Opotiki Entrance:
Navigation Improvements:
Feasibility Study Phase 2

Report prepared for Opotiki District Council

May 2004

Prepared by:
J Dahm, Eco Nomos Ltd
P Kench, Coastal Consultants Ltd

Executive Summary

This report was commissioned by Opotiki District Council to assess and report on the feasibility of options for improving navigability at the mouth of the Otara and Waioeka Rivers.

This study has significantly improved understanding of the sediment, hydrodynamic and morphological dynamics of the Opotiki entrance. Findings have confirmed and refined the conceptual model developed in the earlier desktop study (Dahm and Kench, 2002).

The study also undertook more detailed assessment of the effect of training walls on scour at the entrance and evaluated the effect of training walls on flooding at Opotiki Township.

Results enable the following preliminary conclusions in respect of dual training wall option.

1 Improvement in Navigability

Entrance training walls (the twin mole option) are likely to result in significant improvements in navigability at the Opotiki entrance – as the walls will significantly decrease sediment volumes recirculating through the entrance channel, disrupt the processes maintaining the existing bar, and markedly increase the dominance of seaward-directed sediment transport. Collectively, these processes will promote scouring of the entrance channel and the collapse of the existing ebb tide delta.

Wall spacings of up to 120 m are likely to be adequate to achieve the desired navigable depths (a minimum depth of 2.5m below mean low water spring), though these depths may also be achieved with wider spacings due to ongoing scour of sandy sediment in the area between the training walls.

The improvements are likely to persist for several decades, as the establishment of a new bar seaward of the walls will probably be slow (80-100 years or more).

Maintenance-dredging requirements between the training walls are likely to be minimal due to the marked ebb-dominance of the channel and the limited sand supply to the channel once the walls are in place. However, this will need to be confirmed during detailed design and a precautionary approach should be maintained towards these costs in the interim.

.

Dredging will be required during initial construction to achieve desired navigable depths and to minimise the volumes of sand discharged further seaward that could otherwise shorten the design life of the improvements.

2 Effect on Flood Release

A minimum wall spacing of about 120 m is likely to be required to avoid exacerbating flood levels adjacent to the township. A wider spacing will probably improve flood release.

Further and more detailed modelling of floods and flood release will need to be conducted during detailed design.

3 Scour of Entrance Channel

Sandy areas within the channel will probably continue to deepen over time, due to the limited supply of sand to the entrance once the walls are in place and scour during periodic high river flows.

Scour protection will be required along the margins of the walls to avoid undermining and severe damage during high river flows.

Scour protection will be required to at least 4m below mean sea level, due to the prevalence of sandy sediments above this elevation and the tendency of the entrance to widen rather than deepen during floods. In areas of fine sands, there is potential for considerably deeper scour to develop, possibly extending to depths of 12-16 m below flood levels in some areas (dependent on wall spacing). However, maximum scour is likely to be less than half these depths in those areas where fine gravels or coarser sediments occur.

If the walls are oriented perpendicular to the entrance, a scour hole is likely to form along the western side of the present entrance channel and particular attention will need to be given to scour protection requirements in this area.

Subsurface sediment investigations and physical modelling will be required during detailed design to finalise scour estimates.

4 Upstream Erosion

The landward ends of the training walls will need to be carefully tied into adjacent banks to avoid outflanking by erosion and scour of unprotected upstream areas during high flows.

Erosion along the landward margin of the sand spit on the eastern side of the entrance may eventually lead to breaching of this feature and outflanking of the walls. However, extensive lengths of shoreline armouring works are unlikely to be required in this area in the short-term and it may be possible to manage this erosion with beach nourishment during dredging episodes.

Upstream bank erosion will need to be monitored if training walls are installed.

5 Effect on Sediment Bypassing and Adjacent Beaches

The walls will largely prevent longshore drift from bypassing the entrance. However, net littoral drift along the coast appears to be low and therefore the walls are unlikely to lead to severe erosion of the downdrift (western) shoreline – a common adverse effect with training walls.

Nonetheless, over relatively long periods of time (probably decades rather than years), periodic artificial bypassing of sands may be required to prevent erosion of beach areas to the west of the training walls. Monitoring of shoreline trends will be required.

CONTENTS

Executive Summary 2
CONTENTS 5
1.0 INTRODUCTION 6
2.0 METHODS 7
  2.1 Field investigation 7
  2.2 Data analysis and reduction 9
  2.3 Revision of conceptual model of entrance dynamics 11
  2.4 Modelling 11
  2.5 Implications for design of entrance improvements 12
3.0 FIELD RESULTS 13
  3.1 Environmental Conditions 13
  3.2 Morphological components of the Opotiki river entrance 17
  3.3 Sediments 21
  3.4 Hydrodynamic observations 28
  3.5 Morphological change of the Opotiki river entrance 32
  3.6 Tidal prism calculations 36
4 IMPLICATIONS REVISED CONCEPTUAL MODEL OF OPOTIKI ENTRANCE DYNAMICS 37
  4.1 Background 37
  4.2 Tidal prism v cross-sectional area relationship 38
  4.3 Morphological dynamics of the entrance cross-section 39
  4.4 Opotiki entrance migration 41
  4.5 Ebb delta 42
  4.6 Summary conceptual model of entrance dynamics 43
5.0 IMPLICATIONS FOR ENTRANCE TRAINING WALLS 46
  5.1 Entrance Scour 46
  5.2 Flooding 57
  5.3 Potential for Walls to be Outflanked 60
  5.4 Bar Dynamics and Sediment Bypassing 63
  5.5 Summary of Implications for Training Walls 67
6. REFERENCES 69

1.0 INTRODUCTION

This report was commissioned by Opotiki District Council as part of preliminary work to assess the practicality of navigation improvements at the Opotiki Entrance. This report details various preliminary field investigations undertaken to further confirm and develop the conclusions of an earlier desktop analysis (Dahm and Kench, 2002), which assessed a range of options to improve entrance navigability.

The earlier assessment of improvement options relied on a preliminary conceptual model of entrance dynamics, largely based on a synthesis of existing information, and lessons from comparative experience. The report emphasised the need for field investigations to further confirm and develop conclusions before committing to any improvement option and more detailed design and consenting work.

This report largely focuses on critical issues relevant to the twin training wall (i.e. mole) option, which the earlier report identified as the option most likely to provide useful medium to long-term term improvements in entrance navigability. In particular, the investigations aimed to:

- confirm and refine the conceptual model of sediment transport and flood response in the lower river;
- examine the relationships between peak discharge and entrance scour;
- model the potential effect of varying entrance training wall (or mole) spacings on flood levels; and
- examine issues relevant to upstream erosion and potential for outflanking of training walls.

Limited further observations are also made in respect of sediment transport in the lower river and the bypassing of sediment past the river entrance, though detailed investigation of these issues was beyond the scope of this report.

2.0 METHODS

The study involved a combination of field measurement of currents, sediments, and morphological change; combined laboratory analysis and data processing in order to develop an improved understanding of entrance dynamics against which design implications for entrance improvements could be evaluated; and preliminary modelling of the effect of entrance works on upstream flooding.

2.1 Field investigation

Current measurements

Flows in the Opotiki entrance were measured using an InterOcean Systems S4 bidirectional electromagnetic current meter on October 17 and November 7, 2003 (Figure 2.1). The current meter sampled both current speed and direction. The current meter was suspended from a boat in the middle of the entrance, at approximately 0.6 of the water depth in order to capture the representative depth integrated flow velocity. A lead bomb with flow vane was attached 0.5m below the current meter to minimise vertical movement and yawing of the current meter. Currents were measured continuously at half-second intervals for 2 minutes and averaged to provide a single current measurement every five minutes. This strategy filters out high frequency current oscillations associated with waves.

Figure 2.1 The InterOcean Systems S4 current meter and mounting system deployed in the Opotiki river entrance.

Sediment sampling

Bed sediments were sampled using a pipe dredge (Figure 2.2) towed behind a boat. Eight samples were dried and textural analysis was performed using standard sieve techniques (Gale and Hoare, 1992). Further samples were retrieved and visually analysed and described in the field. To assess temporal changes in bed materials samples were retrieved on successive field trips in order to determine whether proportions of gravel/sand and mud changed significantly at each location.

Figure 2.2 Pipe dredge used to retrieve sediments from the Opotiki entrance and river system.

Surveying

A number of survey techniques were employed to document the morphology and changes in morphology of the Opotiki entrance between field sampling periods. The planform configuration of the entrance was mapped using a Trimble Geoexplorer 3 global positioning system. Surveys were conducted of the high water mark (HWM) and low water mark (LWM) on both sides of the entrance using a 1-second sample rate logging in 'line mode'. Surveys were extended alongshore beyond the immediate influence of the entrance and captured the estuarine shoreline of the eastern spit.

Throat cross-sections were documented using combined auto-level surveys above low water mark and echo-sounding techniques below low water mark. Auto level surveys were conducted from dunes either side of the entrance to temporary markers located in the channel margins. Echo-sound traces were obtained using a Lowrance Echosounder with traces beginning and ending at temporary markers. Data was recorded by an onboard data logger and transferred to computer for post-processing. The two surveys were combined using tidal corrections for the times of each survey. Tidal corrections were conducted using measured water levels from the Opotiki Wharf site operated by EBoP.

The morphology of the eastern spit was also surveyed using standard auto level techniques. A cross-section was surveyed from the estuary to ocean shoreline in the central spit position.

2.2 Data analysis and reduction

Current analysis

Records from the InterOcean Systems S4 were exported from Binary files to excel spreadsheets for data clean up and processing. Water level predictions at the Opotiki Wharf were obtained and plots of water level, mean current speed and current direction generated. Raw data is presented. However, a 30-minute running mean was also calculated for the velocity data and is overlain on the current plot.

Tidal prisms were calculated for each measurement day. Data was extrapolated to produce a 12.5 hour velocity dataset. Velocity obtained at 5-minute intervals was assumed to represent the mean flow across the entire channel cross-section and was multiplied by the cross-sectional area (obtained from surveying) and time increment between velocity sample points (300 seconds) to yield discharge in cubic metres per second (m^3). Values were then summed over each 5-minute period to yield the total volume of water passing through the entrance on the rising and falling tide.

Sediment analysis

Sediment samples were analysed for texture using standard sieve techniques as described by Gale and Hoare (1992). Samples were dried in a laboratory oven at 80 ^oC for a 24 hour period. Samples were then dry-sieved at half phi intervals that ranged from -5 phi to 4.0 phi (32 mm to 0.0063 mm). Summary statistics of the grain-size distributions were calculated using the moment method of Folk and Ward (1954). The percentage of gravel and sand-size material was also determined for each sample.

Visual observations of samples in the field were also made during each field visit. Samples were photographed and examined for the presence of gravel, sand and mud-sized sediment. Precise calculations of the proportion of mud were not undertaken. This is due to the fact that mud-size material does not contribute to the surficial sediments of the channel and spit. Furthermore, it became clear during field investigations that the channel was often cut into clay or pug like materials, portions of which were retrieved when sampling overlying gravels.

Surveys

All auto-level and echo-sound surveys were corrected to a common datum (the Moturiki MSL Datum) using water level measurements at the time of each survey as recorded at the Opotiki Wharf water level recorder. This involved reducing measurements of water level to the tidal elevation at each time interval. GPS surveys were corrected and overlain to provide a comparison of spit and entrance planform configuration between field measurement periods.

2.3 Revision of conceptual model of entrance dynamics

The findings from the field investigations and data analysis were used to check and refine the conceptual model of river entrance processes and dynamics developed during the earlier desktop study (Dahm and Kench, 2002).

This was a critical element of the present project as the conceptual model was fundamental to the analysis and the conclusions of the earlier report - being used to assess the navigation improvements likely to be achieved by each of the options considered, and to identify any issues and environmental effects that may be associated with each of these options (see Dahm and Kench, 2002, Chapter 4, pages 37-71).

The conceptual model, outlined in Chapter 3 of the earlier report (pages 11-36) and summarised in Section 3.6 of the report (pages 33-35), was initially developed largely on the basis of the limited field data then available and on current scientific understanding of such environments (including detailed studies of similar small river and tidal entrances). The field investigations undertaken during the present work were used to test and refine key elements of the model – particularly in relation to scour and erosion, sediment transport and flood release.

2.4 Modeling

Limited modeling was also undertaken during this investigation to examine aspects in relation to scour and flood release – identified in the earlier report as factors particularly critical to the practicality, success and cost of navigability improvements at this entrance.

The procedure of Hughes (2002) used to estimate potential scour in the earlier desktop study was tested and calibrated against field measurements undertaken during this study and then used to further refine estimates of potential scour.

The EBoP numerical river flood model used to design stopbank elevations for Opotiki Township was used to assess the potential impact of training walls on flood release. The modeling investigated the potential impact of a range of training wall spacings. The objective of this work was to ensure that entrance works will not exacerbate flooding in Opotiki township. The findings in relation to entrance scour during river floods were used to develop design scoured sections for this modeling work.

2.5 Implications for design of entrance improvements

Finally, the findings of the field investigations, analysis and modelling were used to review implications for the design of entrance improvements, including costs, practicality, likelihood of success, design life and potential environmental effects. Particular attention was given to the twin training wall option, identified in the earlier report as the option most likely to provide useful medium to long-term improvements in entrance navigability.

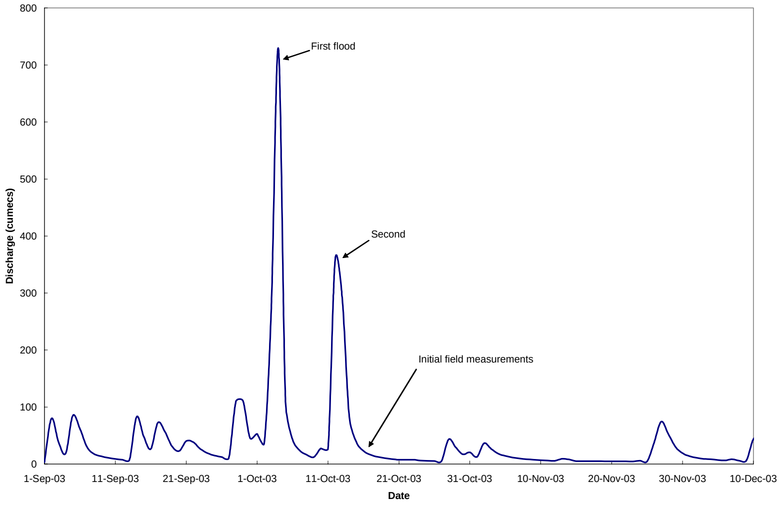
3.0 FIELD RESULTS

3.1 Environmental Conditions

River flows

The period of investigations immediately followed two significant flood events in the Waioeka and Otara Rivers (Figure 3.1).

A. Otara River



B. Waioeka River

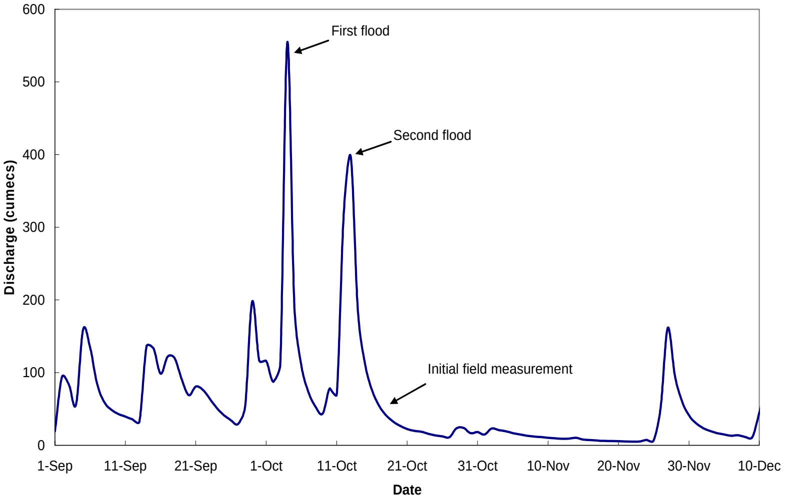


Figure 3.1. Otara (A) and Waioeka (B) river flows preceding and during the field measurement programme.

In the first of these events, on the 3 and 4 October 2003, flows in the Waioeka peaked at 898 cumecs and flows in the Otara at 728 cumecs – equivalent to a 30-year return period flood in the Otara and a 5-year return period event in the Waioeka and a combined peak flow of about 1600 cumecs. The second event on the 12 and 13 October was characterised by peak flows of 782 cumecs in the Waioeka and 358 cumecs in the Otara (combined flow of 1 140 m^3s^{-1}).

The first field measurements in this study, on October 17, occurred less than a week after the second of these major flow events. Over the remainder of the study period, flows in both rivers were generally low (typically less than 10-15 m^3s^{-1}), though a minor fresh occurred on 27 November (Figure 3.1).

Waves

New Zealand lies in a westerly wind system with prevailing deep-water waves approaching from the south to westerly quarter. As these swells refract around the South and North Islands, East Cape acts as an effective barrier that strongly transforms swell energy entering the Bay of Plenty. The east coast and in particular, the Opotiki entrance is on a leeward shore with prevailing winds blowing offshore. As a consequence prevailing winds have little role in generating waves that impact on the Opotiki coast.

There are no historic wave records from the vicinity of the Opotiki entrance. At the regional scale Pickrill and Mitchell (1977) report wave observations at Hicks Bay (East Cape), Tauranga Harbour and Waihi (Table 3.1). Recent wave hindcast modelling covering the last 20 years (undertaken by NIWA for the entire New Zealand coastline) confirm the region-wide wave statistics presented in Table 1.

Table 3.1 Summary wave characteristics – Bay of Plenty. After Pickrill and Mitchell (1979) and Heath (1985).

Location	Significant Wave Height (m)	Wave Period (sec)
Hicks Bay – deep water	1.36	6.47
Hicks Bay – nearshore	0.49	1.17
Tauranga	0.96	-

Waihi	0.39	11.13

The predominant wave approach is from the north through east. Northeasterly waves are generated by tropical depressions moving down from the northwest (north of New Zealand). Consequently storm events are considered to dominate the wave climate in the Bay of Plenty (Pickrill and Mitchell, 1979). For example the recent storm of February 28 and 29, 2004 produced a peak wave over 10 m in height in the Bay of Plenty (EBoP website). The frequency of such events is difficult to predict. Pickrill and Mitchell (1977) also note there appears to be no seasonality in wave conditions in the Bay of Plenty.

Environment Bay of Plenty has recently deployed a wave rider buoy 13 km off the Pikowai coast. As yet records from this instrument are too short to refine the crude generalisations regarding the wave climate near Opotiki. However, as this record is extended it may prove valuable in assisting the design process for river training works at Opotiki

Wave data was not available for inclusion in this report. However, local observations indicate that wave action was generally limited to relatively low swell over the period with no major wave events noted.

Tides

Bay of Plenty experiences low mesotidal to microtidal conditions (Table 3.2). The tidal range at the Opotiki Wharf ranges from 1.29 m to 1.76 m for neap and spring tide conditions respectively. However, maximum water level at the Opotiki Wharf is determined by flood flows in the Otara and Waioeka rivers. In particular, flows in the Waioeka River act to block discharge from the Otara River super-elevating water levels at Opotiki Wharf. For instance, records from July 1998 indicate that the maximum tide level was 1.44 m R.L. while a flood event raised water level to 2.74 m R.L.

Table 3.2 Tidal conditions at selected sites in the Bay of Plenty.

	Mean Spring Range (m)	Mean Neap Range (m)
Tauranga	1.6	1.2
Ohiwa	1.5	1.3
Ohope Wharf	1.7	1.3
Whakatane	1.6	1.2
Opotiki Wharf*	1.76	1.29
Hicks Bay	1.7	1.2

* Based on short-term observations at the Opotiki Wharf.

Tidal observations at the Opotiki Wharf (Otara River, just above the confluence) were used to reduce survey data (including soundings) to MSL. By way of example, Figure 3.2 shows tidal curves measured during the first 2 field investigation periods.

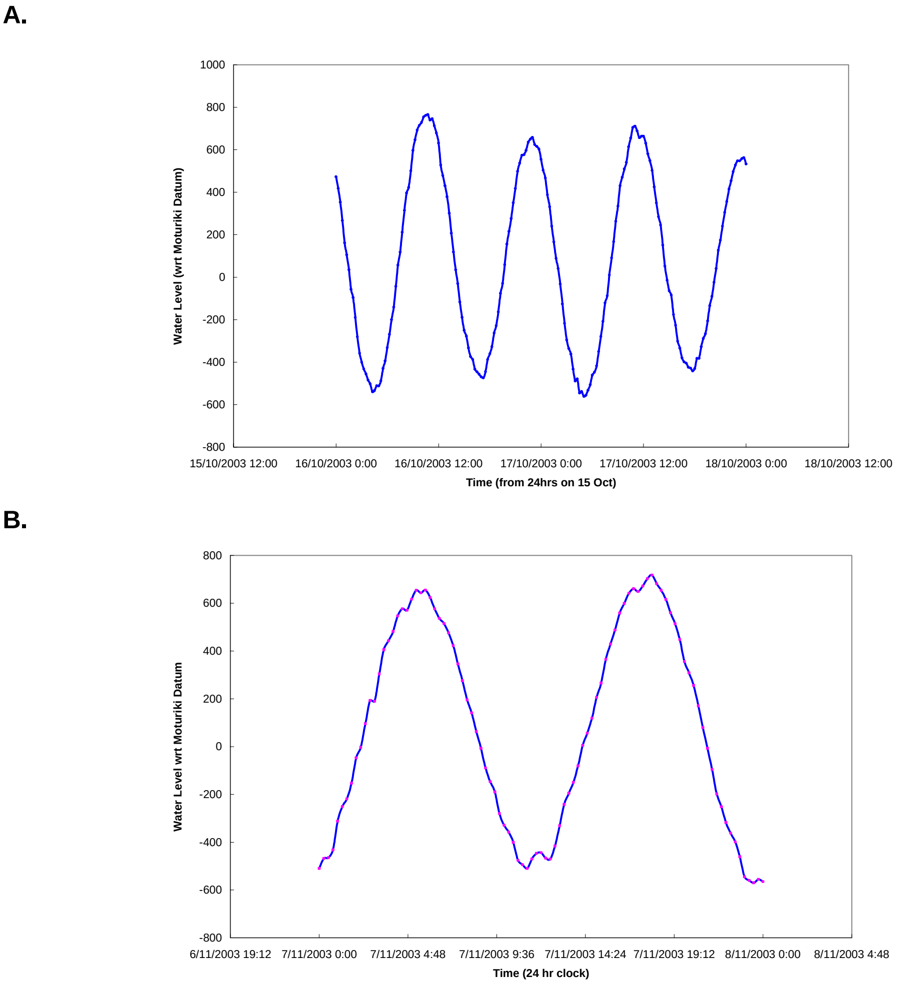


Figure 3.2 Tidal curves Opotiki wharf - field measurements in October (A) and November (B).

3.2 Morphological components of the Opotiki river entrance

The Opotiki entrance forms the outlet for the combined flow of the Waioeka and Otara Rivers. The entrance is located approximately 1 km downstream of the confluence of these two rivers. The area below the confluence can be subdivided into three morphological zones, i) the lower river/estuary from the confluence to the entrance, ii) the narrow entrance gorge and iii) the bar at the harbour entrance – which technically is referred to as an ebb tide delta (Figure 3.3).

Figure 3.3 Morphological components, sample and survey locations of the Opotiki entrance and lower river.

Lower River/Estuary

The morphology of the lower river varies markedly from the confluence to the river entrance. The estuary channel varies in width from 200-500m at high tide, though the main channel is typically only 150-200m wide. Immediately downstream of the confluence the river channel is narrowest (200 m) and has the smallest cross-section in the lower river. The surveyed cross-section just below the confluence (Fig. 3.3) shows the thalweg is hard against the eastern bank. Erosion scarps on the eastern embankment suggest the channel is actively eroding the bank. The position of the thalweg against the eastern embankment further suggests the Waioeka flows dominate the Otara – as do anecdotal observations during floods. The channel shallows markedly on its western boundary to a sand and gravel point bar.

Further downstream, the thalweg crosses to be hard against western bank (about halfway to the entrance) and remains against the western bank to the entrance throat (Figure 3.3). At this location the channel is considerably wider **X m** with a cross-sectional area of **X m^2**. The western bank has been armoured to prevent further erosion and consequently, plays a part in controlling the angle at which the main channel axis enters the entrance and constrains westward migration of the entrance. Consequently, the protection provides a measure of locational stability of the entrance and is likely to require ongoing maintenance or replacement as part of entrance works.

Entrance gorge

The channel narrows markedly at the entrance gorge. A cross-section of the entrance is shown in Figure 3.4 from the bathymetric survey (1995). Previous analysis of aerial photographs and bathymetric charts show the entrance has ranged in width from 80 to 150 m at mid-tide, with a maximum depth of 3.2 m below R.L. (Dahm and Kench, 2002). These variations in entrance width indicate the entrance is highly dynamic and influenced by relative changes in the balance of river and marine processes.

Dahm and Kench (2002) highlighted the fact that detailed studies of the morphological behaviour of the Opotiki entrance have not been undertaken. This report presents data on morphological change and tidal flows at the entrance to support design of entrance improvements.

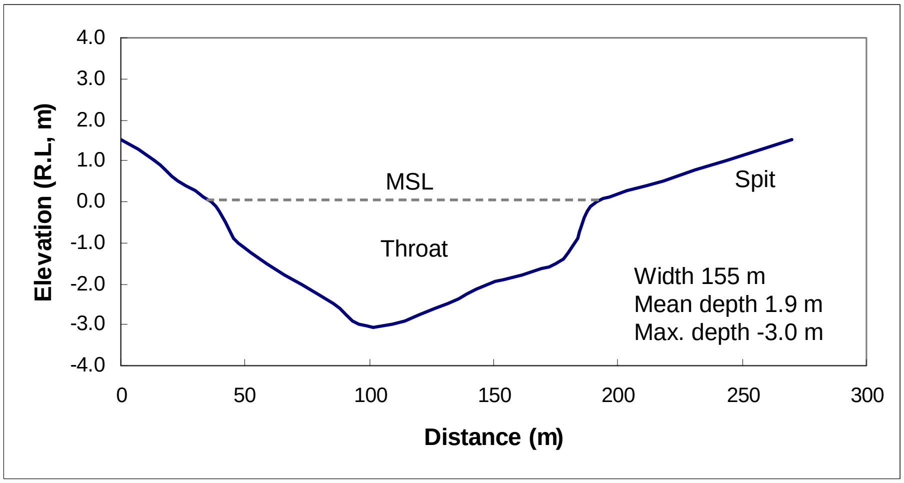


Figure 3.4 Cross-section of the Opotiki river entrance. Derived from bathymetric chart.

Ebb delta

The ebb delta is a shallow subtidal delta that extends seaward from both sides of the river entrance (Figure 3.5). The ebb delta extends approximately 600 m offshore (to about 5 m below Chart Datum, Fig. 3.5) and approximately 1200 – 1500 m alongshore (Dahm and Kench, 2002). As noted by Dahm and Kench (2002) the ebb delta experiences large sediment transport fluxes in response to the changing balance of marine and river processes. Sediment eroded from the river entrance during major river flows will be deposited further seaward on the ebb tide delta. Once the major flow ceases, wave action and flood tide currents will tend to move sediment from the adjacent beaches and nearshore areas of the delta into the entrance gorge, reducing the entrance area. It is possible that significant deposition may even occur during the falling stages of major river flows.

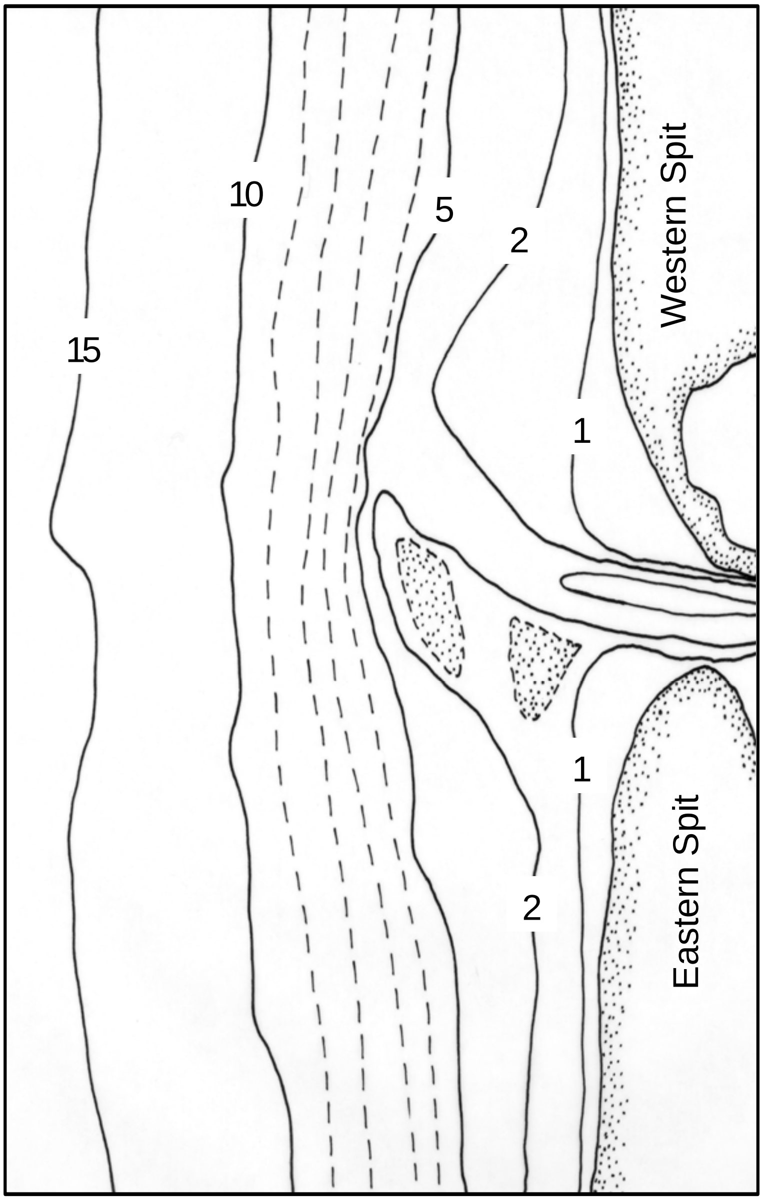


Figure 3.5 Bathymetry of the Opotiki entrance and nearshore. Note planform configuration of the ebb-tide delta as defined by the 5 m contour. Source RNZN hydrographic survey, 1995.

Morphology of spit

Figure 3.6 presents the cross-section morphology of the Opotiki spit and shows it is approximately 80 m wide at its narrowest point. Of note, the estuarine shoreline is scarped and undergoes erosion during high river discharges (Fig. 3.7). The most recent flood debris level is also shown (Fig. 3.6). Under flood and high storm episodes super-elevated water levels markedly reduce the width of the spit. Continued erosion of the landward margin of the spit may render the spit vulnerable to overtopping by storm overwash in the future. Close monitoring of changes in the conformation of the spit should be undertaken so as not to compromise the integrity of proposed river training works.

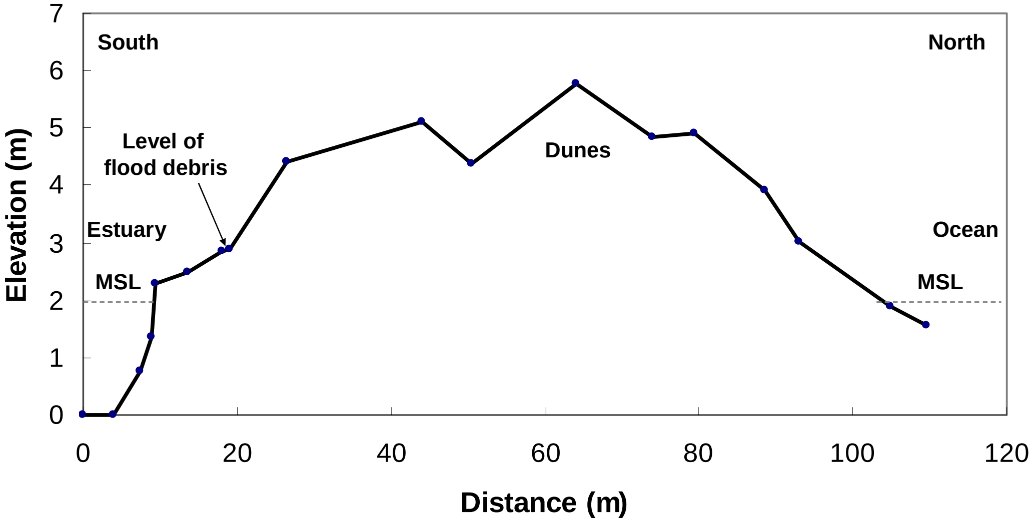


Figure 3.6 Morphology of the Opotiki eastern spit. Cross-section surveyed at narrowest point of spit.

Figure 3.7 Erosion of estuarine margin of eastern spit at point of surveyed cross-section.

3.3 Sediments

Background: coastal sediments

The Opotiki entrance joins the open coast on a large drift-aligned embayment. Sediments along this coast are comprised of quartz/feldspars with additions of lithics, pumice, obsidian and shell. The beach sands to the east and west of the Waioeka River entrance are primarily fine to medium sands, with mean grain sizes typically varying from about 0.2-0.3 mm (Healy, *et al*, 1977; Smith, 1986).

There has been no detailed investigation of sediments of the entrance and ebb delta. However, Croad et al. (1993) reported a mean grain size of 0.5-0.6 mm in 3 samples taken below low tide on the immediate eastern side of the river entrance (i.e. the extreme western end of the spit). They also noted maximum particle sizes of 3.4 to 7 mm in samples. Tonkin and Taylor (2001) presented sediment size data for 5 samples taken from the outer bar. These sediments were primarily medium sands, with about 75% of each sample lying within the size range of 0.2-0.43 mm and a typical d_{50} grain size of about 0.3mm. The samples also contained small amounts of coarser sand and sometimes gravel, typically 5-10% of the sample being coarser than 0.43 mm, with maximum sizes of about 10 mm.

Clearly sediment at the entrance and bar is coarser than alongshore beach sands on either side of the entrance, as also shown by Smith (1986) who examined alongshore trends in sediment texture between the Motu River and Whakatane. The coarsening of sediments is expected in the vicinity of river entrances and is likely to reflect the injection of river sediments to the coast and the effect of increased velocities in the entrance winnowing finer sands from deposits.

Entrance sediments

In the field investigations of October 17, 6 sediment samples were taken from within the entrance area (Fig. 3.3). Results of the textural analysis of samples are presented in Appendix 1.

Sample 1 (from the western side of the entrance) was primarily composed of gravel with secondary additions of sand-size sediment (Figure 3.8, see also bimodal sediment size distribution in Appendix 1). The gravels range in size from 8-25 mm (-3 to –4.5 ϕ, with a modal size range of –4 ϕ (16 mm). Of note, the gravels were very muddy on their surface. The presence of mud-size material indicates either deposition during floods or, that gravels may be embedded in a more cohesive mud boundary.

Figure 3.8 Sample 1 retrieved from the western side of the Opotiki entrance, October 17, 2003.

Samples from the central and eastern side of the entrance (samples 2 and 3, Fig. 3.3, 3.9 and 3.10) were composed primarily of sand-size sediment, with modal grain sizes of 2-2.5 ϕ (0.2-0.25 mm) and mean grain sizes of about 0.23-0.25mm (Appendix 1). However, isolated pebbles of 10-20 mm size were found among the sands in sample 2 (Fig. 3.9).

Figure 3.9 Sample 2 retrieved from the centre of the Opotiki entrance, October 17, 2003. Note presence of a few gravels.

Figure 3.10 Sample 3 sand-size sediments retrieved from the eastern channel entrance, October 17, 2003. Note absence of gravel.

It is important to note that the textural characteristics of sand in the entrance (Samples 2 and 3) are very similar to samples 4-6 from the adjacent shoreline – with all sediment in these samples lying in the 1.5 to 3 ϕ size range, with modal grain sizes of 2-3 ϕ (0.125-0.25 mm) and mean grain sizes of 2-2.34 ϕ (0.2-0.25 mm, Appendix 1).

These samples were taken from western end of the marginal flood tide channel that runs along the shoreline – the bedforms and morphology of this area clearly indicating it is dominated by flood tide and wave directed sediment transport. These sediments are typical of those being recirculated into the entrance by waves and flood tide currents. Therefore, the sandy nature of the sediments on the eastern side of the entrance channel, markedly contrasting with the fine gravel sediments noted on the western side of the entrance, suggests that some infilling of the eastern side of the entrance had occurred since the floods – due to sediments transported into this area under the influence of waves and flood tide currents.

This is also consistent with the pattern of morphological change noted in this area. The preferential infilling of the flood-scoured entrance on the eastern side is also to be expected as a significant marginal flood tide channel runs along the seaward face of the shoreline on the eastern side. This feature would be expected to deliver large volumes of sediment into the entrance under the combined influence of wave breaking (see Section 3.4).

Further sediment sampling conducted in the entrance on the 3 December 2003 (approximately 6.5 weeks later) found sand (similar in texture to samples 3-6) at all sites. This is consistent with significant infilling of the flood scoured entrance. During the sampling, it was also noted that the bottom was hummocky in many areas, suggesting the presence of sand megaripples and very active sediment transport. However, fine gravels similar to Sample 1 were retrieved in the center of the entrance where scoured depths were similar to the depths recorded at the time of the October observations. This suggests that gravels transported down during higher flows underlie sands and armour the entrance. The gravels were only noted in areas below R.L. -4m. In some of the deeper and high velocity areas, juvenile pipis were also recovered and the difficulty of retrieving sample from some of these locations suggested the bottom might have been shell lagged or similar.

In summary, it appears that floods transport fine gravels (i.e. common size ranges of 10-25 mm) to the entrance and these sediments appear to characterize the deeper part of the entrance where they form a lag that armours the channel floor (below R.L. -4m with respect to Moturiki Datum). However, during normal flows, sands are circulated into the entrance under the influence of flood tides and waves and sandy sediments tend to dominate the area.

It is expected that the capacity of flood flows to transport gravel diminish rapidly seaward of the entrance throat. However, the location at which gravel deposition declines is unknown. Visual inspections along the eastern foreshore during the period of study indicated that occasional pebbles (typically 5-20mm) do occur but the beach and ebb tide delta but the sediments are primarily (>99%) sands and shell. Therefore, it appears that the volumes of gravel delivered to the beach system in river floods are relatively minor in comparison to the large volumes of coastal sediment in circulation at the entrance.

Lower river (confluence to entrance)

In addition to sediment sampling in the entrance, samples were retrieved along two cross-sections in the lower river (Fig. 3.3); adjacent to the rock protection on the western bank where the thalweg is hard against the western bank; and just below the confluence of the Otara and Waioeka rivers where the thalweg is hard against and is eroding the eastern bank.

Sampling of the subtidal areas at these sites indicated the bed was characterized by either a gravel armoured bed (rocks retrieved typically having sizes of 20-80 mm) or were bare of sand or gravel sediment. In areas that were bare of sediment, a firm silt/pug was recovered that appeared to be the basement materials in which the river bed is cut. This material represents the channel boundary and appears to provide a limit to scour in these areas. The firm gravel lag noted in other parts of the main channel may also limit scour in the main channel areas.

However, at both cross-sections, samples also indicated the presence of a narrow band of fine gravels that appears to be actively transported – though possibly only during periods of high river flows. These sediments ranged in size from 5 to 20 mm in diameter and were similar to the gravels noted in the entrance.

At the upstream cross-section a pure sand sample was retrieved from the western side of the channel (where the bed shallows to the point bar). However, observations suggest these sands were finer (<0.125mm diameter) than the coastal sands observed in the vicinity of the entrance.

The general absence of sand in the channel indicates that sand: is efficiently transported seaward; was flushed from the channel during the preceding river floods; and clearly had not been deposited in significant quantities since the last flood event. Consequently, while sands and gravels are transported in the reach from the confluence to the entrance, the volumes appear likely to be low.

The intertidal embayment extending about halfway from the entrance to the confluence is largely composed of old, consolidated river deposits (muddy gravels) with little evidence of recent river sediments (other than mud) having been transported or deposited over this area (Fig. 3.11).

Figure 3.11 Intertidal flats on eastern side of the lower river. Note presence of muddy gravels.

However, some sands do occur in the embayment along the back of the entrance spit and extending southwards along the landward margin of the embayment. These sands show evidence of flood tide directed bedforms, after the ebb tide (Fig. 3.12), suggesting the sediments are coastal sands transported into the area via the small channel along the back of the entrance spit. These coastal sands appeared to increase in area over the time of our study suggesting that previous coastal sediments deposited by incoming flood tide currents were stripped by the floods of early October. It is possible that coastal sands may become relative extensive over this area after a sustained period of low or normal flows. However, as noted above, there is little to no evidence of significant volumes of river sand or gravel being transported over this area by river floods.

Figure 3.12 Flood oriented ripple marks on intertidal flats behind the eastern spit, Opotiki entrance.

Overall, the sediment observations and analyses indicate that river sands and gravels (generally less than 50-100 mm diameter and typically 5-20 mm) are transported from the confluence to the river entrance, probably largely during high flows. However, the gravel lagged (and in some areas, bare) nature of the main channel, the relatively narrow widths of active sediments noted in the subtidal river channel, and the very limited nature of recent river sands and gravels in intertidal areas tends to suggest that the volumes of river sands and gravels transported below the confluence may be relatively limited. However, more extensive observations and investigations would be required to confirm this.

The rates of sediment delivery to the Opotiki entrance

Dahm and Kench (2002) undertook a review of sediment fluxes in the vicinity of the Opotiki entrance. They found the direction and magnitude of net alongshore sediment transport has been the subject of a great deal of conjecture in the Bay of Plenty. This is attributable to the lack of detailed quantitative studies of sediment fluxes and the relatively long and open coast in which a number of littoral cells are likely to have established.

On the basis of the analysis of sediments in this study and previous review of sediment processes (Dahm and Kench, 2002) it is concluded that sediment supply to the entrance from the river and westward alongshore drift is low. Previous estimates were 15,000 m^3/yr delivered by the river system (Croad et al., 1993) and 6,000 m^3/yr (Smith, 1986) resulting from alongshore drift, yielding a net input of approximately 20-25,000 m^3/yr. Analysis of surface sediments in this study suggests that river inputs are lower than the 15,000 m^3/yr suggested by Croad et al. (1993). However, it is recommended that a conservative approach be taken, for sedimentation at the entrance, for the purposes of entrance design, maintenance dredging considerations and the life span of any entrance improvements. Consequently, it is recommended that the lower (10,000 m^3), mid-range (20-25,000 m^3) and high (40,000 m^3) values of net annual sediment input to the entrance zone identified by Dahm and Kench (2002) are maintained for future project design considerations.

3.4 Hydrodynamic observations

Experiment 1: Spring Tide, 17 October 2003

Current records from the first current gauging are presented in Figure 3.13. the measurements were obtained from the mid rising to low tide stage under spring tide conditions (tidal range of 1.2 m). There are a number of notable features of the current records:

i) Ebb currents are much larger in magnitude than flood tide currents. Ebb currents peak at 0.65 ms^{-1} whereas peak measured flood flow was 0.25 ms^{-1}.

ii) Peak ebb flow coincides with the mid-falling stage of the tide.

iii) There is a sharp reversal in flow direction from inflow during the rising tide to outflow that coincides with the peak of the tide. In contrast, the velocity and direction data show no sign of reversing at low tide.

iv) There is a notable oscillation of velocity during the falling tide. These oscillations occur at frequencies of 30-45 minutes and represent a pulsing of current as it leaves the entrance. These velocity pulses have amplitudes of ±0.3 ms^{-1}.

Experiment 2: Neap Tide, 7 November 2003

The second current gauging was undertaken across the falling and rising tidal stages under neap tide conditions (tidal range of 0.9 m, Fig. 3.14). Conditions preceding field measurement were not marked by any significant river flow events. The current magnitude and time velocity asymmetry are markedly different to the first measurement period. Key features of the current records include:

i) Ebb currents are relatively constant at approximately 0.3 ms^{-1} during the falling limb of the tide. There is no marked peak in ebb current at mid-falling tide.
ii) There is an increase in velocity to 0.4 ms^{-1} at the latter stages of the falling tide.
iii) Currents show marked variability in direction and peak velocity around low tide. Current magnitude peaks at 1.1 ms^{-1} at 1200 and 1310. Currents for the 3-hour period around low tide also exhibit the pulsing characteristics observed in the first measurement period.
iv) Current direction becomes a constant inflow 2.5 hours into the rising tide.
v) Flood currents range from 0.03 ms^{-1} (2.5 hours into the flood tide) to 0.38 ms^{-1} (5 hours into the flood tide).

Current measurements provide an insight as to the hydrodynamic behaviour of the Opotiki entrance and in particular the influence of river and marine processes that influence the time velocity asymmetry of flow and current magnitude.

The entrance is ebb-dominated with regard to the duration of flow. This is supported by the rapid shift to ebb-discharge at high tide (in the first experiment) and significant lag to flood flows following low tide. The second experiment shows up to a 3-hour lag before a persistent flood flow penetrates the entrance. The variable direction and magnitude of flow at low tide (November 7) reflect the competing flood and ebb flows at low tide. The degree of ebb dominance is likely to be controlled by changes in river flow. Under low river flows the duration of ebb and flood flows may be more symmetrical. In contrast, under high flows the entrance can be expected to be dominated by ebb flow for more than 8 hours in a tidal cycle.

In both experiments the flood currents are generally low in magnitude ranging from 0.2 – 0.4 ms^{-1}. Peak velocity was observed at mid falling tide (0.65 ms^{-1}, experiment 1) and low tide (1.10 ms^{-1}, experiment 2) and both were associated with ebb flow conditions. Reasons for the higher ebb velocity recorded in experiment two are unclear but may be attributable to narrowing of the entrance cross-section. However, they appear to be associated with current pulsing which was observed in both experiments (compare Fig. 3.13 and 3.14). The mechanisms producing current pulsing are unclear.

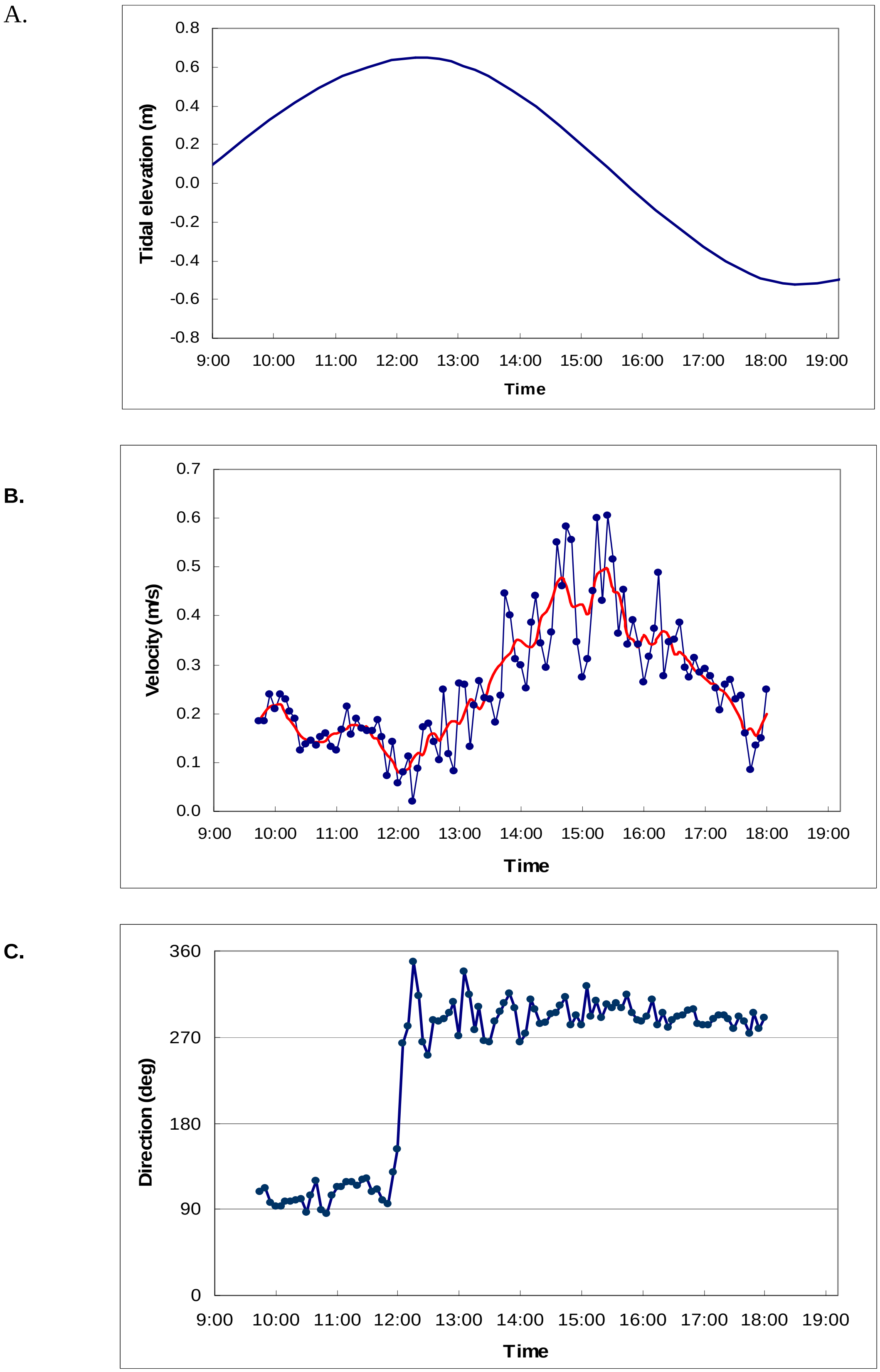
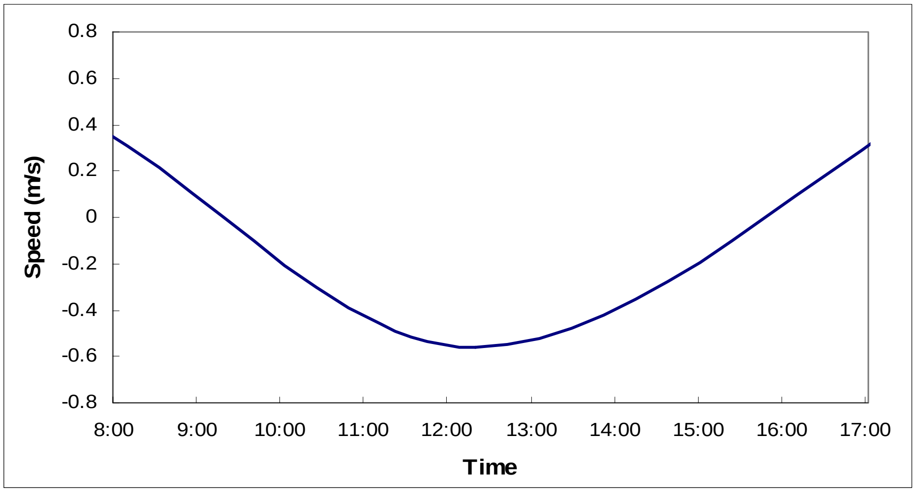
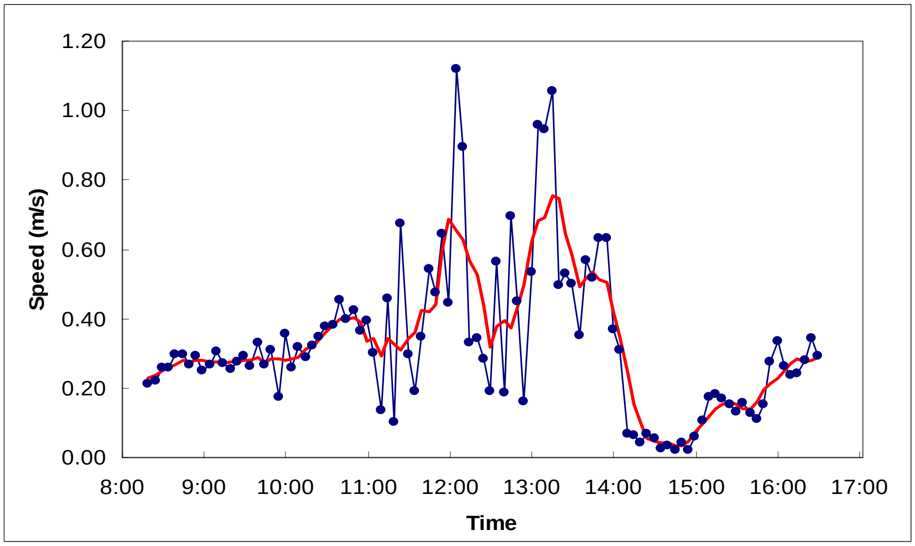


Figure 3.13 Opotiki entrance current gauging 17 October 2003. A) Water level. B) Current speed. C) Current direction.

A.



B.



C.

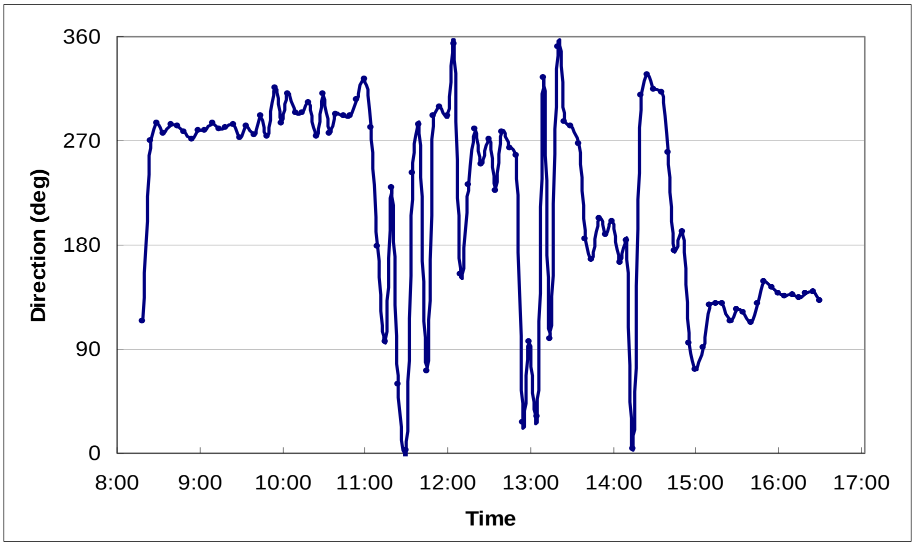


Figure 3.14. Opotiki entrance current gauging 7 November 2003. A) Water level. B) Current speed. C) Current direction.

One possible cause of current pulsing is long period wave set-up that blocks ebb discharge at the entrance. This would promote temporary water back up in the estuary, decelerating ebb flow, and when the wave set-up diminishes water is rapidly evacuated from the lower estuary producing acceleration in ebb flow. In experiment two this occurs at low tide at a time when the entrance cross-section is at a minimum. Unlike a coastal lagoon which is expected to experience zero velocity at low tide, the entrance still conveys river flow. Consequently, periodic water back-up and release in the lower estuary combined with the narrowest cross-section is believed to be responsible for the large velocity peaks observed at low tide.

In summary, the Opotiki entrance can be characterized as ebb-dominated with respect to flow duration and velocity magnitude. The degree of ebb-dominance is strongly dependent on river flow.

3.5 Morphological change of the Opotiki river entrance

Changes in the planform configuration of the Opotiki entrance are presented in Figures 3.15 to 3.17 and summarized in Figure 3.18. There are a number of notable features of these surveys. First, the entrance was found to undergo progressive narrowing throughout the measurement period. The entrance was widest in October following the flood event. Second, while deposition occurred on both sides of the channel the terminal end of the spit exhibits the greatest amount of sedimentation between surveys. The spit tip rapidly extended westward between the first two surveys. The flood shoal, welded to the spit tip, is also shown to have expanded rapidly following the storm. It is likely that sediment scoured from the entrance during the flood was deposited on the ebb delta. Sediment was subsequently transported shoreward by swash processes to expand the flood shoal and enlarge the volume of sediment at the terminal end of the spit.

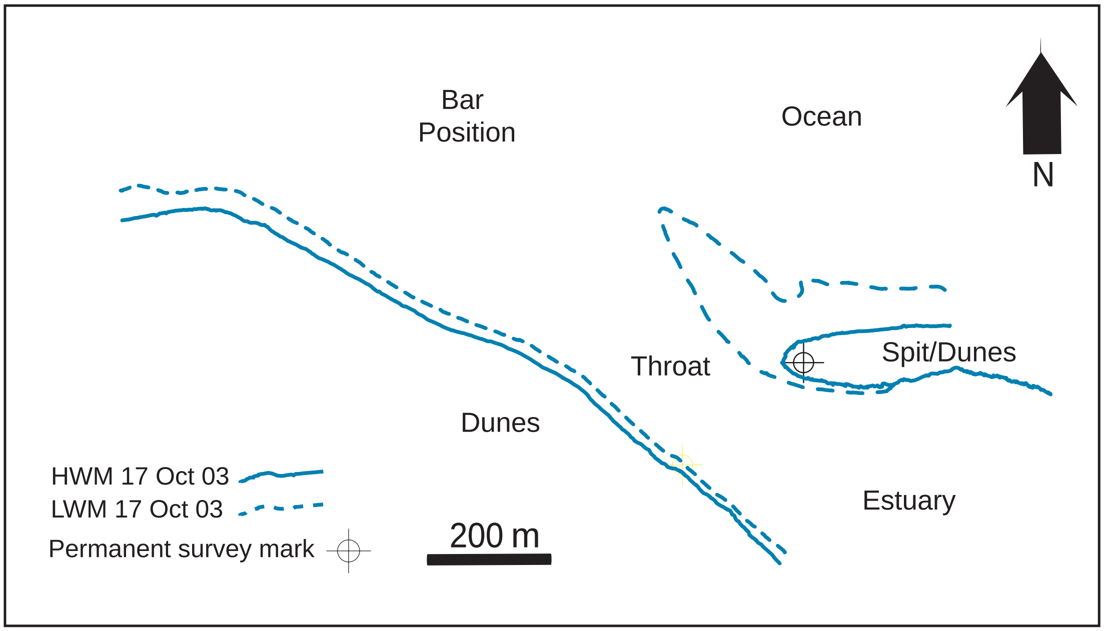


Figure 3.15 Planform configuration of the Opotiki Entrance, 17 October, 2003. Surveyed using a Trimble Geoexploerer III GPS.

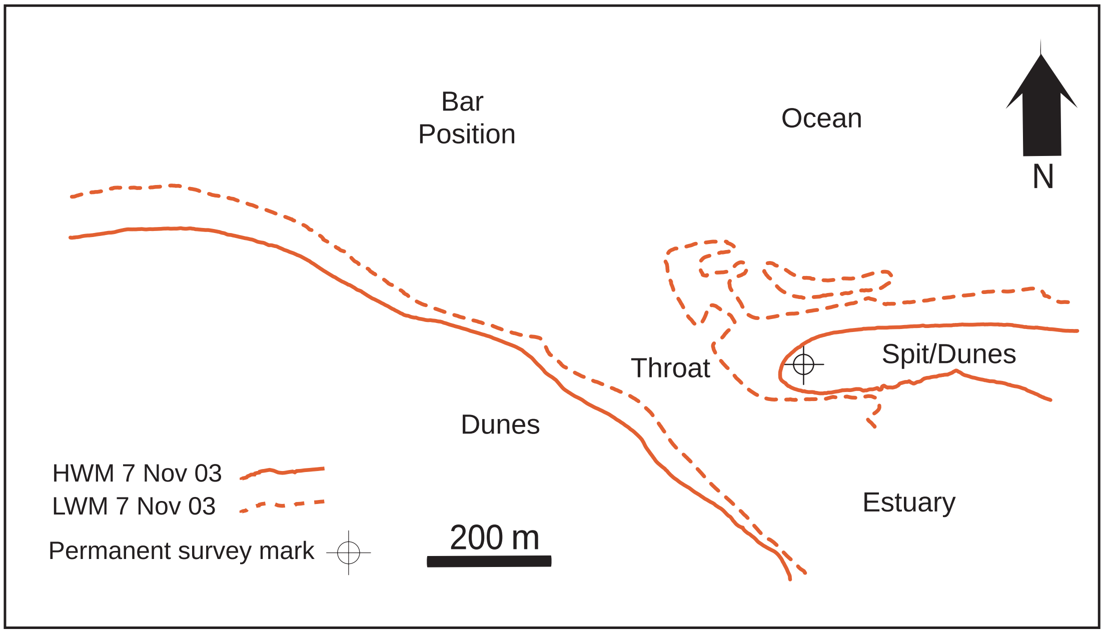


Figure 3.16 Planform configuration of the Opotiki Entrance, 7 November, 2003. Surveyed using a Trimble Geoexploerer III GPS.

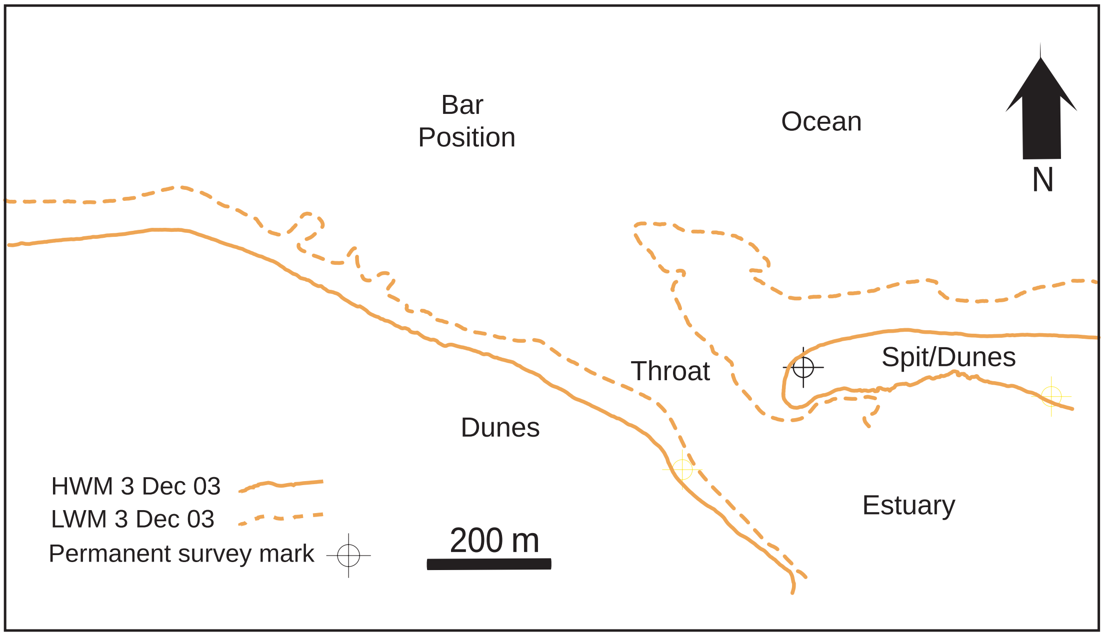


Figure 3.17 Planform configuration of the Opotiki Entrance, 3 December 2003. Surveyed using a Trimble Geoexploerer III GPS.

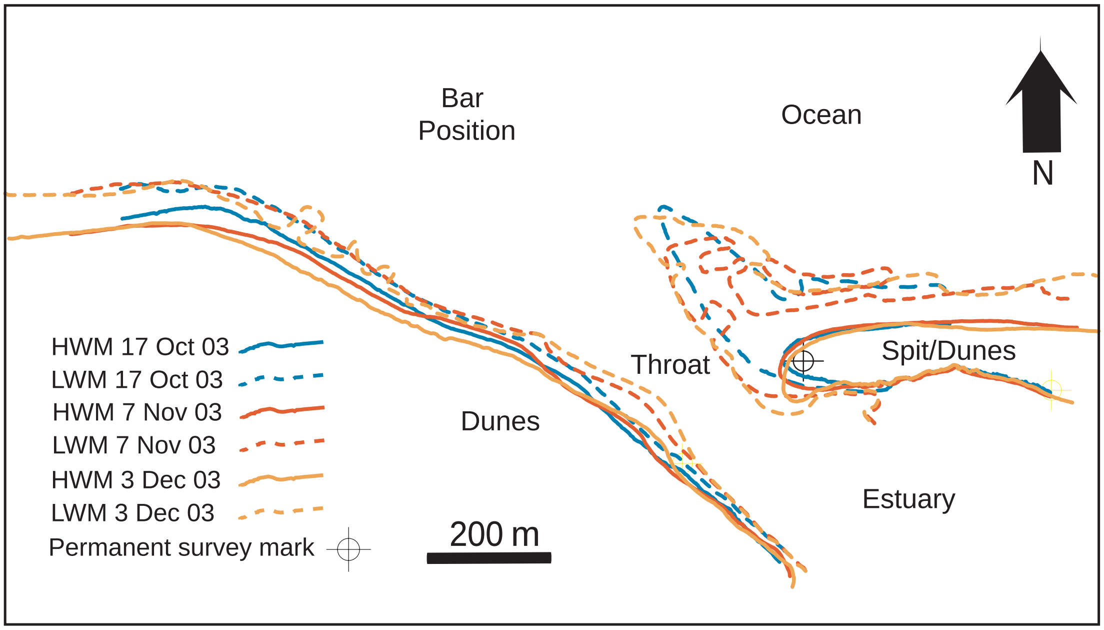


Figure 3.18 Summary changes in planform configuration of the Opotiki Entrance, 17 October, 7 November and December 3rd 2003. Surveyed using a Trimble Geoexploerer III GPS.

Figure 3.19 also presents changes in the entrance cross-section during the measurement period. Results are consistent with gps planform surveys and show progressive infill of the entrance, particularly from the eastern (spit) side of the channel. Specific changes are summarised in Table 3.3. Notably the entrance decreased in cross-sectional over two months by 25% (between October and December).

Of relevance to this report the data indicate the entrance is susceptible to lateral scour rather than deepening. Throughout the measurement period there is little adjustment in maximum entrance depth while lateral boundaries exhibit marked positional shifts. The entrance width reduced markedly from 213 m (October 17) to 150 m (December 3) and the maximum depth decreased by 0.42 m. However, mean depth increased by 0.15 m. This distinction between the behaviour of channel floor and lateral boundaries suggests the floor may be more resistant to scour. Possible mechanisms for this increased resistance could include:

i) more cohesive sediments in the channel floor;

ii) presence of a gravel layer in the channel boundary, which is supported by pipe dredging of samples from the western side of the entrance Section 3.3);

iii) presence of more cohesive sediments (mud) in the channel floor – although none was retrieved through pipe dredge sampling, and;

iv) A structural control underlying the sediment surface.

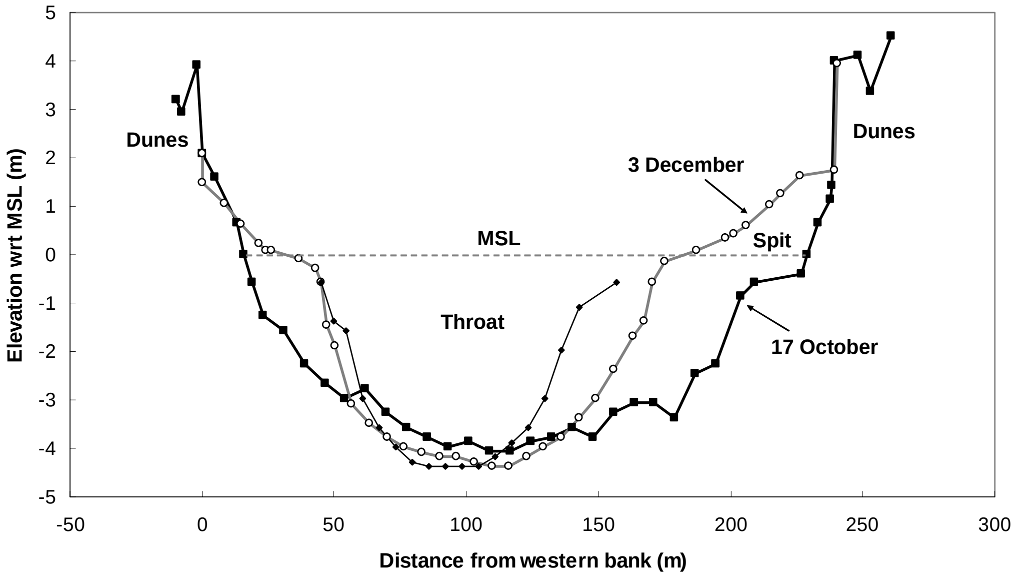


Figure 3.19 Changes in cross-sectional area of the Opotiki river entrance, October – December 2003. Surveys were performed by echosounder and corrected to mean sea level.

Table 3.3 Measured changes in Opotiki entrance cross-section characteristics relative to mean sea level.

	Width (m)	Mean depth (m)	Maximum depth (m)	Cross sectional area (m^2)	Percent change in cross sectional area
17 October	213.4	-2.48	-4.38	529	-
7 November				xxx	
3 December	150.7	-2.63	-3.95	392	25 %

3.6 Tidal prism calculations

Using the surveyed entrance cross-sections and velocity data obtained on October 17th and November 7th a tidal prism was calculated for each day (Table 3.4). Of note, the cross-sectional area of the entrance reduced by approximately 25% between experiments. Despite the reduction in entrance cross-section the calculated flood and ebb prisms are remarkably consistent between measurement periods. Results further highlight the ebb dominance of the entrance with the ebb prism being 1.7-2.0 times larger than the flood prism. To compensate for the smaller cross-section, peak discharges are larger during the second measurement period.

Table 3.4 Summary of tidal prism and peak discharge calculations at the Opotiki Entrance, October 17 and November 7, 2003.

	Ebb Prism (10^6 m^3)	Flood Prism (10^6 m^3)	Peak Ebb Discharge (m^3/s)	Cross Sectional Area (m^2)	Peak Flood Discharge (m^3/s)
17 October	3.54	2.1	327	529	140
7 November	3.67	1.8	439	400	177

Tidal prism calculations are consistent with observations that the entrance was recovering from a significant scour event that occurred in early October. The significant decrease in cross-section and increase in peak discharges, under conditions of near constant tidal prism suggests the entrance cross-section was ‘overfit’ for flow conditions in October , which was conducive to deposition in the entrance.

4 IMPLICATIONS REVISED CONCEPTUAL MODEL OF OPOTIKI ENTRANCE DYNAMICS

Critical to the feasibility of inserting river training structures at the entrance is refinement of the conceptual model of the spatial and temporal dynamics of the river mouth previously developed by Dahm and Kench (2002). This initial model was based on desktop analysis of the Opotiki entrance, a review of behaviour of similar sized river entrances and empirical relationships well-established in scientific literature. This study afforded the opportunity to refine this crude model and validate the theoretical assumptions upon which it was based.

4.1 Background

Naturally occurring river entrances (or tidal inlets) are commonly bounded by sand spits on either side of the channel (as is the case at the Opotiki entrance, Fig. 3.3). Tide, wave and river processes act to transfer energy and materials between the open coast and estuarine environments and control the size of the inlet channel (Bruun, 1978, 1989; Walton and Adams, 1976; Hume and Herdendorf, 1992). River entrances are highly dynamic coastal landforms that change their configuration (cross-sectional area, width and depth), and position on the coast continuously in response to changes in river flow, wave and tidal processes (Hume and Herdendorf, 1992; Kench and Parnell, 1991).

At any point in time the dimensions of the entrance gorge reflect the dynamic balance between the forces acting to keep the channel open (i.e. the river and tidal flows) and those forces which act to close the entrance (i.e. sediment carried into the channel by waves and currents). Consequently, as a natural process, river entrances can migrate alongshore and show considerable variation in width, depth and cross-sectional area over time in response to changes in tidal, wave and river processes and sediment supply.

4.2 Tidal prism v cross-sectional area relationship

Studies from many larger inlets have shown that a sensitive relationship exists between the tidal prism or peak discharge and channel cross-sectional area (O'Brien, 1931, 1969; Jarrett, 1976; Bruun, 1978). Figure 4.1 shows this relationship for a number of New Zealand inlet systems and includes the data obtained from the Opotiki entrance.

However, both Opotiki data points are situated above the equilibrium slope. The October data shows the entrance position was furthest from the equilibrium slope and signifies the entrance cross-sectional area was too large for the measured tidal prism. The subsequent measurement in November is positioned closer to the equilibrium slope and signifies infill of the entrance. The data also show the entrance was able to undergo further (but minor) contraction before it conforms to the equilibrium slope. This supported by other evidence presented in Section 3.0 of flood scour prior to measurement and documented contraction of the entrance cross-section. These results are also consistent with the known rapid morphological adjustment of river entrances (Kench and Parnell, 1991; CCNZL, 2000).

The readjustment of the inlet cross-section occurs almost instantaneously with each tide. In situations where the tidal prism increases a greater erosive force is exerted on the boundary and the cross-sectional area can increase. In contrast, reduction in the tidal prism promotes sedimentation and a decrease in cross-sectional area. In situations where rivers discharge to the coast the tidal prism can change markedly between low and high river flows with consequent dramatic changes in inlet configuration as shown at Opotiki (Fig. 4.1)

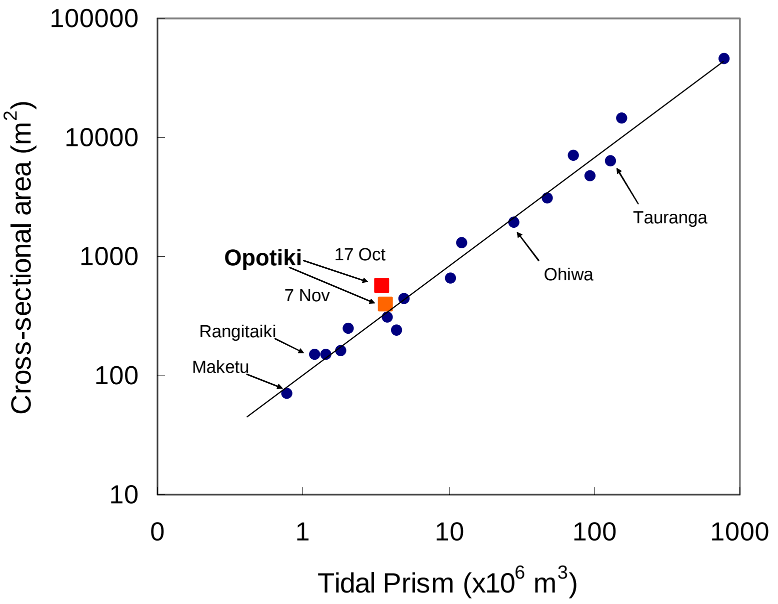


Figure 4.1 Tidal prism cross-sectional area relationship for New Zealand inlet systems including measurements at the Opotiki entrance.

4.3 Morphological dynamics of the entrance cross-section

Table 4.1 presents summary statistics of the morphological dimensions of the Opotiki Entrance and comparison with other small entrances in New Zealand. Significantly these smaller entrances have small tidal prisms and relatively high catchment runoff. During periods of low flow the entrances are almost solely reliant on the tidal prism for flushing. Studies at the Waipu and Rangitaiki River entrances show these small entrances to experience large fluctuations in tidal prism related to the variable nature of river flow. Table 4.2 summarises changes in tidal prisms at these inlets and indicates that river floods can more than double the tidal prism. As noted in Section 3.1 river flow can vary enormously in the Opotiki system ranging from 5 to more than 2000 m^3/s (1600 cumecs measured in the flood on October 3 and 4, 2003). Such large variations in river flow can more than double the tidal prism at the entrance.

Table 4.1 Morphological, tidal prism and river flow characteristics for east coast tidal inlets and river entrances.

Site	Spring tidal prism (10^6 m^3)	Throat width at HT (m)	Max. Throat Depth at HT (m)	Throat Area at MT (10^3 m^2)	Mean daily runoff (m^3/s)	Ratio runoff to prism
*Opotiki	0.95-2.8	150	3.2	0.28	29	30.5
Rangitaiki	1.22	70	5.5	0.15	71	58
Waipu	1.82	132	3.5	0.16	5	2.74

* Data presented by Dahm and Kench based on secondary sources.

Table 4.2 Influence of river floods on entrance tidal prisms.

	Spring Tide Prism (m^3)	Prism enhanced by river flood	Percent increase in prism due to flood
Waipu River*	1 820 532	3 678 000	102%
Rangitaiki River**	1 221 284	3 706 912	203%
Opotiki River	3 700 000	17 000 000	450 %

*Kench 1990, ** Coastal Consultants 2000. Opotiki based on a flood discharge of 800 cumecs for 6 hours. This is considered an underestimate of peak flood prism.

Available data indicates that large fluctuations in tidal prism exert a major control on entrance cross-section characteristics. Table 4.3 presents a summary of the monitoring at the Opotiki entrance with data from similar monitoring at the Waipu and Rangitaiki entrances. These records illustrate that small river-dominated entrances and in particular the Opotiki entrance, are susceptible to large changes in width and cross-section over very short timeframes in response to fluctuations in tidal prism, which is strongly influenced by river discharge.

Table 4.3 Morphological change in river entrance dimensions relative to mean sea level.

Opotiki Entrance				Waipu Entrance			Rangitaiki Entrance			
Month 2003	Width (m)	Mean depth (m)	CSA (m^2)	Month 1989	Width (m)	CSA (m^2)	Month 2001	Width (m)	Mean depth (m)	CSA (m^2)
Oct	213.4	2.48	529	May	96	122.5	March	48	3.10	148.3
Nov	XXX	XXX	XXX	June	194	187.5	June	67	2.62	175.4
Dec	150.7	2.63	397	July	160	192	Sept	51	2.90	146.9
-				August	110	165	Dec	70	3.40	244.0

* Kench, 1990; ** Coastal Consultants, 2002.

During low flow periods the entrance is likely to infill with sediment leading to a decrease in width and cross-sectional area. Under such conditions marine processes dominate the entrance and wave and flood tide currents transport sediment into the entrance channel.

In summary, the Opotiki entrance is morphologically dynamic varying in cross-sectional are by a factor of at least two. Periods of river dominance scour the entrance, whereas periods of low river flow (dominated by marine processes) produce entrance narrowing and shallowing.

4.4 Opotiki entrance migration

In addition to the dynamic variability experienced in entrance cross-sectional area in response to varying river flows, the entrance has historically demonstrated a slow but significant trend for westward migration over the period for which records are available. For instance, the earliest available shoreline survey (SO 2810 conducted in 1866) indicates that the entrance gorge lay 900-1100 m east of the present position, indicating an average rate of westward migration of about 7.5-9.5 m/yr over this period. This westward migration is continuing but appears to have been slower in recent decades. For instance, comparison of aerial photographs flown in 1940 and 2002 indicate westward migration of about 170 m over the last 62 years, an average rate of migration of about 2.8 m/yr.

The westward migration observed over the last 140 years appears to relate both to river channel changes and to westward growth of the spit on the eastern side of the entrance. Significant river channel changes appear to have been a major factor in the entrance alterations between 1866 and the 1940's.

Aerial photographs indicate that while there has been westward extension of the spit, it has become narrower. In 1940, the spit was approximately 155 m wide at its narrowest point - compared to only 80 m in February 2002 (aerial photograph SN50110c, No. 23/9, NZ Aerial Mapping), similar to the surveyed width in 2003 (Fig. 3.6). The narrowing relates primarily to erosion on the inside (harbour) margin of the spit, probably during floods. It is possible the spit will eventually be breached by river flows and/or storm wave washover. Breaching is most likely to occur at the narrowest point of the spit, presently located about 300 metres east of the entrance. Such an event would pose a major threat to the effectiveness and maintenance of river training works. Consequently, it is recommended that the spit width is monitored and plans to avoid spit breaching be developed.

4.5 Ebb delta

The ebb tide delta plays an important role in sediment storage and transport in the coastal system. Deltas act as a “bridge” across an entrance, enabling sediment being moved along the coast to bypass the entrance. The precise mechanism by which sediment bypasses the entrance can vary (Bruun and Gerritsen, 1959; Fitzgerald, 1982, 1988). However, at entrances like Opotiki the main mechanism is typically a form of bar bypassing known as ebb tide delta breaching (Fitzgerald, 1988).

In ebb tide delta breaching the dominant direction of littoral drift produces a preferential accumulation of sediment on the updrift side of the ebb tide delta, the eastern side at Opotiki. At Opotiki, this sediment accumulation causes a downdrift (i.e. western) deflection of the main ebb channel, evident in the survey conducted by Martin McCaulay Morton Ltd. On some occasions, particularly during very low river flows, the channel can be severely deflected and almost run along the face of the western shoreline. However, during high river flows at Opotiki, the main channel cuts a path directly seaward through the ebb tide delta. This cuts off a large portion of the delta (on the western side of the entrance), which slowly migrates landward welding to Waiotahi Beach - thereby completing the bypassing of the entrance. GPS surveys indicate the effect of channel straightening on the form of the lateral flood shoal at the end of the eastern spit.

A more subtle and longer-term form of bypassing may also operate at Opotiki. This process is known as inlet migration spit breaching (Fitzgerald, 1982; 1988). With this mechanism the spit on the updrift side of the entrance gradually extends resulting in alongshore entrance migration – to the west at Opotiki. As the spit extends, it tends to become narrower and is eventually breached by high river flows, forming a new entrance at the point of breaching. The area of the spit cut-off on the downdrift side of the new entrance is thereby bypassed. It is not clear that this form of bypassing has operated at Opotiki. However, the gradual extension and narrowing of the spit on the western side of the entrance suggests this form of bypassing could occur (see Section 4.4).

It can be seen from the above discussion, that the pattern of bar and channel movements observed at Opotiki entrance are critical to the natural operation of the sediment system, particularly to bypassing of sediment across the entrance. However, this process gives rise to extreme difficulties for navigation. Dahm and Kench (2002) indicated the net annual input of sediment to the ebb delta was low (approximately 15 – 20 000 m^3). In contrast, they stated that large volumes of sediment are likely to be recirculated on the ebb delta in the short-term (of the order 10^5 m^3/y). Such large fluxes occur as a result of the large changes in morphology and position of the entrance and associated ebb delta. For example, based on analysis of differences in area of the spit and flood shoals (Fig. 3.18), it is estimated that 28 000 m^3 of sediment was deposited on the eastern spit tip and ebb shoal between October and December 2003. This value is likely to represent an underestimate of the actual flux of sediment. This first order estimate provides confirmation that annual fluxes around the ebb delta and spit are of the order 10^5 m^3.

4.6 Summary conceptual model of entrance dynamics

Process controls on entrance dynamics

- The measured flood-tide prism at the Opotiki entrance ranges from 1.8 -2.1 x 10^6 m^3.
- The measured ebb-tide prism at the Opotiki entrance ranges from 3.5 – 3.7 x 10^6 m^3.
- The Opotiki entrance is ebb-dominated with regard to the velocity, duration of flow throughout a tidal cycle and net sediment transport.

- The entrance experiences extreme short-term variations in discharge controlled largely by seasonal and storm-driven changes in river flow that range between 5 to 2500 m^3/s.
- The entrance experiences low to moderate wave energy. Dominant wave energy is experienced during episodic storm events. Marine influences on entrance hydrodynamics are most dominant during periods of low river flow.

Sediment transport at the Opotiki entrance

- The Opotiki entrance is on a low drift coast. Alongshore transport is in a westward direction at the Opotiki entrance.
- Sediment is transported past the entrance through the processes of bar-bypassing.
- Estimates of net alongshore sediment transport range from 6 000 – 8000 m^3 per year.
- Delivery of river sediment to the entrance is estimated at 15 000 m^3 per year. Observations of bed sediments dominated by gravels in the lower river indicate such a volume may be an overestimate. The volume of sediment is likely to be controlled by the frequency of floods.
- Combining estimates of sediment delivery from both sources approximately 20-25 000 m^3 of sediment may be delivered to the Opotiki entrance on an annual basis. This value is used as a conservative ‘best estimate’. Recognising the uncertainty of sediment transport estimates it is recommended that a low value of 10 000 m^3/y and a high value of 40 000 m^3/y is adopted for design of river training works.

Morphological change at the entrance

- The morphology of the Opotiki Entrance and bar is controlled by the balance between marine and river processes. Seasonal variations in river discharge promote winter widening and summer shallowing (when wave processes exert a stronger influence).
- Changes in entrance morphology can also occur over short timeframes (days to months). Under extreme river discharges the tidal prism and peak entrance discharges produce significant scour of the entrance.

- Marine processes dominate the entrance under low river discharge periods and during periods when storms generate significant wave energy at the coast. Under these conditions wave-driven currents transport sediment toward the entrance promoting sedimentation and reduction in cross-sectional area. Observations confirm the rapid infill of entrance cross-section (544 to 392 m^2) over a two month timeframe. Minimum entrance cross-sectional area is estimated to be as low as 70 m^2 under sustained low discharge periods.

Ebb delta morphology and morphological change

- The ebb delta at the Opotiki entrance is the major subtidal sediment sink within the entrance system.
- The delta experiences seasonal and event-driven changes in position of the channel that flows across the delta.
- During periods of mean and low river discharge the channel assumes an oblique angle to the coast. This is controlled by the extended position of the western spit that promotes northwestward deflection of the channel as it exits the entrance and westward littoral drift.
- Under extreme floods the channel assumes a more perpendicular orientation to the coast, thereby cutting-off a section of the bar that is able to weld to the western shoreline.
- This cyclic channel migration and bar splitting provides the mechanisms for westward alongshore sediment transfer.
- The gross rate of sediment flux on the ebb delta is considered to be at least an order of magnitude larger (10^5 m^3) than the net rate of sediment transport at the entrance (10^4 m^3).

5.0 IMPLICATIONS FOR ENTRANCE TRAINING WALLS

The earlier desk-top review (Dahm and Kench, 2002) noted that dual entrance training walls (also known as moles or jetties) were likely to be the most effective option to achieve medium to long term improvements in navigability at the Opotiki Harbour entrance.

However, the report also highlighted a number of issues requiring further consideration before firm decisions or otherwise could be made on the practicality or appropriateness of the dual mole option, most notably:

- The potential for significant scour between the training walls during high flows
- The potential for the moles to impact on flood release
- The need to ensure the walls were not outflanked by upstream bank erosion
- Interruption of longshore sediment bypassing at the entrance and associated impacts on updrift and downdrift shorelines
- Life span of navigation improvements

This section provides further comment on these issues in the light of the preliminary field investigations and modelling conducted during this investigation. Implications for practicality and success of the measures are then assessed, together with cost implications.

5.1 Entrance Scour

Background

The earlier report identified the potential for serious scour between twin training walls at the Opotiki entrance during high flows, noting that expensive scour protection works could be required to avoid such damage (Dahm and Kench, 2002). Scour is a frequent source of damage to entrance moles.

The issue is particularly relevant to the spacing of any moles. A narrow spacing may ensure good navigational improvements but could also result in excessively severe scour, requiring expensive protection works to avoid undermining of the walls. A narrow spacing may also impact on flood release and aggravate upstream flood levels.

Alternatively, with a very wide spacing, desired navigational improvements may not be obtained or the thalweg (main flow/channel) may meander within the walls and complicate navigation. Ideally, a spacing is required that is sufficiently narrow to ensure desired navigational improvements while also avoiding the potential for excessively severe scour.

The issue of scour is also relevant to the orientation of the walls. The channel between the confluence and the entrance is orientated at an oblique angle to the shoreline, discharging at an angle of approximately 45 degrees (Fig. 3.3). Therefore, flows will tend to impinge directly on the training wall on the western side of the entrance before being redirected seaward. The concentration of flow against the training wall has the potential to result in scour during high flows.

Methods used to assess of scour between training walls

In detailed design of training walls, physical and/or numerical modeling is usually undertaken to determine optimum wall configuration, including spacing, orientation and length. However, such detailed work is beyond the scope of this study. Nonetheless, useful indication can also be obtained with careful use of empirical models. For example, the well-established and simple empirical relationship between tidal prism (P) and entrance cross-sectional area (e.g. O’Brien, 1932; 1969; Jarrett, 1976; Hume and Herdendorf, 1992), discussed in Section 4.2, is commonly used to estimate required training wall spacings at tidal inlet entrances. Some workers have developed relationships specifically for jettied entrances, using numerous field measurements from such environments (Jarrett, 1976).

However, these relationships, while useful for tidal flow conditions (e.g. see Sections 3.0 and 4.0), are difficult to use at environments like the Opotiki entrance where peak river flows exert the primary influence on scour. The relationships are also relatively crude in that tidal prism is simply a proxy for the factors that directly determine equilibrium entrance cross-sectional area (e.g. peak discharge; peak average velocity). The tidal prism-entrance area relationships also fail to take into account complexities such as variation in sediment characteristics, which can exert a major influence on scour (e.g. Hughes, 1999).

However, recent work by the United States Army Corps of Engineers (USACE) has developed a simple expression that can be used to estimate equilibrium scour depth, $h_{e,}$ at jettied entrances as a function of maximum discharge per unit width, q_e, and sediment size, d (Hughes, 1999; 2002). The scour depth, relative to the tide level at maximum discharge, is given by:

$$\boldsymbol{h_e = 0.234q_e^{8/9}{}_{/}\,[g(S_s - 1)]^{4/9}\, d^{1/3}}$$

The relationship was tested and refined using data from dual-jetty systems in the United States and the estimates of equilibrium scour depth are considered conservative (deeper than might actually occur for the specified discharge) as the formula represent the outer envelope of the field data (Hughes, 1999).

The field data collected during this study also provides two sets of measurements that can be used to test the applicability of the USACE procedure in regard to prediction of scour at the Opotiki entrance:

- The enlarged entrance cross-section surveyed on 16 October 2003 – arising from the floods earlier in October.
- The entrance cross-section surveyed on 3 December 2003, which appeared to be approximately in equilibrium with tidal conditions prevailing at that time (though possibly slightly enlarged by the small fresh of 27 November – see Figure 3.1).

The section surveyed in November is not useful for testing the procedure as it is was out of equilibrium with prevailing conditions – the entrance at that time still adjusting (narrowing and infilling) following the scour during the floods of October 2003 (see discussion in Section 3.0 and Fig. 4.1). The scoured depths measured at this time almost certainly do not reflect prevailing flow conditions.

In order to test the procedure, the maximum and average depths measured on the October and December cross-sections were compared to the maximum scour estimate provided by the USACE procedure. The cross-sections used for the calculations are shown in Figure 5.1. As field observations suggest that there may have been some infilling on the eastern side of the scoured entrance prior to the survey of October 16 (Section 3.3), the calculations for this section were conducted using both the measured section and an "adjusted" section – the latter deepened on the eastern side to RL-4m to correct for any post-flood infilling that may have occurred (Figure 5.1).

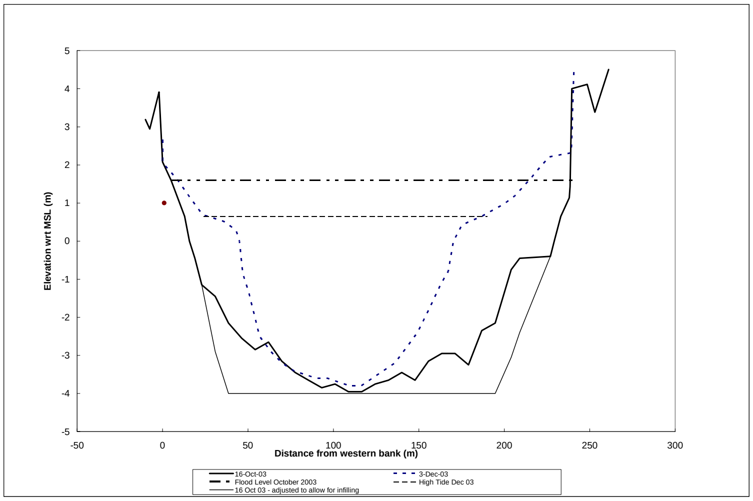


Figure 5.1 Cross sections used for testing of USACE scour model.

The peak flow rates used for the calculations are shown in Table 5.1. The peak discharge used for the October floods was based on the maximum combined flow of the Otara and Waioeka Rivers measured during the two floods, this peak flow occurring in the first of the two floods (see Section 3.1). No current measurements were conducted at the time of the December survey and therefore we used the highest peak flow rate recorded during the previous two measurements (see Section 3.4).

Table 5.1 Comparison of measured and predicted scour depths for post flood conditions of October 2003 and the low flow conditions of December 2003.

Date	Peak Flow (m^3/s)	Width at peak flow (m)	Discharge per unit width ($m^3/s/m$)	Average Measured Scoured Depth (m)	Maximum Measured Scoured Depth (m)	Estimated Max. Scour (USACE Procedure)
October 16	1600	233.5	6.9	3.55	5.55	6
October 16 (adjusted)	1600	233.5	6.9	4.21	5.6	6
December 3	440	125	3.6	2.63	3.8	3.5

In regard to the October measurements (post-flood), the maximum predicted scour is higher than both the *average* and the *maximum* measured scour depths – even when the measured cross section is adjusted for infilling that may have occurred prior to the survey (Table 5.1).

In addition, the *measured* depths noted in Table 5.1 may be slightly over-estimated – in which case the predicted scour would be more precautionary. The measured depths given are with respect to the peak flood level recorded during the two floods (R.L. 1.6 m, Fig. 5.1) – as leveled from a flood-deposited debris line on the river margin of the spit. However, while the maximum scour probably occurred during the earliest and largest of the two floods, locals indicate that the maximum water levels in the lower river were observed during the second and lesser flood - due to tidal influences.

Overall, it appears that the USACE procedure provides reasonable, but also precautionary estimates of maximum scoured depth for the flood conditions experienced in October.

In regard to the low river flow conditions of early December, the maximum predicted scour exceeds the *average* scoured depth measured and is only marginally less (0.1 m) than the *maximum* measured scour depth. Therefore, in this case also, the procedure appears to provide reasonable estimates of scoured depth. Moreover, a small fresh passed through the lower river on 27 November (Fig. 3.1), only a few days before the December survey. Therefore, the peak flow rate that shaped the December cross section was probably somewhat higher than the gauged peak flow from November (440 m^3/s) used for the calculations. Use of a higher peak flow in the calculations would increase the estimated scour.

While it is not possible to draw definitive conclusions from this data set, the procedure provides reasonable and precautionary estimates of both average and maximum scoured depths over a wide range of flow conditions. Therefore, we have adopted the USACE procedure to provide preliminary design estimates of scour for different training wall spacing.

However, it is important to bear in mind that the procedure is only designed to provide estimates of depth where scour is caused by the maximum discharge. The procedure is not designed to predict scour depths formed by vortices associated with flow separation, or depth increases associated with the influence of waves in a channel (Hughes, 1999). Therefore, scour effects in complex environments such as the ends of the training walls will need to be assessed with physical modeling during detailed design.

Spacing required to ensure desired navigation improvements

The brief for this study specifies that commercial use of Opotiki Harbour would require a navigable entrance channel with a minimum depth of 2.5m below mean spring low water. The USACE procedure is used to estimate the minimum wall spacing likely to be required to achieve this scoured depth at low to normal flows – the most prevalent flow conditions.

Velocity measurements conducted during this investigation suggest that peak discharge during low to normal river flows (combined river flows of only 10-25 m^3/s or less) is of the order of 300-450 m^3/s (Section 3.0). Therefore, an average peak flow of 375 m^3/s has been assumed for the purposes of calculations. Figure 5.2 presents the maximum scoured depths likely to form under these flow conditions, with various wall spacings, as estimated using the USACE procedure.

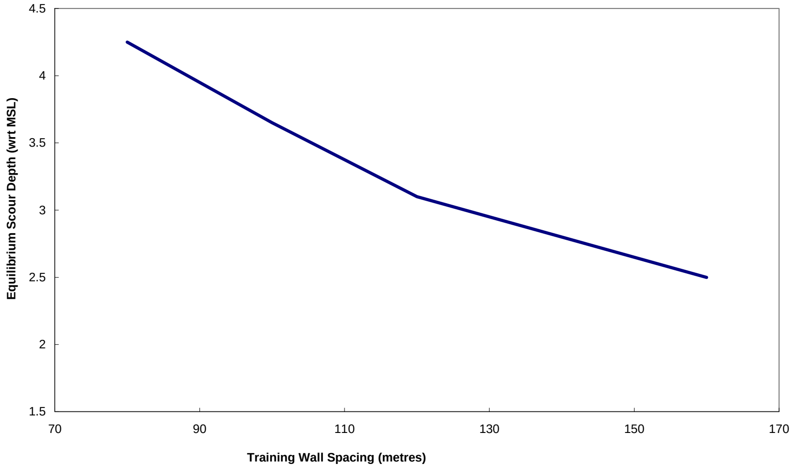


Figure 5.2 Estimated scour depth of the Opotiki entrance for normal flow conditions with varying training wall spacing.

These calculations suggest that a wall spacing of 120 m or less would be required to achieve design depths.

However, these calculations only consider scour related to peak discharge. It should be highlighted that the presence of training walls will preclude the large volume of sediments presently transported into the entrance via flood tides and waves. This will increase the dominance of ebb-directed sediment transport at low to normal flows and is likely to lead to deepening of the channel. Moreover, with minimal sediment transported down the river channel during normal flows (Section 3.0), the scoured cross-sections formed by high flows will probably tend to persist – with only limited infilling likely between high river flows. Therefore, the minimum desired scour depths might possibly be obtained with wider wall spacing if this proves to be required.

Assessment of maximum likely scour at peak flows

Assessment of the maximum likely scour during high river flows is necessary to estimate the minimum wall spacing required to avoid excessive scour.

As noted in Section 3.5 the elevation of the deepest scour (about R.L. –4m) did not vary between the post flood measurement of October 2003 and the normal flow cross-section of December 2003. Rather than deepening, the flood scour widened the entrance (Fig. 5.1).

We believe this is probably a function of sediment characteristics. Our investigations noted that sediments above R.L. –4m tend to be sandy (typically with a modal grain size of about 0.25 mm) while deeper areas appeared to be largely fine gravels (size range of 2-25 mm, with modal grain sizes about 8 and 16 mm; Section 3.3 and Appendix 1).

Gravel sediments require much higher scour velocities than sands. Figure 5.3 shows the maximum velocities required to scour sands of 0.25 mm are about half those required to scour coarser sediments of 2 mm and 4 mm – as estimated using the procedure of Hughes (1999). As the modal grain size of the fine gravels is actually about 8-16mm (Appendix 1), the scour velocities required for these materials would be even higher than shown in figure 5.3 (The data used by Hughes does not appear to have included sediment with modal grain sizes as coarse as 8-16 mm and so we have not used the method to estimate the scour velocities for these sizes).

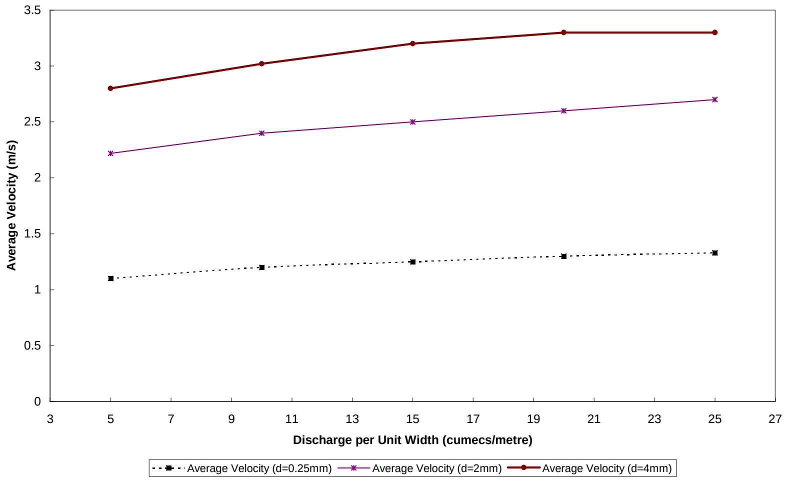


Figure 5.3 Scour velocities required for differing sediment sizes determined using the procedure of Hughes (1999, 2002). d in legend refers to mean sediment sizes stipulated.

Therefore, as flood velocities increase, it is probable that the sands on the side of the entrance channel begin to scour much earlier than the gravels in deeper areas – so that the entrance tends to widen rather than deepen in response to high flows.

However, once training walls and associated scour protection are in place, widening will be limited and most scour will occur by deepening. The depths of scour that can potentially occur under these circumstances depend on the nature of the bed sediments (Figure 5.4). In those areas where gravels are present, there is likely to be much less scour than areas where subsurface sediments are primarily fine sands (Figure 5.4).

Figures 5.5 to 5.8 show maximum predicted scour depths likely to be associated with mole spacings ranging from 100-160m for different mean sediment sizes. It can be seen that the maximum predicted scour with a channel composed of fine gravel is less than half that predicted for a channel composed of fine sand. For example, with training wall spacing of 120m, potential maximum scour is 16 m for fine sand (d=0.25 mm) compared to only 6-8 m for fine gravel (d=2-4mm, Fig. 5.6). As the gravels at depth in the Opotiki entrance are generally coarser than 2-4 mm (Section 3.3), the maximum likely scour depths will probably be less.

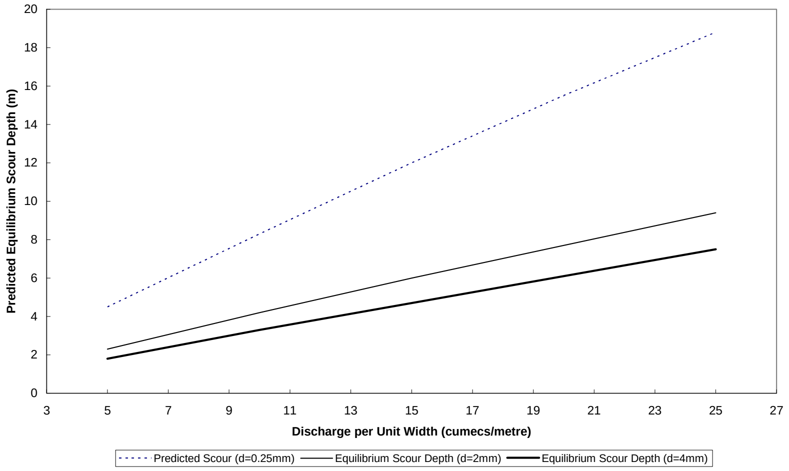


Figure 5.4 Variation in predicted scour as a function of sediment size. d in legend refers to mean sediment sizes stipulated.

Therefore, in areas in which gravels predominate below RL –4m, the maximum scour associated with peak flood discharges will probably be less than less than 6-8m relative to water levels at peak flows – provided that flow vortices are avoided. Water levels at peak flow will depend to some extent on tides and storm surge but will probably be at least RL 1.5-2m for peak discharges (higher at design water levels – see Section 5.2). Therefore, in areas with gravels at depth, maximum scoured depths seem unlikely to extend below about RL –6-7m, even with peak discharges of about 2500 m^3/s. However, in areas where fine sands predominate, scour may be very considerably deeper.

As gravels will probably predominate at the landward end of the walls and sands further seaward (where decelerating flood velocities may not be competent to transport coarser sediments), it is possible that higher levels of scour will be observed towards the seaward end of the walls. However, once training walls are in place, it is also possible that gravels may gradually extend along the full length of these features – so that the potential for scour will decrease over time.

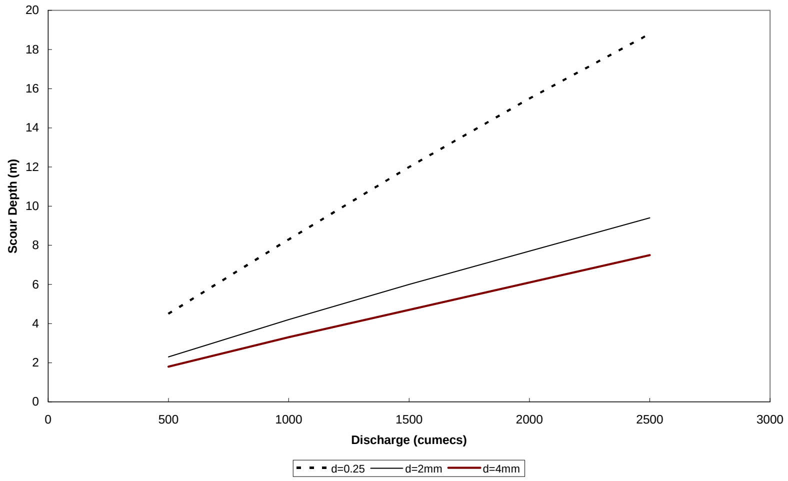


Figure 5.5 Variation in predicted scour depth with sediment size for wall spacing of 100m.

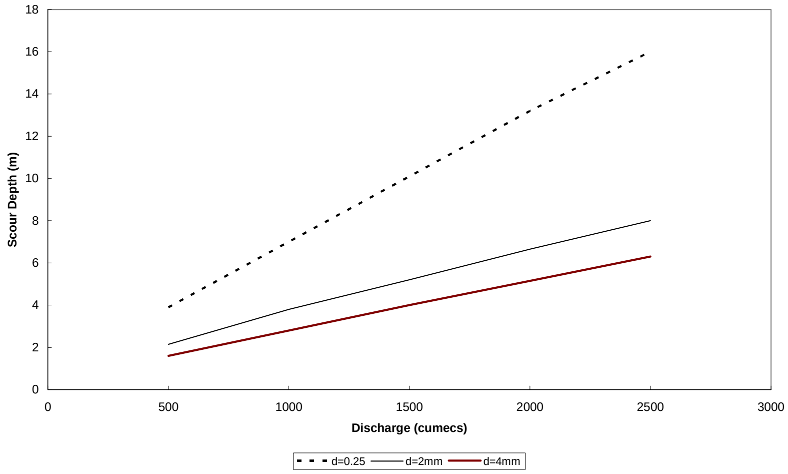


Figure 5.6 Variation in predicted scour depth with sediment size for wall spacing of 120m.

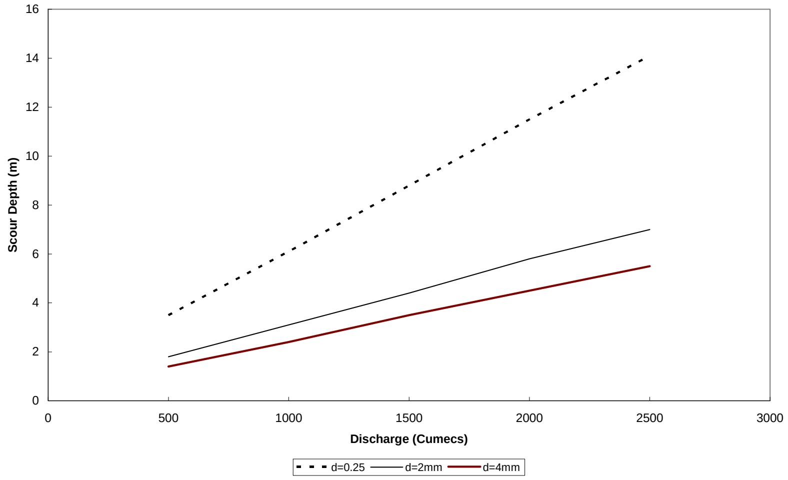


Figure 5.7 Variation in predicted scour depth with sediment size for wall spacing of 140m.

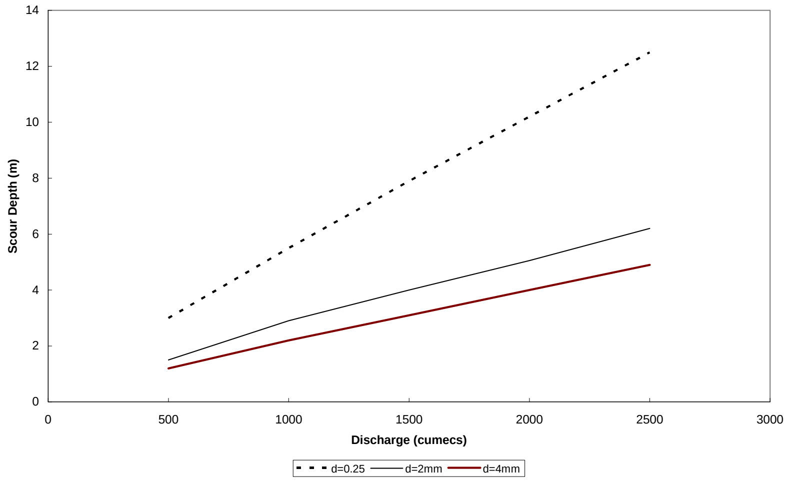


Figure 5.8 Variation in predicted scour depth with sediment size for wall spacing of 160m.

As noted earlier, with moles perpendicular to the shoreline, river flow will impinge on the landward end of the western training wall promoting scour. However, gravels that line the entrance channel may limit scour.

The seaward extent of gravel is unknown. Scour is likely to be much greater in areas without gravel. Consequently, further investigations will be required during detailed design to assess the nature of subsurface sediments and geology over the full length of the training walls. Scour should also be further examined by physical modeling during detailed design, including the potential for scour at the end of the walls due to the interaction of peak discharges and waves.

Summary

- Scour calculations suggest that a mole spacing of 120 m or less would be required to scour the entrance channel to the desired navigational depths. However, the effect of the training walls on sediment transport may mean that the desired depths could be obtained with wider wall spacing.
- The maximum scour likely to occur with peak flows will be heavily dependent on subsurface sediment characteristics and, to a lesser extent, on wall spacing. In areas of fine sand, there is potential for deep scour during peak flows – possibly up to 18 m depending on wall spacing. In areas with subsurface gravels (or other materials

limiting scour), maximum scour depths are likely to be less than 6-8m below flood level.

- Scour protection is likely to be required to at least R.L. –4m, regardless of wall spacing, due to the prevalence of sand above this depth and the tendency of the entrance to widen rather than deepen during peak flows.
- Subsurface investigations and physical modeling will be required during detailed design to finalise scour protection requirements.

5.2 Flooding

Opotiki is located on a low-lying flood plain and has a long history of flooding problems associated with both the Otara and Waioeka Rivers – with major floods in 1918 and 1964 and a large number of lesser events (Ericksen, 1974). The risk from flooding is aggravated by complex energy losses at the confluence of the Waioeka and Otara Rivers, where peak flows from the two rivers virtually meet head on (UniServices, 2001; EBoP, 2001).

In response to flooding problems, stopbanks and other protection works have been undertaken over time. The present stopbanks are designed to provide protection to the township from flood events up to and including a 1% AEP event, with 450mm freeboard (Mr Peter Blackwood, Environment Bay of Plenty, pers. comm., February 2004). The stopbanks have been designed using a computation hydraulic model built by Environment Bay of Plenty using Danish Hydraulic Institute Mike11 and Mike11-GIS software (EBoP, 2001) and a physical model of the confluence area (UniServices, 2001).

It is important that any entrance training walls do not aggravate flood levels around the township and thereby compromise the level of flood protection provided by existing works.

In order to assess the potential impact of training walls on water levels under design flood conditions, various entrance training wall options were evaluated using the computational hydraulic model developed by Environment Bay of Plenty.

There are some uncertainties and limitations with the existing model. These include:

- The complex effects that occur at the confluence during major flows in the Waioeka and Otara are difficult to accurately model.
- The entrance cross-section used in the existing model does not allow for scour that may occur during floods.
- Additional cross-sections are probably required to more accurately schematise the bathymetry below the confluence.

Notwithstanding these limitations, the numerical model has been carefully calibrated and verified using water levels measured after past floods, and is regarded as providing adequate information for flood level predictions (Wallace, 1999). Therefore, we believe it is quite adequate for the indicative modelling required for this report. However, if it is decided to proceed with the training walls, more sophisticated modelling will be required for detailed design.

Modelling looked at the impact of the training walls on design flood levels relative to existing design predictions used for flood protection for both the Waioeka and Otara Rivers. The design flood scenarios adopted for the modelling were the same as those used for design of the existing stopbanks, namely:

- A 100-year (1% AEP) flood in the Waioeka River combined with a 20-year (5% AEP) flood in the Otara. This option was used to model impact of the training walls on flood water levels in the Waioeka River.
- A 100-year flood in the Otara River combined with a 20-year flood in the Waioeka. This option was used to model the impact of the training walls on water levels in the Otara River.

The downstream boundary conditions assumed a 5% AEP storm surge elevation and an allowance of 0.49m for projected sea-level rise over the next 100 years, as adopted for stopbank design. It is important to include consideration of projected sea-level rise, as the training walls are likely to have a design life of at least 100 years.

Modelling was undertaken using a range of training wall spacings ranging from 100-160 m, considered to be the narrowest and widest spacing appropriate at this site. A length of 500 m was assumed for the walls, the approximate length likely to be required for any training walls at this site (Opus, 1995; Dahm and Kench, 2002). The modelling assumed that the channel between the training walls will not scour below R.L. –4 m, based on the maximum scoured depths observed after the October 2003 floods. This is a ‘worst case’ assumption (in terms of flood release) and, as noted in the preceding section, it is possible that greater depths of scour may occur. Greater scour would result in less adverse impact on upstream water levels than predicted by the modelling.

The water level profiles predicted for each of the training wall spacings are compared to existing design predictions in Figures 5.9 and 5.10.

In the Waioeka River, modelling suggests that:

- A training wall spacing of 100 m has the potential to increase design flood levels by 100-250 mm in areas adjacent to the township.
- A spacing of 120 m results in flood water levels similar to the design profile (i.e. maintains status quo).
- A mole spacing of 140 m or more is likely to result in lowered flood levels (Fig. 5.9).

Similar results are also observed for design flood conditions in the Otara River above the confluence (Figure 5.10).

Results suggest a training wall spacing of at least 120 m is likely to be required to ensure design flood levels are not elevated.

As noted above, the modelling has made relatively conservative assumptions in respect of scour. If further investigations indicate that greater scour is likely, flood levels will be less than predicted by model results. Nonetheless, any risk of increasing design flood levels is unlikely to be acceptable, given the limited freeboard with the existing stopbanks and the vulnerability of the town to flooding. Detailed investigations and modelling would be required before a spacing of less than 120 m could be adopted.

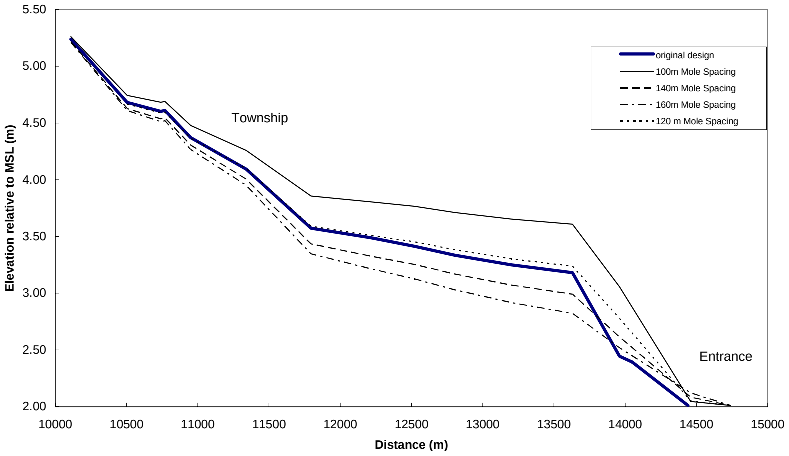


Figure 5.9 Model results of the effect of different mole spacing on design flood levels in the Waioeka River from the entrance to above the Opotiki township.

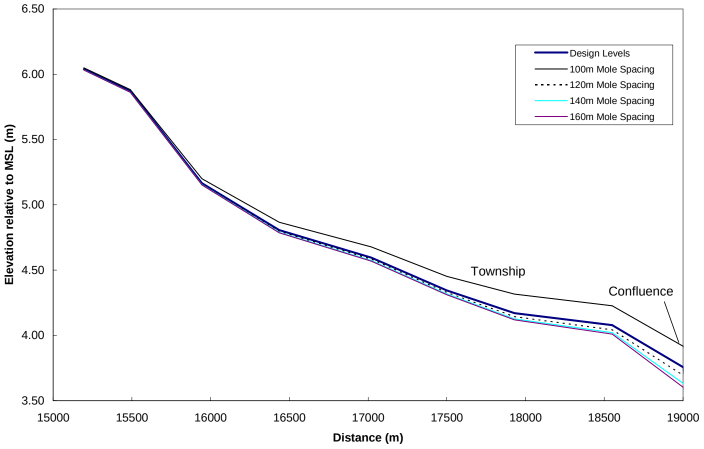


Figure 5.10 Model results of the effect of different mole spacing on design flood levels in the Otara River from the confluence to above the Opotiki township.

5.3 Potential for Walls to be Outflanked

The preliminary assessment report noted that upstream bank protection might be required in some areas to prevent the walls being outflanked (Dahm and Kench, 2002). The primary issues identified related to:

- Outflanking of the landward ends of the training walls due to channel expansion upstream of the walls during floods.
- The potential for breaching of the spit east of the wall by erosion and/or wave overtopping during severe flood or storm conditions.

- An historic trend for westward migration of the entrance.

Channel expansion during floods

The field data from this study indicates that the entrance expands in width during major floods, with erosion of both eastern and western banks. As noted in Section 5.1, scour protection extending to at least R.L. –4 m (and probably deeper) will be required along the entire inside walls of the moles to prevent scour during floods from undermining the structures.

In addition the landward end of both walls will need to be tied back some distance into the adjacent banks to ensure they are not outflanked by scour and bank erosion in unprotected areas immediately upstream.

Potential for spit breaching

Breaching of the spit to the east of the walls is undesirable (see Section 4.4) as it could result in damage to the eastern wall or significantly reduce entrance channel depths.

The height and width of the present spit is such that breaching of the spit does not appear to be an immediate threat. The cross-section surveyed across the spit is reasonably wide (80 m) with well-formed dunes extending to about R.L. 3.5 m (Fig. 3.6).

The narrowing of the spit over the past 50-60 years (Section 4.4) appears to have been largely due to river erosion on the landward side. Field inspection during this investigation indicated that further erosion (typically about 3-5m) occurred along the landward margin of the spit following the floods of October 2003 (Fig. 3.7). While this erosion is relatively minor in relation to the remaining width of the spit, the continuation of this trend could eventually narrow the spit sufficiently to result in breaching – either by erosion and/or wave overtopping.

As stated earlier, action will inevitably be required to minimise erosion along the landward margin of the spit if construction of training walls proceeds. In view of the limited rate of erosion in this area, it would probably be practical to manage erosion using an environmentally soft approach – for instance, pumping dredged sand into the area to widen the spit during construction and maintenance dredging operations. Hard protection is unlikely to be required in the immediate future.

Erosion of the ocean foreshore of the spit appears to be less of an issue. Available data suggests that the shoreline in this area is in, or near, a state of dynamic equilibrium, fluctuating backwards and forwards (Dahm and Kench, 2004). If training walls are installed, further advance of this shoreline may also occur due to trapping of sands on the updrift (eastern) side of the moles and onshore migration of sands from the present bar (once the processes maintaining this feature are disrupted by the training walls).

Entrance migration

As discussed in Section 4.4 the entrance has exhibited long-term westward migration. Experience with entrance training walls indicates that properly designed structures are effective at arresting alongshore migration (Parchure and Teeter, 2002). However, the fundamental causes of the longshore migration have to be considered and design must allow for these.

The westward migration of the Opotiki entrance appears to relate to westward extension of the spit on the eastern side and to changes in the upstream river channel (Dahm and Kench, 2002). The installation of training walls will cease the westward extension of the spit, as the walls will exclude longshore drift from the entrance area.

Erosion of the western bank some 500m upstream of the entrance, where the thalweg impinges directly, also appears to have been a factor in westward migration of the entrance over the last 60-65 years – moving the thalweg westward over time. The negligible westward migration over the last 20 years may be related to the rock armouring of this bank.

In the immediate future, there is probably no further need for rock protection on the western margin upstream of any training wall – provided the training wall is extended well into the adjacent shoreline at its landward end. Nonetheless, ongoing monitoring of erosion upstream of the entrance should be undertaken if training walls proceed.

5.4 Bar Dynamics and Sediment Bypassing

The preliminary study highlighted that twin training walls are likely to have a significant influence on the sediment dynamics and morphology of the ebb tide delta system (Dahm and Kench, 2002), in particular the pattern of sediment circulation and bar morphology, and sediment bypassing. These matters are generally among the most significant issues for entrance training wall structures, impacting on design life of navigation improvements and the potential effects of the training walls on the local environment and adjacent shorelines (Dahm and Kench, 2002).

Sediment circulation and bar morphology

The study has confirmed that large volumes of sediment are recirculated between the entrance and the ebb tide delta (Section 4.5). Sediment discharged seaward from the entrance is deposited on the ebb tide delta (entrance bar) and then recirculated landward by waves. Flood tide dominated channels running close to the beach on both shorelines intercept much of the landward moving sediment and recirculate large volumes of sands back into the entrance channel - aided by wave action which suspends large amounts of sand in the moving water column (Section 4).

The measurements undertaken during this study suggest that, over the period between 16 October and 3 December 2003, something in the order of 28 000 cubic metres on the eastern of the entrance alone by waves and flood tide currents. These large volumes of sediment in active circulation are critical to maintenance of the existing bar.

It is clear from the study that most, if not all, of this sediment is derived from incoming flood tidal flows and that the volumes of sand coming down the river under normal flow conditions is extremely low (Section 3.3).

Once training walls are installed, the sediment circulation pattern will largely be disrupted – as flood tide currents flowing along the face of the shoreline will no longer be able to transport large volumes of sediment into the entrance channel. Flood tide currents will still enter the channel from the seaward end of the walls (during normal flow conditions) but the volumes of sediment transported by these incoming currents will be significantly less, due to the lesser wave action and tidal velocities in this deeper water. This supports the conclusions of Dahm and Kench (2002) that the existing bar will rapidly break down once training walls are in place, with most of this sediment moving landward and attaching to the shorelines on either side of the entrance. This process has also been documented at a number of sites where training walls have been installed.

As discussed in Section 5.1, the breakdown of the existing sediment transport pattern and the constriction of ebb and river flows will significantly increase the dominance of seaward directed sediment transport, promoting scour between the training walls.

These impacts, the breakdown of the existing bar and ongoing scour between the training walls, are likely to significantly increase channel depths. Therefore, the study confirms that training walls are likely to result in significant improvements in navigable depth at the Opotiki entrance.

Sediment bypassing

The existing ebb tide delta plays a critical role in sediment bypassing of the present river entrance (Section 4.5). Once training walls are in place, sediment bypassing will be disrupted until a new bar has established seaward of the walls.

Interruption of sediment bypassing by training walls commonly leads to sediment accumulation against the updrift side of a harbour entrance and to erosion on the downdrift side (Dahm and Kench, 2002). This is probably the single most common adverse effect noted in the literature on jettied entrances. However, the significance of this impact depends largely on the volume of net littoral drift, generally only being a serious issue on coasts with large volumes of net littoral drift.

Available information suggests that the volumes of net westward littoral drift are low in the vicinity of the Opotiki entrance. For instance, Smith (1998) estimated net littoral drift as only 6000 cubic metres per year. Dahm and Kench (2002) estimated the volume of sediment that has accumulated along the slowly prograding Waiotahi Beach west of the entrance, noting that this progradation suggested an average net sediment input of about 8000 cubic metres per year – from both net littoral drift and other net sediment sources (e.g. river input).

Therefore, updrift sediment accumulation and downdrift erosion are unlikely to be a significant issue with training walls at this site. However, over periods of several decades, the effect may lead to the need for sediments to be artificially bypassed. Therefore, in estimating longer-term operating costs for any training walls, it would be prudent to allow for artificial bypassing (e.g. by dredging and pumping) with an average of 6-8000 cubic metres per year likely to be an upper limit.

Design life of improvements and maintenance dredging requirements

Once training walls are in place, a new bar will gradually re-establish due both to sediment trapped on the updrift side of the entrance and to sand/gravel sediments discharged from the river entrance. In the absence of maintenance dredging or other appropriate action, harbour improvements will ultimately diminish as this new bar develops (Dahm and Kench, 2002). At Opotiki this process is likely to be slow due to:

- The low levels of net longshore drift prevalent in this area.
- The limited volumes of sand and gravel sediments discharged from the harbour entrance (Section 3.3).
- Onshore movement of some of the sands discharged from the river entrance
- The large volume of sediment likely to be required to re-establish an ebb tide delta in the depths prevailing seaward of the moles (likely to be in excess of 2-3 million cubic metres).

However, the rate of bar re-establishment will be influenced by the amount of dredging undertaken during installation of walls. If there is limited dredging and sands are left to gradually scour, large volumes of sand could potentially be discharged from the entrance over the first few years (probably in the order of 100-200,000 cubic metres).

Conversely, dredging to form the channel will reduce the volume of sands discharged from the entrance and lengthen the design life of improvements.

The dredged sand could also be used to mitigate erosion on the landward side of the spit and on the downdrift shoreline.

In summary, it is probable that bar re-establishment will be relatively slow and reasonable navigational improvements will be maintained for many decades.

Maintenance dredging requirements

Once the desired depths have been established maintenance-dredging requirements are likely to be very low due to the following factors:

- Ongoing scour of the channel (due to the strong dominance of ebb-directed sediment transport).
- Limited ingress of sediments into the channel during flood tides.
- The relatively low volumes of river sand and gravel that appear to be transported to the entrance.
- Periodic scour by large river flows.

If relatively wide wall spacing is adopted, the thalweg may tend to meander at low flows and this might result in some shoal development within the channel. However, high discharges will likely prevent significant shoal development at the Opotiki entrance. Nonetheless, this aspect should be further examined by physical modeling during detailed design.

At some jettied entrances, sedimentation problems have been experienced with sand moved along the outside of the jetties and into the seaward end by the action of rips and flood tidal currents. We suspect this is unlikely to be a major issue at this site, given the length (probably at least 500 m) of the moles and depths of 4-5 m at the seaward end. In the unlikely event that problems were experienced, remedial measures such as jetty spurs (e.g. Bottin, 1997) can be implemented at a later date.

Sedimentation problems can also be experienced with sand entering the channel through jetty structures that are not sand tight. The potential for this will depend on the final breakwater design adopted. Given the strong ebb dominance and the relatively low volumes of sediment likely to enter by such means, even with a relatively permeable jetty, we consider it is unlikely to be an issue at Opotiki.

Overall, maintenance-dredging requirements seem likely to be minimal – but this will need to be confirmed during detailed design and a precautionary approach should be maintained in the interim (as discussed in section 3.3).

5.5 Summary of Implications for Training Walls

This investigation has enabled the findings of the feasibility study into navigation improvements at the Opotiki entrance to be confirmed and refined. The major findings are:

- Entrance training walls (the twin mole option) are likely to result in significant improvements in navigability at the Opotiki entrance.
- Entrance training walls with spacings of up to 120 m are likely to be adequate to achieve the desired navigable depths (a minimum depth of 2.5m below mean low water spring). The desired navigable depths may also be achieved with wider wall spacings due to the likelihood of ongoing scour of sandy sediment in the area between the training walls.
- A minimum wall spacing of 120 m may be required to avoid exacerbating flood levels. Wider spacings would probably improve flood release.
- Sandy areas within the channel are likely to continue to scour over time due to the dominance of ebb-directed sediment transport, periodic high flows and the limited supply of sands to the entrance.
- Scour protection will be required along the channel margins of the walls to elevations of at least R.L. –4 m due to the prevalence of sandy sediments above this elevation and the tendency of the entrance to widen rather than deepen during floods.
- In areas of fine sands, there is potential for considerably deeper scour to develop during high flows, possibly extending to depths of 12-16 m below flood levels in

some areas (dependent on wall spacing). However, maximum potential scour is likely to be less than half these depths in those areas where fine gravels or coarser sediments occur.

- If the walls are oriented perpendicular to the entrance, a scour hole is likely to form along the western side of the present entrance channel and particular attention will need to be given to scour protection requirements in this area.
- Subsurface sediment investigations will be required along the length of the training wall during detailed design to finalise scour estimates.
- Physical modelling will also be required to further assess scour, optimise wall spacing and orientation and assess wave and current effects (including scour) at the seaward ends of the wall.
- The landward ends of the training walls will need to be carefully tied in to adjacent banks to avoid outflanking by erosion during high flows.
- Upstream bank erosion will need to be monitored, including erosion on the landward side of the spit. However, extensive lengths of shoreline armouring works are unlikely to be required in these areas in the short-term.
- Navigation improvements are likely to persist for several decades and establishment of a new bar will probably be slow (80-100 years or more).
- Dredging is likely to be required during initial construction to achieve desired navigable depths. This will also minimise the volumes of sand discharged further seaward, extending the life span of navigation improvements.
- Maintenance-dredging requirements between the training walls are likely to be minimal, though a precautionary approach should be adopted towards such costs until detailed design has confirmed these preliminary indications.
- Over relatively long periods of time (decades rather than years), periodic artificial bypassing of sands may be required to prevent erosion of beach areas to the immediate west of the training walls.

6. REFERENCES

Bottin, R. R. 1997: Coastal Engineering Technical Note: Monitoring completed navigation projects, lessons learned III. Coastal Engineering Technical Note VI-29, US Army Corps of Engineers.

Bruun P. 1978 *Stability of Tidal Inlets*. Elsevier, 506 p.

Bruun, P 1989. *Port Engineering (fourth edition).* Gulf Publishing, Houston Texas, 1146p.

Bruun, P and Gerritsen, F 1959 Natural bypassing of sand at coastal inlets. *Journal of Waterways and hydraulics Division,* American Society of Civil Engineers, Paper 2301, pp 75-107

Burgess, RF and McLean, JS 1975 Bar depth and beach changes around a New Zealand river mouth port: Wanganui 1850-1970. Paper presented to Australian Conference on Coastal and Ocean Engineering 1975.

Coastal Consultants NZ Ltd. (CCNZL) 2000 Extension *scoping report for the Matahina two peaks proposal: geomorphological issues at the Rangitaiki river entrance*. Unpublished report to Beca Carter Hollings and Ferner Ltd.

Coastal Consultants NZ Ltd. (CCNZL) 2002 Geomorphological monitoring of the Rangitaiki river entrance. Unpublished report to Beca Carter Hollings and Ferner Ltd.

Croad RN, Moynihan SH, Edwards MK and Rowe GH 1993 Preliminary investigation of a new barge port facility at Opotiki. *Works Consultancy Services*, Central Laboratories Report 93-23312.

Dahm, J and Kench, P 2002 Feasibility Study: Opotiki Entrance navigation Improvements. Report prepared for Opotiki District Council, November 2002.

Fitzgerald, DM 1982 Sediment bypassing at mixed energy tidal inlets. *Proceedings 18th Coastal Engineering Conference,* ASCE, 1094-1118.

Fitzgerald, DM 1988 Shoreline erosional-depositional processes associated with tidal inlets. Pages 186-225 of *Lecture Notes on Coastal and Estuarine Studies, DG Aubrey and L Weishar, eds., Vol 29.* Springer Verlag, New York.

Heath RA, 1985 A review of the physical oceanography of the seas around New Zealand – 1982. *NZ J Marine and Freshwater Research*, 19:79-124.

Healy TR, Harray GK, and Richmond B 1977 Bay of Plenty: Coastal erosion survey. Occasional Report No. 3, Dept. Earth Sciences, University of Waikato, Hamilton.

Hughes, S. A. 1999 Equilibrium Scour Depth at Tidal Inlets. Coastal Engineering Technical Note IV-18, March 1999. 11p.

Hughes, S. A. 2002 "Equilibrium Cross-Section Area at Tidal Inlets," *Journal of Coastal Research,* Vol 18, pp 160-174.

Hume T.M. and Herdendorf C.E. 1992 Factors controlling tidal inlet characteristics on low drift coasts. *Journal of Coastal Research,* 8:355-375.

Jarrett, JT 1976 Tidal Prism Inlet Area Relationships. US Army Coastal Engineering Research Centre *GITI Report 3.*

Kench P.S. and Parnell K.E. 1991 The morphological behaviour and stability of a small tidal inlet: Waipu, New Zealand. In: Bell R.G., Hume T.M. and Healy T.R. (ed). Coastal Engineering - '*Climate for Change', Proceedings 10th Australasian Conference on Coastal and Ocean Engineering,* Water Quality Centre publication 21:221-226.

O'Brien, MP 1931 Estuary tidal prisms related to entrance areas. *Civil Engineering* Vol 1, pp 738-739.

O'Brien, MP 1969 Equilibrium flow areas of inlets on sandy coasts. *Journal of the Waterways and Harbors Division,* ASCE, No. WWI, 43-52.

Parchure, TM and Teeter, AM 2002 Lessons learned from existing projects on shoaling in harbors and navigation channels. US Army Corps of Engineers *REDC/CHL CHETN-XIV-5*, June 2002, 17p.

Pickrill RA and Mitchell JS, 1979 Ocean wave characteristics around New Zealand. *NZ Journal Marine and Freshwater Research*, 13:501-520.

Smith RK 1986 Motu river sediments: A source of eastern Bay of Plenty beach material. In Motu River: A description of its catchment, channel, waters and sediments. Miscellaneous Publication 92, Water and Soil Directorate, Ministry of Works and Development, Wellington.

Smith RK 1998 Environmental impact assessment of a proposed mining operation to remove 2, 000 m3 of sand annually from Snells Beach, Opotiki. NIWA Client Report: WCO90201 prepared for Waiotahi Contractors Ltd, Whakatane.

Tonkin and Taylor 2001 Opotiki District Council: Opotiki Harbour Sand Fluidisation Potential. Report prepared by Tonkin and Taylor Ltd for Opotiki District Council, May 2001. 8p + appendix.

Walton T.L. and Adams W.D. 1976 Capacity of inlet outer bars to store sand. *Proceedings ASCE 15th Conference on Coastal and Ocean Engineering*, pp. 1919-1937.

APPENDIX 1: Sediment Data

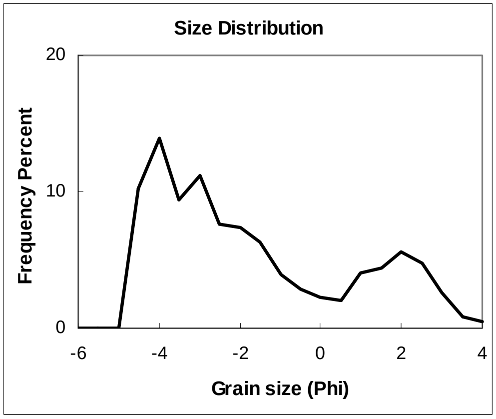
Opotiki Entrance Sample 1

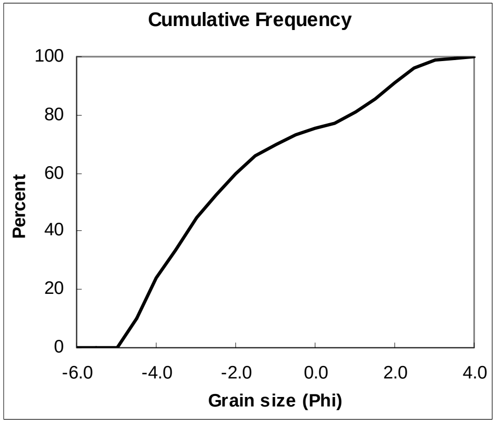
Phi	Weight	Weight Percent	Cum. Freq.
-6	0	0.00	0.00
-5.5	0	0.00	0.00
-5	0	0.00	0.00
-4.5	76.57	10.22	10.22
-4.00	104.69	13.98	24.20
-3.50	70.71	9.44	33.64
-3.00	84.14	11.23	44.88
-2.50	57.46	7.67	52.55
-2.00	54.89	7.33	59.88
-1.50	47.08	6.29	66.16
-1.00	29.32	3.91	70.08
-0.50	21.62	2.89	72.96
0.00	16.85	2.25	75.21
0.50	15.47	2.07	77.28
1.00	29.91	3.99	81.27
1.50	33.38	4.46	85.73
2.00	41.99	5.61	91.33
2.50	35.47	4.74	96.07
3.00	19.77	2.64	98.71
3.50	6.08	0.81	99.52
4.00	3.59	0.48	100.00

STATISTICAL PARAMETERS

Moment method (Folk, 1967)

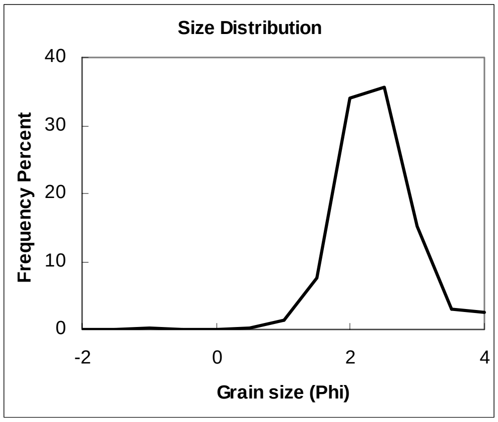
Mean	**Phi**	**-1.95**
Mean	**mm**	**3.86**
Std Dev.		**5.63**

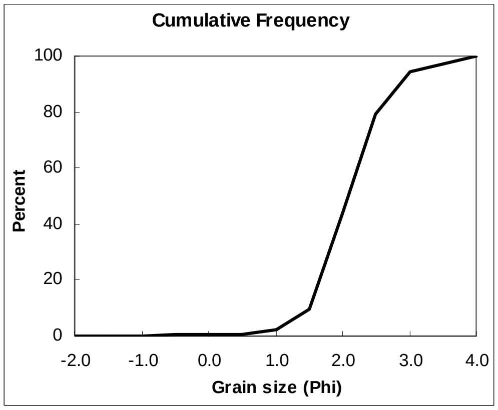




Opotiki Entrance Sample 2

Phi	Weight	Weight Percent	Cum. Freq.
-4.5	0.00	0.00	0.00
-4.00	0.00	0.00	0.00
-3.50	0.00	0.00	0.00
-3.00	0.00	0.00	0.00
-2.50	0.00	0.00	0.00
-2.00	0.00	0.00	0.00
-1.50	0.00	0.00	0.00
-1.00	0.09	0.20	0.20
-0.50	0.04	0.09	0.29
0.00	0.05	0.11	0.41
0.50	0.14	0.32	0.72
1.00	0.56	1.27	1.99
1.50	3.35	7.59	9.58
2.00	15.04	34.07	43.65
2.50	15.75	35.67	79.32
3.00	6.66	15.08	94.41
3.50	1.34	3.04	97.44
4.00	1.13	2.56	100.00





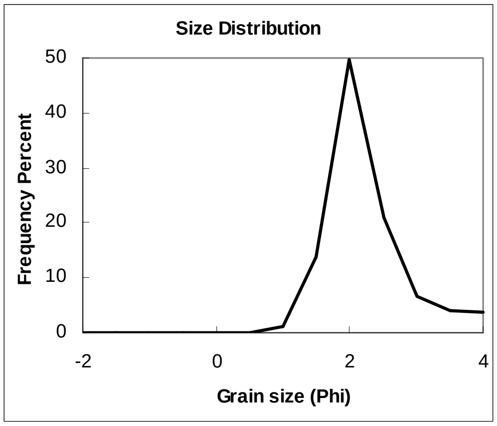
STATISTICAL PARAMETERS

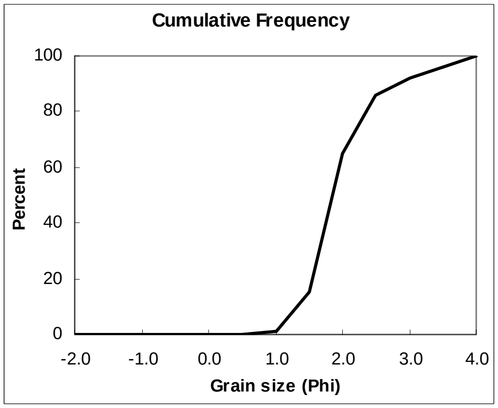
Moment method (Folk, 1967)

Mean	Phi	2.11
Mean	mm	0.23
Std Dev.		0.35

Opotiki Entrance Sample 3

Phi	Weight	Weight Percent	Cum. Freq.
-4.5	0.00	0.00	0.00
-4.00	0.00	0.00	0.00
-3.50	0.00	0.00	0.00
-3.00	0.00	0.00	0.00
-2.50	0.00	0.00	0.00
-2.00	0.00	0.00	0.00
-1.50	0.00	0.00	0.00
-1.00	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
0.00	0.02	0.04	0.04
0.50	0.03	0.05	0.09
1.00	0.65	1.15	1.24
1.50	7.84	13.91	15.15
2.00	28.01	49.69	64.84
2.50	11.79	20.92	85.75
3.00	3.68	6.53	92.28
3.50	2.25	3.99	96.27
4.00	2.10	3.73	100.00

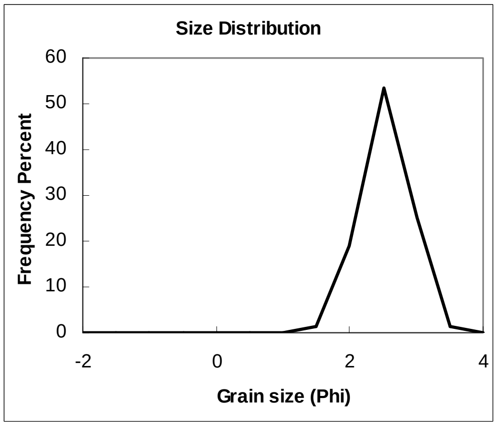


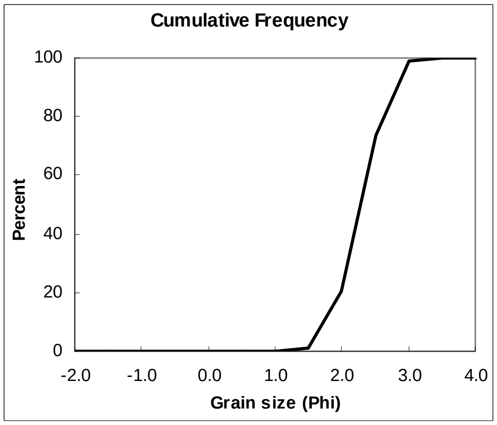


STATISTICAL PARAMETERS Moment method (Folk, 1967)		
Mean	Phi	1.97
Mean	mm	0.25
Std Dev.		0.36

Opotiki Entrance Sample 4

Phi	Weight	Weight Percent	Cum. Freq.
-4.5	0.00	0.00	0.00
-4.00	0.00	0.00	0.00
-3.50	0.00	0.00	0.00
-3.00	0.00	0.00	0.00
-2.50	0.00	0.00	0.00
-2.00	0.00	0.00	0.00
-1.50	0.00	0.00	0.00
-1.00	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.50	0.00	0.00	0.00
1.00	0.02	0.04	0.04
1.50	0.66	1.27	1.31
2.00	9.78	18.88	20.19
2.50	27.67	53.42	73.61
3.00	13.00	25.10	98.71
3.50	0.63	1.22	99.92
4.00	0.04	0.08	100.00

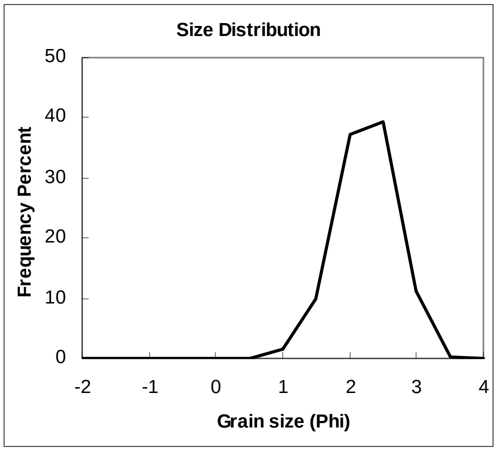


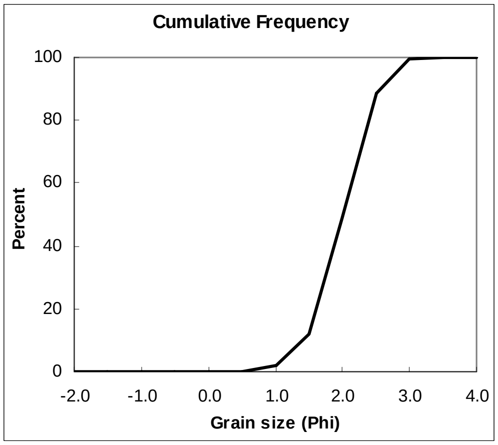


STATISTICAL PARAMETERS Moment method (Folk, 1967)	
Mean Phi	**2.28**
Mean mm	**0.21**
Std Dev.	**0.14**

Opotiki Entrance Sample 5

Phi	Weight	Weight Percent	Cum. Freq.
-4.5	0.00	0.00	0.00
-4.00	0.00	0.00	0.00
-3.50	0.00	0.00	0.00
-3.00	0.00	0.00	0.00
-2.50	0.00	0.00	0.00
-2.00	0.00	0.00	0.00
-1.50	0.00	0.00	0.00
-1.00	0.00	0.00	0.00
-0.50	0.02	0.03	0.03
0.00	0.01	0.02	0.05
0.50	0.06	0.10	0.15
1.00	0.98	1.62	1.76
1.50	6.06	9.99	11.75
2.00	22.59	37.24	48.99
2.50	23.87	39.35	88.34
3.00	6.81	11.23	99.57
3.50	0.23	0.38	99.95
4.00	0.03	0.05	100.00





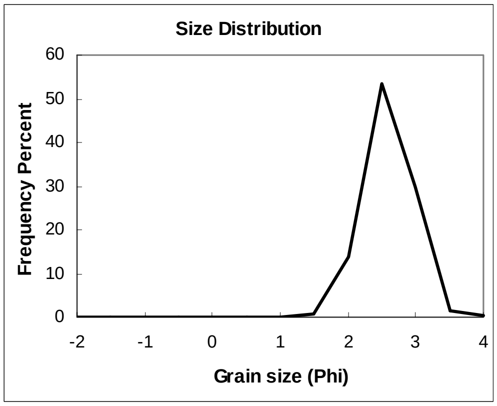
STATISTICAL PARAMETERS

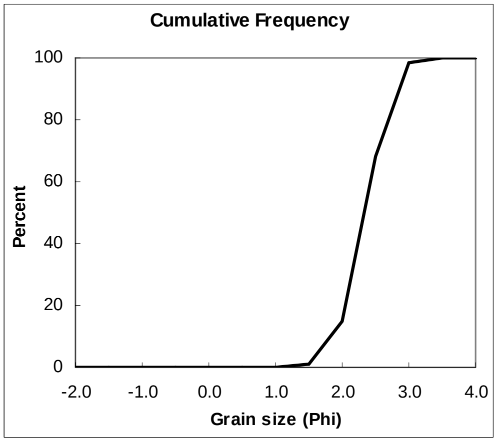
Moment method (Folk, 1967)

Mean	**Phi**	**2.00**
Mean	**mm**	**0.25**
Std Dev.		**0.21**

Opotiki Entrance Sample 6

Phi	Weight	Weight Percent	Cum. Freq.
-4.5	0.00	0.00	0.00
-4.00	0.00	0.00	0.00
-3.50	0.00	0.00	0.00
-3.00	0.00	0.00	0.00
-2.50	0.00	0.00	0.00
-2.00	0.00	0.00	0.00
-1.50	0.00	0.00	0.00
-1.00	0.00	0.00	0.00
-0.50	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.50	0.01	0.02	0.02
1.00	0.05	0.08	0.10
1.50	0.53	0.89	0.99
2.00	8.32	14.00	14.99
2.50	31.71	53.35	68.34
3.00	17.77	29.90	98.23
3.50	0.91	1.53	99.76
4.00	0.14	0.24	100.00





STATISTICAL PARAMETERS

Moment method (Folk, 1967)

Mean	**Phi**	**2.34**
Mean	**mm**	**0.20**
Std Dev.		**0.13**

Appendix 2: Summary of Velocity and Discharge Data: Opotiki Entrance 17 October, 2003

Time	Speed	Dir	CSA	Q/s	Total Q
05:45:00	2.04		455	9	2785
05:50:00	7.22		458	33	9911
05:55:00	12.37		460	57	17075
06:00:00	12.43		463	58	17253
06:05:00	13.24		465	62	18478
06:10:00	13.52		468	63	18973
06:15:00	13.62		470	64	19217
06:20:00	14.41		473	68	20443
06:25:00	15.19		475	72	21665
06:30:00	15.21		478	73	21811
06:35:00	15.75		481	76	22706
06:40:00	15.85		483	77	22971
06:45:00	16.37		486	80	23850
06:50:00	16.38		488	80	23990
06:55:00	16.68		491	82	24557
07:00:00	16.88		493	83	24981
07:05:00	18.31		496	91	27238
07:10:00	18.47		498	92	27617
07:15:00	18.68		501	94	28075
07:20:00	18.81		504	95	28414
07:25:00	18.89		506	96	28680
07:30:00	20.39		509	104	31113
07:35:00	20.83		511	106	31944
07:40:00	21.39		514	110	32967
07:45:00	23.02		516	119	35655
07:50:00	23.84		519	124	37108
07:55:00	23.96		521	125	37479
08:00:00	18.47		**524**	97	29033
08:05:00	18.31		**527**	96	28921
08:10:00	23.96		**529**	127	38029
08:15:00	20.83		**532**	111	33221
08:20:00	23.84		**534**	127	38204
08:25:00	23.02		**537**	124	37067
08:30:00	20.39		**539**	110	32988
08:35:00	18.81		**542**	102	30576
08:40:00	12.43		**544**	68	20300
08:45:00	13.62		**547**	74	22348
08:50:00	14.41		**550**	79	23755
08:55:00	13.52		**552**	75	22391
09:00:00	15.21		**555**	84	25307
09:05:00	15.85		**557**	88	26493
09:10:00	13.24		**560**	74	22232
09:15:00	12.37		**562**	70	20866
09:20:00	16.68		**565**	94	28264
09:25:00	21.39		**567**	121	36409

09:30:00	*15.75*		***570***	*90*	*26929*
09:35:00	*18.89*		***572***	*108*	*32443*
09:40:00	*16.88*		***575***	*97*	*29120*
09:45:00	18.47	107.7	**578**	107	32005
09:50:00	18.31	111.8	**580**	106	31868
09:55:00	23.96	96.7	**583**	140	41885
10:00:00	20.83	93.3	**585**	122	36573
10:05:00	23.84	93.4	**588**	140	42040
10:10:00	23.02	98	**590**	136	40771
10:15:00	20.39	97.9	**593**	121	36269
10:20:00	18.81	98.6	**595**	112	33603
10:25:00	12.43	101.1	**598**	74	22300
10:30:00	13.62	86.6	**601**	82	24540
10:35:00	14.41	103.7	**603**	87	26074
10:40:00	13.52	119.2	**606**	82	24567
10:45:00	15.21	88.5	**608**	93	27754
10:50:00	15.85	85.7	**611**	97	29043
10:55:00	13.24	104.9	**613**	81	24362
11:00:00	12.37	112.8	**616**	76	22856
11:05:00	16.68	112.6	**618**	103	30948
11:10:00	21.39	118.5	**621**	133	39850
11:15:00	15.75	118.8	**624**	98	29464
11:20:00	18.89	114.4	**626**	118	35482
11:25:00	16.88	121.4	**629**	106	31836
11:30:00	16.37	122.5	**631**	103	31000
11:35:00	16.38	107.8	**634**	104	31144
11:40:00	18.68	111.3	**636**	119	35660
11:45:00	15.19	99.1	**639**	97	29114
11:50:00	7.22	94.8	**641**	46	13894
11:55:00	14.09	128.7	**644**	91	27222
12:00:00	5.64	152.5	644	36	10896
12:05:00	7.86	262.7	641	50	15125
12:10:00	11.22	281.3	639	72	21505
12:15:00	2.04	348.7	636	13	3894
12:20:00	8.77	313.2	634	56	16675
12:25:00	17.08	264.6	631	108	32344
12:30:00	17.96	251.2	629	113	33873
12:35:00	14.29	287.9	626	89	26842
12:40:00	10.44	286.7	624	65	19530
12:45:00	24.8	289.3	621	154	46203
12:50:00	11.72	36.7	618	72	21745
12:55:00	8.16	306	616	50	15077
13:00:00	26.2	270.9	613	161	48209
13:05:00	25.96	338.8	611	159	47569
13:10:00	13.15	314.4	608	80	23995
13:15:00	21.78	277.4	606	132	39576
13:20:00	26.76	301.6	603	161	48420
13:25:00	23.26	266.1	601	140	41909
13:30:00	22.93	264	598	137	41138
13:35:00	18.3	285.9	595	109	32691
13:40:00	23.79	297	593	141	42317
13:45:00	44.67	32.2	590	264	79115
13:50:00	40.03	316	588	235	70590
13:55:00	31.18	300	585	182	54745

14:00:00	29.93	264.6	583	174	52321
14:05:00	25.06	274.1	580	145	43616
14:10:00	38.54	308.9	578	223	66781
14:15:00	44.06	299.4	575	253	76009
14:20:00	34.39	283.8	572	197	59063
14:25:00	29.35	284.6	570	167	50183
14:30:00	36.61	294.2	567	208	62315
14:35:00	55.04	294.7	565	311	93264
14:40:00	46.11	302.2	562	259	77779
14:45:00	58.22	311.8	560	326	97760
14:50:00	55.58	281.8	557	310	92901
14:55:00	34.73	292	555	193	57785
15:00:00	27.42	282.2	552	151	45412
15:05:00	31.04	323.6	550	171	51169
15:10:00	45.13	290.8	547	247	74051
15:15:00	60.01	307.8	544	327	98007
15:20:00	43.09	290.4	542	233	70043
15:25:00	60.46	303.5	539	326	97815
15:30:00	51.63	300.2	537	277	83134
15:35:00	36.34	304.9	534	194	58236
15:40:00	45.32	299.6	532	241	72279
15:45:00	34.09	313.8	529	180	54108
15:50:00	39.01	294.9	527	205	61618
15:55:00	34.1	287.1	524	179	53601
16:00:00	26.32	286.8	521	137	41170
16:05:00	31.61	291.5	519	164	49203
16:10:00	37.26	308.9	516	192	57712
16:15:00	48.77	282.6	514	251	75166
16:20:00	27.64	295.3	511	141	42388
16:25:00	34.56	280.3	509	176	52735
16:30:00	35.11	286.9	506	178	53306
16:35:00	38.51	291.6	504	194	58172
16:40:00	29.34	292	501	147	44096
16:45:00	27.28	297.5	498	136	40791
16:50:00	31.41	298.5	496	156	46725
16:55:00	28.38	283.4	493	140	42000
17:00:00	29.11	282.7	491	143	42858
17:05:00	27.62	282.1	488	135	40452
17:10:00	25.17	289	486	122	36671
17:15:00	20.62	292.8	483	100	29884
17:20:00	25.82	292.8	481	124	37223
17:25:00	26.94	288.2	478	129	38631
17:30:00	22.85	278.6	475	109	32591
17:35:00	23.55	290.9	473	111	33409
17:40:00	15.82	286.1	470	74	22322
17:45:00	8.42	274.1	468	39	11816
17:50:00	13.42	294.7	465	62	18730
17:55:00	14.96	278.5	463	69	20764
18:00:00	25	290.6	460	115	34508
18:05:00	*15.45*		*458*	*71*	*21208*
18:10:00	*17.8*		*455*	*81*	*24288*
18:15:00	*8*		*455*	*36*	*10920*
			Ebb Prism		**3542973**
			Flood Prism		**2093974**

Appendix 3: Summary of Velocity and Discharge Data: Opotiki Entrance 7 November, 2003

Time	**Speed**	**Dir**	**CSA**	**Q/s**	**Total Q**
06:05:00	*2*		***588***	*12*	*3528*
06:10:00	*2.7*		***585***	*16*	*4741*
06:15:00	*3.4*		***583***	*20*	*5942*
06:20:00	*4.1*		***580***	*24*	*7132*
06:25:00	*4.8*		***577***	*28*	*8311*
06:30:00	*5.5*		***574***	*32*	*9478*
06:35:00	*6.2*		***572***	*35*	*10633*
06:40:00	*6.9*		***569***	*39*	*11777*
06:45:00	*7.6*		***566***	*43*	*12910*
06:50:00	*8.3*		***564***	*47*	*14032*
06:55:00	*9*		***561***	*50*	*15142*
07:00:00	*9.7*		***558***	*54*	*16240*
07:05:00	*10.4*		***555***	*58*	*17327*
07:10:00	*11.1*		***553***	*61*	*18403*
07:15:00	*11.8*		***550***	*65*	*19467*
07:20:00	*12.5*		***547***	*68*	*20520*
07:25:00	*13.2*		***544***	*72*	*21561*
07:30:00	*13.9*		***542***	*75*	*22591*
07:35:00	*14.6*		***539***	*79*	*23610*
07:40:00	*15.3*		***536***	*82*	*24617*
07:45:00	*16*		***534***	*85*	*25613*
07:50:00	*16.7*		***531***	*89*	*26597*
07:55:00	*17.4*		***528***	*92*	*27570*
08:00:00	*18.1*		***525***	*95*	*28531*
08:05:00	*18.8*		***523***	*98*	*29481*
08:10:00	*19.5*		***520***	*101*	*30420*
08:15:00	*20.2*		***517***	*104*	*31347*
08:20:00	21.3	114.4	**515**	110	32880
08:25:00	22	270	**512**	113	33781
08:30:00	25.91	285.2	**509**	132	39574
08:35:00	25.97	276.6	**506**	132	39454
08:40:00	29.64	283.7	**504**	149	44787
08:45:00	29.55	282.9	**501**	148	44410
08:50:00	26.87	278.1	**498**	134	40163
08:55:00	29.4	270.8	**496**	146	43705
09:00:00	24.89	278.8	**493**	123	36797
09:05:00	26.57	279.5	**490**	130	39064
09:10:00	30.61	284.8	**487**	149	44754
09:15:00	27.19	279.7	**485**	132	39532
09:20:00	25.46	280.9	**482**	123	36809
09:25:00	27.46	284.3	**479**	132	39476
09:30:00	29.22	272	**476**	139	41768
09:35:00	26.25	282.8	**474**	124	37309
09:40:00	32.9	274.5	**471**	155	46492
09:45:00	26.74	292	**468**	125	37569
09:50:00	31.05	273.3	**466**	145	43371
09:55:00	17.54	315.9	**463**	81	24357

10:00:00	35.61	285	**460**	164	49159
10:05:00	25.97	310.3	**457**	119	35639
10:10:00	31.7	293.8	**455**	144	43244
10:15:00	29.02	293.6	**452**	131	39351
10:20:00	32.12	302.8	**449**	144	43293
10:25:00	34.7	274.3	**447**	155	46487
10:30:00	37.72	310.7	**444**	167	50225
10:35:00	38.03	276.3	**441**	168	50327
10:40:00	45.46	292.5	**438**	199	59789
10:45:00	39.92	292.1	**436**	174	52177
10:50:00	42.23	291.1	**433**	183	54852
10:55:00	36.29	305.4	**430**	156	46840
11:00:00	39.24	322.7	**428**	168	50328
11:05:00	29.93	280.8	**425**	127	38143
11:10:00	13.41	178.3	**422**	57	16980
11:15:00	45.87	96.3	**419**	192	57708
11:20:00	10.22	229.8	**417**	43	12774
11:25:00	67.28	60.2	**414**	278	83546
11:30:00	29.82	2.3	**411**	123	36786
11:35:00	19.14	242.6	**408**	78	23455
11:40:00	34.97	283.6	**406**	142	42568
11:45:00	54.46	70.7	**403**	219	65849
11:50:00	47.69	291.4	**400**	191	57274
11:55:00	64.53	298.7	**398**	257	76971
12:00:00	44.42	291.9	**395**	175	52622
12:05:00	112.04	353.9	**392**	439	131813
12:10:00	89.3	155.1	**389**	348	104331
12:15:00	32.92	232.2	**387**	127	38192
12:20:00	34.53	280	**384**	133	39779
12:25:00	28.47	250.3	**384**	109	32797
12:30:00	19.2	271.2	**387**	74	22275
12:35:00	56.59	226.4	**389**	220	66115
12:40:00	18.56	277.4	**392**	73	21835
12:45:00	69.57	264.1	**395**	275	82415
12:50:00	44.8	257.9	**398**	178	53437
12:55:00	16.1	26.6	**400**	64	19335
13:00:00	53.3	96	**403**	215	64446
13:05:00	95.72	32.2	**406**	388	116518
13:10:00	94.51	324.6	**408**	386	115816
13:15:00	105.51	99.1	**411**	434	130157
13:20:00	49.75	351.4	**414**	206	61778
13:25:00	53.03	286.7	**417**	221	66283
13:30:00	50.07	282.9	**419**	210	62992
13:35:00	35.03	267.7	**422**	148	44356
13:40:00	56.79	184.6	**425**	241	72373
13:45:00	51.59	167.7	**428**	221	66167
13:50:00	63.19	202.9	**430**	272	81561
13:55:00	63.26	189.5	**433**	274	82167
14:00:00	36.89	200.3	**436**	161	48217
14:05:00	30.86	165	**438**	135	40587
14:10:00	6.81	183.4	**441**	30	9012
14:15:00	6.41	3.6	**444**	28	8535
14:20:00	4.4	309.5	**447**	20	5895
14:25:00	6.93	326.8	**449**	31	9341

14:30:00	5.37	315	**452**	24	7282
14:35:00	2.69	312	**455**	12	3670
14:40:00	3.45	260	**457**	16	4735
14:45:00	2.21	174.8	**460**	10	3051
14:50:00	4.28	190.8	**463**	20	5943
14:55:00	2.01	95.7	**466**	9	2808
15:00:00	6.07	72.8	**468**	28	8528
15:05:00	10.4	91.1	**471**	49	14696
15:10:00	17.52	128	**474**	83	24901
15:15:00	18.05	129.2	**476**	86	25801
15:20:00	16.93	128.8	**479**	81	24339
15:25:00	15.13	114.2	**482**	73	21874
15:30:00	13.09	124.4	**485**	63	19032
15:35:00	15.71	121.5	**487**	77	22969
15:40:00	12.82	113	**490**	63	18848
15:45:00	11.22	129.9	**493**	55	16588
15:50:00	15.09	148	**496**	75	22432
15:55:00	27.76	143.8	**498**	138	41493
16:00:00	33.7	137.9	**501**	169	50647
16:05:00	26.45	135.3	**504**	133	39967
16:10:00	23.91	136.7	**506**	121	36324
16:15:00	24.04	135	**509**	122	36718
16:20:00	28.19	138.2	**512**	144	43286
16:25:00	34.47	139.5	**515**	177	53211
16:30:00	29.46	131.7	**517**	152	45717
16:35:00	*28.46*		***520***	*148*	*44398*
16:40:00	*27.46*		***523***	*144*	*43062*
16:45:00	*26.46*		***525***	*139*	*41709*
16:50:00	*25.46*		***528***	*134*	*40341*
16:55:00	*24.46*		***531***	*130*	*38956*
17:00:00	*23.46*		***534***	*125*	*37555*
17:05:00	*22.46*		***536***	*120*	*36137*
17:10:00	*21.46*		***539***	*116*	*34703*
17:15:00	*20.46*		***542***	*111*	*33253*
17:20:00	*19.46*		***544***	*106*	*31787*
17:25:00	*18.46*		***547***	*101*	*30304*
17:30:00	*17.46*		***550***	*96*	*28805*
17:35:00	*16.46*		***553***	*91*	*27289*
17:40:00	*15.46*		***555***	*86*	*25758*
17:45:00	*14.46*		***558***	*81*	*24210*
17:50:00	*13.46*		***561***	*75*	*22645*
17:55:00	*12.46*		***564***	*70*	*21064*
18:00:00	*11.46*		***566***	*65*	*19467*
18:05:00	*10.46*		***569***	*60*	*17854*
18:10:00	*9.46*		***572***	*54*	*16224*
18:15:00	*8.46*		***574***	*49*	*14578*
18:20:00	*7.46*		***577***	*43*	*12916*
18:25:00	*6.46*		***580***	*37*	*11237*
18:30:00	*5.46*		***583***	*32*	*9542*
18:35:00	*4.46*		***585***	*26*	*7831*
			Ebb Prism		**3674102**
			Flood Prism		**1750873**