015)
Wave-dominated tidal inlet systems:

Opening and closure of intermittently open natural inlets

By

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An electronic version of this thesis is available at http://repository.tudelft.nl/.
In order to finish my Master of Science degree and obtain the Dutch title “Ingenieur”, I had to write a thesis based on a scientific research. This scientific research is in the field of Coastal Engineering and carried out over the period November 2014 until September 2015. I have had the opportunity to conduct my research at two great universities, my home university, Delft University of Technology and the University of Queensland in Brisbane. The last few months I have had the opportunity to finalize my research and write my thesis report at the hydraulic institute Deltares in Delft.

The whole period of my thesis work was a very educating and especially rich experience in my life. I really enjoyed the process of conducting a thesis work, working with the obtained data, create a new empirical formula and develop two analytical models in MATLAB. But above all seeing the link between the measured data and the existing equations was very satisfying. Staying abroad was a very eye-opening experience and enabled me to see the opportunities in my field of work outside the Netherlands.

Many people helped me along the way and made it possible for me to be here today. I would like to thank everyone involved and especially the following persons;

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The Australian coastline has gained my full interest during this study and I certainly would like to continue working in such a beautiful place on earth.

To the reader,

Thank you for showing your interest in my study!

Best Regards,

Linda Rijkenberg
Tidal inlet systems are found all over the world. These highly dynamic coastal features can be classified into three main types, according to the main (hydraulic) forces working on the inlet; waves, tide and river discharge. A tidal inlet is described as an opening in the shoreline that provides a connection between the ocean and a bay and is maintained by tidal currents. Tidal inlet systems are the whole area of the near shore ocean, inlet and bay with river catchment area and can be classified as wave-dominated, tide-dominated or river-dominated tidal inlet systems. Recently, Thuy (2013) developed a dimensionless hydraulic parameter tool to classify tidal inlet systems by means of the three hydraulic forces.

The study focusses on wave-dominated tidal inlet systems. There are three sub-classes for wave-dominated tidal inlet systems, namely wave-dominated deltas, wave-dominated estuaries and intermittently open natural inlets. The question arises how the intermittently open natural inlets can be distinct from the other sub-classes. This type of sub-class has an alternately open or closed connection to the ocean, which is indicated by the word intermittently. A natural inlet is defined as an inlet with no other human interventions (e.g. jetties, groynes and dredging work) at the inlet entrance other than artificial breaching of the entrance berm when the lagoon water level exceeds a critical value.

The distinction for the sub-class can be integrated into the wave-dominated classification parameter, therefore the overall objective is to make a contribution to the wave-dominated classification parameter of Thuy (2013) to make a more accurate classification for the sub-class intermittently open natural inlets. The overall objective is too extensive to be answered completely by only this study, therefore a specific objective is formulated. The specific objective is to predict the lagoon water level of intermittently open natural inlets forced by waves, tide and river discharge. The prediction of the lagoon water level will indicate the important forcing working on the inlet, while the entrance is in an open state.

In this study two intermittently open natural inlets along the New South Wales coast, Australia, are studied. Different opening and closing events, as well as the period in between opening and closure, where the inlet entrance remains open for a number of tidal cycles are analysed. The important forces that affect the lagoon water level are identified.

In total nine opening/closure events are found in the data and analysed. The raw data is obtained from Manly Hydraulic Laboratory in Sydney, Australia. Raw data included, offshore wave climate, tidal water levels, lagoon water level and rainfall. To get a more accurate representation of the wave climate near the research sites, the offshore wave climate is adjusted by the wave transformation formulas; Snell’s Law and the breaker criterion to get the near shore wave climate.

Based on the analysis of the nine closure and opening events the following conclusions are found;

1. Opening occurs when a significant rainfall increases the lagoon water level and the hydraulic head forcing is large enough. The breach occurs naturally or manually and mostly during low tide.
2. The waves are dominant during inlet closure and they dominantly approach the inlet in shore-normal direction.
3. The lagoon water level is elevated above the ocean water level when high waves or/and extensive rainfall occur when the inlet is in an open connection to the ocean.

The lagoon water level is a crucial parameter for prediction of the entrance state open or closed. Therefore, it is important to understand in which way the high waves will affect the elevation of the lagoon water level.
Abstract

Two analytical models are introduced to understand the forces that work on the open inlet. A basic energy equation, after Nielsen (2009), is the starting point of both models. The basic energy equation describes the river discharge and flood tide as inflow parameters, but the effect of waves is not taken into account. The result of this basic energy equation shows a strong underestimated of the lagoon water level. As a result an extra lifting force is introduced in the extended version of the basic energy equation.

The first introduced model is the extended energy equation. The data analysis indicated that shore-normal waves are dominant during the elevation of the lagoon water level. The shore-normal wave forcing is introduced by means of a wave overwash discharge. The wave overwash discharge is estimated with the wave pump efficiency model, after Nielsen et al. (2008). Next to the river discharge and flood tide, the wave overwash is an extra inflow parameter in the extended energy equation. The outcome of this model gives an underestimation of the lagoon water level, although the model performs better than the basic energy equation. A Brier Skill Score of 0.486 is calculated for this model. The Brier Skill Score (BSS) indicates the relative performance of the new model compared to the relative performance of the basic model. A value closer to 1 indicates an increase of the performance compared to the basic model.

The second introduced model is an alternative approach of the basic energy equation. The difference between the lagoon and the ocean water level at the peaks of the lagoon water level is the starting point for the elevated forcing. The data analysis and the extended model together indicate that the near shore wave heights are very important for the elevation of the lagoon water level. Accordingly the elevation of the lagoon water level is assumed to be a function of the near shore wave height. The alternative model gives a better performance of the lagoon water level than the basic and the extended model, with a BSS of 0.627. The alternative model is more accurate at low tide than at high tide.

The two models are verified with another different closure event at a different site. The verification indicates likewise that the prediction of the alternative model is better than the basic and the extended model.

Based on this study it is recommended to further develop the alternative model for further research of different tidal inlet systems. A meaningful addition to the model could be the introduction of an entrance width that varies in time. During closure the inlet entrance gets narrower, which will result in different forcing and a different response of the lagoon water level.
# Table of contents

Acknowledgement .................................................................................................................................................. v

Abstract................................................................................................................................................................. vii

List of figures ......................................................................................................................................................... xii

List of tables ......................................................................................................................................................... xvi

List of equations .................................................................................................................................................. xvii

1. Introduction .................................................................................................................................................... 1
   1.1. The New South Wales intermittently open natural inlet systems ............................................................... 3
   1.2. Problem definition, research objective and research questions ................................................................ 4
   1.3. Methodology .......................................................................................................................................... 5
   1.4. Thesis outline......................................................................................................................................... 6

2. Tidal inlet dynamics ........................................................................................................................................ 7
   2.1. Introduction ............................................................................................................................................ 7
   2.2. Morphological elements of tidal inlet systems.......................................................................................... 8
   2.3. Tidal forcing on inlet entrances ............................................................................................................... 8
   2.4. Equilibrium state theories ....................................................................................................................... 9
   2.5. Tidal inlet system classification ............................................................................................................. 10
      2.5.1. Geological classification............................................................................................................... 10
      2.5.2. Hydraulic classification ................................................................................................................. 12
      2.5.3. Classification by attractors ........................................................................................................... 13
   2.6. Characteristics of intermittently open natural inlets ................................................................................ 15
   2.7. Entrance dynamics of intermittently open natural inlets ........................................................................ 16
      2.7.1. Opening processes ...................................................................................................................... 16
      2.7.2. Closure processes ....................................................................................................................... 18
   2.8. Intermittently open natural inlet classifications ....................................................................................... 19
   2.9. Modelling of closure events of intermittently open natural inlets ............................................................. 20

3. Data description ........................................................................................................................................... 23
   3.1. New South Wales natural inlets ............................................................................................................ 23
   3.2. Research sites ..................................................................................................................................... 25
      3.2.1. Lake Avoca ......................................................................................................................................... 25
      3.2.2. Cockrone Lagoon ........................................................................................................................ 26
   3.3. Data overview...................................................................................................................................... 28
      3.3.1. Lagoon water level data ............................................................................................................... 28
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8. Conclusions</td>
<td>80</td>
</tr>
<tr>
<td>6. Conclusions and Recommendations</td>
<td>81</td>
</tr>
<tr>
<td>6.1. Conclusions</td>
<td>81</td>
</tr>
<tr>
<td>6.2. Recommendations for further research</td>
<td>83</td>
</tr>
<tr>
<td>References</td>
<td>85</td>
</tr>
<tr>
<td>Appendices</td>
<td>89</td>
</tr>
<tr>
<td>Appendix A</td>
<td>90</td>
</tr>
<tr>
<td>Appendix B</td>
<td>102</td>
</tr>
<tr>
<td>Appendix C</td>
<td>104</td>
</tr>
<tr>
<td>Appendix E</td>
<td>116</td>
</tr>
<tr>
<td>Appendix F</td>
<td>120</td>
</tr>
<tr>
<td>Appendix G</td>
<td>123</td>
</tr>
<tr>
<td>Appendix H</td>
<td>125</td>
</tr>
<tr>
<td>Appendix I</td>
<td>132</td>
</tr>
</tbody>
</table>
# List of figures

| Figure 1-1: Schematisation of a tide-dominated tidal inlet system, after Nichols (2009). | 1 |
| Figure 1-2: Schematisation of a river-dominated tidal inlet system, after Nichols (2009). | 2 |
| Figure 1-3: Schematisation of a wave-dominated tidal inlet system, after Nichols (2009). | 2 |
| Figure 1-4: New South Wales (red) marked on the map of Australia, adopted from HACCPAustralia (2015). | 3 |
| Figure 1-5: Lake Conjola, New South Wales, Australia obtained from NSWPublicWorks (2015). | 4 |
| Figure 1-6: Tidal inlet features, after Smith (1984). | 4 |
| Figure 2-1: Schematic view of typical tidal inlet. A) plan view b) longitudinal section after Hinwood and Aoki (2013). | 8 |
| Figure 2-2: Ebb and flood tidal currents in front of the entrance channel after O’Brien and Morrough (1969). | 8 |
| Figure 2-3: Outflowing current pattern in the entrance channel, after Thuy (2013). | 9 |
| Figure 2-4: In and outgoing tidal jet, after Bosboom and Stive (2013). | 9 |
| Figure 2-5: Classification of intermittently closed estuaries by Roy et al. (2001): Left open entrance, Right closed entrance. | 11 |
| Figure 2-6: Stages of maturity: A. Youthful B. Intermediate after Roy et al. (2001). | 11 |
| Figure 2-7: The NSW tidal inlet classified following Thuy (2013). | 13 |
| Figure 2-8: Attractor flow map for a typical intermittently open natural inlet with indication of channel stability, after Hinwood and McLean (2015). | 14 |
| Figure 2-9: Attractor flow map with river flood flows and sediment pulse by Hinwood and McLean (2015). | 14 |
| Figure 2-10: Example of an open and closed entrance state, obtained from Gordon (1990). | 16 |
| Figure 2-11: Locals surfing standing wave during opening Lake Avoca April 2011, adopted from YouTube TalkingStones (2011). | 17 |
| Figure 2-12: Entrance opening by large hydraulic head difference, after Kraus (2008). | 17 |
| Figure 2-13: Wave overwash breaching, after Kraus (2008). | 18 |
| Figure 2-14: Schematic explanation of inlet closure due to alongshore (Mechanism 1) and cross-shore (Mechanism 2), obtained from Ranasinghe et al. (1999). | 21 |
| Figure 3-1: Location of Lake Avoca and Cockrone Lagoon relative to Sydney obtained from (Google Maps). | 25 |
| Figure 3-2: Lake Avoca source: NSWPublicWorks (2015). | 26 |
| Figure 3-3: Cockrone Lagoon source: NSWPublicWorks (2015). | 27 |
| Figure 3-4: Closed entrance of Cockrone Lagoon, water level is almost as high as the entrance berm, source: NSWPublicWorks (2015). | 28 |
| Figure 3-5: Location of the water level gauge at Lake Avoca and Cockrone Lagoon source: NSWPublicWorks (2015). | 28 |
| Figure 3-6: Lake Avoca lagoon water level, January to February 2013. | 29 |
| Figure 3-7: Cockrone Lagoon lagoon water level, January to February 2013. | 29 |
| Figure 3-8: Tide gauge and offshore wave buoy source: NSWPublicWorks (2015). | 30 |
| Figure 3-9: Sydney tide gauge, January to February 2013. | 30 |
| Figure 3-10: Kincumber rainfall station Doyle St. source: NSWPublicWorks (2015). | 31 |
| Figure 3-11: Kincumber hourly rainfall, January to February 2013. | 31 |
| Figure 3-12: Significant wave height and direction rose for the Sydney buoy from 03/03/1992 to 31/03/2013, obtained from Kulmar et al. (2013). | 32 |
| Figure 3-13: Offshore significant wave height wave rose, January to February 2013, from Sydney wave rider buoy. | 32 |
| Figure 3-14: Offshore significant and maximum wave height, January to February 2013, from Sydney wave rider buoy. | 33 |
| Figure 3-15: Offshore average wave direction, January to February 2013, from Sydney wave rider buoy. | 33 |
List of figures

Figure 3-16: Offshore zero-crossing wave period, January to February 2013, from Sydney wave rider buoy............ 33
Figure 3-17: Offshore statistic wave period, January to February 2013, from Sydney wave rider buoy................. 34
Figure 3-18: Lake Avoca closed entrance 28/07/2012 adopted from Google Earth.................................................. 34
Figure 3-19: Lake Avoca open inlet entrance 06/02/2013 adopted from Google Earth........................................... 35
Figure 3-20: Cockrone closed inlet entrance 28/07/2012 adopted from Google Earth............................................. 35
Figure 3-21: Cockrone lagoon open entrance 06/02/2013 adopted from Google Earth....................................... 35
Figure 4-1: Dominant offshore wave direction in relation to the research sites Lake Avoca and Cockrone Lagoon, obtained from Google Earth ................................................................. 38
Figure 4-2: Offshore wave height compared to the calculated near shore wave height with the zero-crossing and the statistical wave period ........................................................................................................ 40
Figure 4-3: Offshore incident wave direction compared to the near shore incident wave direction..................... 40
Figure 4-4: Near shore wave height for Lake Avoca (120) and Cockrone Lagoon (130).......................................... 41
Figure 4-5: Near shore wave direction for Lake Avoca (120) and Cockrone Lagoon (130)...................................... 41
Figure 4-6: Lake Avoca event July 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction .......................................................................................................................... 43
Figure 4-7: Lake Avoca event November 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ........................................................................................................... 44
Figure 4-8: Lake Avoca event June 2011; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction .................................................................................................................. 45
Figure 4-9: Lake Avoca event February 2013; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ............................................................................................................. 46
Figure 4-10: Lake Avoca event March 2013; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ........................................................................................................... 47
Figure 4-11: Cockrone Lagoon event August 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction .................................................................................................... 49
Figure 4-12: Cockrone Lagoon event June 2011; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ........................................................................................................... 50
Figure 4-13: Cockrone Lagoon event March 2012; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ........................................................................................................ 51
Figure 4-14: Cockrone Lagoon event April 2013; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction ........................................................................................................... 52
Figure 5-1: The reference event as input for the two models; Lake Avoca June 2011 .................................................. 56
Figure 5-2: Definition sketch of a tidal lagoon, adopted from Bruun (1968).............................................................. 57
Figure 5-3: Rainfall to River discharge Lake Avoca June 2011 ................................................................................. 61
Figure 5-4: Basic energy equation model output, channel width 50m, Lake Avoca June 2011 .................................. 62
Figure 5-5: Comparison of the basic model with the measured data ................................................................. 63
Figure 5-6: Schematisation of wave overwash discharge, after Laudier, Thornton, and MacMahan (2011)............. 64
Figure 5-7: Wave overwash width of 100m in blue at Lake Avoca, source Google Earth at 04/07/2013...................... 65
Figure 5-8: The wave overwash discharge, river discharge and lagoon water level, Lake Avoca June 2011 ............ 66
Figure 5-9: The extended energy equation, channel width 50m, Lake Avoca June 2011 ........................................ 67
Figure 5-10: Comparisson of the extended model with the measured data .......................................................... 68
Figure 5-11: The difference between the lagoon and ocean water level, with corresponding significant near shore wave height, Lake Avoca July 2010 ...................................................................................... 70
Figure 5-12: Correlation wave height and the elevation of the lagoon water level .................................................. 70
Figure 5-13: Estimation of X(waves) with 65 lagoon water level peaks, Lake Avoca ................................................. 71
Figure 5-14: Alternative energy equation without inertia, channel width 50m, Lake Avoca June 2011 ................. 72
Figure 5-15: Comparison of the alternative model with the measured data .......................................................... 73
Figure 5-16: Verification event for the models, Cockrone Lagoon March 2012 ......................................................... 74
List of figures

Figure 5-17: The three models, basic, extended and alternative compared to the measured lagoon water level. ....75
Figure 5-18: Comparison of the three models, basic (upper), extended (middle) and alternative (lower) with the measured data. .................................................................................................................................76
Figure 5-21: The three models, basic, extended and alternative compared to each other for a width of 50m. ....77
Figure 5-19: Rainfall vs waves affecting the lagoon water level, Lake Avoca, Sept 2011............................................79
Figure 5-20: Closed inlet entrance at Lake Avoca on 13/09/2011, the yellow line indicates 100m, source Google Earth. ....80

Figure A-1: Lagoon water level Avoca Lagoon, July 2009- June 2010.................................................................91
Figure A-2: Lagoon water level, Avoca Lagoon, July 2010- June 2011.................................................................92
Figure A-3: Lagoon water level, Avoca Lagoon, July 2011- June 2012.................................................................93
Figure A-4: Lagoon water level, Avoca Lagoon, July 2012- June 2013.................................................................94
Figure A-5: Lagoon water level, Cockrone Lake, July 2009- June 2010.................................................................95
Figure A-6: Lagoon water level, Cockrone Lake, July 2010- June 2011.................................................................96
Figure A-7: Lagoon water level, Cockrone Lake, July 2011- June 2012.................................................................97
Figure A-8: Lagoon water level, Cockrone Lake, July 2012- June 2013.................................................................98
Figure A-9: Rainfall, Kincumber at Doyle Street, July 2010- June 2011.................................................................99
Figure A-10: Rainfall, Kincumber at Doyle street, July 2011- June 2012..............................................................100
Figure A-11: Rainfall, Kincumber at Doyle street, July 2012- June 2013..............................................................101
Figure B-1: Tide at four stations, Sydney, Crowdy Head, Tomarree and Jervis Bay, 10/11/2013 until 11/11/2013....102
Figure B-2: Tide gauges Sydney and Tomaree, raw and smoothened, 10/11/2013 until 13/11/2013. ..............103
Figure B-3: Tide gauge Sydney and Tomaree, raw and smoothened, 10/11/2013 until 11/11/2013. ..................103
Figure C-1: Lake Avoca event July 2010; Offshore wave climate, wave height, wave direction, wave period........104
Figure C-2: Lake Avoca event November 2010; Offshore wave climate, wave height, wave direction, wave period.105
Figure C-3: Lake Avoca event June 2011; Offshore wave climate, wave height, wave direction, wave period........105
Figure C-4: Lake Avoca event February 2013; Offshore wave climate, wave height, wave direction, wave period.106
Figure C-5: Lake Avoca event March 2013; Offshore wave climate, wave height, wave direction, wave period......106
Figure C-6: Cockrone Lagoon event August 2010; Offshore wave climate, wave height, wave direction, wave period. .............107

Figure C-7: Cockrone Lagoon event June 2011; Offshore wave climate, wave height, wave direction, wave period. 107
Figure C-8: Cockrone Lagoon event March 2012; Offshore wave climate, wave height, wave direction, wave period. 108
Figure C-9: Cockrone Lagoon event April 2013; Offshore wave climate, wave height, wave direction, wave period.108
Figure D-1: Lake Avoca Oct/Nov 2009, bay area times 1. .................................................................................110
Figure D-2: Lake Avoca Oct/Nov 2009, bay area times 1.3. ...............................................................................110
Figure D-3: Lake Avoca May/June 2010, bay area times 1. .................................................................................111
Figure D-4: Lake Avoca May/ June 2010, bay area times 1.3. ............................................................................111
Figure D-5: Lake Avoca, Nov 2010, bay area times 1. .......................................................................................112
Figure D-6: Lake Avoca Nov 2010, bay area times 1.3. ......................................................................................112
Figure D-7: Lake Avoca, March 2011, bay area times 1. ....................................................................................113
Figure D-8: Lake Avoca, March 2011, bay area times 1.3. ................................................................................113
Figure D-9: Lake Avoca, April 2012, bay area times 1. ......................................................................................114
Figure D-10: Lake Avoca April 2012, bay area times 1.3 ..................................................................................114
Figure D-11: Lake Avoca, April 2013, bay area times 1. ...................................................................................115
Figure D-12: Lake Avoca, April 2013, bay area times 1.3. ...............................................................................115
Figure E-1: Basic model Lake Avoca June 2011, channel width 30m. .................................................................116
| Figure E-2: | Basic model Lake Avoca June 2011, channel width 60m. | 116 |
| Figure E-3: | Extended model Lake Avoca June 2011, channel width 30m. | 117 |
| Figure E-4: | Extended model Lake Avoca June 2011, channel width 60m. | 117 |
| Figure E-5: | Alternative model Lake Avoca June 2011, channel width 30m. | 118 |
| Figure E-6: | Alternative model Lake Avoca June 2011, channel width 60m. | 118 |
| Figure E-7: | Basic, Extended and Alternative model Lake Avoca June 2011, channel width 30m. | 119 |
| Figure E-8: | Basic, Extended and Alternative model Lake Avoca June 2011, channel width 60m. | 119 |
| Figure G-1: | Lake Avoca, November 2010, elevation of the lagoon water level and the corresponding near shore wave height. | 123 |
| Figure G-2: | Lake Avoca, February 2013, elevation of the lagoon water level and the corresponding near shore wave height. | 123 |
| Figure G-3: | Lake Avoca, March 2013, elevation of the lagoon water level and the corresponding near shore wave height. | 124 |
| Figure H-1: | The rainfall to river discharge for Cockrone Lagoon, March 2012. | 125 |
| Figure H-2: | Basic model Cockrone Lagoon March 2012, channel width 30m. | 125 |
| Figure H-3: | Basic model Cockrone Lagoon March 2012, channel width 50m. | 126 |
| Figure H-4: | Basic model Cockrone Lagoon March 2012, channel width 60m. | 126 |
| Figure H-5: | Wave overwash and river discharge, Cockrone Lagoon March 2012. | 127 |
| Figure H-6: | Extended model Cockrone Lagoon March 2012, channel width 30m. | 127 |
| Figure H-7: | Extended model Cockrone Lagoon March 2012, channel width 50m. | 128 |
| Figure H-8: | Extended model Cockrone Lagoon March 2012, channel width 60m. | 128 |
| Figure H-9: | Alternative model Cockrone Lagoon March 2012, channel width 30m. | 129 |
| Figure H-10: | Alternative model Cockrone Lagoon March 2012, channel width 50m. | 129 |
| Figure H-11: | Alternative model Cockrone Lagoon March 2012, channel width 60m. | 130 |
| Figure H-12: | Basic, Extended and Alternative model Cockrone Lagoon March 2012, channel width 30m. | 130 |
| Figure H-13: | Basic, Extended and Alternative model Cockrone Lagoon March 2012, channel width 60m. | 131 |
| Figure I-1: | Lake Avoca May 2010, rainfall shows elevation of the lagoon water level, high waves don't. | 132 |
| Figure I-2: | Lake Avoca April 2012, only extensive rainfall gives an elevation of the lagoon water level. | 133 |
| Figure I-3: | Lake Avoca July 2013, high waves give elevation of the lagoon water level, open entrance. | 134 |
| Figure I-4: | Lake Avoca open inlet entrance on 04/07/2013. | 134 |
# List of tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>The 27 indicated natural inlets from NSW coast *obtained from Roper et al. (2011)</td>
<td>24</td>
</tr>
<tr>
<td>3-2</td>
<td>Specifications of Lake Avoca source: *NSWPublicWorks (2015), ^BMT WBM (2012), 'Google Earth and lagoon water level data from MHL</td>
<td>26</td>
</tr>
<tr>
<td>3-3</td>
<td>Specifications Cockrone Lagoon source: *NSWPublicWorks (2015), ^BMT WBM (2012), 'Google Earth and lagoon water level data of MHL</td>
<td>27</td>
</tr>
<tr>
<td>3-4</td>
<td>Overview used data: description, period and location, obtained from ManlyHydraulicsLaboratory (1985-2015)</td>
<td>36</td>
</tr>
<tr>
<td>5-1</td>
<td>Run-off coefficients and the delay of the system for six extreme rain events Lake Avoca, ^ = Roper et al. (2011) and * ManlyHydraulicsLaboratory (1985-2015)</td>
<td>60</td>
</tr>
<tr>
<td>5-2</td>
<td>The Brier Skill Score for the extended and alternative model, compared to the basic model, for events at Lake Avoca and Cockrone Lagoon</td>
<td>78</td>
</tr>
</tbody>
</table>
## List of equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Parameters of Thuy (2013)</td>
</tr>
<tr>
<td>2-2</td>
<td>Classification from Thuy (2013)</td>
</tr>
<tr>
<td>4-1</td>
<td>Snell's Law, after Holthuijsen (2007)</td>
</tr>
<tr>
<td>4-2</td>
<td>The offshore group velocity [m/s], after Nielsen (2009)</td>
</tr>
<tr>
<td>4-3</td>
<td>The near shore group velocity, at the breaker point [m/s], after Nielsen (2009)</td>
</tr>
<tr>
<td>4-4</td>
<td>Breaker criterion (short)</td>
</tr>
<tr>
<td>4-5</td>
<td>Shallow water refraction coefficient</td>
</tr>
<tr>
<td>4-6</td>
<td>Shallow water shoaling coefficient</td>
</tr>
<tr>
<td>4-7</td>
<td>Breaker criterion, after Nielsen (2009)</td>
</tr>
<tr>
<td>4-8</td>
<td>The offshore wave number [-], after Nielsen (2009)</td>
</tr>
<tr>
<td>5-1</td>
<td>The basic energy equation after Nielsen (2009),</td>
</tr>
<tr>
<td>5-2</td>
<td>The average channel velocity</td>
</tr>
<tr>
<td>5-3</td>
<td>The channel friction term</td>
</tr>
<tr>
<td>5-4</td>
<td>The channel depth as function of the tide</td>
</tr>
<tr>
<td>5-5</td>
<td>River discharge</td>
</tr>
<tr>
<td>5-6</td>
<td>The lagoon water level at closed inlet entrance, without any losses</td>
</tr>
<tr>
<td>5-7</td>
<td>The extended velocity formula, after Thuy (2013)</td>
</tr>
<tr>
<td>5-8</td>
<td>The extended energy equation, after Thuy (2013)</td>
</tr>
<tr>
<td>5-9</td>
<td>The friction term</td>
</tr>
<tr>
<td>5-10</td>
<td>The wave pump efficiency formula, after Nielsen et al. (2008)</td>
</tr>
<tr>
<td>5-11</td>
<td>The near shore wave energy flux, after Nielsen (2009)</td>
</tr>
<tr>
<td>5-12</td>
<td>The root mean square wave height from the offshore significant wave height</td>
</tr>
<tr>
<td>5-13</td>
<td>The lifting height as function of tide</td>
</tr>
<tr>
<td>5-14</td>
<td>The basic energy equation without river discharge</td>
</tr>
<tr>
<td>5-15</td>
<td>The basic energy equation without river discharge and inertia</td>
</tr>
<tr>
<td>5-16</td>
<td>The alternative energy equation</td>
</tr>
<tr>
<td>5-17</td>
<td>The alternative energy equation at the peaks without friction</td>
</tr>
<tr>
<td>5-18</td>
<td>The empirical function of X(Waves)</td>
</tr>
<tr>
<td>5-19</td>
<td>The Brier Skill Score (BSS), after van Rijn et al. (2003)</td>
</tr>
<tr>
<td>D-1</td>
<td>The rainfall to river discharge starting formula</td>
</tr>
<tr>
<td>D-2</td>
<td>The derivation of the rainfall to river discharge starting formula</td>
</tr>
<tr>
<td>D-3</td>
<td>The simplification due to a small $\delta t$</td>
</tr>
<tr>
<td>D-4</td>
<td>The rainfall to river discharge formula</td>
</tr>
<tr>
<td>F-1</td>
<td>The basic energy equation</td>
</tr>
<tr>
<td>F-2</td>
<td>The alternative energy equation without inertia</td>
</tr>
<tr>
<td>F-3</td>
<td>The sinusoidal formulation of the lagoon water level</td>
</tr>
<tr>
<td>F-4</td>
<td>The Fourier expansion of the formulation of the lagoon water level</td>
</tr>
<tr>
<td>F-5</td>
<td>The Hilbert transformation for the amplitude in the lagoon</td>
</tr>
<tr>
<td>F-6</td>
<td>Derivation of the Alternative energy equation</td>
</tr>
<tr>
<td>F-7</td>
<td>The alternative equation</td>
</tr>
<tr>
<td>F-8</td>
<td>The alternative equation as input for MATLAB</td>
</tr>
</tbody>
</table>
Around the world, coasts vary in shape and features. The Dutch coast for example has on the west coast long straight and broad stretches of beach and two different tidal inlet systems in the north and south. The west coast of England experiences a dominant discharge of the river Thames and the west coast of Norway characterizes itself by long and high sounds. Those features are shaped over decades by tectonic movement, different sediment supplies and hydraulic forcing of tide, river and waves. A lot of research has been done on all different types of coastal features. The coastal features considered in this study is characterised by tidal inlet systems. A tidal inlet, according to Bosboom and Stive (2013), is;

“An opening in the shore that provides a connection between the ocean or sea and a basin and is maintained by tidal currents.”

As described above the coast along the world experiences different tidal inlet systems. The different systems are distinguished by means of the three hydraulic forces; tide, waves and river. In the north of the Netherlands a typical tide-dominated tidal inlet system with barrier islands can be found, named the Wadden Sea. Although the waves are a very important forcing on the tidal inlet as well, the tide dominates the behaviour of the whole system. Figure 1-1 shows a schematisation of a tide-dominated tidal inlet system adopted from Nichols (2009).

The dominant discharge of the river Thames in the North Sea is an indication for the second type of tidal inlet systems. This type of tidal inlet system is titled river-dominated. The river discharge dominates the other forces working on the inlet. The river mouth contains tidal sand bars and small tidal creeks with mud flats, both are clearly seen at low tide. Figure 1-2 gives a schematisation of this type of tidal inlet system.
One more system of tidal inlets can be distinguished, the wave-dominated tidal inlet systems. Wave-dominated tidal inlet systems can be found along coasts with high energetic wave forcing. For example, along the coast of west-Africa, the south-west coast of Europe, west and east coast of Australia, New Zealand and the east coast of America. Figure 1-3 shows a schematisation of this type of tidal inlet system.

Wave-dominated tidal inlet systems are divided into three sub-classes, namely wave-dominated delta’s, wave-dominated estuaries and intermittently open natural inlets. Nichols (2009) describes the difference between deltas and estuaries as how the river mouth is characterised. Delta river mouths build itself out into the sea, where estuary river mouths discharge suspended sediment into a lagoon or bay.

The sub-class intermittently open natural inlet is described as, a wave-dominated tidal inlet systems which open and close frequently. Here, the term natural indicates that the tidal inlet isn’t influenced by any human interventions other than manually opening of the beach berm. The term intermittently open refers to a tidal inlet which alternates between an open and closed connection to the ocean.

Tidal inlet systems are an important source for the community and nature. It is important to know how tidal inlet systems behave under different circumstances, so coastal managers can control the tidal inlet behaviour when undesirable events occur. Coastal managers desire to influence opening and closure processes to reduce unhealthy water quality and flooding hazards. The hydraulic forcing is highly dynamic and the interaction between the forces makes the behaviour of the inlet extremely complex to describe. The opening and especially closure of intermittently open natural inlets has been a subject of discussion over many years now. Different closure procedures have been described and modelled and are discussed in chapter 2.
1. Introduction

1.1. The New South Wales intermittently open natural inlet systems

Hundreds of tidal inlet systems can be found along the coast of New South Wales (NSW), Australia. The state NSW is located at the south-east coast of Australia and the coast is 1200km long. This part of Australia is connected to the Pacific Ocean and in the far south to the Tasman Sea. The sediment along this coast can be categorised as sandy. The shoreline is relatively irregular with headlands, drowned valley formations and rocky outcrops. The beaches are mainly formed between or after the shelter of headlands and rocky outcrops. There are a few large rivers discharging into the ocean and many relatively short rivers with small catchment areas dominate the hinterland.

The coast experiences a micro-tidal regime which is mainly semi-diurnal of character and has a tidal range of maximum 2m. Figure 1-4 shows the orientation of NSW (in red) in Australia.

![Figure 1-4: New South Wales (red) marked on the map of Australia, adopted from HACCPAustralia (2015).](image)

The waves arrive predominant from south-south-east direction, following Kulmar, Modra, and Fitzhenry (2013). Although the offshore wave climate and the tidal regime show little variation along whole of the NSW coast, the specific hydraulic characteristics for every tidal inlet system differ significantly. Due to the irregularity of the coast, the near shore wave climate is specific for every site.

Classifications are a good tool to divide tidal inlet systems into different groups and specify the characteristics. Recent classification study has been carried out by Thuy (2013), who classified tidal inlet systems using a hydraulic perspective. The classification is based on the main hydraulic forces: tides, waves and river. She verified her classification with the tidal inlet systems along the NSW coast and found 151 wave-dominated tidal inlet systems, 100 of those are sub-class intermittently open natural inlets. The other 51 have the sub-class wave dominated estuary (35) or wave dominated delta (16).

The characteristic for intermittently open natural inlets is the alternately open and closed behaviour of the entrance channel. Intermittently open natural inlets can be found at locations where there is small tidal amplitude in the ocean, high wave energetic forcing, high sediment availability and less significant river discharge. The lagoon characteristics are a small catchment area and small lagoon/bay area. An example of an intermittently open natural inlet is shown in Figure 1-5. The figure shows Lake Conjola located in the state New South Wales, Australia. The connection between the ocean and the lagoon is called the inlet entrance, inlet, or simply the entrance. The tide propagates in and out of the entrance. The sandy sediment deposition is clearly seen by the light colours in the picture. The spit at the left hand side of the channel, in Figure 1-5, is called the berm or entrance berm.
1. Introduction

The lagoon basin consists mostly of mud and the entrance of sand. The sand bar in front of the entrance in the ocean is called the ebb tidal delta and consists of swash bars, see also Figure 1-6. The sand bar in the lagoon/bay is called the flood tidal delta and consists of tidal flats and flood channels. The deeper part at the entrance is the throat or main ebb channel.

1.2. Problem definition, research objective and research questions

Thuy (2013) conceived a hydraulic classification method to categorise tidal inlet systems. The approach utilizes dimensionless parameters to present the relative strength of the three main forces. The classification identifies 3 categories: tide-dominated, river-dominated and wave-dominated. The categorization is based on the yearly averaged river discharge, yearly averaged offshore significant wave height and the yearly averaged potential peak tidal discharge. The tidal inlet systems along the NSW coast are classified following this method. Thuy (2013) indicated 151 wave-dominated tidal inlets. The wave-dominated tidal inlets have sub-class intermittently open natural inlets.
1. Introduction

(100), wave-dominated estuary (35) or wave-dominated delta (16). The contribution of this study to the classification is a better understanding in which way the waves influence the intermittently open natural inlets. This understanding can result in a more specified classification parameter and eventually distinguish the intermittently open natural inlets. The classification makes use of yearly averaged parameters and that may not be accurate. The overall research objective of this study is:

To contribute to the wave-dominated classification parameter of Thuy (2013) to make a more accurate classification for the sub-class intermittently open natural inlet systems.

The overall objective is supported by a specific objective to limit the study scope. To make a general contribution to the parameter, different intermittently open inlets must be studied. The research area of this study is the intermittently open natural inlets along the NSW coast. The specific research question focusses on the forces which influence the lagoon water level.

The lagoon water level indicates the inlet entrance state open or closed and therefore implies the forces for closure and opening. The specific objective of this research is:

To predict the lagoon water level behaviour of intermittently open natural inlet systems forced by waves, tide and river discharge.

The research objective is supported by four research questions. The first question indicates the state-of-the-art knowledge about natural inlets in general. The knowledge gap for natural inlet dynamics and inlet classifications will be clear for this study.

RQ1: What is the state-of-the-art knowledge for behaviour of natural inlet entrances?

This study makes use of data obtained along the NSW coast. A data analysis gives insight in the different forces working on the entrance and the forced behaviour of the lagoon water level. The second research question gives an indication of the behaviour and the interaction of the three main forces and the lagoon water level.

RQ2: How do waves, tide, rainfall and the lagoon water level behave in the period of an open inlet entrance?

From the obtained raw data analysis the lagoon water level gives a good indication of the behaviour of the inlet due to the forcing. The third research question implies the dominant hydraulic forces which close the inlet entrance.

RQ3: What are the dominant forces during closure events regarding the behaviour of the lagoon water level?

The dominant forces during closure events are the starting point for simulation of the lagoon water level. The lagoon water level is simulated by means of an energy equation. The fourth research question will give a better understanding in which way the dominant forces influence inlet closure.

RQ4: In which way do the dominant forces influence inlet closure?

The four research questions together support the research objectives. Together the objectives will lead to conclusions and recommendations.

1.3. Methodology

The first part of this thesis provides a literature review of the state-of-the-art knowledge about natural inlets. The general knowledge about tidal inlet systems is important for understanding the tidal inlet features and the various types of forcing, which the inlet can experience. Several classification systems are used to categorize tidal inlet systems. As the study focusses on the closure and opening procedure, various closure and opening mechanism
1. Introduction

theories are described. Some of those ideas are applied by means of modelling. A few model studies are reviewed to gain knowledge about modelling and different theories of closure events.

In the second part the obtained data and observational area are introduced. The data used in this research are provided by the Manly Hydraulics Laboratory (MHL) in Australia. The MHL measures a large variety of data along the NSW coast. The data contain hourly offshore significant wave climate, hourly rainfall measurements, 15-minute ocean tide elevation and 15-minute lagoon water level data. The lagoon water levels are obtained at different tidal inlet systems. A total of 27 intermittently open natural inlet systems have been identified out of the obtained data and two of these are applicable for this study.

The third part analyses nine opening and closure events at the two research sites. The opening and closure events are defined by means of the measured lagoon water level data. The offshore wave data used for the analysis needs to be processed to near shore wave climate. The near shore wave climate is calculated by using wave transformation formulas from literature. The nine events show a breach of the entrance, tidal response in the lagoon water level and a closure of the lagoon entrance. The time frame for this research over which the lagoon water level is obtained is July 2009- June 2013. Every event is extensively explained and analysed. One of the major conclusions regarding this part is the significance of the lagoon water level as indication of the forcing on the inlet.

The conclusion regarding the lagoon water level is the starting point of the fourth part. By means of two analytical models, simulations of the lagoon water levels are made. The simulation of the lagoon water level gives insight of the dominant wave forcing on the inlet. The model is compared to the real data for one specific event. Rainfall data is used to derive the river discharge. The first model is an extended version of the energy equation with wave forcing. The second model has the behaviour of the lagoon water level as starting point. A linear relation between the behaviour of the lagoon water level and the near shore wave height is developed. The models have been calibrated for one particular channel width. Verification of the model has been done with another different closure event.

1.4. Thesis outline

The report has the following structure.

Chapter 2 represents a literature review. A review about the tidal inlet systems in general and intermittently open natural inlets in particular is described. The chapter discusses classifications of different tidal inlet systems. Furthermore, this chapter gives insight into the current theories and state-of-the-art modelling of closure and inlet stability. The first research question can be answered after this chapter.

Chapter 3 represents the data used in this study. The data include ocean tide, offshore wave climate, rainfall and lagoon water level. Two intermittently open natural inlets are selected as research sites. The selected research sites are Lake Avoca and Cockrone Lagoon. The characteristics of the two research sites and the obtained data are discussed in this chapter.

Chapter 4 describes in total nine different opening and closure events at Lake Avoca and Cockrone Lagoon. The events are analysed and the different external forces visualised. The answer on the second research question is described by means of the analyses. One of the major conclusions is the importance of understanding the lagoon water level for indication of the interactions on the main forces. The third research question is conducted from this conclusion and is the starting point of chapter 5.

Two types of analytical models for estimation of the lagoon water level are described in chapter 5. The third and fourth research questions are the subject of this chapter.

Chapter 6 gives conclusions regarding the overall and specific objectives and the research questions. An overview of all the findings during the study is presented and recommendations for further research given.
Tidal inlet systems have been studied for an extensive period of time. This chapter summarises the latest and most relevant studies for this thesis. Tidal inlet systems have been investigated by several researchers from different backgrounds, such as ecology, coastal management, geomorphology and hydraulic dynamics. A lot of information is to be found with a lot of different hypothesis about inlet mechanisms. This chapter will indicate the state-of-the-art knowledge of behaviour of natural inlet systems relevant for this study.

2.1. Introduction

Bosboom and Stive (2013) describe a tidal inlet as an opening in the shore that provides a connection between the ocean and a lagoon and is maintained by tidal currents. The connection between the ocean and a basin is also called the inlet or entrance channel. Tidal inlet system refers to the whole system including the lagoon and catchment area, inlet and the near shore ocean. Another characteristic of a tidal inlet system is the significant influence of sediment dynamics. This distinguishes tidal inlet systems from large and open embayment or passageways along rocky coasts, for example sounds and gulfs, the sediment transport rates don't have much influence on those coastal features.

The sediment rates and channel dimensions for a tidal inlet system are mainly governed by the volume of water exchange at the inlet mouth, the tidal prism. The tidal prism is the amount of water transported in and out by the tidal currents.

The diversity in morphology, sediment transport rates and hydrological forcing of tidal inlet systems indicate the complexity of their processes. The factors responsible for this diversity are a combined variety in oceanography, geology and meteorology for every site. The tidal range, sediment characteristics, storm frequency and intensity and fresh water influx are a few examples of those factors. It is even more complex because of the interaction between the factors. The tidal inlet, over the long term, can experience an equilibrium state. This means that the rate of sediment brought in the inlet is the rate of sediment brought out of the inlet. Theoretically, when this equilibrium is disturbed the entrance tends to close or scour.

Roy et al. (2001) describes that the forming of tidal basins, lakes and lagoons mainly took place during the global Holocene sea level rise. The low-lying areas flooded due to the rising sea level. The process of basin forming during that period of time occurred due to tectonic subsidence, fluvial erosion and glacial action. Later human interferences had also impact on basin forming only on a smaller scale. The interferences include land reclamation, water, oil and gas attraction and peat-harvesting. Another way of basin forming is due to forming of enclosing barriers in front of a body of water. This area is then called the back barrier area. The tidal inlet systems are all formed at low-lying coastal plains on coasts with a moderate to strong tidal energy and with little sediment discharge from the rivers.

Haines (2006) explained the development of tidal inlet systems over decades, with the focus on sea level rise and more frequent extreme storm events, will lead to a landward and upward shift of the inlet and will increase the lagoon water levels. Combined with the increasing expansion of infrastructure and development around the coastal areas this will significantly increase the flooding hazards.
2. Tidal inlet dynamics

2.2. Morphological elements of tidal inlet systems

In general the geometry of tidal inlet systems can be divided into two different types; tidal inlet systems with barrier islands and tidal inlet systems as interruption of a beach stretch. An example of the barrier type of inlet is the Wadden Sea area. The gap between every barrier island is called the inlet. In this study the inlets as an interruption of a beach stretch are important.

The type of tidal inlet system for this study is characterised by a tidal basin, this is also called a lagoon, estuary or lake. The typical tidal inlet geometry for this study is shown in Figure 2-1.

![Figure 2-1: Schematic view of typical tidal inlet. A) plan view b) longitudinal section after Hinwood and Aoki (2013).](image)

The main morphological elements of the tidal inlet are: ebb tidal delta, flood tidal delta and the channel entrance or inlet. The ebb tidal delta is the sand formations and a deep channel at the sea side of the entrance which are reworked by the ebb tide. The flood tidal delta is the sand formation and shallow channels at the basin side of the inlet.

2.3. Tidal forcing on inlet entrances

The tide keeps the inlet entrance in an open state by the equal strength of the ebb and flood tidal currents. Bruun (1968) recognized this phenomenon and explained the ability of narrow inlet entrances staying narrow as they are. The return flow eddies formed during ebb have always a direction towards the inlet entrance. This keeps natural inlet entrance fairly narrow. See Figure 2-2.

![Figure 2-2: Ebb and flood tidal currents in front of the entrance channel after O'Brien and Morrough (1969).](image)

Thuy (2013) measured the entrance velocities over different tidal cycles for a tidal inlet. She noticed that eddies formed during ebb tide also occur in the inlet entrance. The flood tide makes scarps at both sides of the banks of the
inlet entrance and transport the sediment inward of the tidal inlet. The ebb tide takes the imported sediment out again, but the formed eddies at the banks of the channel deposit some sediment at the sides again. In this way the inlet entrance stays stable. This is shown in Figure 2-3.

Bosboom and Stive (2013) formulated a different type phenomenon of tidal currents working on an inlet. The tidal ebb flow in the inlet channel has much momentum that can't spread out fast enough when leaving the inlet. This is called a tidal jet and shown in the left figure of Figure 2-4. On the other hand the tidal flood flow into the lagoon has to accelerate and is inertia dominated, right figure. This means that the highest velocities go along with the shortest path through the inlet. Just around the tips of inlet berm. So the tidal residual current pattern is towards the entrance directed, as shown in both figures in Figure 2-4.

The three theories imply that the inlet entrance stays stable under steady tidal current conditions and no contribution of other forces.

2.4. Equilibrium state theories

The earliest quantitative works on entrance morphology are that of O'Brien and Morrough (1969), Bruun and Gerritsen (1960) and Escoffier (1977). The theories are based on the fact that the inlet entrance is in an equilibrium state, or evolve to an equilibrium state.

Bruun and Gerritsen (1960) defined the stability of tidal inlet systems in terms of the rate of change in geomorphological characteristics. Those characteristics are described as the ratio of tidal prism per spring tidal cycle and total quantity of sediment transported into the inlet system due to alongshore transport. The formula is applicable to inlets with limited river discharges.

O'Brien and Morrough (1969) defined a relationship between the inlet cross-section below mean sea level and the tidal prism, if the inlet entrance is in equilibrium. The O'Brien approach is similar to the Bruun approach only the geomorphological characteristics are defined as the inlet cross sectional area. Stive, Ji, Brouwer, van de Kreeke, and
2. Tidal inlet dynamics

Ranasinghe (2011) reviewed the O’Brien approach and concluded that the relation between the cross-sectional area and the tidal prism is only a good approximation for stable inlets.

Escoffier (1977) has the theory that the entrance behaves as a dynamic equilibrium state of the cross-sectional area in response to the entrance velocity. For example, when the entrance velocity changes in magnitude, the tidal inlet system gives a response. The response results in a larger or smaller cross-sectional area. Escoffier introduced the concept of morphological equilibrium. Morphological equilibrium can give a negative or positive feedback. Negative feedback means that when the system is out of balance it will return to its equilibrium state. Positive feedback indicates that when the system is out of balance it will go further from the equilibrium state.

All three of the theories don’t take sediment characteristics and the river influence into account. The waves are only defined in the Bruun theory as an alongshore transport. Different wave forcing at wave-dominated tidal inlet systems are very important, but this is not represented in the theories.

2.5. Tidal inlet system classification

Around the world inlets differ in shape, dynamics, geology and functions. A classification of tidal inlet systems gives structure and better understanding to inlet systems. The inlet behaviours must be well understood to make classifications. Researchers have made several types of classifications based on different aspects of the tidal inlet systems. They all agree that tidal inlet systems experience three different predominant forces namely; waves, tide and river discharge. The classifications can be subdivided into 3 different points of view which are discusses below.

2.5.1. Geological classification

Roy et al. (2001) made a classification based on geological, morphological and ecological criteria over a longer-term (decades and centuaries). He describes three main tidal inlet systems, namely tide-dominated, wave-dominated and intermittently closed based on the geological criteria. For each type of tidal inlet he determined four common morphological zones. These zones correspond to the ecological state of the estuary. The ecological state is distinguished in maturity. The maturity of the tidal inlet indicates the development in decades of the tidal inlet. This classification is well known and applied in the coastal engineering field.

The intermittently closed estuaries are area of interest for this study. Roy et al. (2001) describes this type of estuaries as follows: The intermittently closed estuary becomes isolated from the ocean for a longer period of time by a combination of climatic and other reasons. Figure 2-5 shows the general geomorphological features of intermittently closed estuaries for an open and a closed inlet entrance.
2. Tidal inlet dynamics

The lagoons, when closed, are non-tidal for a long time of period. After a heavy rainfall their beach berms are breached by storm waves and/or high water level differences between ocean and lagoon. This process is often manipulated by man to prevent the lagoon from flooding. The unpredictability of the rainfall in this area means that the opening behaviour is intermittent and inconsistent. He indicates that wave exposure at the entrance is also important for the degree of openness of the inlet. The morphological zones described for this type of inlet system are the marine tidal delta zone, central mud basin and fluvial delta. Most of the intermittently estuaries are youthful to intermediate of stage, see Figure 2-6.

This classification has been made to predict the biological and ecological effect of human interventions and can be used as a tool for practical management responses. The preliminary findings from this study can be used for better relations between estuary geometry and forces. The classification gives a good overview which forces are expected to work on the inlet and gives a good indication of the morphological zones.
2. Tidal inlet dynamics

2.5.2. Hydraulic classification

A different way to classify the tidal inlet system instead of looking at the geological features is looking at the hydraulic forcing. The hydraulic forces contain tidal currents, wave forcing and river discharge. Thuy (2013) classified the inlets by these three main forces. She derived three parameters. The three parameters compared to each other give 3 classes. The classes are wave-dominated, tide-dominated and river-dominated inlet systems. The parameters represent the river discharge, wave discharge and peak tidal discharge.

Equation 2-1: Parameters of Thuy (2013).

1) \(Q_f\)  
yearly averaged river discharge [m³/s]

2) \(\sqrt{gH^5}\)  
yearly averaged wave forcing [m³/s]

3) \(\bar{Q}_{\text{tide}} = \omega_o a_o A_b\)  
yearly averaged peak tidal discharge [m³/s]

Where, \(H\) = annual significant wave height [m], \(g\) = gravitational acceleration [m/s²], \(\omega_o\) = the tidal angular period [s], \(a_o\) = the annual tidal amplitude [m], \(A_b\) = the lagoon area [m²].

The classification is applied on the tidal inlet systems along the NSW coast. The wave influence is calculated with the yearly averaged offshore significant wave height, which is estimated by Kulmar et al. (2013), the value is a height of 1.6m. The peak tidal discharge is a function of the yearly averaged tidal amplitude of the ocean, the angular tidal period and the bay area. The yearly averaged tidal amplitude is 0.5m. The yearly averaged angular period is on average 12.25 hours, as the tide has a semi-diurnal character. The river discharge is calculated with the annual river discharge. The classification is applied on 178 tidal inlet systems along the coast of NSW. In total 151 are wave-dominated, 18 are tide-dominated and 9 are river-dominated. The conditions for the classification are as follows:

Equation 2-2: Classification from Thuy (2013).

\[
\frac{\bar{Q}_{\text{tide}}}{\sqrt{gH^5}} < 75 \quad \text{Wave-dominated}
\]
\[
\frac{\bar{Q}_{\text{tide}}}{\sqrt{gH^5}} > 75 \quad \text{Tide-dominated}
\]
\[
\frac{Q_f}{\sqrt{gH^5}} \geq 2 \quad \text{River-dominated}
\]

Figure 2-7 shows the NSW tidal inlets classified by the hydraulic classification. The intermittently open natural inlets are indicated as ICOLLs in the figure. Generally, the tide over wave parameter and river over wave parameter are both small for ICOLLs.
2. Tidal inlet dynamics

It is recognised in Thuy (2013) that the inlets which always stay open are tide-dominated. The classification based on the hydraulic forcing is a better classification to understand the external forcing which causes closure of the entrance, however the annual significant wave height is a limited condition to make a proper indication of closure mechanism.

2.5.3. Classification by attractors

The most recent classification of tidal inlet systems is from Hinwood and McLean (2015). They used a hydrodynamic sediment model to identify two attractors working on an inlet. The model is a simple dynamic process model and simulates the evolution of the estuary entrance for hundreds of years for thousands of cases. An attractor is defined as the long term state at which the tidal inlet system will evolve to under steady conditions. The attractors have been identified as functions of the environmental conditions and the initial depth of the entrance. The two different dimensionless attractors are river discharge and tidal forcing. The classification of Haines (2006) dominantly open or dominantly closed entrance is used as identification of the average state of the inlet entrance. This classification is described in section 2.8. The attractors explain and indicate the occurrence of intermittently behaviour. The research is obtained on behalf of the need for predictability of estuaries becoming intermittently open natural inlets. The factors leading this process and the evolution of an estuary in the long term regime have been identified with the research.

The morphological changes at the entrance channel are important for the state towards the inlet behaves. The model simulates the scour and deposition of the entrance channel. The attractor flow maps, see Figure 2-8 and Figure 2-9, indicates the river discharge on the vertical axis and the entrance depth divided by the tidal amplitude in the lagoon on the horizontal axis. The river flow is made non-dimensional according to a relationship with the tidal prism, tidal amplitude and lagoon area.

When the value of entrance depth over tidal amplitude in the lagoon is above 3.5, the tide is dominant, but only if the river discharge is below the critical value of approximately 0.2. This means that the entrance depth is 3.5 times larger than the tidal amplitude. The river flow is dominant when the entrance depth over the tidal amplitude is negative or small, values -1 to 1.5. Above the critical river value, the river creates the entrance and the tide maintains the inlet entrance. One of the conclusions is that a decrease in river flow has a major contribution to closure. If the river flow decreases below the critical flow, $Q_c$, as seen in Figure 2-8 and Figure 2-9, the entrance will be much more vulnerable for closure through tide and wave forces.
2. Tidal inlet dynamics

Figure 2-8 indicates the entrance state for a typical intermittently open natural inlet (ICOLL in the figures), stable means the entrance is not likely to be an ICOLL and vulnerable means the entrance is most likely to be an ICOLL. Figure 2-9 indicated the channel behaviour when two external pulses are implemented in the model. This figure is created for intermittently open natural inlets. The external pulses are a river flood flow and a sediment pulse. The river flood flow can be described as discharge after a heavy rainfall. The sediment pulse is coupled to storm waves with high sediment transport.

![Figure 2-8: Attractor flow map for a typical intermittently open natural inlet with indication of channel stability, after Hinwood and McLean (2015).](image)

![Figure 2-9: Attractor flow map with river flood flows and sediment pulse by Hinwood and McLean (2015).](image)
Intermittently open natural inlets are characterised to have a river flow that drops below the critical value and this will put them into zones C-F. Both the sediment pulse and the flood flows are rapid events. The evolution to the tidal attractor is many times longer, therefore the period in stage C will be months to years.

An inlet entrance in zones E or F will be evolving to the river attractor. Mostly the entrance depth is higher than the ocean low tide, which results in a raised mean lagoon water level, this reduces the tidal prism significantly. When the river flow is reduced the scouring rate decreases and the inlet tend to close. The movement of sediment due to only the tide is slow in this zone. This means that the external pulses change the channel stability rapidly. The external pulses are sediment pulse due to onshore sediment transport by for example wave overwash and river flood-opening which causes entrance enlargement. These external pulses ensure oscillating between the zones E and F and are typical for intermittently open natural inlets.

The inlet entrances in zone C or D are evolving to the tidal attractor. The external forcing from flood flows and moderate sediment pulse are not significant enough to influence the channel stability. Although, a large sediment pulse will push the estuary into the zone E or F and the channel tends to close.

From this study it can be concluded that an inlet entrance evolving to a tidal attractor, which indicates a stable channel behaviour particular zone C, can be pushed out of balance and evolve to the river attractor (zone E or F). The force which pushes the channel out of balance is a large sediment pulse, which corresponds to the large wave forcing. Depending on the regularity of flood flows, the estuary stays in the intermittently open natural inlet behaviour.

Nevertheless, Hinwood and McLean (2015) stated that the occurrence of sediment pulses of high sediment supply occurring in estuaries in zones C-F are far from an attractor for most of the time. Even estuaries that are in zone B may experience instabilities if the river flow drops below the critical flow. This means that it is unlikely that there is a consistent pattern for ICOLL dimensions related to the tide and river flow. Important are the tide, former channel depth and the history of sediment supply and river flow.

The main causes of closure due to waves are large coastal sediment supply and low river flow. There must be said that the model is designed for long term evolution and the ability to make short term predictions is limited. Improvement in this classification could lead to a better distinction between the different sorts of wave characteristics. Currently, the waves are characterised as a sediment pulse, but doesn’t give any details about the waves or the direction of the sediment transport.

2.6. Characteristics of intermittently open natural inlets
Intermittently open natural inlets are specific because of the alternately stage of an open or closed entrance. The inlet entrance is mostly either dominantly open or dominantly closed, because the river discharge and tidal forcing are not significant enough to keep the entrance open all the time. Both the bay area and catchment area are small, therefore the river discharge is very sensitive to extreme periods of rain. The tidal amplitude is not large, up to 1m, this indicates a micro-tidal regime.

Due to the highly dynamic wave regime and the high sediment availability, minimal one side of the adjacent coast consists of sandy sediment. The closure of the entrance has high correlated to the sediment availability.
2. Tidal inlet dynamics

2.7. Entrance dynamics of intermittently open natural inlets

The dynamics at the entrance of a tidal inlet system are highly complex. Waves interact in complex ways with the bed topography. The constant tidal forcing with variations in high and low tide move sediment back and forth at the coast and high rainfall events give a pulse of river discharge flowing out of the inlet.

The intermittently open natural inlet experiences two entrance stages, see Figure 2-10, open and closed. When there is a sufficient increase of water in the lagoon, the closed entrance will be overtopped and drains into the ocean. The tidal inlet system experiences a tidal influence when the inlet is in an open connection to the ocean. The inlet entrance closes when marine sand obstructs the inlet entrance. This is possible by the tidal currents and/or by wave transport.

An open inlet has an open connection with the ocean; a tidal influence can be seen in the inlet. An inlet is closed when there isn’t any open connection to the ocean. The process from open to closed inlet system is called closure of inlet entrance, or closing processes. And the process from closed to open is the called opening of the inlet entrance or opening processes.

2.7.1. Opening processes

Opening of the tidal inlet entrance can occur in two different ways, namely naturally and manually. Manual opening of an inlet entrance is done mechanically. The council can commission the opening of an inlet when a trigger level of the lagoon water level is reached. The trigger level is estimated to prevent severe flooding of the hinterland. The opening is usually done by an excavator. The excavator digs a gully in the entrance berm and when the tide is low the water in the lagoon is flowing rapidly into the ocean. Eventually, the velocity is strong enough to scour the gully and the inlet entrance will be formed. Sometimes the locals open up the entrance themselves to ride the standing waves which occur in the inlet entrance, see Figure 2-11.
The natural opening of an inlet entrance is mainly because of the large difference in water levels between the ocean and the lagoon, as shown in Figure 2-12. The difference of water levels is called the hydraulic head. When the hydraulic head is large enough the water will flow from the higher level to the lower level. The ocean has mainly water level differences because of the tide. The lagoon water level is dominantly managed by the rainfall and evaporation.

The natural opening occurs in two methods, first by sufficient lagoon water level increase due to rainfall. The rainfall itself is not strong enough to force a breach; it will first fill the estuary. McSweeney, Kennedy, and Rutherfurd (2014) explained that any increase in basin water levels has a more direct impact on entrance condition in the final stages of infilling, as the flood accommodation space is limited. If there has been sufficient rainfall in a certain period the lagoon water level reaches the top of the entrance berm. After the water level exceeds the berm height and overtops the berm area. The berm scours and breaches when the velocity exceeds a certain value. When the inlet entrance is formed, the channel discharge slowly decreases as the lagoon water levels subside, velocities reduce and ocean influence increases.

There is a second method for natural opening of the inlet entrance. This opening mechanism is called opening by wave overwash and occurs mainly at small lagoon areas. The significant storm waves give a discharge of ocean water into the lagoon and that can force a breach. The overtopping discharge quickly scours an entrance channel through the barrier and reopens the inlet to the ocean. As seen in Figure 2-13.
In this study seepage and ground water flow is not taken into account. But they also can have a great contribution to the breaching of the inlet entrance.

It has to be said that not every opening event will scour an inlet entrance. Sometimes the inlet channel is formed after a few tidal cycles. Another note is that the sediment availability directly after the breach is increased as most of the sediment is deposited in front of the inlet entrance. So it can occur that the entrance close rapidly within 3-4 days after breaching. Mackenzie, Maher, and Walker (2004) discussed that rapid closure at that moment has more to do with the sediment availability then the external closure forces.

When the inlet entrance is opened manually the sediment taken out by the excavator is dumped next to the entrance. The entrance berm becomes therefore higher then after a natural breach. This has also influence on the closure of the entrance again.

### 2.7.2. Closure processes

Inlet closure procedures can be described in several ways. In this section more general ways of closure processes are presented. The forces which close the inlet can be distinguished in a tidal and wave forcing. Additional to the forces, two important factors always contribute to closure of an inlet entrance. These two factors are high sediment availability and minor river influence. The closure can only occur when there is sufficient sediment available. Most of the time there is enough sediment, because of the breach of entrance prior to the closure. During the process of closure the outflow of water can’t be high. Therefore the river discharge has to be minor to the inflowing velocities.

The tidal closure forcing can be distinguished in two different ways. First the balance between ebb and flood tidal currents is not equal. When the flood tidal currents are stronger then the ebb tidal currents the inlet experiences a sediment import. Gordon (1990) describes for example, the ebb tide experiences obstruction at the entrance of the inlet. Bosboom and Stive (2013) stated the imbalance of ebb and flood tide can also occur due to the inlet geometry. This occurs for example when the ebb channels are significant deeper than the flood tidal (higher) flats. The sediment is deposited at the higher flats and not taken out with the ebb velocity again.

Secondly the different effect of spring and neap tide on the inlet entrance in combination with waves. Weir, Hughes, and Baldock (2006) measured the berm migration in front of an inlet entrance. During spring tide the beach berm grows vertically and during neap tide the lower berm has a slower horizontal accretion. The vertical growth can also occur due to significant swash overtopping. Weir et al. (2006) describes closure due to the spring and neap tide cycle as follows. When the lagoon has a small tidal prism and the beach is exposed to an energetic wave climate, then the lagoon entrance rapidly closes off through vertical accretion of the berm fronting the lagoon. Depending on the phase of the neap-spring tidal cycle closure can be achieved in a couple of days and almost always within one neap-spring tidal cycle.
The closure forcing by waves can be distinguished in alongshore and a cross-shore transport. First the alongshore closure process, in case of longshore sediment transport the sediment availability from the adjacent coast is important. Tidal inlets with significant alongshore sediment transport will migrate into the predominant longshore direction. Several researchers investigated the different ways of sediment bypassing during alongshore transport, for example Hayes (1980). The mechanisms behind the bypassing of alongshore transport is very complicated and kept out of the scope of this study. The alongshore transport is in this study only related to the incident wave angle.

Secondly the onshore sediment transport. The availability of sediment in the near shore and upper beach face is important for onshore sediment transport. Bond, Green, Cooper, and Humphries (2013) did measurements at an inlet in South Africa and it can be stated that closure can be related to wave overwash over the entrance berm of the inlet. Baldock, Weir, and Hughes (2008) measured a closure event at an inlet along the NSW coast. They stated that the overtopping and wave overwash is an important force for closure of small inlet systems. Overwash at the berm crest is usually in short durations and around high tide. The overwash mechanism is as follows, the waves approach shore-normal the entrance berm and when they are sufficiently high, waves overtop the berm. Sediment from the berm is transported into the lagoon directly behind the berm. The redistribution of the sediment by the tide in the inlet entrance can close the inlet off.

Together, wave and tide are important mechanisms for closure. For example, the wave impact is always inwards directed, towards the entrance. The falling tide is unable to achieve balancing removal of the sediment compared to the rising tide. Moreover, the first flood tide after a breach is significant for redistribution of the sediment at the entrance. The waves stir the sediment in the surf zone adjacent to the entrance and are available for transport. The transported sediment is deposited in the entrance channel by the flood tide.

In conclusion, a closure is normally associated with a combination of the following factors: flood tide, storm surge event, wave overwash, the spring tidal cycle, sediment availability and low rainfall in the catchment.

### 2.8. Intermittently open natural inlet classifications

Recently, the question which has been raised from a coastal management perspective is to classify the different intermittently open natural inlets. Coastal managers want to know which factors are important for different types of intermittently open natural inlets to take measures to prevent the tidal inlet systems from for example flooding. Two researchers made two different classification systems especially for this type of tidal inlet system. One classification is based on a water management perspective and the criteria are mainly based on the ecology of the inlet. The other classification is based on the geomorphology of the tidal inlet system.

Haines (2006) studied 66 inlets along the NSW coast from a water management perspective. The classification is based on the state of the inlet entrance and makes a distinction between a dominantly open or dominantly closed entrance. Dominantly closed means, the inlet is closed 60% of the time or more. Dominantly open means that the inlet is closed 20% of the time or less. There are a very few intermittently open natural inlets which are equally open and closed and they are disregarded from the classification. The entrance closure index which represents the percentage closed and open are calculated over a long term period.

Haines (2006) research describes the behaviour of the inlet with respect to the water quality. The classification which he used for his research demonstrates a number of factors influencing the open or closed state of the entrance. The factors for this study include:

- Catchment Size
- Ocean Entrance Exposure; approach angle of the waves
- Catchment/ Waterway Ratio; catchment area against entrance cross-section
- Geomorphic control; adjacent coast features
2. Tidal inlet dynamics

Haines looked at the overall impact of those factors, namely dominantly open or dominantly closed inlet entrance. This classification suggests that the waves and the exposure of waves at the entrance of the inlet are important factors for the dominantly open or dominantly closed stage of the inlet entrance. An inlet classified as dominantly closed has an entrance exposure of a wave angle bigger than 60° and for dominantly open or dominantly closed the wave exposure angle is smaller than 60°. This indicates that the alongshore transport, with an incident wave angle > 60°, always close the inlet entrance. For incident wave angles smaller than this value, other factors become important.

A more recent classification of intermittently open natural inlets has been made by McSweeney et al. (2014). They looked at the geomorphology of 115 estuaries along the coast of Victoria, Australia. The state Victoria is located under the state NSW. This classification is applicable on micro tidal and wave-dominated coasts and distinguished three types of intermittently open natural inlets. The types are beach controlled, channel controlled and tidal creek. It is necessary to consider the differences in geometry between the tidal inlet systems in order to implement effective management strategies.

The classification is based on the balance between the basin capacity (accommodation space and estuary volume), entrance and channel dimensions, wave conditions and berm height (hydraulic head over the berm). Those four factors are the main control on the entrance morphodynamics. The natural openings are initiated by the river processes increasing the basin water level, but the marine processes are the main influence of the duration of the open inlet entrance.

This classification gives insight in the geological features and not in the specific hydraulic features that force the inlet to close. It recognises the importance of marine processes on closure processes, but not in what manner or strength. Marine processes, following McSweeney et al. (2014), include wave energy, wave driven onshore sediment transport and drift or tidal inlet currents.

2.9. Modelling of closure events of intermittently open natural inlets

Three recent studies for modelling of closure of intermittently open natural inlets are described in the following section. Ranasinghe, Pattiaratchi, and Masselink (1999) have made a general study about the two closure mechanisms by waves, namely alongshore and cross-shore transport. Baldock et al. (2008) studied swash overwash rates at inlet entrance of Belongil beach, NSW. Morris and Turner (2010) modelled the morphodynamics of the Narrabeen lagoon, NSW.

Ranasinghe et al. (1999) studied the seasonal tidal inlet systems in Western Australia. This means that the inlet entrances are in a regular patterns open and closed to the ocean. Their model study makes a distinction between two different closure procedures:

- Interaction between inlet current and alongshore sediment transport
- Interaction between inlet current and onshore sediment transport

A process based numerical model has been used to identify the natural processes for inlet closure. The model has been verified by Bruun criteria for inlet stability, using idealised conditions the model agreed with the criteria. The alongshore transport can be seen from the incidence wave angle of >20° and onshore transport of an incident wave angle of <20°. Figure 2-14 shows the explained closure mechanisms by one of the two sediment transport mechanisms. Mechanism 1 is the closure by alongshore transport and mechanism 2 is the closure by onshore transport.
2. Tidal inlet dynamics

From this study it has been found that the cross-shore transport is the dominant process leading to inlet closure when the offshore incident wave angle is <20°. This happens when the alongshore transport rates are low. The alongshore closure happens when the incidence wave angle is >20°. The contribution of this research is the distinction between longshore and cross-shore transport.

Baldock et al. (2008) made a process-based parametric model and applied it to predict wave overwash transport into and infilling of the estuary entrance. The research site has a small lagoon area, called the waterway, and has an area of 0.3km² and is located in NSW. The catchment area is large and has an area of 30km². The adjacent coast is long and small beach stretches. A cape restricts the alongshore transport current in a large degree. The observations were made following a mechanical opening of the entrance and show very rapid vertical growth of an initially low beach berm as a result of swash overtopping and sediment overwash. The sediment rates were obtained from a 12 days survey at either side of spring tide. During the experiment there was no significant rainfall event. The model performs best during large overwash rates, it doesn’t predict well on slow growth. This model only takes the wave overwash into account.

Morris and Turner (2010) modelled events at the Narabeen lagoon, Sydney, NSW. The data campaign for this research site has been undertaken for a year. The campaign started when the flood tidal delta was removed manually from the lagoon entrance area, so the natural closure processes can been studied. The contribution of Morris’s research is to quantify the sediment ingress volumes, rates and pathways within the accreting flood-tide delta of the lagoon entrance and quantify thereby the main driving mechanisms. Storm events in this study are defined as offshore wave height higher then 3m. The storm events account for 80% of the annual sediment volume. Morris concluded that the alongshore transport for the sediment import at Narrabeen lagoon was not significant, more important was the availability of sediment at the inlet entrance and the available accommodation space. Accommodation space is the extra space which is available for sediment accretion.
2. Tidal inlet dynamics
3. Data description

This chapter describes the research sites and the data obtained from Manly Hydraulics Laboratory (MHL). The data include offshore wave climate, rainfall, ocean tide and lagoon water level. The last section gives a summary of this chapter and an overview of the data used in this study.

3.1. New South Wales natural inlets

The research area of this thesis is the coast of the state New South Wales at the south-east side of Australia, as shown in Figure 1-4. In contrast to the Dutch coast line, the NSW coast line is very irregular with many rocky outcrops and long headlands extending into the Pacific Ocean. The NSW coast experiences a semi-diurnal tidal character. The maximum spring tidal range is nearly 2m, this refers to a micro-tidal regime following Bosboom and Stive (2013). Storm and swell waves control the hydrodynamics system of the south-east Australian coast, obtained from Roy et al. (2001). Kulmar et al. (2013) stated that the dominant offshore wave direction is south-south-east and the yearly averaged significant wave height is 1.6m.

Out of all the tidal inlet systems along the NSW coast, which have a lagoon water level gauge, two natural inlet systems are found applicable for this study. The qualification for the two natural inlet systems is as follows. The obtained lagoon water level data set contains data from around 280 tidal inlet systems and the data period for this study is July 2009 until June 2013. By means of five criteria the sites are qualified. The criteria are:

1. At least one closure event during a data period from July 2009 until June 2013.
2. Relatively fast closures, after 5-20 days; in those cases the entrance state responds immediately on the changing forces.
3. Natural inlet: there are no jetties or other manly made constructions at the entrance of the inlet. The inlet entrance needs to experience natural behaviour.
4. Adjacent coast contains sandy beaches at both sides of the entrance; sediment transport must be possible in all directions.
5. No rocky outcrops at the inlet entrance: the rocky outcrops will significantly influence the wave characteristics and therefore sediment transport.

The first two criteria are obtained from the lagoon water level data and the last three are observed with use of Google Earth. After the first 2 criteria only 27 natural inlet systems remain. In Table 3-1, the 27 natural inlet systems are ranked from the largest to the smallest estuary area. The last three columns represents criteria 3 to 5. The indication of an x means the criterion is valid and – the criterion is invalid. The catchment and estuary area data are from a technical report: State of catchments 2010, Roper et al. (2011).
3. Data description

Table 3-1: The 27 indicated natural inlets from NSW coast *obtained from Roper et al. (2011).

<table>
<thead>
<tr>
<th>Location</th>
<th>Catchment Area * (km²)</th>
<th>Estuary Area * (km²)</th>
<th>Beach at the adjacent coast (both sides)</th>
<th>No rocky outcrops at entrance</th>
<th>Fast closures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sussex Inlet</td>
<td>315.75</td>
<td>40.759</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tarbuck bay (Smiths Lake)</td>
<td>27.97</td>
<td>10.011</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Wallaga Lake</td>
<td>263.84</td>
<td>9.145</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lake Cathie</td>
<td>105.50</td>
<td>7.861</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Lake Conjola</td>
<td>139.09</td>
<td>6.694</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wollumboola</td>
<td>34.13</td>
<td>6.328</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Swan Lake</td>
<td>26.38</td>
<td>4.675</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Wonboyn</td>
<td>335.44</td>
<td>3.689</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Durras Lake</td>
<td>58.38</td>
<td>3.599</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Bega River</td>
<td>1934.83</td>
<td>3.306</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Narrabean Lagoon</td>
<td>52.41</td>
<td>2.311</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bonville</td>
<td>113.47</td>
<td>1.496</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lake Tabourie</td>
<td>46.14</td>
<td>1.449</td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Valla</td>
<td>89.80</td>
<td>1.084</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Narrawallee</td>
<td>80.92</td>
<td>0.862</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Lake Curola</td>
<td>28.22</td>
<td>0.714</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Lake Avoca</td>
<td><strong>10.77</strong></td>
<td><strong>0.673</strong></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wamberal</td>
<td>5.82</td>
<td>0.517</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Black Lagoon</td>
<td>31.35</td>
<td>0.359</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Cockrane Lagoon</td>
<td>6.85</td>
<td>0.331</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Salt Water Lagoon</td>
<td>11.11</td>
<td>0.282</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Terrigal</td>
<td>8.94</td>
<td>0.282</td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Crooked Creek</td>
<td>31.99</td>
<td>0.260</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dee Why Lagoon</td>
<td>4.27</td>
<td>0.239</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Woolgooga</td>
<td>21.02</td>
<td>0.155</td>
<td>x</td>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>Werri Lagoon</td>
<td>16.48</td>
<td>0.142</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Curl Curl Lagoon</td>
<td>4.65</td>
<td>0.065</td>
<td>-</td>
<td>-</td>
<td>x</td>
</tr>
</tbody>
</table>

Three tidal inlet systems are suitable for this study: Lake Avoca, Cockrane Lagoon and Dee Way Lagoon. However, the lagoon water level data shows a lot of noise for Dee Way Lagoon. Therefore the chosen study areas are Lake Avoca and Cockrane Lagoon. The lagoon water level data over the study period of the two research sites are shown in Appendix A.
3.2. Research sites

The natural inlet systems Lake Avoca and Cockrone Lagoon are located 5 km apart from each other and about 50 km north from Sydney. Figure 3-1 shows the research sites relative to Sydney.

The natural inlet systems are part of the Gosford Lagoons, which consists of four tidal inlet systems. Lake Avoca is the largest of the four and Cockrone Lagoon the smallest, according to BMT WBM (2012). The other two lakes are Wamberal Lagoon and Terrigal Lagoon, they are located north of Lake Avoca. Even though the natural inlet systems are located near each other, there isn’t any correlation found in the data between the inlets in time of breaches and closures.

The different moments of breaching are mainly related to the catchment area and estuary volume. The amount of rainfall discharging in the lagoon area is the largest for Lake Avoca because of its biggest catchment area. The increase of lagoon water level is faster for a small lagoon area then for a big lagoon area. Therefore the exact date of breaching is different for both inlets. The difference in moments of closure is because of the exact moment of breaching and the local wave conditions in the period after breaching. The wave characteristics are different due to the direction of the inlet entrance towards the ocean and the irregularity of the adjacent coast. The tidal characteristics differ not significantly for the two research sites as they are located close to each other.

3.2.1. Lake Avoca

Lake Avoca is the biggest lagoon of all the Gosford Lagoons. The entrance breaches 3-4 times a year and is on average open 14 unfollowing days. Therefore, the entrance experiences a dominantly closed regime. Following BMT WBM (2012), the lagoon can be described as saline, pH value is around 10. The lagoon area is rather small and the average depth of the lagoon is shallow. The variations in lagoon water depth are large.

The Avoca beach shoreline is about 1.7 km long and contains quartz sand. The Lake Avoca sediments are mostly fine sand and some coarse sand in the upper northern and western lagoon arms. Only the Saltwater Creek discharges into Lake Avoca.
3. Data description

Figure 3-2 shows an aerial photograph of Lake Avoca and the inlet entrance, obtained from NSWPublicWorks (2015), where the entrance is in a closed stage. The urbanised areas are situated mainly at the beaches and the lake sides. The lake area is surrounded by forest. Around 48% of the catchment area is urbanised and 52% is forested.

The lagoon area consists of two lakes, namely Avoca Lake and Saltwater Creek. There is a bridge at the beginning of Avoca Lake. And there is an island in the middle of the Saltwater Creek, the island is called Barreena island. The entrance is located nearly in the middle between the beaches. At the south end of the beach a large rocky headland is situated, this rocky headland is not situated at the inlet entrance.

The specifications for Lake Avoca are summarized in Table 3-2. AHD stands for Australian Height Datum, this is nearly at mean sea level. The estuary area and volume are based on a lagoon water level of 0.60m AHD.

<table>
<thead>
<tr>
<th>Geographic Location</th>
<th>33°27'50.57&quot; South</th>
<th>151°26'07.39&quot; East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuary area</td>
<td>0.673 km² *</td>
<td></td>
</tr>
<tr>
<td>Estuary volume</td>
<td>293.2 ML *</td>
<td></td>
</tr>
<tr>
<td>Catchment area</td>
<td>10.77 km² *</td>
<td></td>
</tr>
<tr>
<td>Entrance direction</td>
<td>120° North *</td>
<td></td>
</tr>
<tr>
<td># of openings in obtained data period</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Longest and shortest time open from data</td>
<td>[3-40] days</td>
<td></td>
</tr>
<tr>
<td>Trigger level</td>
<td>2.09 m AHD ^</td>
<td></td>
</tr>
<tr>
<td>Lowest point lagoon</td>
<td>-3.17 m AHD *</td>
<td></td>
</tr>
<tr>
<td>Average lagoon depth</td>
<td>0.4 m *</td>
<td></td>
</tr>
<tr>
<td>Average entrance channel length</td>
<td>300 m</td>
<td></td>
</tr>
<tr>
<td>Average entrance channel width</td>
<td>30-50 m</td>
<td></td>
</tr>
<tr>
<td>Managed berm height</td>
<td>2.7-2.8m AHD^</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-2: Specifications of Lake Avoca source: *NSWPublicWorks (2015), ^BMT WBM (2012), 'Google Earth and lagoon water level data from MHL.

3.2.2. Cockrone Lagoon

Cockrone Lagoon is the smallest lagoon of the Gosford Lagoons and has the least urbanised areas. Around 70% of the catchment area is forest and 30% is urbanised. The Cockrone Creek and Merchants Creek discharges in the lagoon. The lagoon inlet entrance is dominantly closed. The entrance breaches 2-3 times a year and stays open for 12 days on average. The average depth of the lagoon is rather low with the deepest point at -0.1m AHD. Therefore the lagoon experiences water quality problems and has commonly plumes of blue algae, during long periods of closure. The beach shoreline is 1.6 km long and consists of quartz sand. Cockrone Lagoon has fine sand sediment and coarse sand near the mouth of the Cockrone Creek.
In Figure 3-3 shows an aerial photo of Cockrone Lagoon and the inlet entrance. The inlet entrance is in a closed state. The lagoon area consists of one lake. The urbanised area is mainly located at the beaches and the inlet entrance. Near the inlet entrance at the right hand side in Figure 3-3, an embankment is placed to protect the bank from eroding and damage the residential area. The entrance is located in the middle of the beaches. Two large rocky headlands at either side of the beach shelter the inlet. The rocky headlands are located far from the inlet entrance.

![Cockrone Lagoon](image)

Figure 3-3: Cockrone Lagoon source: NSWPublicWorks (2015).

Table 3-3 summarises some specifications of Cockrone Lagoon. The estuary area and volume are based on a lagoon water level of 0.60m AHD.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic Location</td>
<td>33°29'37.57&quot; South '</td>
</tr>
<tr>
<td></td>
<td>151°25'43.79&quot; East '</td>
</tr>
<tr>
<td>Estuary area</td>
<td>0.331 km² *</td>
</tr>
<tr>
<td>Estuary volume</td>
<td>187.4 ML *</td>
</tr>
<tr>
<td>Catchment area</td>
<td>6.85 km² *</td>
</tr>
<tr>
<td>Entrance direction</td>
<td>130° North '</td>
</tr>
<tr>
<td># of openings in obtained data period</td>
<td>11</td>
</tr>
<tr>
<td>Longest and shortest time open from data</td>
<td>[4-30] days</td>
</tr>
<tr>
<td>Trigger level</td>
<td>2.53 m AHD ^</td>
</tr>
<tr>
<td>Lowest point lagoon</td>
<td>-0.1 m AHD *</td>
</tr>
<tr>
<td>Average lagoon depth</td>
<td>0.6 m *</td>
</tr>
<tr>
<td>Average entrance channel length</td>
<td>250-250 m '</td>
</tr>
<tr>
<td>Average entrance channel width</td>
<td>30-40 m '</td>
</tr>
<tr>
<td>Managed berm height</td>
<td>3.3-3.5m^ AHD</td>
</tr>
</tbody>
</table>

Table 3-3: Specifications Cockrone Lagoon source: *NSWPublicWorks (2015), ^BMT WBM (2012), 'Google Earth and lagoon water level data of MHL

Figure 3-4 shows a closed entrance of Cockrone Lagoon, the lagoon water level is almost as high as the entrance berm.
3. Data description

3.3. Data overview

The Manly Hydraulics Laboratory (MHL) provided the data for this study. The NSW government recognizes the importance of understanding the behaviours of tidal inlet systems and arranges measurements for various data. MHL carries out the coastal related measurements. The data for this study includes hourly offshore wave climate data, 15-minute tide data, hourly rainfall data and 15-minute lagoon water level data. The data of the tide, waves and rainfall give detailed information about their behaviour during the considered period. The following sections describe the locations of the measure equipment, the characteristics of the obtained data and give a plotted example of the data. The period of the data is from 25/01/2013 until 25/02/2013. This period is taken because it includes the moment of the open inlet entrance of Lake Avoca and Cockrone Lagoon, visualised in Figure 3-19 and Figure 3-21.

3.3.1. Lagoon water level data

The lagoon water level is measured at or near the inlet entrance, as shown in Figure 3-5. The water level gauge for Lake Avoca is located at the bridge at the beginning of Avoca Lake. At Cockrone Lagoon the water level gauge is situated directly at the inlet entrance, at the beginning of the embankment. The measurements are taken every 15 minutes. The water levels are referenced to Australian Height Datum (AHD). This raw data is used to indicate the entrance state for the data analysis in chapter 4 and in chapter 5 for validation of the models.

A subset of the lagoon water levels for Lake Avoca and Cockrone Lagoon are shown in Figure 3-6 and Figure 3-7. The lagoon water level shows several increases of the lagoon water level, one breach and the tidal influence.

The increase of water level, in Figure 3-6, is probably after an extensive rainfall. The trigger level for the Lake Avoca entrance is 2.09 m AHD. Presumably, the breach of the entrance is manually done by an excavator as the lagoon
water level reaches the trigger level. The breach is directly followed by a tidal response of the signal. A closure can be seen as the transition between the tidal influence and the smooth line, after 17/02/2013 until 21/02/2013. The vertical line ‘A’ corresponds to the open entrance state of Figure 3-19.

Figure 3-6: Lake Avoca lagoon water level, January to February 2013.

Figure 3-7 shows the Cockrone Lagoon lagoon water level and it shows several increases of water level, one breach, tidal response and one closure. The lagoon trigger level for Cockrone Lagoon is 2.53 m AHD. From left to right, a presumable extensive rainfall increases the lagoon water level just below the trigger level. The second increase of the water level exceeded the trigger level with 0.07 m and the inlet opens. Probably, this breach occurred naturally as it opens suddenly. The vertical line ‘A’ corresponds to the open entrance state of Figure 3-21.

Figure 3-7: Cockrone Lagoon lagoon water level, January to February 2013.

The breaches at both of the research sites are almost at the same time. This happened by coincidence. There is no correlation found between the moments of opening and closure of both inlets. Appendix A shows the lagoon water level data for both inlets over the period July 2009 until June 2013. The reason that the inlets are not correlated is mainly the difference in catchment areas, trigger level heights and lagoon areas.

3.3.2. New South Wales coast tidal range

The tide gauge is located in the Sydney Ria, at Middle Head, see Figure 3-8. This gauge is in operation since September 1987 and measures the water level every 15-minutes, following NSWPublicWorks (2015). The tidal water levels are referenced to the Fort Denison tide gauge in Sydney. The Fort Denison tide gauge is located at -0.925m AHD. The data is smoothened to reduce small fluctuations at the peaks and troughs in the signal and referenced to AHD. There is no significant delay in the tidal signal over a distance of 130km, see Appendix B. Therefore the Sydney tidal gauge can be used for the analysis of chapters 4 and 5.
3. Data description

Figure 3-8: Tide gauge and offshore wave buoy source: NSWPublicWorks (2015).

Figure 3-9 shows the signal of the ocean tide at Sydney Middle Head. The tide along this part of NSW has a semi-diurnal character, which means the tidal cycle occurs twice daily. The tidal velocity is roughly in phase with the tidal elevation. The neap and spring tidal cycle is every forth-night. The tide has a large daily inequality during neap tide, around 1m. The daily inequality is the result of different tidal constituents. The tidal constituents indicate the influential strength of the moon and the sun at that place on earth. Nielsen (2009) mentioned that the tidal currents along this part of Australia are very weak. The tidal waves are much likely standing waves of uniform phase. The vertical line ‘A’ corresponds to Figure 3-19 and Figure 3-21. At this exact moment the ebb tide is shown and the tidal cycle is just after neap tide, so breaches of both inlets were just before neap tide.

Figure 3-9: Sydney tide gauge, January to February 2013.

3.3.3. Kincumber rainfall data

The hourly rainfall data is obtained at the Kincumber Water Quality Control Centre. The rainfall station is located exactly between the two research sites, see Figure 3-10. The distance from the entrances to the rainfall station is around 4 km.
3. Data description

Figure 3-10: Kincumber rainfall station Doyle St. source: NSWPublicWorks (2015).

Figure 3-11 shows the rainfall over the period 25/01/2013 until 25/02/2013. A heavy rainfall can be seen just before the breaches shown in Figure 3-6 and Figure 3-7. At the end of the analysed period another significant rainfall is shown and it results in an increase of lagoon water level for both research sites. In Appendix A, the daily rainfall data over the period July 2010 until June 2013 can be found.

Figure 3-11: Kincumber hourly rainfall, January to February 2013.

3.3.4. Offshore wave conditions

The offshore wave data is collected at the Sydney offshore wave rider buoy, see Figure 3-8. The hourly directional wave monitoring buoy is located at a depth line of -92m this is about 15km offshore. The buoy measures and calculates hourly the significant wave height, the maximum wave height, zero-crossing wave period, the wave peak period and the average wave direction.

The wave climate of the Sydney region can generally be characterised, following Kulmar et al. (2013), as long-period moderate to high energy south-easterly swell underlying a highly variable wind-wave regime. The Sydney buoy provides the longest directional wave data, from 03/03/1992. The buoy is located at an offshore depth of 92m, has a dominant wave direction of SSE and mean annual significant wave height of 1.62m. Figure 3-12 shows the significant wave height and direction of the Sydney buoy measured over a period of 21.09 years, from 03/03/1992 until 31/03/2013.
3. Data description

Morris and Turner (2010) indicated that the wave climate is highly energetic and highly variable. This is due to the fact that the waves are generated by distant extreme storms due to cyclones and local sea breezes at any time during the year.

The analysis of the opening and closure events in chapter 4 selects the significant wave height as presented for the wave forcing. The significant wave height is the average height of the 33% highest waves in the record. The wave rose in Figure 3-13 shows the significant wave height and the average direction for the period 25/01/2013 until 25/02/2013. The maximum significant wave height is 4.99m. The mean significant wave height is 1.92m in this period. This is higher than the annual averaged significant wave height of 1.62m. The dominant direction over this period is south-east.

Figure 3-14 shows the offshore significant wave height and the offshore maximum wave height in one graph. The maximum wave height is the largest wave height measured in an hour.
The offshore average wave direction is shown in Figure 3-15. The measurements at the buoy are obtained with accelerometers and a compass. In this way the buoy measures both the vertical and horizontal motion. The vertical and horizontal motion is converted to three orthogonal data: vertical, north-south and east-west. The data is converted to a wave direction referenced to north.

The zero crossing wave period is plotted in Figure 3-16. This period is calculated following the zero-crossing method. Figure 3-17 shows the statistical $T_{p1}$ wave period, which is overall higher than the zero-crossing wave period. Both wave periods are considered in the estimation of the near shore wave climate in this study. The zero-crossing period gives a better estimation of the near shore wave climate and is therefore used in chapter 4. In chapter 5 the wave overwash discharge is calculated with the use of the statistical wave period, because the statistical wave period gives a more correct approximation for the wave energy of the offshore waves.
3. Data description

3.4. Open and closed entrance state

The inlet entrance states for Lake Avoca and Cockrone Lagoon have been observed through the use of Google Earth. In total 32 time frames from both lagoons are obtained. Lake Avoca has 10 closed and 3 open entrance states and Cockrone lagoon 17 closed and 2 open entrance states. Figure 3-18 and Figure 3-19 show respectively a closed and open inlet entrance of Lake Avoca. Figure 3-20 and Figure 3-21 show a closed and open inlet entrance for Cockrone Lagoon. The overall lagoon water level data shows no correlation between the opening and closure periods of both lagoons. Spit forming due to alongshore transport hasn’t been observed at both inlet entrances.

The closed entrance state of Lake Avoca on 28/07/2012 is shown in Figure 3-18. The lagoon is filled with water and it can be seen that the water level of the lagoon reaches towards the ocean. The water level height is 1.25m AHD and the entrance breaches on 01/02/2012 at a height of 1.90m AHD. The values are obtained from Appendix A.

Lake Avoca experiences an open inlet entrance on 06/02/2013 is shown in Figure 3-19. Section 3.3. shows the data at that moment for Lake Avoca. The vertical line ‘A’ in Error! Reference source not found. and Figure 3-8 to Figure 3-17 corresponds to Figure 3-19. It is ebb tide at this moment and the lake is almost empty. The lagoon water level height is 0.45m AHD, obtained from Figure 3-6Error! Reference source not found.. During flood tide, the lagoon is filled by the ocean water.
Figure 3-19: Lake Avoca open inlet entrance 06/02/2013 adopted from Google Earth.

Figure 3-20 shows the closed inlet entrance of Cockrone Lagoon on 28/07/2012. The lagoon water level height is 1.5m AHD, value obtained from Appendix A. The inlet doesn't breach until 02/02/2013 at a lagoon water level of 2.5m AHD.

Figure 3-20: Cockrone closed inlet entrance 28/07/2012 adopted from Google Earth.

Cockrone lagoon open inlet entrance on 06/02/2013 is shown in Figure 3-21. Section 3.3. shows the behaviour of the different parameters at this specific moment. The lagoon water level is 0.75m AHD, obtained from Figure 3-7. The ocean tide shows low tide. Figure 3-7 indicates that the inlet breached at ebb tide 4 days before the image. Noteworthy is the funnel shape mouths of the creeks discharging in the lagoon area, which corresponds to a tide-dominated tidal inlet system. The inlet entrance in front of the two creeks is a wave-dominated tidal inlet system. It can be concluded that tidal inlets evolve of shape in time.

Figure 3-21: Cockrone lagoon open entrance 06/02/2013 adopted from Google Earth.
3.5. Data summary

Numerous tidal inlets are located along the whole coast of Australia. Not all of the tidal inlet systems are relevant for this research. Two applicable research sites are selected on basis of in total five criteria. The criteria are related to the lagoon water level data obtained from Manly Hydraulics Laboratory (MHL). Furthermore, the geomorphology characteristics of the inlets were visualized with Google Earth. The final two research sites are located in New South Wales, Australia and titled Lake Avoca and Cockrone Lagoon. The raw data for the analysis of opening and closure events are also obtained from the MHL. This data consists of tide, rainfall and offshore wave data, examples are shown in this chapter. Historical Google Earth pictures show open and closed entrance stages from the research sites. These pictures are supported by the data.

All the used data is provided by Manly Hydraulics Laboratory. An overview of the used data is given in Table 3-4.

<table>
<thead>
<tr>
<th>Data</th>
<th>Station</th>
<th>Frequency</th>
<th>Period</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant wave height</td>
<td>Sydney directional wave rider buoy</td>
<td>hourly</td>
<td>10/10/1985 to 01/11/2014</td>
<td>-33° 46' 08&quot; [N] 151° 24' 43&quot; [E]</td>
</tr>
<tr>
<td>Wave direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero crossing wave period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lagoon water level data</td>
<td>Lake Avoca water level gauge</td>
<td>15-minute</td>
<td>01/01/2009 to 01/01/2015</td>
<td>-33° 27' 47&quot; [N] 151° 25' 47&quot; [E]</td>
</tr>
<tr>
<td>Lagoon water level data</td>
<td>Cockrone Lagoon water level gauge</td>
<td>15-minute</td>
<td>01/01/2009 to 01/01/2015</td>
<td>-33° 29' 35&quot; [N] 151° 25' 37&quot; [E]</td>
</tr>
<tr>
<td>Tide water level data</td>
<td>Crowdy Fishermans Wharf Tide gauge</td>
<td>15-minute</td>
<td>10/04/2013 to 25/02/2015</td>
<td>-31° 83' 87&quot; [N] 152° 75' 00&quot; [E]</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Rainfall at Kincumber</td>
<td>hourly</td>
<td>01/01/2009 to 01/01/2015</td>
<td>-33° 28' 53&quot; [N] 151° 23' 40&quot; [E]</td>
</tr>
</tbody>
</table>

Table 3-4: Overview used data: description, period and location, obtained from Manly Hydraulics Laboratory (1985-2015).
4. Inlet opening and closure events

In total nine inlet closure events are described by means of the data explained in chapter 3. The analysis describes the inlet stages of the entrance. This is done in three stages. The stages are:

1. The breach of the inlet entrance.
2. An open inlet entrance and occasionally reopening.
3. Closure of the inlet entrance.

The conclusions are given in section 4.7.

4.1. Introduction

The three main forces (tide, waves and rainfall) influence the inlet entrance at the same time. The lagoon water level indicates the entrance state, namely open or closed. The closure forcing is working on the inlet between breaching and the actual closure. Therefore it is important to know how every force acts during a period of an open inlet entrance.

The period of an open inlet entrance is obtained by means of the lagoon water level data, showed in Appendix A. Lake Avoca experiences in total 14 periods of an open inlet entrance and 5 are clean enough represented to be applicable for this study. Cockrone Lagoon experiences 12 periods of an open inlet entrance and 4 are applicable for this study. The analysis uses the raw data of the lagoon water level, ocean tide and the rainfall data. The offshore wave climate is adjusted to obtain the more relevant near shore wave climate. The near shore wave climate for this study is important to give an approximation of the waves that force the inlet entrance.

Thuy (2013) classified Lake Avoca and Cockrone Lagoon in her study. Both inlets are classified as wave-dominated tidal inlet systems. The classification uses the yearly averaged offshore wave height and the yearly averaged tidal amplitude. In this way the wave forcing is the same for every tidal inlet system. It is suggested that the wave parameter can be optimised by use of the near shore wave characteristics.

The near shore wave climate is calculated with two wave transformation formulas. First, the near shore wave height is calculated with the breaker criterion from Nielsen (2009). This formula is based on the refraction and shoaling coefficients and only applicable for shallow water conditions. Second, the near shore wave direction is calculated with Snell's Law, adopted from Holthuijsen (2007).

The choice has been made to not use any numerical models to estimate the near shore wave climate for the following reasons. First, the presented formulas give a fairly good approximation of the near shore wave climate. Secondly, the processes which influence the near shore wave climate can be understood better. In this way the approach is kept elementary and the origin of the values are easy to indicate.
4. Inlet opening and closure events

4.2. Data processing

Waves approaching the shore are often refracted, as result of obliquely incident waves combined with decreasing depth contour lines, for example around headlands. The coast of NSW is highly irregular with many headlands and rocky outcrops. Figure 4-1 visualises the two research sites and the highly irregular surrounding coast. The waves from the dominant wave direction are refracted by the large headlands at the research sites. The Lake Avoca entrance is in a facing direction of 120°N to the ocean and the Cockrone Lagoon entrance is in a facing direction of 130°N to the ocean. This indicates the difference in wave patterns at the inlet entrances.

![Figure 4-1: Dominant offshore wave direction in relation to the research sites Lake Avoca and Cockrone Lagoon, obtained from Google Earth.](image)

For that reason the near shore wave characteristics are different at every inlet entrance. By use of the wave transformation formulas Snell’s Law and the breaker criterion the near shore wave direction and height are estimated. The input for the wave transformation formulas are the offshore wave characteristics from the Sydney directional wave monitoring buoy.

Snell’s Law translates the offshore wave direction to a near shore wave direction. If a wave travels over a decreasing bottom profile with an angle the wave will slowly change direction as it approaches the shore. The depth variation along the wave crests changes wave characteristics. The crest moves faster in deeper water than it does in shallow water. If the wave approaches the beach obliquely, the wave crest turns towards the shore. This is called refraction. Snell’s Law is a simple formula to calculate refraction.

\[
\frac{\sin \alpha_o}{c_o} = \frac{\sin \alpha_b}{c_b}
\]

Where;

\[
c_o = \frac{g T_{z-c}}{2\pi}
\]

And;

\[
c_b = \sqrt{gh_b}
\]

Where; \(\alpha_o\) = the offshore incident wave angle [rad], \(\alpha_b\) = the near shore incident wave angle [rad], \(h_b\) = the breaker depth [m], \(\pi = \text{pi [-]} \approx 3.1416\) and \(T_{z-c}\) = the zero-crossing wave period.
4. Inlet opening and closure events

The breaker criterion estimates the near shore wave height and the breaker depth. The breaker depth is the depth at which the near shore wave starts to break. The combining effect of shoaling and refraction gives a change of wave height just before breaking. The near shore wave height can be calculated from the offshore wave conditions with the breaker criterion. The breaker criterion is defined in Nielsen (2009). Nielsen (2009) derived the simplified formula from the shallow water expressions for the refraction coefficient \[ K_r \] and the shoaling coefficient \[ K_s \].

\[ H_b = H_o K_r K_s = \gamma_b h_b \]

With;

\[ K_r = \sqrt{\cos \alpha_o} \]

\[ K_s = \frac{1}{4 \sqrt{4 k_o h_b}} \]

This leads to:

\[ H_b = \sqrt{H_o^4 \cos \alpha_o^2 \frac{\gamma_b}{4 k_o}} = \gamma_b h_b \]

Where;

\[ k_o = \frac{4 \pi^2}{g T_x^2 - c} \]

Where; \( H_o \) = the near shore wave height [m], \( H_o \) = the offshore wave height [m] and \( \gamma_b \) = the breaker index, chosen 0.80 [\].

Snell's law and breaker criterion are both based on the assumption that the contour depths are situated straight and parallel to the coast.

A comparison of the offshore and the calculated near shore wave characteristics is given in Figure 4-2 and Figure 4-3. Figure 4-2 shows the offshore and near shore wave height. The offshore wave height is mostly equal or higher than the calculated near shore wave height. Figure 4-3 shows the offshore and near shore wave directions. When the wave directions are shore normal directed the near shore wave heights are slightly higher.

Figure 4-2 shows the calculated near shore and offshore wave heights. Both the zero-crossing wave period (red) and the statistical wave period (yellow) are considered for calculation of the near shore wave height. The statistical wave period gave overall larger wave heights than the offshore wave height. The average near shore wave height calculated with the statistical wave period is 2.01m, the average near shore wave height calculated with the zero-crossing period is 1.78m and the average offshore wave height is 1.91m. Therefore the zero-crossing wave period is used in the wave transformation formulas.
4. Inlet opening and closure events

The local wave direction (blue) in the ocean has large fluctuations, but due to the refraction, the calculated near shore wave direction (red) has less fluctuations, see Figure 4-3. The positive values are waves coming from the south, travelling to the north and the negative values are the other way around. The dotted horizontal lines indicate wave angle of 60° and 20° degrees incident wave angle. Haines (2006) described a dominantly closed inlet entrance at wave exposure directions of >60°. Ranasinghe et al. (1999) described if an inlet experience >20° incident wave angle, the longshore transport process is dominant. When the incident wave direction is <20°, predominantly the cross-shore transport process close is dominant. Noteworthy, the directions of the waves reverse several times in a period of one month. This phenomenon is also taken into account during the analysis of the closure events.

Assuming that the shallow water approximation is valid for the breaker zone, the wave heights are slightly overestimated. The refraction coefficient in the breaker criterion assumes that the wave approaches the inlet close to shore-normal. In reality the wave direction can still occur slightly obliquely to the inlet entrance. The offshore waves travelling to the research sites will be strongly refracted by the adjacent large headlands. Therefore it is assumed that the waves at the breaker point are already strongly refracted to shore-normal direction.
4. Inlet opening and closure events

Figure 4-4 and Figure 4-5 show the difference between the near shore wave characteristics for both research sites. The difference in entrance facing direction gives the difference in wave height and wave directions. Both figures are smoothed. The difference in wave height between the two research sites has a maximum of 0.25m. Therefore the inlet entrances experience slightly different wave forcing at the same time. The wave direction is slightly shifted, the alongshore and cross shore transport have different magnitudes for both inlet entrances.

![Figure 4-4: Near shore wave height for Lake Avoca (120) and Cockrone Lagoon (130).](image1)

![Figure 4-5: Near shore wave direction for Lake Avoca (120) and Cockrone Lagoon (130).](image2)

4.3. Analysis procedure

In total nine events are analysed. All of the events start with a closed inlet entrance until breaching. When the inlet entrance is in an open connection to the ocean, the tidal response influences the lagoon water level data. When the inlet is closed to the ocean again, the lagoon water level shows a more or less constant line. The standard deviation of the lagoon water level drops to zero.

There are five events described for Lake Avoca and four for Cockrone Lagoon. The description is divided into three stages. Stage I defines the behavior of the three main forces around breaching of the entrance. In stage II, the period of an open inlet entrance is described. The open inlet entrance shows a clear tidal response. In several cases the entrance is likely to close but after a significant rainfall the entrance opens up again. Lastly, in stage II an overview of the average wave height, number of change of wave direction and the overall tidal cycle during the whole period. Stage III expresses the development of the three forces during the actual closure event. Important to mention is the difference between wave direction $>20^\circ$ and $<10^\circ$, above $20^\circ$ is assumed as alongshore directed and smaller than $10^\circ$ is assumed to be shore-normal to the inlet entrance. A first estimation of the alongshore and cross-shore wave direction is made by this distinction.
4. Inlet opening and closure events

4.4. Lake Avoca closure events

In total five closure events are described. The heading indicates the period of the event and the number of the figure.

4.4.1. July 2010 (Figure 4-6)

Stage I
The inlet entrance is closed until 08/07 12:00pm, the rainfall which started on 07/07 develops a significant river discharge. The near shore significant wave height in this period before breaching is above 1.5m. The lagoon water level reaches 2.07m AHD. The trigger water level for Lake Avoca is 2.09m AHD, so it is assumed that the entrance opened manually. The breach occurred at high tide and discharges its volume in the ocean during the falling tide, just after neap tide. At the moment of ebb tide the hydraulic head over the entrance berm is the largest and so the hydraulic force is great enough to breach the inlet entrance.

Stage II
The tidal influence is clearly seen after the breach for 20 days. Around 10/07 the wave height drops below 1.5m. And when the wave height is lower than 1m, which occurs around 11/07, the lagoon water level gives a perfect response to the ocean tide. The ocean tide fulfills one spring-neap cycle during the period of an open inlet entrance. Within this period the influence of rainfall is not strong. Neap tide occurs around 20/07 and at this time the wave height increases again above 1.5m. The incident wave angle in this period increases to 20°, but slowly decreases to 10° within a period of 5 days. Noteworthy, the lagoon water level is significantly elevated above the ocean tide water level. The average wave height during the period of an open inlet entrance is 1.42m, with the peak around 16/07 of 2.17m. The wave direction reverses in total 4 times of direction over the whole period.

Stage III
After 24/07 the tidal influence in the lagoon water level is strongly reduced. The semi-diurnal high-high tide elevates the lagoon water level, but the high-low tide doesn’t. The water which is brought in at flood is not able to discharge in its total volume at ebb tide. It is assumed that the inlet entrance at this stage is slowly closing. The incident wave direction in this period is around 10 degrees, which is almost shore-normal. After the last reverse of incident wave angle around 28/07 12:00pm, the entrance is completely closed and there isn’t any high-high tidal influence anymore. The closure occurs from neap to spring tide and the tidal range is on average 1m. The rainfall at the time of complete closure doesn’t reopen the entrance. It is assumed that the entrance berm is build up until 1 m AHD. The inlet constricts at each high tide.
4. Inlet opening and closure events

Figure 4-6: Lake Avoca event July 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.

4.4.2. November 2010 (Figure 4-7)

Stage I
The wave height before the berm breach is rather high, with a maximum of 2.36m. The significant rainfall occurs on 05/11 and ensures an increase of the lagoon water level. The lagoon water level reaches a maximum of 1.98m AHD before the entrance opening occurs at ebb tide -0.75m AHD, just before spring tide. It is assumed that the breach occurred naturally, because of the large hydraulic head and the lagoon water level didn’t reach the trigger level.

Stage II
The total duration of the open inlet entrance is 14 days. Directly after the breach the wave height decreases to a height of 1.6m. The entrance shows a clear tidal influence until 14/11. The rainfall in this period is small. The wave height in the few days before 14/11 is around 1m and the wave direction around 20 degrees. On 13/11 the wave height increases to a height around 1.34m and a significant elevation in lagoon water level is seen. The tide goes to neap tide at this period and tidal range is around 0.5m. The lagoon water level indicates a closure at 14/11, the rainfall on 16/11 12:00pm ensures the tidal influence again. The wave height over these 3 days is around 1.25m and the wave direction reverse from direction exactly at the time of the rain. The wave direction changes again on 18/11 and the tidal influence can only be seen at high tide. At this moment the tidal cycle goes from neap to spring tide. In the period of an open inlet entrance the wave direction reverses 5 times, the average wave height is 1.35m and with a maximum of 2.37m at 19/11 12:00pm. The offshore wave height was measured on 3.24m.

Stage III
The closure of this event starts approximately between 14/11 and 15/11, but the rainfall on 16/11 reopens the entrance again. The rainfall produced in total 30mm over 7 hours. It is assumed that after the rainfall and reopening a
4. Inlet opening and closure events

Lot of sediment available is. The wave direction reversed twice in the last 5 days before closure, which is also noteworthy. The complete closure occurs after the high wave event on 19/11, simultaneously the wave direction changes and one hour of heavy rainfall of 22mm. This rainfall event is not enough to reopen the entrance again. The entrance berm is build up until 0.68m AHD. With every high tide the berm is built even more.

![Figure 4-7: Lake Avoca event November 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.](image)

4.4.3. June 2011 (Figure 4-8)

This event will be used in the next phase of the study.

**Stage I**
Extensively rainfall occurs from 29/05 until 03/06, in this period a total amount of 132mm rain has been fallen. It is expected that the lagoon water level reaches the trigger level. The lagoon water level increases up to 2.07m AHD at 31/05 12:00pm. It is assumed that the entrance is opened manually. The lagoon water level is near the trigger level and the rain forecast at that moment would exceed the trigger level. The breach occurs at ebb tide and after neap tide. The wave height increases from 2m to a maximum of 3.88m at the moment of opening. The wave direction changes from south-north to north-south.

**Stage II**
Directly after the breach the tide influences the lagoon water level. The wave height decreases to a minimum wave height of 0.78m at 08/06 12:00pm. In this period there is no extreme rain event and the waves change again of direction. The lagoon water level responds perfect on the tidal forcing and the inlet stays open. At 09/06 the wave direction reaches 20 degrees and keeps that direction until 13/06. The wave height increases to a value above 2m after 10/06. A significant rainfall begins after 11/06. The lagoon water level shows an elevation above the ocean water level. When the waves are the highest, with a maximum of 3.367m and an offshore height of 4.05m, the maximum
4. Inlet opening and closure events

The difference between the ocean water level and lagoon water level is 0.65m. The wave angle decreases to a shore-normal direction. The mean wave height is really high, 2.43m. The wave direction changes in the whole period from south-north to north-south 2 times. The tide shows one spring-neap cycle.

Stage III
The closure happens within one tidal cycle and under heavy rainfall. The rainfall has an amount of 145mm in 6 days. The ocean tide is at high spring tide when the inlet starts to close, the ebb level reaches -0.65m AHD. The wave height has a slight drop from 3m to 2.5m. Furthermore the wave direction increases from nearly 0 to 8 degrees. The ebb tidal influence is small and after the next high tide the entrance is closed. At the moment of the last high tide the wave height increases once more to 3m, but immediately drops down to 1.2m and simultaneously the wave angle increases again to 20 degrees. The berm must be built up to a minimum level of 1.4m AHD. The closure happens during spring tide.

![Figure 4-8: Lake Avoca event June 2011; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.](image)

4.4.4. February 2013 (Figure 4-9)
This event is refers to the Google Earth images, Figure 3-19 and Figure 3-21, found in Section 3.4.

Stage I
The significant rain event for the breach starts already at 27/01 for 4 days, the total amount of rain is around 235mm. The lagoon reaches a water level of 2.01m AHD. This is less than the trigger level, but 3 days after the rain the inlet entrance breaches. It is assumed that the breach is done artificially because of the predictions for a new rain event, which will definitely exceed the trigger level. During the first rain event the wave height is at its maximum 3.95m. At time of the breach the wave height decreases to 2m. The wave direction reverses from -10 to 20 degrees. Directly
4. Inlet opening and closure events

after the breach the wave direction is above 20 degrees and the waves are 2.5m on average. The lagoon water level shows a clear tidal response.

Stage II
Directly after the breach a two day rainfall event of 60mm, this gives an elevation in the lagoon water level. The wave height at this moment, 03/02 12:00pm, is about 3.5m. The wave height is decreasing significantly to a minimum of 0.65m on 08/02. Meanwhile the waves change direction again. The tidal response becomes less strong after 06/02, at this exact time the waves change direction. In Chapter 3 the inlet entrances of Lake Avoca is described with a Google Earth image on this particular date. The entrance doesn’t close and the waves are low, around 1.2m. The wave angle is -20 degrees, which indicates alongshore transport. After 10/02 the wave direction changes to south-north with an angle of 20 degrees. The lagoon water level shows a closure. The wave heights stay low during this whole period. Meanwhile there is a rainfall event from 11/02 until 12/02 12:00pm. The water level increases to a maximum value of 1.17m. This indicates that the berm height is at least this high. At the following ebb tide the hydraulic head is too large and the entrance breaches. A tidal influence can be seen again. The average wave height over this period is 1.61m and the ocean tide has a neap-spring cycle. The first (almost) closure happens during spring tide. The wave direction changes 2 times during an open inlet entrance.

Stage III
The actual closure happens on 12/02 at high tide. The tidal cycle is from spring to neap tide. The tidal response is very week after the first closure. The wave direction is around 10 degrees south-north. The wave height is around 1.25m. The actual closure berm is built to a height of 0.72m AHD. The entrance was already closed at 12/02, but a significant rainfall opened the inlet entrance again. The availability of sand after the breach is high and the relative low waves together with the relative high tide are able to close the inlet rapidly.

Figure 4-9: Lake Avoca event February 2013; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.
4. Inlet opening and closure events

4.4.5. March 2013 (Figure 4-10)

Stage I
The rainfall start around 01/03 and continues for 3 days, in total 140mm water has fallen in those days. The breach of the inlet occurs on 02/03 at 1200pm at high tide. It is assumed that this is a natural breach. The lagoon water level reaches a maximum of 1.88m AHD. This is 0.20m lower than the trigger level. The wave height is at its maximum with a height of 3.78m. The lagoon water level decrease slower compared to the other breaches. This is because the breach occurred just before high tide, just after spring tide. The incident wave angle is around 15 degrees south-north. The rain keeps falling and therefore the elevation of the lagoon water level above the ocean water level is high. The tidal influence is strongly seen by high tide and less by low tide.

Stage II
During the open entrance period the wave heights start with a maximum of 3.78m, which is a significantly high. After 04/03 the wave height is decreased to a value around 1.2m, with a minimum of 0.74m and stays that low until the closure. At the start of the open entrance there is some rainfall, but after that there is no rainfall during this whole period. The wave direction changes from south-north to north-south on 05/03 that is around neap tide. The wave direction changes in total 2 times. The average wave height is around 1.63m and the tide starts with spring tide and just before the second spring tide the inlet is closed. The wave direction is on average around +/- 15 degrees.

Stage III
The entrance is completely closed at 10/03 just after high tide. At the same time the incident wave angle goes from -20 to shore-normal. The berm height after closure is at least 0.86m AHD. Closure occurs during low waves, around 1m.
4. Inlet opening and closure events

4.5. Cockrone Lagoon closure events
In total four closure events are described. The heading indicates the period and the number of the figure.

4.5.1. August 2010 (Figure 4-11)

Stage I
Rainfall starts at 28/07 a total amount of 30mm falls in one day. The lagoon water level reaches a level of 2.48m. The trigger level for Cockrone Lagoon is 2.53m AHD. The entrance opens on 30/07 around 12:00pm at low tide, after spring tide. It is assumed that the inlet entrance is opened naturally. Just before opening the wave direction changes direction. The wave height is rather small, around 1.5m. The tidal response is clearly seen in the lagoon water level signal. The tidal cycle goes to neap tide.

Stage II
The tidal range when the inlet is open is small, around 1m. When the tidal cycle reaches neap tide the inlet closes. The waves stay low until this closure moment this is at 03/08. The wave height reaches its maximum 4.46m, the offshore wave height is measured on 6.4m. Additionally a rain event occurred and 35mm of rain fell. The inlet stays closed for two days and the lagoon water level increases until a level of 1.54m AHD. On 05/08 the inlet entrance opens again. The wave heights are low again around 1m and the wave direction is shore-normal. And after 1.5 day the inlet closes again under the same wave conditions and just after neap tide. The average wave height in this period is 1.52m and the minimum is 0.58m. The tide experiences only a neap cycle.

Stage III
The final closure of entrance is just before 07/08. The wave height increases slightly around 2m. The closure is at high tide, towards spring tide. The water level is steady at a value of 1.06m AHD this is also the minimum height of the entrance berm.
4. Inlet opening and closure events

Stage I
The total volume of rainfall reaches a value of 135mm in 4 days. The wave height until breaching is around 2m. The breach occurs after 30/05 and the maximum lagoon water level is 2.65m AHD. The lagoon water level exceeds the trigger level, therefore it is assumed that the breach is manually done by an excavator.

Stage II
The wave height strongly increases after the breach until a maximum of 3.80m. The wave direction reverses directly after breaching and is around 15 degrees north-south. On 01/06 some data is missing. The wave height decreases again until a minimum of 0.78m. At this time the inlet is already closed. The wave direction changes around 06/06 and the tidal response becomes weaker for the low-high tide. There is no significant rainfall within this period. The mean wave height is 2.26m and the wave direction changes from direction 2 times. There is no rainfall during the closure processes. The tidal cycle starts at neap tide and the entrance is closed just before neap tide again.

Stage III
The closure process starts after 06/06 the tidal influence for the low-high tide decreases. The actual closure is on 08/06 at high tide. There is a small elevation of the water level at 10/06. After this date the inlet is completely closed and the entrance berm height is minimal 1.11m AHD. The wave direction changes around 06/06. The wave height decreases slowly. On 10/06 the wave height increases again to 2.26m AHD at high tide and the small elevation is shown.

Figure 4-11: Cockrone Lagoon event August 2010; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.

4.5.2. June 2011 (Figure 4-12)

Stage I
The total volume of rainfall reaches a value of 135mm in 4 days. The wave height until breaching is around 2m. The breach occurs after 30/05 and the maximum lagoon water level is 2.65m AHD. The lagoon water level exceeds the trigger level, therefore it is assumed that the breach is manually done by an excavator.

Stage II
The wave height strongly increases after the breach until a maximum of 3.80m. The wave direction reverses directly after breaching and is around 15 degrees north-south. On 01/06 some data is missing. The wave height decreases again until a minimum of 0.78m. At this time the inlet is already closed. The wave direction changes around 06/06 and the tidal response becomes weaker for the low-high tide. There is no significant rainfall within this period. The mean wave height is 2.26m and the wave direction changes from direction 2 times. There is no rainfall during the closure processes. The tidal cycle starts at neap tide and the entrance is closed just before neap tide again.

Stage III
The closure process starts after 06/06 the tidal influence for the low-high tide decreases. The actual closure is on 08/06 at high tide. There is a small elevation of the water level at 10/06. After this date the inlet is completely closed and the entrance berm height is minimal 1.11m AHD. The wave direction changes around 06/06. The wave height decreases slowly. On 10/06 the wave height increases again to 2.26m AHD at high tide and the small elevation is shown.
4. Inlet opening and closure events

4.5.3. March 2012 (Figure 4-13)

This event is used for verification of the models in chapter 5.

Stage I
The rainfall occurs around 21/02 with a volume of 80mm in 3 days. The lagoon water level reaches a value of 2.61m AHD this is larger than the trigger level. Therefore it is assumed that the opening is done manually. The breach is at 22/02 12:00pm, the ebb tide creates a large hydraulic head and the lagoon is discharged into the ocean. The lagoon water level signal shows a bottom value of -0.16m AHD. It is assumed that the entrance bottom is at this point. There is no outflow of water anymore. The wave height at this moment is around 1.5m and the wave direction is 20 degrees from south-north. Just before breaching the tide reached spring tide.

Stage II
The lagoon water level shows a clear tidal response with a minimum of -0.16m AHD. All the water that flows in at high tide, is flowing out at ebb tide. The wave height is around 1m and the wave direction changes from direction one time. A significant rainfall occurs from 01/03 and the wave height increases until 2.5m. The lagoon water level responds with an elevation. The tide reaches its neap tidal cycle. The wave height stays above 2m and the elevated lagoon water level increases even more. The tide after 03/03 towards spring tide, the wave height decreases to 1.5m and there is minor rain. After 08/03 the wave height reaches its maximum 3.50m. The wave direction becomes shore-normal and the lagoon water level shows an elevation. There is no closure although the waves are onshore directed and significantly high. The wave height decreases again until a minimum of 0.43m. This is at 14/03 and the wave direction changes again. The waves stay low and the wave direction reaches 20 degrees north-south. The average wave height in this whole period is 1.49m and the wave direction changes 5 times.
Stage III
The closure of the inlet happens at 16/03 at high tide. The tidal cycle goes to neap tide and the wave direction is 20 degrees north-south. The wave heights are very low, around 1m. After the closure a weak response of the high-high tide is seen and the water level reaches until 0.85m AHD. The berm is built up minimal 0.85m AHD. At 17/03 there is a rainfall of 20mm, but it is not strong enough to breach the inlet again.

Stage I
The significant rainfall occurs before the breach and starts at 03/04 the total volume rain in 4 days is 105mm. The breach occurs at 06/04 around 12:00pm. The lagoon water level reaches 2.62m AHD and breaches at ebb tide. This is larger than the trigger level and therefore the opening is assumed manually. The wave direction is from north-south with 15 degrees at the moment of breaching and the wave height is around 1m.

Stage II
After the breach the tidal amplitude is clearly seen. The wave heights stay low, around 1m and the tide experience spring tide. The wave direction turns to above 5 degrees. The minimum wave height in this period is 0.46m. After 13/04 the inlet is closed at high tide this is just after spring tide. The wave heights are around 1.5m and there is no significant rainfall. The inlet stays closed at a level around 1m AHD until the extensive rainfall on 20/04 with an amount of 65mm in two days. The wave height increased to its maximum 4.5m. The lagoon water level increases until 2.10m AHD, which corresponds to a berm of the same height. The inlet breaches again on 21/04. The wave height drops and the wave direction decreases to shore-normal. The tidal influence is seen for 4 cycles. The average wave
4. Inlet opening and closure events

height over this period is 1.38m and the wave direction changes 4 times. The tide experiences on full spring-neap cycle.

**Stage III**

The final closure is at 25/04, the wave heights drop from breach until closure to a height of 1.25m. The wave direction is shore-normal, below 5 degrees. After the closure the high-high tidal response is seen and finally the spring high tide is higher than the lagoon water level. The lagoon water level doesn’t respond on this high tide, so the entrance berm is minimal 1.22m AHD.

![Figure 4-14: Cockrone Lagoon event April 2013; Lagoon water level, Ocean water level, Rainfall, Near shore wave height and direction.](image)

4.6. Discussion

The analysis of nine closure events gave a good first indication of the forces working on the inlet entrance. The parameters tide, rainfall, wave height and direction were analysed, and described separately. However, the interaction between the parameters is far more complex. At this moment it is not possible to visualise the complexity of the parameters in a way to give an adequate qualitative comparison. However the findings of the analysis already address three discussion points.

*Elevated lagoon water level*

The lagoon water level is mostly elevated above the tide level. The maximum elevation can be seen when high wave heights and/or extensive rainfall occur in the data records. Often high waves occur when the inlet entrance tend to close. The elevated lagoon water level can give an indication of the forcing during closure. Therefore the tide, waves and rainfall processes are related to the lagoon water level in chapter 5. This relation of the lagoon water level by the three main forces will give a better indication of the closure processes.
4. Inlet opening and closure events

Cross-shore or alongshore sediment transport
The calculated near shore incident wave directions during the analysed periods are between 25° and 0° and predominant during closure lower than 20°. Out of the literature review, Ranasinghe et al. (1999) indicated that incident wave angles smaller than 20° relates to a dominant cross-shore transport. A study by Morris and Turner (2010) examined the inlet entrance of the Narrabeen Lagoon, NSW. They found that the longshore transport has no direct relation with closing processes. The analysis together with the two findings out of the literature signifies the cross-shore wave forcing. Therefore, in chapter 5, the cross-shore wave forcing is assumed to have significant contribution to the closure procedures. The cross-shore wave forcing will assumed to be the dominant wave forcing and is visualised as a wave overwash discharge.

Tidal neap/spring cycle
The influence of spring and neap tide is more likely to be dependent of the exact moment of opening. The analysis concluded that the breach of an inlet often occurs around neap tide and the closure is mostly during a tidal cycle going to spring tide. More analysis of events can give a decisive answer weather the spring/neap tidal cycle influence closure due to tidal cycle berm building or depends on the moment of opening. Nevertheless it is expected that the neap/spring tide berm growth is significant after closure to strengthen the inlet berm while the inlet is closed, this process requires a few tidal cycles. Tide will rework the sediment deposited at the entrance and together with aeolian transport will close the inlet after the wave forcing closed the entrance.

From an analytical point of view during neap tide the gradient difference between the lagoon water level and the ocean water level at ebb and flood is smaller. The sediment deposit between low and high tide occurs during lower velocities. At spring tide the gradient is larger between ebb and flood and the velocities are higher. But at high tide the waves penetrate further into the inlet entrance, so transports more sediment towards the inlet entrance. The sediment deposition from neap to spring tide is going slowly more towards the lagoon. It is suggested to analyse the tide and waves interactions closer to give exact suggestions for closure processes during storm waves in combination of the tidal cycle.

4.7. Conclusions
The obtained data described in chapter 3 has been adjusted for the analysis of the research sites. In total nine closure events have been analysed. The closure events include five events at Lake Avoca and four events at Cockrone Lagoon. The analysis is separated into three stages and the conclusions are given per stage. The first stage is the breach of the inlet entrance. The second stage is the open inlet entrance and the third stage describes the closure of the inlet. The general conclusions for the analysis are described below, followed by the conclusions for each stage separately.

General conclusions:
- The last high-high tide indicates the minimum berm height of the entrance berm. At the following high tide the ocean isn’t able to reach over the berm into the lagoon. The inlet is closed.
- Rainfall during a closed inlet is not always strong enough to open the inlet entrance. The lagoon has to be filled up to a certain stage where the hydraulic head becomes significant or the rain must be of an extensive amount.
- The duration of closure varies significant. Occasionally, the inlet closes rapidly and other times the inlet closes slowly. This can be seen from the tidal influence just before complete closure. Some closure events show one last low-high and high-high tide. The low-high and high-high tide is due to the daily inequality of the tide. Other times the low-high tide isn’t seen any more in the lagoon water level. Only the high-high tide shows an elevation in the lagoon a few times in a row.
- The storm and high wave regime is an important factor for closure mechanisms. The classification wave-dominated tidal inlet system already indicates that the inlets are influenced mainly by waves. This is satisfied
4. Inlet opening and closure events

by the data analysis. The near shore wave characteristics are separated in a wave height and a wave direction. Kulmar et al. (2013) gave an overview of the dominant wave characteristics along the NSW coast. The average offshore significant wave height is 1.6m. The analysis of the open inlet entrance shows higher average near shore wave heights. The average significant near shore wave height for Lake Avoca is 1.68m. For Cockrone Lagoon the average significant near shore wave height is 1.66m.

Conclusions for every stage:

1. Stage I: Breach of the inlet entrance

Natural breaching occurs due to a combination of extensive rainfall and high waves equal or higher than 1.5m. Heavy rainfall regularly occurs in combination with high waves. Little showers of rain don’t have much effect on a significant increase of the lagoon water level. Furthermore, breaching occurs nearly always around low tide, when the hydraulic head is the largest. The velocities during the breach are the highest and can scour a channel over the entrance berm. When the entrance channel is wide and deep enough, the tidal influence can be seen in the lagoon water level signal. The hydraulic head is more important than the forcing from the actual rainfall.

2. Stage II: Open inlet entrance and reopening

The significant elevation of the lagoon water level before closure happens due to a combination of waves and rainfall.

The combination of rainfall and high waves can give a re-opening of the inlet entrance. During re-opening the rainfall is around or above 30mm a day. Before the re-opening the lagoon water level increases significant.

The lagoon water level is slightly behind the ocean tide. The peaks of the lagoon water level are later than of the ocean water level.

3. Stage III: Complete closure

The closure occurs mainly at the tidal cycle from neap to spring tide, except when an inlet has been or experiences a semi-closure. Then closure also occurs from spring to neap tide. The wave heights vary between 1m to 3m and the direction is mostly <15° during closure processes. Occasionally a rain event occurs during closure, it is assumed that the river discharge due to the rain is not enough to keep the entrance open. Concluded, during closure processes the wave height may not be extremely high, but the high-high tide brings the waves further towards the inlet entrance. The waves are shore-normal directed and rainfall can occur but cannot keep the entrance open.
Chapter 4 introduces the importance of the lagoon water level, for indication of the entrances state and the influence of the main forces on the inlet entrance. Therefore the lagoon water level will be estimated by means of two newly introduced analytical models based on an existing energy equation.

5.1. Introduction
The lagoon water level is an important parameter to describe the inlet entrance state, as demonstrated in chapter 4. A tidal response can be seen when the inlet is open and a more or less constant horizontal line while it is closed. The discussion of chapter 4 shows the significance of the cross-shore transport during closure processes. This chapter will give contribution to the specific objective of this study.

To predict the lagoon water level behaviour of intermittently open natural inlets forced by waves, tide and river discharge.

The estimation of the lagoon water level is based on an energy equation adopted from Nielsen (2009). This energy equation is the starting point for two types of propositions. The terminology in this chapter for the energy equation is the basic energy equation. The first proposition introduces an extension to the basic energy equation, the wave overwash discharge. The second proposition is an alternative approach of the basic energy equation. The alternative approach takes the influence of the waves as function of the elevated lagoon water level into account.

The predictions have been made for one particular closure event of Lake Avoca. The event is from 06/06/2011 until 20/06/2011, see Figure 5-1. This event has been chosen for several reasons. First, the tidal amplitude and the abrupt closure of the inlet are clearly seen in the lagoon water level records. Secondly, the rainfall and waves have significant impacts at different moments in the visualised period. Therefore the significance of both forces can be visualised more or less separately.

At the start of the period the river discharge is zero and the waves are low. After a while the wave height increases slightly and there is a significant rainfall. Simultaneously the lagoon water level shows an elevation above the ocean tide. Finally, the waves increase even further, the rainfall decreases and the lagoon water level elevates even higher above the ocean tide. The inlet entrance closed on 17/06/2011. The wave direction over the whole period is from the south and stays on average just above ten degrees, this corresponds to nearly shore-normal directed wave forcing.

Both models are verified with another closure event of Cockrone Lagoon, the results can be found in section 5.5. To compare the performance of the newly introduced models to the basic energy model the Brier Skill Score is introduced. The explanation and the qualitative performance of the models are shown in section 5.7.
5. Modelling of the lagoon water level

5.2. Basic energy equation

The most general formula to estimate the lagoon water level is the basic energy equation. The basic energy equation describes the tidal propagation into the lagoon. Additionally to the tide, the river discharge has also an inflow of water into the lagoon. The tide propagating into the lagoon depends on:

- The tidal range.
  The tidal range is the difference between high tide and low tide. Idealistic, this difference is brought in during flood and out during ebb.
- The lagoon area.
  The lagoon area is the area of the lagoon water surface. This area varies in time due to the trapezoidal-tub shape of the lagoon. In the models the lagoon area is taken constant.
- Roughness of the channel.
  The roughness of the channel will influence the velocities in the inlet and the height of the tidal range. The rate of influence depends on the length of the channel, sediment characteristics, entrance and exit losses, bottom profile, depth and width of the channel.
5. Modelling of the lagoon water level

The energy equation is obtained from Nielsen (2009), see Equation 5-1. This equation calculates the lagoon water level as function of the ocean water level, the inertia and friction of the channel.

**Equation 5-1: The basic energy equation after Nielsen (2009).**

\[
\eta_b = \eta_o - \frac{L_c}{g} \frac{d\langle u \rangle}{dt} - \left[ k_{\text{ent}} + k_{\text{ex}} + \frac{f L_c}{4 h_c} \right] \frac{\langle u \rangle \langle u \rangle}{2g}
\]

Where: \( \eta_b \) = the bay/lagoon water level [m], \( \eta_o \) = the ocean water level [m], \( L_c \) = the channel length [m], \( g \) = the gravitation acceleration constant [m/s²], \( \langle u \rangle \) = the average (over channel width and depth) velocity [m/s], \( k_{\text{ent}} \) = the entrance friction coefficient [\( \cdot \)], \( k_{\text{ex}} \) = the exit friction coefficient [\( \cdot \)], \( f \) = the channel friction term [\( \cdot \)], \( h_c \) = the channel depth [m].

The average, average means averaged over channel width and depth, landward velocity \( \langle u \rangle \) in the channel is related to the change in lagoon water level and the river discharge \( Q_f \):

**Equation 5-2: The average channel velocity.**

\[
\langle u \rangle = \frac{A_b}{A_c} \frac{d\eta_b}{dt_c} - \frac{Q_f}{A_c}
\]

Where: \( A_b \) = the bay/lagoon area [m²], \( A_c \) = the channel area [m²], \( t_c \) = the time [s], \( Q_f \) = the river discharge [m³/s].

The friction term is defined as follows;

**Equation 5-3: The channel friction term.**

\[
f = \frac{8k^2}{\ln \frac{12R_c}{k_s}}
\]

Where: \( f \) = the channel friction term [\( \cdot \)], \( k \) = Von Karman constant (0.41) [\( \cdot \)], \( R_c \) = the hydraulic radius [m], \( k_s \) = the friction coefficient [\( \cdot \)].

A simplified layout for this formula is given by Figure 5-2. The ocean water level is indicated at the left and the river inflow at the right. The channel is assumed to be rectangular and the velocity is averaged over the width and depth.

![Figure 5-2: Definition sketch of a tidal lagoon, adopted from Bruun (1968).](image)

The channel roughness coefficients are obtained from Thuy (2013), who simulated the lagoon water level based on the same formula and had the goal to estimate the tidal response function in the lagoon. The entrance friction coefficient is between 0.05 and the exit friction coefficient is 0.1. This is generic for natural tidal inlet systems.
5. Modelling of the lagoon water level

The river discharge can be calculated from the rainfall, this is explained in 5.2.1. Other unknown parameters regarding the equation are the lagoon area, channel length, depth and width.

The entrance channel geometry is an important parameter in the equation. There hasn’t been any documentation found about the channel geometry for the study sites and this specific period of an open entrance. Therefore, the channel length is estimated from Google Earth and the channel width obtained by a classification.

The classification of McSweeney et al. (2014) indicates a general channel width for tidal inlet systems with a lagoon area around 0.2km\(^2\) and catchment area around 25km\(^2\). The inlet channel has been described to have a width on average of 56.1m. As a result of the sensitivity of the channel width in the equation and the assumption the channel width will vary significant during closure, three different values are taken. The values are 30m, 50m and 60m.

The channel length is estimated using Google Earth and defined from the ocean water line at the beach until the end of the channel. The differences in channel length are small and therefore the average channel of 300m is taken. The channel length is not a very sensitive parameter in the equation.

The lagoon area is obtained from Roper et al. (2011), and is determined for a lagoon water level of 0.6m AHD. In reality the lagoon water level is dominantly above a water level of 0.6m AHD. Due to the trapezoidal shape of the lagoon and the difference in low and high tide, the value of the lagoon area will be dominantly underestimated during periods where the lagoon water level is higher than 0.6m AHD. The sensitivity in the equation for this parameter is small.

The channel depth in the basic equation is a constant value, while in reality the channel depth changes due to the height of the tide. The channel depth will be larger at high tide than at low tide. For a more accurate calculation of the lagoon water level this value has been made a function of the tide. The channel depth is described as follows;

\[
h_{c,\text{real}} = \frac{\eta_a + \eta_b}{2} - h_{c,\text{chosen}}
\]

Where; \(h_{c,\text{real}}\) = the time dependent channel depth [m] and \(h_{c,\text{chosen}}\) = the chosen channel depth [m].

The chosen channel depth is estimated as calibration parameter of the formula. The lowest point as output of the model is calibrated with the lowest point of the real lagoon water level.

5.2.1. River discharge

The river discharge is a function of the amount of rainfall and the catchment area characteristics. The rainfall evolves in a flow of water towards the river and the river discharges the water into the lagoon. When the lagoon entrance is closed and there are no other extensive losses, like evaporation, this velocity gradually increases the lagoon water level. The total amount of rainfall in the catchment area is not the total amount of river discharge that will discharge directly into the lagoon. Two parameters influence the amount and the delay of the river discharge. The parameters are; the run-off coefficient and the delay of the system.

The run-off coefficient is defined as a percentage of the rainfall that will discharge into the lagoon. The rain will not drain its total volume to the lagoon. This depends on the size of the forested and urban areas in the catchment. Generally, the urban areas have a run-off coefficient between 0.26-0.44 and forested areas between 0.08-0.1. For comparison asphalt has a run-off coefficient of 0.97. BMT WBM (2012) stated that the catchment area of Lake Avoca is for 48% urbanised and 52% forested. The run-off coefficient for the year 2007 is around 0.26, as indicated by Roper et al. (2011).
Another effect due to the characteristics of the catchment area is the delay of the system. This delay indicates the period in hours between the actual rainfall and the actual river discharge into the lagoon. The following formula used to determine the two parameters and calculate the river discharge is shown in Equation 5-5. The derivation of this formula can be found in Appendix D.

\[ Q_f(t) = \left( 1 - \frac{dt}{T} \right) Q_f(t - dt) + \frac{dt}{T} A_c R(t) r \]

Where; \( T = \) the delay of the system [s], \( t = \) time [s], \( dt = \) time step [s], \( A_c = \) the catchment area [m²], \( R = \) the rainfall [m], \( r = \) the run-off coefficient [-].

The determination of the delay \( T \) and the run-off coefficient \( r \) is as follows. When the lagoon is in a closed connection to the ocean and there are no extensive losses, the river discharge will show an elevation of the lagoon water level in the data. This elevation can be estimated with:

\[ \frac{d\eta_b}{dt} = \frac{Q_f(t)}{A_b} \]

Noteworthy, the lagoon area will change in size over time. The lagoon geometry is not rectangular of shape, but more likely to be trapezoidal. The smallest width is located at the bottom and the largest at the surface. The banks of the lagoon increase gradually under a small angle. Therefore, the lagoon water level can inundate over a long distance, while the increase of water level occurs. Eventually, the river discharge will give a smaller increase in change of the water level when the lagoon is totally filled, compared to when it is almost empty.

Both, the run-off coefficient and the delay of the system depend on the lagoon area. A sensitivity analyse has been done to indicate the influence of the lagoon area on the two parameters. Roper et al. (2011) defined the lagoon area on a lagoon water level of 0.6m AHD. The lagoon area times 1 and times 1.3 is taken. The two parameters are calculated for both sizes of lagoon areas separately.

One other limitation of this approach is the ratio between drought and rain. For example, when there hasn't been much rainfall in the weeks before a rain event occurs, it is more likely that the rain will be drained straight into the soil and the river discharge decreases. However, when it already has been raining for an extensive period of time, the rainwater will go straight to the river and the river discharge increases. This occurs due to the ground being saturated.

The last limitation indicated from the calculations is the rainfall which falls into the lagoon. When the rain falls, the lagoon area experiences also an increase of water volume from the direct rainfall. This is not taken into account in the formula. At this stage, with the obtained data, it is unknown what the effect is of the rainfall, which falls directly in the lagoon area. Therefore the calculated river discharge is overestimated.

Six significant rainfall events express the two parameters for Lake Avoca, seen in Table 5-1. An overview of the calculated events and the estimation of the two parameters for Lake Avoca can be found in Appendix D. The last column of the table indicates ratio between drought and rain before the event.
5. Modelling of the lagoon water level

<table>
<thead>
<tr>
<th>Date</th>
<th>Start level [m] AHD</th>
<th>Delay [h]</th>
<th>Run-off coefficient [-]</th>
<th>Increase of the run-off coefficient [%]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Oct- 2 Nov</td>
<td>1.1</td>
<td>5</td>
<td>0.20</td>
<td>0.23</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A week after an period of open inlet entrance, not much rain in that period</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 May- 13 June</td>
<td>1.2</td>
<td>8</td>
<td>0.18</td>
<td>0.23</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gradually increase of the water level, not much rain before</td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 Nov- 7 Dec</td>
<td>0.7</td>
<td>8</td>
<td>0.30</td>
<td>0.40</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Little rain in the month before</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Mar- 28 Mar</td>
<td>0.85</td>
<td>8</td>
<td>0.23</td>
<td>0.30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Little to no rain from Dec2010- Mar 2011</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Apr- 26 Apr</td>
<td>0.85</td>
<td>8</td>
<td>0.37</td>
<td>0.45</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not much rainfall, only 31 March 35mm day</td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Apr- 25 Apr</td>
<td>0.75</td>
<td>8</td>
<td>0.47</td>
<td>0.60</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A lot of rain before, also an open entrance 7 to 9 April</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>0.37</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1: Run-off coefficients and the delay of the system for six extreme rain events Lake Avoca, ^ = Roper et al. (2011) and * = ManlyHydraulicsLaboratory (1985-2015).

The parameter the delay of the system is not influenced by the difference in lagoon area. However, the run-off coefficient is sensitive to the lagoon area and the ratio between drought and rain. The run-off coefficient is larger when there rain has been fallen in the former days, see the event of April 2013 compared to the other events. Furthermore, an increase of the lagoon area gives an increase in run-off coefficient. The increase of lagoon water level is given, but the lagoon area is larger and therefore the river has to discharge more water to reach the real increase of the lagoon water level. The difference between the lagoon area times 1 and times 1.3, is an increase of 26% on average. The river discharge is calculated with a lagoon area which is measured at a lagoon water level height of 0.6m AHD. Therefore the river discharge is slightly underestimated as it is hypothesize that the lagoon area is slightly larger most of the time. The river discharge for the model is calculated with the following chosen values; the delay of the system is 8 hours and the run-off coefficient is 0.30.

5.2.2. Result

The calculated river discharge for the modelled period appears in Figure 5-3. The blue line is the calculated river discharge and the bar plot is the rainfall times the run-off coefficient. The bar plot displays the actual rainfall which will discharge into the lagoon area. The rainfall just before 06/06/2011 doesn't have any influence on the river discharge at this date. The river discharge is zero until 11/06/2011, the rainfall at that moment gives a discharge of 0.75m³/s. Just before 13/06/2011 the river discharge reaches its maximum, for this period. At the peak of the rainfall the lagoon water level shows an elevation, shown in the lower panel of Figure 5-3. The next high peak of the river discharge also falls simultaneous with the extra elevation of the lagoon water level. Overall, the discharge of the river is considerably low, with a maximum lower than 3.5m³/s.

The influence of the river discharge will be diverged by the size of the lagoon surface area. At the inlet, the influence of the river discharge has been significantly decreased. Furthermore, the highest water level elevation is not at the highest river discharge, which suggests another parameter is influencing the lagoon water level.
5. Modelling of the lagoon water level

At time of closure the inlet area experiences a river discharge, but this discharge is not strong enough to open up the inlet entrance. The rainfall appearing in this period doesn’t influence the closure processes.

The outputs of the basic energy equation can be found Appendix G. The channel calibration gives a channel depth of -0.1m AHD. The channel depth indicates the lowest point in the model. The water level can’t get lower than this point. The calibration ensures that the model starts with a channel depth according to the real lagoon water level signal. Figure 5-4 shows the basic model outcome for a channel width of 50m.

The model (blue) in the figure gives an overall underestimation of the real lagoon water level (red). In the first few days the model represents the lagoon water level acceptable, until the rainfall starts and the model continues at the same height. The river discharge doesn’t influence the lagoon water level and is not large enough to generate the elevation of the lagoon water level.
5. Modelling of the lagoon water level

The prediction of the lagoon water level perfectly agrees with the theory of the basic energy equation, without any other inflow. The gradient of the blue and red lines are very similar, especially at rising tide. This indicates a reasonable approximation of the friction factor. The falling tide is dampened this could indicate that the inertia factor is too dominant. The friction combined with the inertia in the system corresponds well with the real lagoon water level.

The models with a channel width of 30 and 60m shows that the width influences the lagoon amplitude, the model results can be seen in Appendix E. The low tide does not fall simultaneous with the real lagoon water level. A wider width gives a better prediction of the high tide, but gives a lower lagoon water level at the troughs. The modelled lagoon water level never exceeds the tidal water level (yellow).

Concluded from the basic model outcomes, this model gives an underestimation of the real lagoon water level. The underestimation for a channel width of 50m is shown in Figure 5-5. The river discharge does not have much influence in the model. The underestimation of the model indicates that the basic energy equation misses a process working on the inlet. Presumable the wave forcing has to be included in the model. The next section takes the wave forcing into account.
5. Modelling of the lagoon water level

5.3. Extended energy model

The basic energy equation shows an overall underestimation of the lagoon water level. Therefore the extended energy formula is conceived. Chapter 4 describes a second force which elevates the lagoon water level, namely the waves. The waves are assumed to approach the shore in shore-normal direction. The shore-normal wave forcing is quantified by means of a wave overwash discharge.

Different formulas are described to calculate an overwash discharge as a function of the wave height and other parameters. Thuy (2013) considered several wave overwash formulas. The wave pump efficiency was the most applicable for natural inlets following her study. The wave pump efficiency formula, after Bruun and Viggosson (1977), is explained in Section 5.3.1.

The extended energy formula has as origin the basic energy equation. The velocity is positive in landward direction. Adjoining with the river discharge, the wave overwash discharge is adjusted in the model. The velocity is adjusted from Equation 5-2 and can be re-written as;

\[ \langle u \rangle = \frac{A_b}{A_c} \frac{d \eta_b}{dt} - \left( \frac{Q_f}{A_b} + \frac{Q_{\text{over}}}{A_b} \right) \]

Equation 5-7: The extended velocity formula, after Thuy (2013).

Then the basic energy equation can be written as;

\[ \eta_b = \eta_o - \frac{L_c}{g A_c} \left( A_b \frac{d^2 \eta_b}{dt^2} - \frac{d Q_f}{dt} - \frac{d Q_{\text{over}}}{dt} \right) - \frac{F}{2 g} \left( \frac{A_b}{A_c} \right)^2 \left( \frac{d \eta_b}{dt} - \left( \frac{Q_f}{A_b} + \frac{Q_{\text{over}}}{A_b} \right) \right) \left( \frac{d \eta_b}{dt} - \left( \frac{Q_f}{A_b} + \frac{Q_{\text{over}}}{A_b} \right) \right) \]

Equation 5-8: The extended energy equation, after Thuy (2013).

Where the friction term \( F \);

\[ F = \left[ k_{\text{ent}} + k_{\text{ex}} + \frac{f L_c}{4 R_c} \right] \]

Equation 5-9: The friction term.
5. Modelling of the lagoon water level

5.3.1. Wave overwash discharge

Wave overwash occurs when high waves arrive at the berm and inlet entrance. The high waves are likely to overtop the berm crest. This will result in a discharge over the crest of the berm, see Figure 5-6. The water which flows over the berm gives an elevation of lagoon water level. Different researchers developed empirical formulas to calculate wave overwash. Most of the formulas are established to calculate overtopping and overwash at breakwaters and dikes.

![Schematisation of wave overwash discharge, after Laudier, Thornton, and MacMahan (2011).](image)

Thuy (2013) compared 5 formulas including wave pump efficiency after Nielsen, Guard, Callaghan, and Baldock (2008) and the Swash model, after Guard and Baldock (2007) with measurements of wave overwash events at Lake Conjola, NSW, Australia. The wave pump efficiency and the swash model are developed for natural beaches. She concluded that both models are close to the measured data.

The wave pump efficiency model calculated overall somewhat less overwash discharge compared to the Swash model. However the wave pump efficiency model matches better with the tidal range and has better agreement with low tides. Therefore the wave pump efficiency model has been chosen for calculation of the wave overwash discharge. One more preference for using this model is the number of input parameters. The wave pump efficiency model doesn’t require a beach slope, which as far as this study goes hasn’t been measured for the research sites.

The wave pump efficiency formula is formulated as follows;

\[
Q_{\text{over}} = L_{\text{berm}} \varepsilon \frac{E_f}{\rho \Delta h}
\]

Where; \(Q_{\text{over}}\) = the wave overwash discharge [m³/s], \(L_{\text{berm}}\) = the berm stretch per unit length [m], \(\varepsilon\) = the efficiency coefficient [-], \(E_f\) = the wave energy flux [W/m], \(\rho\) = the density of water [kg/m³] and \(\Delta h\) = the lifting height [m].

The principle of this formula is the lifting height \(\Delta h\) at which the water must be pumped over the berm equals the wave energy flux \(E_f\) times an efficiency \(\varepsilon\). The efficiency is obtained from Callaghan, Nielsen, Cartwright, Gourlay, and Baldock (2006). They measured atoll flushing and empirically estimated an efficiency of 0.035 for offshore wave climate. This value is confirmed by Thuy (2013) for natural inlet systems.

The wave energy flux is calculated by offshore wave climate;

\[
E_f = \frac{1}{16} \rho g H_{\text{rms}}^2 \frac{g T_{p1}}{2\pi}
\]

Where; \(H_{\text{rms}}\) = the offshore root mean square wave height and \(T_{p1}\) = the peak period.
The peak period is calculated by spectral analysis. Spectral analysis provides a method to examine the energy level of a range of wave periods. In this way it is possible to determine the period of the waves with the most energy. The former used zero-crossing period is averaged over all the measured wave periods and therefore swell waves can experience a reduction, while those waves carry the most energy. The calculation of the wave overwash uses the energy flux, therefore the peak period is chosen.

Wave energy is proportional to the root-mean-square wave height, which can be calculated from the significant offshore wave height.

Equation 5-12: The root mean square wave height from the offshore significant wave height.

\[ H_{rms} = \frac{1}{2} \sqrt{2} H_o \]

The wave pump efficiency coefficient is determined on the offshore significant wave height, therefore the offshore wave characteristics are chosen.

The lifting height \( \Delta h \) is calculated as a function of the berm height and the tide. At periods of low tide lifting height is higher, than at periods of high tide;

Equation 5-13: The lifting height as function of tide.

\[ \Delta h = \text{crest berm} - \eta_{ocean} \]

Berm height measurements were not carried out for this study. The classification of McSweeney et al. (2014) indicates an average berm height of 0.85m AHD for intermittently open natural inlets. This value is very low for both research sites. Thuy (2013) obtained a berm height of 1.5m AHD from field measurements in 2011 and 2012 for Lake Conjola, NSW. The average berm height at Lake Avoca is taken at 1.5m AHD after breaching as indicated by Thuy (2013).

The berm stretch per unit length of the overwash over the berm is assumed to be 50m at both sides of the inlet entrance. Figure 5-7 shows a former satellite picture with an open inlet entrance at Lake Avoca on 04/07/2013. The former satellite picture of Lake Avoca with an open inlet entrance in Google Earth indicates an inundation width (dark collared beach) for the waves of 100m is convincingly.

Figure 5-7: Wave overwash width of 100m in blue at Lake Avoca, source Google Earth at 04/07/2013.
5. Modelling of the lagoon water level

5.3.2. Results

The wave overwash discharge, shown in Figure 5-8 upper graph, is significant compared to the river discharge shown in the same figure, middle graph. The peaks of the wave overwash fall simultaneously with the elevated lagoon water level, lower graph. The increase of the lagoon water level is seen after 10/06/2011. This falls together with a wave overwash above 10m³/s. The lagoon water level reaches its maximum around 15/06/2011 and the wave overwash reaches its peak of 49m³/s at the same time. It can be said that there is a strong correlation between the waves and the elevation of the lagoon water level. This relation is stronger than the relation between the lagoon water level and the river discharge.

Figure 5-8: The wave overwash discharge, river discharge and lagoon water level, Lake Avoca June 2011.

Figure 5-9 shows the plot of the extended model for a channel width of 50m. The result (blue) shows an overall underestimation compared to the real lagoon water level (red). The results of the extended energy equation for the three different channel widths are given in Appendix E. The extended version of the energy equation gives for all different channel widths a better estimation than the basic energy equation, but there is still and underestimation. The channel depth in this model is calibrated on -0.1m AHD for a channel width of 50m.
In particular, at the beginning of the period the model compared to the data shows a good match. The tidal signal of the model coincides with the tidal signal of the lagoon water level. This implies that the friction and inertia values are an accurate estimation. The peaks of the extended model fall together with the tide.

At the moment that the river discharge and the wave overwash discharge become significant the rising tide in the model gives a good approximation, but the falling tide in the model is lagging behind. While the outgoing tide pushes the water out of the lagoon, the waves forcing is still inward directed. This could give an explanation of the larger gradient of the lagoon water level at ebb.

Around 12/06/2011 the model and the data differ significantly. The wave overwash is relatively low at this moment and the model underestimates reality. Potential cause at this moment is the possibility of a constriction of the entrance channel. The width of the entrance channel is a fixed value in the formula. Constriction of the entrance channel can give higher lagoon water levels when the water flows in and out. Furthermore the depth of the channel will decrease as well and this can also cause an elevated lagoon water level.

Around 15/06/2011 the wave overwash discharge is relatively high, with a maximum of 71 m³/s. Directly after the model shows a lot of fluctuations and doesn't correspond to the real data.

Figure 5-10 indicates an overall underestimation, but there are some modelled points which are the same as the measured data.
5. Modelling of the lagoon water level

The forcing by waves isn’t optimised yet. The model gives an overall underestimation and at the moment of high overwash discharges the model shows a lot of variation compared to the real data. The wave forcing is important for the prediction of the lagoon water level. The next section explains the second introduced model including a newly introduced wave forcing.

5.4. Alternative energy model without inertia

Instead of searching for the forces that increase the lagoon water level, the elevated lagoon water level will be the starting point. It is a fact that the lagoon is elevated above the ocean water level. For simplicity and as conclusion out of chapter 4 and the extended model it is assumed that only the waves are significant during closure processes.

The elevation of the lagoon water level above the ocean water level is obtained from the data and related to the near shore wave height. The basic energy equation is simplified by neglecting the river discharge. The basic energy equation becomes;

\[
\eta_b = \eta_o - \frac{L_c}{g A_c} \left( A_b \frac{d^2 \eta_b}{dt^2} \right) - \frac{F}{2g} \left( \frac{A_b}{A_c} \right)^2 \left| \frac{d\eta_b}{dt} \right| \left( \frac{d\eta_b}{dt} \right)
\]

In many shallow basins, the flow velocity is friction dominated. Therefore the inertia factor is assumed to be very small, because of the relatively short channel length. Inertia develops strongly over a long channel length, for example in the Western Scheldt, the Netherlands.

Equation 5-15 shows the basic energy equation without inertia and river discharge.

\[
\eta_b = \eta_o - \frac{F}{2g} \left( \frac{A_b}{A_c} \right)^2 \left| \frac{d\eta_b}{dt} \right| \left( \frac{d\eta_b}{dt} \right)
\]

This formula doesn’t take any extra inflow in the lagoon into account. The extra elevation of the lagoon is now called \( X_{\text{waves}} \) and added by the ocean water level. The exact definition of \( X_{\text{waves}} \) is given in the next section. In a
5. Modelling of the lagoon water level

The definition of the elevated lagoon water level is given. The extra elevation of the lagoon water level is correlated to the near shore waves. See Appendix H for the derivation of Equation 5-16.

\[ \eta_b = \eta_o + X_{\text{waves}} - F \left( \frac{A_b}{A_c} \right)^2 \left| \frac{d\eta_b}{dt} \right| \left| \frac{d\eta_b}{dt} \right| \]

5.4.1. External forcing which elevates the lagoon water level

The parameter \( X_{\text{waves}} \) is calculated as follows. The gradient of the water level in the lagoon is zero at the moment that the lagoon water level experiences a maximum or minimum. Therefore the velocity and the friction factor are equal to zero.

The peaks in the lagoon water levels are influenced by the tide and the waves. The troughs are dependent on the bottom of the lagoon and the tide. The peaks are the indicated part to estimate the influence of the waves. The formula at the peaks of the lagoon water level, where the friction factor is zero, as shown in Equation 5-17:

\[ \eta_{b,\text{peak}} = \eta_{o,\text{peak}} + X_{\text{waves},\text{peak}} \]

The parameter \( X_{\text{waves}} \) is the difference between the lagoon and the ocean water level. Chapter 4 analysed in total five closure events for Lake Avoca. Four events are used to estimate a function for \( X_{\text{waves}} \). The fifth event is the validation event. This event is described in this chapter, June 2011 event, and can only be used as comparison of the modelled lagoon water level to the real lagoon water level data. If the June 2011 event will be used for the approximation of \( X_{\text{waves}} \), it will influence the outcome of the modelled lagoon water level in a positive way.

Figure 5-11 shows the Lake Avoca July 2010 open entrance state. The blue line shows the lagoon water level and the red line the ocean water level. The peaks of the lagoon water level are indicated and the corresponding ocean water levels are obtained. The difference between the two water levels is calculated and related to the near shore wave height at that specific moment.

The upper graph of Figure 5-11 shows the circular data points at the peaks of the lagoon water level and the corresponding ocean tide. The values near the circles indicate the water level height. The lower graph in Figure 5-11 shows the near shore wave height, the circles are related to the moment of lagoon water level peaks and the value is the near shore wave height at that exact moment. The circles are nearly every 12.25 hours. That corresponds with the semi-diurnal character of the tide. The mean wave height in this period is 1.42m and the mean difference between the lagoon and the ocean water level is 0.23m. Appendix G shows the plots of the other 3 events.
5. Modelling of the lagoon water level

In total 65 lagoon water level peaks are indicated. Figure 5-12 shows the 65 peaks with the corresponding wave height. The blue line is the wave height and the orange line is the elevation of the lagoon above the ocean water level. When the wave height is relatively high, the elevation of the lagoon water level is also higher. The range of the elevation of the lagoon water level is much smaller than the range of the wave heights. Remarkable it the 15th point, the elevation is really high, but the wave height is small. This is due to the fact that a heavy rainfall can have a significant influence on the lagoon water level too. The correlation here is only to the wave heights and not to the rainfall or river discharge. The neglecting of the rainfall in this case can lead to an overestimation of $X_{\text{waves}}$. 

Figure 5-11: The difference between the lagoon and ocean water level, with corresponding significant near shore wave height, Lake Avoca July 2010.

Figure 5-12: Correlation wave height and the elevation of the lagoon water level.
5. Modelling of the lagoon water level

The elevation of the lagoon water level is calculated and related to the estimated near shore wave height. This is done for all four events and plotted in Figure 5-13.

![Figure 5-13: Estimation of X(Waves) with 65 lagoon water level peaks, Lake Avoca.](image)

The regression line through all the points gives the function for \( X_{\text{waves}} \). Equation 5-18 is round off to three decimals. The regression line is forced through the origin, because it is assumed that zero wave height will give zero elevation of the lagoon water level.

Equation 5-18: The empirical function of X(Waves).

\[
\eta_b - \eta_o = X_{\text{waves}} = 0.16 \times H_{\text{sign}}
\]

The mean wave height from all the data points is 1.41m, this corresponds with a difference between the lagoon and ocean water level of 0.23m. This corresponds perfect to the July 2010 event. The regression line indicates that the lagoon water level is 16% of the near shore wave height elevated above the ocean water level. The wave set-up along beach stresses can be approximated 25%-30% of the near shore wave height, as satisfied by Bosboom and Stive (2013) and Nielsen (2009). The obtained formula \( X_{\text{waves}} \) is assumed to be a good approximation for the elevation of the lagoon water level by wave forcing.

5.4.2. Results

The alternative model gives the following result, see Figure 5-14. The overall result is an overestimation at high tide of the real lagoon water level. The channel depth is calibrated on -0.3m AHD. This calibration indicates the minimum channel depth for the model, so that the troughs of the model fall simultaneously with the data.

Noteworthy the perfect response of ebb and flood, especially before 11/06/2011, where the wave height is low and there is no significant rainfall. The low-high tide corresponds perfect with the lagoon water level.

As soon as the river discharge starts at 12/06/2011 the model gives an underestimation of the low tide. At the moment of high waves, around 14/06/2011, the modelled low tide corresponds better with the real data. This could indicate that the rainfall should be taken into account separately and not integrated in \( X_{\text{waves}} \).
5. Modelling of the lagoon water level

The peaks and throughs fall more simultaneously than the extended model. This indicates that the friction factor gives better estimation than in the previous model. Although the friction factor can still be assumed to be too high as the peaks are higher and the falling tide is longer and steeper.

This model neglected inertia in first instance, to simplify the model and to calculate the effect of the wave forcing. From this model it can be assumed that the inertia is an important factor, although the channel is short. There is a small lag between the model and data line during ebb. This lag increases when the wave forcing increases.

![Figure 5-14: Alternative energy equation without inertia, channel width 50m, Lake Avoca June 2011.](image)

The overestimation at the peaks has probably to do with the empirical formulation of $X_{(waves)}$. The conclusions of chapter 4 indicated that rainfall events regularly occur together with high waves. The elevation of the lagoon water level is then a combination of rainfall and wave forcing. Taking this into account $X_{(waves)}$ is overestimated.

The estimation of $X_{(waves)}$ is calculated at the peaks of the lagoon water level. The modelled line traverses at the peaks of the lagoon water level. The overestimation is mainly just before the peak of the data. So $X_{(waves)}$ gives an overestimation between the moment of the peak of the ocean water level and the peak of the lagoon water level. When the ocean water level peaks, the high waves penetrate the entrance further inside than when the ocean water level experiences falling tide. Therefore it is assumed that $X_{(waves)}$ experiences a delay at the peaks of the ocean tide. The velocities in the ocean are already offshore directed. The waves are further from the entrance than when there is flood. When the lagoon water level catches up with the ocean water level it peaks, but then elevates. Therefore it can be assumed that the waves have an overestimated impact at the peaks of the ocean water level, than at the ebb in the ocean. So, $X_{(waves)}$ is overestimated due to a delay from flood to ebb.
The presumable constriction of the channel just before closure could still be an important parameter. At 12/06/2011 the modelled lagoon water level doesn't show a correlation with the data. It can be assumed that the elevation has also to do with the constriction of the entrance channel. Around 16/06/2011 the ebb tide is elevated has a better approximation of the high wave forcing than the extended model. Figure 5-1 shows that around this period the wave direction is nearly shore-normal.

Figure 5-15 indicated the modelled lagoon water level compared to the measured data and visualizes the over and underestimation of the model. The lower lagoon water levels correspond well with the measured data, but the high water levels are widely spread.

![Figure 5-15: Comparison of the alternative model with the measured data.](image)

5.5. Verification

The models are verified with an event at the second research site, namely Cockrone Lagoon. The event is from 26/02/2012 until 17/03/2012, as shown in Figure 5-16. The whole event from opening towards closure is extensively explained in Section 4.5.3. The start date for the modelled period is chosen when there is no significant river discharge and there are low waves.

The period starts with no rainfall and low waves. The lagoon water level reaches until -0.12 m AHD at ebb tide. The tidal response of the lagoon water level falls simultaneously with the ocean water level. Around 01/03, the wave height increases and the rainfall starts, the lagoon water level is elevated. The near shore wave height at that period is around 2m. After 09/03 there is no rainfall and the wave height drops from the maximum of 3.5m to 1m. Around 13/03 the wave direction reverses from direction, this is three days before closure. The inlet closes around 16/03. The basic, extended and alternative models are used to calculate the lagoon water level.
5. Modelling of the lagoon water level

The river discharge is calculated with a run-off coefficient of 0.27 and a delay of 8 hours. The delay of the system is adopted from the calculations for Lake Avoca and the estimation of the run-off coefficient by Roper et al. (2011). The run-off coefficient for the year 2007 is estimated at 0.23. Due to comparison with Lake Avoca run-off coefficient for Cockrone Lagoon is chosen on 0.27.

The berm height for the wave overwash discharge is chosen on 1.5m. Although the trigger level and the maintained berm height are higher, the lagoon water level height directly after closure is around the same height as Lake Avoca. Therefore the same berm height has been chosen. Over this period, the maximum wave overwash discharge is $56m^3/s$.

Both, the calculated river discharge and the calculated wave overwash discharge can be found in Appendix H.

The channel depth for the models are calibrated on -0.4m AHD for the basic and the extended models and -0.5m AHD for the alternative model. The channel length is kept the same, 300m. The models are carried out for the widths of 30, 50 and 60m.

The outcomes for the different models for a channels width of 50m are presented in Figure 5-17. The visualised periods are slightly shorter than the period shown in Figure 5-16, this is because of the comparison shown in Figure 5-18. The period when the inlet is closed is not taken into account at the comparison, as it doesn't give an accurate estimation.
5. Modelling of the lagoon water level

As expected the basic model will present the least accurate fit and the alternative model the most accurate fit. All three models perform better under low wave forcing and no rainfall. The channel depth is calibrated at the first lowest point in the measured data.

Figure 5-18 shows the model output against the measured data. The basic and the extended model give both an overall underestimation and the alternative model gives an over and underestimation. The lower lagoon water level heights have a better fit than the higher heights. The high tide is more complicated to simulate than the low tide. The alternative model has a wider spread, but more modelled points agree upon the measured data.
5. Modelling of the lagoon water level

Hereby, the three models are proofed to perform accurate for a different event at the research site Cockrone Lagoon.
5. Modelling of the lagoon water level

5.6. Model performance

The two newly introduced models are compared to the basic energy equation. In order to give a quantitative comparison of the two “new” models to the basic model, the Brier Skill Score (BSS) is introduced. This assessment tool to quantify the model performance is obtained from van Rijn et al. (2003)

Equation 5-19: The Brier Skill Score (BSS), after van Rijn et al. (2003).

\[
BSS = 1 - \frac{\sqrt{\sum (d_{new} - d_{measured})^2}}{\sqrt{\sum (d_{basic} - d_{measured})^2}}
\]

Where; \(d_{new}\) = the new model output, \(d_{measured}\) = the real (measured) data and \(d_{basic}\) = the basic model output (in this case the lagoon water level in [m]).

The outcome of the BSS can have a value of:

- 0; the new model is as good as the basic model
- Between 1 and 0; the new model is better than the basic model, closer to one is an increase in performance
- < 0; the new model is worse than the basic model
- > 1; not possible

Figure 5-19 recalls the three models, only for the period that the entrance is open. The closed inlet entrance is taken out of the period to make a good comparison of the performance of the three models. The red graph is the measured lagoon water level and the blue graph is the model. The modelled lagoon water level is taken for a channel width of 50m.

![Figure 5-19: The three models, basic, extended and alternative compared to each other for a width of 50m.](image-url)
5. Modelling of the lagoon water level

The BSS for the extended and alternative models are shown in Table 5-2. The scores are calculated for the both events, Lake Avoca June 2011 and Cockrone Lagoon March 2012.

<table>
<thead>
<tr>
<th>Model</th>
<th>Lake Avoca</th>
<th>Cockrone Lagoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended model</td>
<td>0.486</td>
<td>0.176</td>
</tr>
<tr>
<td>Alternative model</td>
<td>0.627</td>
<td>0.317</td>
</tr>
</tbody>
</table>

Table 5-2: The Brier Skill Score for the extended and alternative model, compared to the basic model, for events at Lake Avoca and Cockrone Lagoon.

From this it can be said that the alternative model performs better than the extended model relative to the basic model.

5.7. Discussion

This study shows that both models, the extended and the alternative model, predict the elevation of the lagoon water level fairly well, although the elevation is underestimated in the former and overestimated in the latter. In this section two discussion points are defined.

1. Elevation of lagoon water level by wave set-up.
2. Elevation of the lagoon water level by wave overwash discharge.

Firstly, wave set-up is the increase of the mean water level due to the presence of waves. Waves approaching a beach provide a wave set-up at the fore shore. The wave set-up will increase the mean water level. This phenomenon can give an increase on the lagoon water level.

Gordon (1990) measured the effect of wave set-up as lifting force of the lagoon water level. He recognises that the wave set-up initially produces a net inflow of water and sediment into the lagoon. On the falling stage this can result in an extra scouring of the inlet entrance as the lagoon water level and the wave heights return to normal. More water flows out then in the next flood flows in. From this it can be said that an elevation of the lagoon water level will scour the inlet. This is contradicting with the outcome of the inlet data analysis, the inlet tends to close after a significant elevation of the lagoon water level.

Hanslow and Nielsen (1992) measured wave set-up at a NSW trained river inlet entrances and concluded that there is no significant elevation due to the wave set-up. This finding is also satisfied by You, Nielsen, Hanslow, and Pritchard (2012). Trained river inlets are always open and are not able to close or decrease in width. Therefore it is not knows whether the wave set-up can have a significant influence on the intermittently open natural inlets.

Secondly, the wave overwash is assumed to give a significant discharge into the lagoon. This is observed at Lake Conjola, NSW, by Thuy (2013) and Patterson (1999). The wave overwash occurs during a severe storm, where the high waves coupled with aeolian forcing overtop the entrance berm and gives a significant discharge of sediment into the lagoon. The sediment is coming from the entrance berm.

During this study it is assumed that the wave overwash doesn’t influence the lagoon water level when the inlet is in a closed connection with the ocean. The berm is much higher when the entrance is closed then when the inlet entrance is in an open connection. This is due to the fact that the berm building continues after closure by wave and wind forcing. At the moment of breaching, the lagoon water will flow over a wider width of the entrance berm out of the inlet. After breaching when the first flood comes in, the ocean water will flow over a smaller part of the former berm, now called the side of the inlet channel. The sides of the channel are lower than when the inlet was closed. The overwash occurs at the sides of the inlet channel.

Several examples of a closed and one open entrance in interaction with the influence of high waves and significant rainfall are visualised in Appendix I. The assumption that the high waves don’t overtop the entrance berm during a closed entrance is satisfied.
The next example satisfies the assumption that a closed inlet entrance isn’t influenced by the high waves. Figure 5-20 shows that only the rainfall around 09/09/2011 has a significant influence on the lagoon water level. The high waves occurring around 10/09 until 13/09/2011 doesn’t show any elevation of the lagoon water level in the signal. The Google Earth aerial photo, Figure 5-21, is taken on 13/09/2011 and shows a closed inlet entrance. The waves are decreasing at that moment. The aerial photo shows clearly the inundation width over the beach by the dark coloured sand. The dark sand reaches until the lagoon, although at the same moment the lagoon water level data doesn’t show any elevation. Therefore it can be correctly assumed that the waves don’t have influence on the lagoon water level while the inlet is closed. See Appendix I for more examples.

Figure 5-20: Rainfall vs waves affecting the lagoon water level, Lake Avoca, Sept 2011.

Figure 5-21 shows a closed inlet entrance on 13/09/2011, obtained from Google Earth. The yellow line is an indication of 100m distance.
The question arises now whether the wave overwash discharge influences the lagoon water level while the entrance is open is still debatable. The extended model with an overwash width of 100m has still an underestimation. The alternative model which takes the wave forcing as an elevation gives a better estimation.

5.8. Conclusions

The extended and alternative analytical models, give both a good first prediction of the lagoon water level. The forcing by waves is significant and is concluded by means of both models. The first model gives an overall underestimation, while the second model gives an overall overestimation. Concluded, the best performance of the prediction of the lagoon water level is the alternative model.

The other conclusion concerns the cross-sectional area of the channel. It is indicated by both models that the cross-sectional area of the channel is a sensitive parameter. Especially the width of the channel can change significantly just before closure. Therefore, the hydraulic radius in the energy equation is important.

Within the hydraulic radius the channel depth is defined. During the period of closure the depth will decrease as well. This could indicate the constriction of the channel with respect to time. Probably, a relation could be described between the wave height and the hydraulic radius of the geometry of the inlet. This constriction of the channel can also have an effect on the elevation of the lagoon water level.
The last chapter of this thesis presents conclusions regarding the objective and the research questions. Recommendations for further research have been indicated in the last section.

6.1. Conclusions

In this study the hydraulic forcing on two intermittently open natural inlets are indicated. The overall objective has as goal to contribute to the wave-dominated classification parameter, with this study only two intermittently open natural inlets are studied. Therefore the contribution to the parameter is limited and it is suggested to apply this type of study to different intermittently open natural inlets around the world. Based on this study only, it is suggested to adopt the near shore wave height, rather than the offshore wave height in the parameter. More research could confirm this suggestion.

The whole period from opening until closure of two New South Wales, Australia, intermittently open natural inlets are analysed by means of wave climate, rainfall, ocean tide and lagoon water level data. The important parameters during these processes are indicated. One of the main conclusions is the importance of understanding the lagoon water level behaviour. This understanding indicates the interactions of the main forces on the inlet. The specific objective of this research is:

*To predict the lagoon water level behaviour of intermittently open natural inlets forced by waves, tide and river discharge.*

By means of analytical modelling, the lagoon water level is simulated to indicate the dominant forcing during an open entrance state until closure. The performance of the alternative model is the best for predicting the lagoon water level.

To support the objective four research questions have been formulated. The research questions are recalled from chapter 1 and answered below. After the fourth research question some general conclusions.

**RQ1: What is the state-of-the-art knowledge for behaviour of natural inlet entrances?**

The behaviour of inlet entrances can be described in four stages;

**Opening stage**

The behaviour of the opening of a natural inlet entrance can be described in two ways. Firstly, a natural breach by means of a significant hydraulic head over the entrance berm. The hydraulic head is a result of a relatively high lagoon water level due to rainfall and a low ocean water level, e.g. during low water spring tide. Secondly, a manual breach by using an excavator when a defined trigger lagoon water level is reached. This trigger level is determined by the city council of the tidal inlet system, to prevent flooding of the lagoon shores.

The processes that increase the opening are the rise in the lagoon level in combination with a relatively low ocean water level, resulting in a large hydraulic head. The lagoon water level increases due to two forces. The first force is the rainfall; the rainfall gives a significant river discharge and elevates the lagoon water level. The second force is the wave overwash discharge, which gives a significant inflow over the entrance berm and elevates the lagoon water level.
6. Conclusions and Recommendations

**Open inlet stage**
The tide dominates the lagoon water level when the entrance is in an open stage. Besides the tide the waves and river discharge can give an elevation in lagoon water level.

**Closing stage**
The closing stage is the most difficult behaviour of the four stages. Two forces can cause closure of the inlet entrance. The two forces are waves and tide. The waves force the entrance to closure in two ways, namely via cross-shore and alongshore sediment transport. The tidal forces close an inlet entrance due to berm building during a neap/spring tidal cycle, this in combination with wave forcing. When the incoming tide is stronger than the outgoing tide the inlet can experience a flood dominance tidal asymmetry and this will force an import of sediment and close the inlet entrance.

**Closed inlet stage**
The closed inlet behaviour is the simplest of the four stages. The inflow of water by river discharge or at stormy conditions of wave overwash gives an elevation of the lagoon water level. The entrance berm will be strengthened by tide, waves and aeolian sediment transport.

**RQ2: How do waves, tide, rainfall and the lagoon water level behave in the period of an open inlet entrance?**
The waves, tide, rainfall and lagoon water level behaviour are described for an open inlet entrance by the plots in chapter 4. The period covers an opening stage, open inlet stage and closing stage. The waves, tide and rainfall forcing are described individually.

The lagoon water level responds to the behaviour of the three forces. Noteworthy heavy rainfall is often accompanied by high waves. Other correlations are not found between the three main forces.

Based on the data analysis it can be concluded that the lagoon water level can give a good indication of the forces working on the natural inlet and also indicates whether an inlet is likely to close. This can be indicated by the elevation of the lagoon water level and the decrease of tidal amplitude in the lagoon.

**RQ3: What are the dominant forces during closure events regarding the behaviour of the lagoon water level?**
Chapter 4 gives an analysis of in total nine closure events. The lagoon water level is assumed to give indications of the entrance state. The dominant forcing which are indicated by the behaviour of the lagoon water level are the rainfall and the wave forcing. The wave forcing is frequently dominantly high in the period before closure and mostly combined with heavy rainfall.

Noteworthy is the elevation of the lagoon water level just before closure, which can be correlated to the high waves and heavy rainfall. The incident wave direction in this period is on average <15°. Therefore is assumed that the cross-shore waves are dominant during closure. Consistently, the inlet closure happens at high tide. Closures typically occur during spring high tide, because the gradient between the lagoon and the ocean water level is smaller than at neap high tide. The wave forcing has a stronger influence and penetrates further into the entrance.

**RQ4: In which way do the dominant forces influence inlet closure?**
The dominant forces influence the inlet closure by sediment import. The waves have a large influence on the lagoon water level and therefore on the inlet. The elevation of the lagoon water level just before closure indicates that the sediment import occurs by the elevation force of the waves. The last high tide transports the sediment available into the inlet entrance. The river discharge forcing is small compared by the sediment import. According to the alternative model the lagoon water level has a relation with the near shore wave height, this model is an elegant way to formulate the wave influence on the lagoon water level. The lagoon water level indicates the entrance state of the inlet.
The conclusions above can be applied to the New South Wales intermittently open natural inlet with fast opening and closure cycles, no rocky outcrops at the inlet entrance and beach stretches at both sides of the inlet entrance. Other characteristics are defined in chapter 3.

Further conclusions which have been made from this study are listed below;

**Based on the findings of the literature review**
During closure procedures the wave height can have stormy characteristics. The tide in the ocean has a spring and neap tidal cycle and is independent from the wave height in the ocean. The water flowing in and out during a tidal cycle (tidal prism) can be different during high wave events.

Tidal prism calculated on basis of only the tide is not enough for small tidal inlets which have an elevation of lagoon water level forced by waves. The elevation gives a greater inflow and outflow than only the tidal prism. Therefore it can be indicated for intermittently open natural inlets that the theories regarding the tidal prism as for example Bruun (1968), could be specifically optimised.

**Based on the findings during the modelling**
The inlet channel geometry is very important. By means of varying channel widths in the modelling stage the significance of the channel geometry can be seen. The hydraulic radius in the energy equation is strongly influenced by the channel geometry.

### 6.2. Recommendations for further research
After this study a lot of new questions arise from the results and conclusions. The recommendations are divided in a field work study, Thuy (2013) classification and further modelling.

**Field work study:**
The first recommendation is an extensive field work at, for example, Lake Avoca inlet. This field work should be carried out from the moment of an opening event until the closure of the entrance again. It is recommended to measure the following data; the near shore wave height, the wave overwash discharge at several points over the entrance berm, the channel geometry at several moments, inlet currents and wave set-up at the inlet entrance and adjacent beach.

Another recommendation is the use of a drone during different stages of the inlet entrance. The Google Earth satellite pictures gave already a clarifying illustration of the geometry of the tidal inlet system. A drone can make overview pictures or movies of the development of the inlet entrance, this could be intensively documented and analysed and give more insight about entrance geometry.

For verification of the approximation of the river discharge it is suggested to measure the river discharge, for example Saltwater creek, when the inlet is in a closed stage and compare with the rainfall data. It is also recommended to measure the influence of the rainfall/river discharge on the inlet entrance. Which rainfall intensity develops a significant river discharge force to keep the inlet entrance open?

Measurements of the wave climate near the inlet entrance will give important information about the incident wave angle and the force which will elevate the lagoon water level. Give high waves immediately an elevation to the lagoon water level? The waves in combination with the tidal cycle is also very important to document.
6. Conclusions and Recommendations

*Thuy (2013) classification:*

For the classification it is recommended to research other intermittently open natural inlets. For example, intermittently open natural inlets with a dominantly obliquely incident wave angle. It is suggested that the incident wave angle and entrance facing direction would give a good indication of the differences of the subclasses. Nevertheless, the near shore wave height is suggested to be very important for the classification.

*Further modelling:*

A start has been made for the modelling of the lagoon water level. To optimise the modelling, three recommendations for further modelling will be explained. Firstly, take a closer look at the wave set-up and their influence on an open inlet entrance. Different formulas for wave set-up as an extension of the basic model can give better estimations. The wave set-up could give a clarification for the elevation.

Secondly, it is recommended to do more and precise sensitivity analyses of different cross-sectional areas. There could be a relation between the wave height and the hydraulic radius of the inlet. In this study there hasn’t been any reliable documentation found of the entrance channel geometry during open and closed inlet stages. Furthermore a implementation of the Escoffier curve, after Escoffier (1977), could give an indication of the entrance geometry just before closure and during closure.

Thirdly, a sensitivity analysis of wave height combined with the tidal cycle. Low waves with a neap/spring cycle and high wave with the same neap/spring cycle and the effect on the lagoon water level on these analyse. Does the tide influence the elevation of the lagoon water level, the waves or both?
References


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Patterson, B. P. (1999). Lake Conjola Entrance Study (pp. 224). North Sydney.


The raw data over the studied period is presented in this Appendix. The location of the measured data is indicated. The data contains:

- Lagoon water level data at Avoca Lagoon.
- Lagoon water level data at Cockrone Lake.
- Daily rainfall data at Kincumber.

The data is over a period of July 2009 until June 2013 for the lagoon water levels and from July 2010 until June 2013 for the rainfall data. The rainfall data is over a shorter period, because the entrances of both research sites stay closed over the period of July 2009- June 2010. The rainfall data is only important just before opening and during closure.
Figure A-1: Lagoon water level Avoca Lagoon, July 2009- June 2010.
Figure A-2: Lagoon water level, Avoca Lagoon, July 2010- June 2011.
Figure A-3: Lagoon water level, Avoca Lagoon, July 2011- June 2012.
Figure A-4: Lagoon water level, Avoca Lagoon, July 2012 - June 2013.
Figure A-5: Lagoon water level, Cockrone Lake, July 2009- June 2010.
Figure A-6: Lagoon water level, Cockrone Lake, July 2010- June 2011.
Figure A-7: Lagoon water level, Cockrone Lake, July 2011- June 2012.

WATER LEVEL REFERENCED TO AUSTRALIAN HEIGHT DATUM

DATA LOSS
Figure A-8: Lagoon water level, Cockrone Lake, July 2012- June 2013.
Figure A-9: Rainfall, Kincumber at Doyle Street, July 2010- June 2011.

----- DATA LOSS -----
Figure A-10: Rainfall, Kincumber at Doyle street, July 2011- June 2012.
Figure A-11: Rainfall, Kincumber at Doyle street, July 2012- June 2013.
In this study, the tide gauge from Sydney is used. Whether this assumption is accurate enough will be explained in this Appendix.

Tidal records are taken from four gauges around the research sites. The four stations are: Sydney, Tomaree, Crowdy Head and Jervis Bay. The locations of the gauges are found in Section 3.5: Data Summery. Figure B-1 shows the four tide gauges. The distances are described in km from the Sydney tide gauge. The vertical axis is the height in m AHD and the horizontal axis is taken over a period of 10/11/2013 until 11/11/2013.

Jervis Bay deviate significant from the other three gauges, this is because the gauge is located within the shelter of a harbour and gives a manipulated signal. Crowdy Head, Sydney and Tomaree give similar responses of the ocean tide.

![Figure B-1: Tide at four stations, Sydney, Crowdy Head, Tomarree and Jervis Bay, 10/11/2013 until 11/11/2013.](image)

The stations Sydney and Tomarree are the tide gauges nearest to the research sites. The Sydney gauge about 50km south from the research sites and Tomarree about 80km north of the research sites. The data is smoothened to indicate the peaks of the tide. The peaks fall nearly simultaneously, the delay between the two signals is significant small. The difference in height is small and both signal are alternately higher or lower than the other signal. Figure B-2 shows the signal for Sydney and Tomaree for 5 tidal cycles. Figure B-3 shows the two gauges over a period of one day. It can be seen that the delay as well as the difference in height are both significant small.
Figure B-2: Tide gauges Sydney and Tomaree, raw and smoothened, 10/11/2013 until 13/11/2013.

Figure B-3: Tide gauge Sydney and Tomaree, raw and smoothened, 10/11/2013 until 11/11/2013.
The nine events described in Chapter 4 are supported by offshore wave climate plots. This Appendix shows the plots.

Figure C-1: Lake Avoca event July 2010; Offshore wave climate, wave height, wave direction, wave period.
Figure C-2: Lake Avoca event November 2010; Offshore wave climate, wave height, wave direction, wave period.

Figure C-3: Lake Avoca event June 2011; Offshore wave climate, wave height, wave direction, wave period.
Figure C-4: Lake Avoca event February 2013; Offshore wave climate, wave height, wave direction, wave period.

Figure C-5: Lake Avoca event March 2013; Offshore wave climate, wave height, wave direction, wave period.
Appendix C

Figure C-6: Cockrone Lagoon event August 2010; Offshore wave climate, wave height, wave direction, wave period.

Figure C-7: Cockrone Lagoon event June 2011; Offshore wave climate, wave height, wave direction, wave period.
Figure C-8: Cockrone Lagoon event March 2012; Offshore wave climate, wave height, wave direction, wave period.

Figure C-9: Cockrone Lagoon event April 2013; Offshore wave climate, wave height, wave direction, wave period.
Appendix D

The methodology of the calculation of the river discharge can be found in Section 5.2.1. This Appendix gives the derivation of the rainfall to river discharge formula and the outcomes of the calculations. An overview of the outcomes can be found in Section 5.2.1. Recall; $T =$ the delay of the system and $r =$ run-off coefficient.

**Equation D-1:** The rainfall to river discharge starting formula.

$$ T \frac{\delta Q_f}{\delta t} + Q_f = A_c R(t) r $$

**Equation D-2:** The derivation of the rainfall to river discharge starting formula.

$$ T \frac{Q_f(t) - Q_f(t - \delta t)}{\delta t} + Q_f(t) = A_c R(t) r $$

$$ T \frac{Q_f(t) - T Q_f(t - \delta t)}{\delta t} + Q_f(t) = A_c R(t) r $$

$$ (\frac{T}{\delta t} + 1) Q_f(t) - \frac{T}{\delta t} Q_f(t - \delta t) = A_c R(t) r $$

$$ Q_f(t) = \frac{T}{\delta t} \frac{Q_f(t - \delta t)}{1 + \frac{T}{\delta t} + 1} + \frac{A_c R(t) r}{T} $$

**Equation D-3:** The simplification due to a small $\delta t$.

Where, with $\frac{\delta t}{T} = \text{small}$

$$ \frac{T}{\delta t} + 1 = \frac{T}{T} \frac{\delta t}{T} = \frac{1 + \frac{T}{\delta t} \approx 1 - \frac{\delta t}{T}}{1 + \frac{T}{\delta t}} $$

And, when $T$ is big and $\delta t$ is small

$$ \frac{1}{\frac{T}{\delta t} + 1} \approx \frac{\delta t}{T} $$

**Equation D-4:** The rainfall to river discharge formula.

$$ Q_f(t) = \left(1 - \frac{\delta t}{T}\right) Q_f(t - \delta t) + \frac{\delta t}{T} A_c R(t) r $$

The graphs on the following pages are the outcomes of the formula for a bay area times 1 and times 1.3. For the conclusions from these graphs see Section 5.2.1. The plotted rainfall in the bars is times the run-off coefficient.
Figure D-1: Lake Avoca Oct/Nov 2009, bay area times 1.

Figure D-2: Lake Avoca Oct/Nov 2009, bay area times 1.3.
Figure D-3: Lake Avoca May/June 2010, bay area times 1.

Figure D-4: Lake Avoca May/June 2010, bay area times 1.3.
Figure D-5: Lake Avoca, Nov 2010, bay area times 1.

Figure D-6: Lake Avoca Nov 2010, bay area times 1.3.
Figure D-7: Lake Avoca, March 2011, bay area times 1.

Figure D-8: Lake Avoca, March 2011, bay area times 1.3.
Figure D-9: Lake Avoca, April 2012, bay area times 1.

Figure D-10: Lake Avoca April 2012, bay area times 1.3.
Figure D-11: Lake Avoca, April 2013, bay area times 1.

Figure D-12: Lake Avoca, April 2013, bay area times 1.3.
Appendix E

In this Appendix plots of the basic, extended and alternative model for the widths 30 and 60m.

Basic model

Figure E-1: Basic model Lake Avoca June 2011, channel width 30m.

Figure E-2: Basic model Lake Avoca June 2011, channel width 60m.
Figure E-3: Extended model Lake Avoca June 2011, channel width 30m.

Figure E-4: Extended model Lake Avoca June 2011, channel width 60m.
Appendix E

**Alternative model**

Figure E-5: Alternative model Lake Avoca June 2011, channel width 30m.

Figure E-6: Alternative model Lake Avoca June 2011, channel width 60m.
The modelled period has been shortened, so only the period of an tidal response is compared.

All three models together 30m width.

![Figure E-7: Basic, Extended and Alternative model Lake Avoca June 2011, channel width 30m.](image)

All three models together 60m width.

![Figure E-8: Basic, Extended and Alternative model Lake Avoca June 2011, channel width 60m.](image)
Appendix F

Section 5.4. explains the methodology for the alternative model. This Appendix shows the derivation of the Alternative model from the Basic energy equation.

**Equation F-1: The basic energy equation.**

\[
\eta_o = \eta_b + \frac{L_c \, d\langle u \rangle}{g \, dt} + F \frac{1}{2g} \langle u \rangle \langle u \rangle \\
\langle u \rangle = \frac{A_b}{A_c} \, \frac{d\eta_b}{dt} \left[ Q_f + \frac{Q_{over}}{A_b} \right] \\
F = \left[ k_{ent} + k_{ex} + \frac{f L_c}{4R} \right] \text{with } f = \frac{8k^2}{\left( \ln \frac{12R}{k_s} \right)^2}
\]

Due to the short channel length the inertia term can be neglected. The friction is merged to shorten the equation. The extra elevation term \( X_{(waves)} \) is included. Read Section 5.4.1 for explanation of \( X_{(waves)} \).

**Equation F-2: The alternative energy equation without inertia.**

\[
T = \frac{F}{2g} \left( \frac{A_b}{A_c} \right)^2 \\
\eta_b = \eta_o + X_{(waves)} - T \left[ \frac{d\eta_b}{dt} \right] \frac{d\eta_b}{dt}
\]

Intermezzo:

The water level in the bay is sinusoidal, as seen in the lagoon water level records of an open entrance, therefore the lagoon water level can be described as, and the derivative as:

**Equation F-3: The sinusoidal formulation of the lagoon water level.**

\[
\eta_b = -a_b \cos \omega t \\
\frac{d\eta_b}{dt} = \omega a_b \sin \omega t
\]

Where (Fourier expansion);

**Equation F-4: The Fourier expansion of the formulation of the lagoon water level.**

\[
\left| \frac{d\eta_b}{dt} \right| \frac{d\eta_b}{dt} = (\omega a_b)^2 | \sin \omega t | \sin \omega t \approx \omega a_b \frac{8}{3\pi} \omega a_b \sin \omega t = \omega a_b \frac{8}{3\pi} \frac{d\eta_b}{dt}
\]

With bay amplitude (Hilbert transformation);

**Equation F-5: The Hilbert transformation for the amplitude in the lagoon.**
\[ \alpha_b = \sqrt{\eta_b^2(t - dt) + \left(\frac{1}{\omega} \eta_b(t - dt) - \eta_b(t - 2dt)\right)^2} \]

The Fourier expansion is combined with the alternative energy equation and simplified.

**Equation F-6: Derivation of the Alternative energy equation.**

\[ T\left[\frac{d\eta_b}{dt}\right] + \eta_b = \eta_o + X_{(waves)} \]

\[ T\omega a_b \frac{8}{3\pi} \frac{d\eta_b}{dt} + \eta_b = \eta_o + X_{(waves)} \]

Where;

\[ T_1 = T\omega a_b \frac{8}{3\pi} \]

So, similar to rainfall to river discharge, explained in Appendix D;

\[ T_1 \frac{d\eta_b}{dt} + \eta_b = \eta_o + X_{(waves)} \]

\[ \frac{T_1}{dt} \eta_b(t) - T_1 \eta_b(t - \delta t) dt + \eta_b(t) = \eta_o(t) + X_{(waves)}(t) \]

\[ \frac{T_1}{dt} \eta_b(t) - T_1 \eta_b(t - \delta t) dt = \eta_o(t) + X_{(waves)}(t) \]

\[ \left(\frac{T_1}{dt} + 1\right) \eta_b(t) - \frac{T_1}{dt} \eta_b(t - \delta t) = \eta_o(t) + X_{(waves)}(t) \]

\[ \left(\frac{T_1}{dt} + 1\right) \eta_b(t) - \frac{T_1}{dt} \eta_b(t - \delta t) = \eta_o(t) + X_{(waves)}(t) \]

Define the lagoon water level \( \eta_b \):

**Equation F-7: The alternative equation.**

\[ \eta_b(t) = \frac{T_1}{dt} \eta_b(t - dt) + \frac{1}{\frac{T_1}{dt} + 1} \left(\eta_o + X_{(waves)}\right) \]

Where, has small time steps \( dt \), so \( \frac{dt}{T_1} \) is small;

\[ \frac{T_1}{dt} + 1 = \frac{T_1}{dt} * \frac{dt}{\frac{T_1}{dt} + 1} = \frac{1}{1 + \frac{dt}{T_1}} \approx 1 - \frac{dt}{T_1} \]

And, when \( T_1 \) is big and \( dt \) is small, so;

\[ \frac{1}{\frac{T_1}{dt} + 1} \approx \frac{dt}{T_1} \]
Eventually in MATLAB;

\[ \eta_b(t) = \left( 1 - \frac{dt}{T_1} \right) \eta_b(t - dt) + \frac{dt}{T_1} \left( \eta_0 + X_{waves} \right) \]

\[ T_1 = T \omega a_b \frac{8}{3\pi}, \text{ is in seconds} \]

\[ a_b = \sqrt{\eta_b^2(t - dt) + \left( \frac{1}{\omega} \frac{\eta_b(t - dt) - \eta_b(t - 2dt)}{dt} \right)^2} \]

\[ T = \frac{F}{2g} \left( \frac{A_b}{A_c} \right)^2 \]

\[ F = \left[ k_{ent} + k_{ex} + \frac{f L_c}{4R} \right] \text{ with } f = \frac{8k^2}{\left( \ln \frac{12R}{k_s} \right)^2} \]
Appendix G

The definition of the elevation force by the waves is explained in Section 5.4.1. This Appendix shows the data of the elevation of the lagoon water level and the corresponding near shore wave height, which together leads to the empirical relation \( X_{waves} \).

Figure G-1: Lake Avoca, November 2010, elevation of the lagoon water level and the corresponding near shore wave height.

Figure G-2: Lake Avoca, February 2013, elevation of the lagoon water level and the corresponding near shore wave height.
Figure G-3: Lake Avoca, March 2013, elevation of the lagoon water level and the corresponding near shore wave height.
The models are verified by another event at another location. The location is Cockrone Lagoon and the event is from 26/02/2012 until 17/03/2012. The model outcomes of the three models are displayed in the following pages.

Basic model

Figure H-1: The rainfall to river discharge for Cockrone Lagoon, March 2012.

Figure H-2: Basic model Cockrone Lagoon March 2012, channel width 30m.
Figure H-3: Basic model Cockrone Lagoon March 2012, channel width 50m.

Figure H-4: Basic model Cockrone Lagoon March 2012, channel width 60m.
Extended model

Figure H-5: Wave overwash and river discharge, Cockrone Lagoon March 2012.

Figure H-6: Extended model Cockrone Lagoon March 2012, channel width 30m.
Figure H-7: Extended model Cockrone Lagoon March 2012, channel width 50m.

Figure H-8: Extended model Cockrone Lagoon March 2012, channel width 60m.
Alternative model

Figure H-9: Alternative model Cockrone Lagoon March 2012, channel width 30m.

Figure H-10: Alternative model Cockrone Lagoon March 2012, channel width 50m.
The modelled period has been shortened, so only the period of an tidal response is compared.

All three models together 30m width.
All three models together 60m width.

Figure H-13: Basic, Extended and Alternative model Cockrone Lagoon March 2012, channel width 60m.
The discussion, Section 5.7., is about the overwash and wave set-up as elevation height of the lagoon water level. The graphs in this Appendix shows the lagoon water level corresponding to the rainfall and high waves.

Figure I-1 shows an elevation of the lagoon water level around 19/05/2010 until 24/05/2010. This corresponds to the rainfall during the same period. The wave height is low, around 1.5m. When the wave heights are high, with a maximum of 3m, the lagoon water level doesn’t change. Even though the tide has a spring tidal character, this means that the higher waves can travel further to the shore.

Figure I-1: Lake Avoca May 2010, rainfall shows elevation of the lagoon water level, high waves don’t.
Figure I-2 shows that high waves, around 11/04/2012, 20/04/2012 and 26/04/2012, do not influence the lagoon water level when the inlet is in a closed connection to the ocean. The significant rainfall around 18/04/2012 does affect the lagoon water level. The lagoon water level indicates the minimum height of the berm, in this case around 1.75m.

Figure I-2: Lake Avoca April 2012, only extensive rainfall gives an elevation of the lagoon water level.
Figure I-3 shows Lake Avoca July 2013 event and Figure I-4 shows a picture of an open inlet entrance at 04/07/2013. In Figure I-3 it can be seen that the lagoon water level is elevated above the ocean water level at the moment of the satellite picture. The waves are moderate with a maximum of 2.5m. It can be concluded that the waves have an impact on the lagoon water level while the entrance is open and not when the entrance is closed. Around 30/06/2013 the rainfall causes a remarkable elevation of the lagoon water level. It can be concluded that the rainfall, provided that significant, has a large impact on the lagoon water level. After 05/07/2013 the lagoon water level corresponds to the ocean water level and both the waves are low and the there is no significant rainfall. The entrance gradually closes and is completely closed around 18/07/2013.