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# BANK EROSION FROM SMALL CRAFT WAVE WAKE IN SHELTERED WATERWAYS

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## SUMMARY

The wave wake generated by large vessels has received high-profile research and regulatory responses in recent years. Conversely, recreational vessel wave wake can impact significantly on sheltered waterways, yet the sector receives little research funding and is often regulated with simplistic criteria. Small craft wave wake, comprising smaller waves and shorter periods, can be quantified adequately with fewer variables, opening the possibility for over-arching guidelines that are not site-specific.

This paper analyses past small craft wave wake studies, including bank erosion studies, to determine which measures of erosion potential are the most descriptive. Past approaches using a single criterion are shown to be generally inadequate and often misleading. A multi-criteria approach has been adopted to ensure that all the erosive components of high-speed, small craft wave wake are accounted for. A possible implementation method is discussed.

## NOMENCLATURE

| | |
|---|---|
| E | Energy per metre wave crest length [$Jm^{-1}$] |
| $E_m$ | Energy of the maximum wave [$Jm^{-1}$] |
| Fr | Length Froude number [$v(gL)^{-1/2}$] |
| $Fr_h$ | Depth Froude number [$v(gh)^{-1/2}$] |
| g | Acceleration due to gravity [$9.81ms^{-2}$] |
| h | Water depth [m] |
| H | Wave height [m] |
| $H_m$ | Maximum wave height [m] |
| L | Waterline length [m] |
| n | Wave decay exponent |
| T | Wave period [s] |
| $T_m$ | Period of the maximum wave [s] |
| $T_1$ | Period of the leading wave [s] |
| v | Vessel speed [$ms^{-1}$] |
| y | Lateral distance between vessel sailing line and measurement point [m] |
| $\gamma$ | Constant |
| $\pi$ | Pi |

## 1. INTRODUCTION

Vessel wave wake (also commonly referred to as wash or wake wash) has been a prime topic for study over the past two decades, though it no longer attracts quite the same attention since industry has gained a general understanding of the primary issues. Sufficient science has been developed to allow for the regulation of the most damaging vessels without actually perfecting the science.

It is known that wave wake issues can differ considerably depending upon the size and/or speed of the vessel(s) and the location(s) in which they operate. As a result, it may be useful to categorise particular scenarios into the following three distinct regions, with reference to examples of rivers and harbours in Australia:

a) *Highly Sensitive Regions* - This region includes very sheltered waterways such as rivers with very limited fetch and/or width. They often have steep, cohesive banks that are highly susceptible to erosion by vessel wave wake. Vessel speeds are likely to be restricted to a small range of sub-critical depth Froude numbers. Vessel operation at trans-critical depth Froude numbers should be avoided and operation at super-critical depth Froude numbers may be limited to only very small craft (less than about five metres length). Examples include the lower Gordon River, upper reaches of the Parramatta River and sections of the Noosa River.

b) *Moderately Sensitive Regions* - This region includes semi-sheltered estuaries such as the lower reaches of large rivers and harbours or areas where shorelines have been artificially armoured to withstand increased wave action. Vessel speeds are likely to be restricted to a range of sub-critical depth Froude numbers. The possible exceptions may include certain small craft and larger wave wake-optimised craft that could operate at some super-critical depth Froude numbers. In such cases, multiple criteria may be required to determine acceptable speeds for each vessel type (this is discussed in more detail in later sections). Operation at trans-critical depth Froude numbers should be limited to acceleration and deceleration between the sub and super-critical conditions. Examples include the lower reaches of the Parramatta and Brisbane Rivers and sheltered areas of Sydney Harbour.

c) *Coastal Regions* - In these more exposed regions, wave wake criteria generally only apply to large high-speed craft operating at trans or super-critical depth Froude numbers. Minimal problems eventuate from almost all vessels operating at sub-critical speeds. Some existing criteria applied to high-speed vessels are based on acceptable levels from 'conventional' (i.e., not high-speed) vessels operating at sub-critical speeds. Often the criteria are imposed due to adverse safety risks for other users of the waterway (and shoreline) as a result of large/long vessel waves generated at high speeds. Examples include Scandinavian coastal regions and Marlborough Sounds in New Zealand.

The differences between types of waterways are discussed further in Section 12.

The limited number of regions where wave wake is of concern within Australia (such as those of the Gordon, Parramatta and Brisbane River ferry services) have been the subject of individual studies that have sought vessel-specific solutions, as opposed to an over-arching methodology that would allow for a desktop evaluation of any vessel in any waterway, Macfarlane and Cox (2007).

Australia does have a relatively large recreational boating population that utilises the limited sheltered waterways available. This is not dissimilar to the USA, where the majority of recreational boating is enjoyed on fresh water lakes and rivers, as well as sheltered coastal waterways, rather than the open ocean itself. It therefore makes sense to attempt to develop guidelines for vessel wave wake that allows for the sustainable use of sheltered waterways.

In Australia, this has generally come in response to a perceived erosion event. It can be said with some certainty that maritime regulatory authorities have been reactive in their approach to wave wake and erosion. A partial exception are the Gordon River services which, operating within a National Park and World Heritage Area, are regulated by a land management rather than maritime agency. There the initial response in the early 1990s was reactive, but became proactive with the implementation of a long-term monitoring and vessel certification process that is on-going today, Bradbury *et al* (1995), Bradbury (2007a).

## 2. RELEVANT WAVE WAKE STUDIES

The Australian Maritime College (AMC) has conducted studies of wave wake and erosion in several recreational sheltered waterways in South-east Queensland, Macfarlane and Cox (2004). The Queensland Government had a pressing desire to find the causal links between the wave wake of certain vessels and the erosion they may have caused in the Noosa, Brisbane, Bremer, Maroochy and Mary Rivers. One aim was to raise awareness of potential effects of new classes of vessels and activities such as wakeboarding before erosion occurs, so that regulatory bodies are not reliant solely on reactionary measures.

The AMC's studies collected wave wake data from controlled field experiments on a range of small craft, but without actually measuring corresponding erosion. Instead, erosion studies undertaken on the Gordon River prior to 1995 were re-analysed in an attempt to derive relationships between measured small craft wave wake and erosion thresholds. A set of operating criteria were developed from the re-analysed Gordon River data.

In a separate study of different bank types, similar controlled field experiments were conducted on the Gordon River between 1997 and 2005 by the Tasmanian Department of Primary Industry and Water, but in this instance both the wave wake and the subsequent shoreline disturbance were recorded, Bradbury (2007b), Macfarlane (2006). An aim of this paper is to compare the results of these two different studies and define the areas of correlation.

## 3. WAVE WAKE AND BANK EROSION

### 3.1 INTRODUCTION

At the outset, it must be accepted that there may never be a rigorous theory that links vessel wave wake and erosion. This is similarly the case in coastal engineering, where beach erosion is predicted by a number of largely empirical and statistical rules developed over many decades. Those rules may have a grounding in basic science and engineering, but they are underpinned by empirical equations and a reality that can only be represented statistically, with accompanying error as a consequence. One only has to review The Coastal Engineering Manual (formerly the Shore Protection Manual) by The US Army Corps of Engineers (2002), to see that it is weighted heavily with model test results and empirical tables.

Similarly, it must also be accepted that most natural waterways are dynamic environments subject to erosional and/or depositional processes. Not all erosion events can be blamed on vessel wave wake. In many instances local land use practices such as riparian (river bank) vegetation removal and farming, as well as waterway issues such as regulation, channelisation, extractive processes and up- or downstream development (of flood protection or harbours, for instance), can be the root cause of upstream erosion. Recreational boating often simply becomes the focus of attention for an otherwise existing and complex problem.

In contrast to naturally-occurring wave climates, a vessel's wave wake is characterised by short event duration and a broad spectral spread of wave parameters that do not lend themselves to the application of conventional statistical methods. Instead, the principle statistics of concern may well relate to the extent to which certain wave wake parameters exceed those of the existing wave climate in a particular area.

### 3.2 RECREATIONAL CRAFT

In developing comprehensive, but simple, bank erosion criteria for recreational craft, a number of factors must be realised:

1. Recreational boating is not a substantial direct revenue source for marine regulatory authorities, so receives limited attention, hence limited funding.
2. When funding for maritime scientific investigation is limited and a political solution must be found, recreational boaters are soft targets. It is often easier and cheaper to apply a blanket speed limit to boating activities than to police it.
3. Vessel wave wake complaints are often used to mask other community concerns such as the noise generated by high-speed craft and the loss of amenity. Communities and governments react strongly to tangible evidence such as bank erosion, regardless of the cause, whereas noise and loss of amenity are more subjective, somewhat less tangible, and therefore less likely to attract regulation.
4. Shoreline erosion can very often be the result of land use issues, engineering works, river regulation or climate change and sea level rise.
5. Regulators, builders and owners of small craft have scant information relating to vessel parameters such as displacement, dimensions and hull design. Often only very simplified parameters must be relied upon to determine wave wake potential.
6. Every possible combination of bank type, bank material, riparian vegetation and river bathymetry cannot be covered, and indeed may not need to be.
7. The influence of environmental variables such as shallow water must be limited as they introduce an exceptional number of additional parameters.

Fortuitously, the vast majority of recreational vessels using sheltered waterways are small, high-speed monohulls, typically used for water skiing and recreational fishing. There are often a smaller number of slow-speed vessels such as professional fishing vessels, houseboats and workboats, and some commercial charter and ferry operators. If the vessel length is sufficiently large and it is engaged in a commercial operation, case-by-case testing and approval can be implemented.

## 4. RELEVANT WAVE WAKE CHARACTERISTICS

For the purposes of studying small craft wake waves, four parameters are necessary to adequately describe a wave – height, period, water depth and direction of propagation. For the purpose of comparing vessels or a single vessel at a range of speeds the last two can often be held reasonably constant at site appropriate values, leaving height and period as the key variables.

It is necessary to identify the waves of geomorphological interest and focus upon them. Of the two vessel-generated wave types, transverse and divergent, it is the divergent systems that dominate in high-speed vessel wakes. Transverse waves can be significant when generated by displacement hull forms or heavy, transom-sterned high-speed craft traversing at displacement speeds, and especially where the waterways are very narrow. Transverse wave height (and therefore energy) decays faster than divergent wave height with lateral separation from the sailing line, but this decay becomes bounded by the shoreline. Being more of a concern with slow vessel speeds, transverse waves are best controlled by changes to operating speeds and vessel design. The focus here is on small recreational craft, and therefore on divergent waves.

For other applications a degree of vessel induced erosion may be acceptable but limits may need to be placed on how much erosion is to be permitted. Earlier work on the Gordon (von Krusenstierna 1989, Nanson *et al* 1994) drew attention to an increase in the rate of erosion as waves became larger (as opposed to simply higher) and found that simple measures could explain much of the erosion. However, allowing some erosion is more complicated because one must then consider the cumulative effects of all waves exceeding the erosion threshold.

In analysing vessel wave wakes, the two parameters of maximum wave height and the corresponding wave period for the highest wave (often termed the *maximum* wave) have therefore been adopted as the primary measures. The importance of quantifying wave wakes with simple measures is critical when assessing small craft wave wake impacts. If the measures were complicated, statistically difficult to represent or costly to collect and collate, regulatory authorities would be reluctant to pursue a path of boating management through scientific understanding. Blanket speed limits might be a typical response but these, which to be effective must be specified for the 'worst offender', are likely to be overly restrictive for other vessel classes.

Our primary measures, height of the maximum wave and its corresponding period, appear to exhibit certain predictable relationships at high vessel speeds, which is essential to development of a simple but sound method for predicting small craft wave wake. Cox (2000) demonstrated for high-speed craft travelling at sub-critical depth Froude numbers that divergent wave height is largely a function of length-displacement ratio and the corresponding period is largely a function of vessel waterline length. Analysis using the AMC's wave wake database, Macfarlane and Renilson (2000), and by others (Warren, 1991) clearly supports this. Vessel hull form has only a limited bearing on high-speed, deep water wave wake, as demonstrated in Figures 1 and 2 (data obtained from the AMC wave wake database). Figure 3, taken from field tests in Queensland, shows how high-speed wave period (divided by the square-root of L) collapses to a narrow, constant band at high speeds.

In Figure 4, the most common wave wake parameters, such as energy, power and height, show growing values with increasing vessel speed, peaking at a certain speed (normally about Fr = 0.5) and then decreasing back to a lower level. Similarly, wave period also grows with increasing vessel speed, peaks, but tends to level off rather than decrease at higher speeds. Regardless of which wave wake parameter is used as the erosion indicator, it is clear that there may be two distinct operating speed ranges – slow speed and high speed, with intermediate transitional speeds to be especially avoided.

Planing craft in particular are burdened by this “transition hump” where resistance and hence wave wake is high. In some sports, such as wake boarding, this is viewed by the proponents as beneficial. Many boaters will explain anecdotally how they believe it is better to travel at high speeds in sheltered areas and this reasoning has long been used as a justification for transiting at speed. The current science would not support such a generalisation since the waves from small planing vessels have been demonstrated to be capable of eroding both muddy and sandy banks (even at the greatest distance allowed by the sheltered waterbodies examined).

## 5. WAVE MEASUREMENT

If waves are measured too close to the passing vessel (within one boat length laterally, though this can be speed-dependent), the measured waves may be subject to localised interactions. If they are measured too far from the vessel, the dispersing wake waves may be substantially affected by the existing wind wave environment.

During the Noosa and Maroochy River field studies the reference point for wave measurement was standardised so that the results were directly comparable. The nominal lateral distance from the sailing line to the wave probe was set at 23 metres. This distance had some relevance to these locations, as they have an average width of about 100 metres. It was surmised that most vessels would navigate in the centre half of the river, so would not normally stray closer to the bank than one-quarter of the width. The 1997-2005 Gordon River studies, having been undertaken by different personnel and for different reasons and on a river almost twice as wide, had a greater lateral separation of a nominal 50 metres between measurement point and sailing line.

To compare the results of trials where different lateral separations between sailing line and measurement point are used, wave heights must be corrected according to their decay with distance. The relationship between the maximum diverging wave height and lateral distance of deep water waves varies according to Equation 1 (Macfarlane and Renilson, 1999):

$$H_m = \gamma \, y^n \qquad \text{(Equation 1)}$$

The variable $\gamma$ is a vessel-dependent function of speed. The exponent “n” has theoretical values of $-^1/_3$ and $-^1/_2$ for divergent and transverse waves respectively when measured at the points of intersection of these two wave trains, Sorensen (1973). During field trials the wave measurement point is most likely not at the point of intersection, so the exponent values may vary. It was decided that a $-^1/_3$ decay exponent was appropriate for deep water divergent waves, recognising that it is not necessarily absolute (nor applicable in those relatively rare cases where transverse waves have greater geomorphic effect). Analysis of the AMC’s wave wake database shows that the deep water, divergent wave decay exponent generally varies between a range from -0.22 to -0.4, where -0.33 is considered a reasonable engineering approximation (Macfarlane, 2002).

## 6. USEFUL WAVE WAKE MEASURES IN SHELTERED WATERWAYS

Historically, wave height has been used as the primary comparative measure for vessel wave wake. It is possibly the simplest parameter to measure and this fulfils another desirable requirement – it is within public perception where subjective visual observation must substitute for engineering measurement. Similar comments were made by Lesleighter (1964) in his analysis of ski boat wave wake on the Hawkesbury River, where he found that inflated anecdotal claims of excessive wave wake height could not be substantiated by measurement.

In the authors’ opinion, the historical use of wave height alone, or indeed any single criterion, cannot possibly reflect the true erosion potential of a vessel’s wave wake. Wave period is a strong indicator of the potential to move sediment in any shoreline environment, either through the period-dependent orbital velocity below the surface of shallow, but unbroken, waves, or through the gravity driven jets of plunging breakers. Period, along with height, is required to calculate both wave energy and wave power. Sheltered waterways generally see only a wind wave environment. Wind waves of short fetch (and even waves of longer fetch, such as wind-driven ocean seas) exhibit a disproportionate growth relationship between wave height and period, disproportionate in that wave height grows more rapidly than period but both have equal weighting in calculating wave energy. Table 1 shows example hindcast wind waves values for different wind speeds and fetches.

It is clear that increasing either fetch or wind speed leads to much faster growth in wave height than wave period. Consequently it can be argued that sheltered waterways experience occasional wind wave height variations of several hundred percent, but with limited accompanying wave period growth. Sheltered shorelines in a wind wave environment are often dynamically stable. Beach areas, if they exist, adjust in response to the prevailing wave climate and sediment budget. Other landforms in low wave energy environments may typically owe their genesis to processes not associated with waves. When there is a substantial increase in incident wave period beyond what such landforms would normally experience the shoreline may experience erosion. Not only are the longer period waves more energetic but orbital currents capable of entraining sediment extend to greater depths. Where mud flats are present, shoaling long-period wake waves may form higher breakers more likely to plunge. Small craft traversing at high speeds in sheltered waterways can generate wave periods far longer than those which occur naturally.

The geomorphic impact of wind waves is not evenly felt throughout river systems and the greatest impacts occur at the downwind ends of reaches. In contrast, vessel wave wake impacts are more evenly spread throughout the waterway, with diverging waves especially impacting upon shorelines that would not otherwise be subjected to a significant incident wave climate. The wave wakes of high-speed craft, in particular, are dominated by the divergent wave system and, as the depth Froude number becomes super-critical, all waves propagate obliquely to the sailing line.

## 7. WAVE ENERGY OR POWER?

Wave energy and wave power are both used in coastal engineering. Assuming a simplified, sinusoidal wave form, wave energy (per wavelength and unit crest width) is proportional to $H^2T^2$ and wave power (derived from energy density) is proportional to $H^2T$.

Power is a useful descriptor of wave energy over a period of time, such as may be found in the statistical analysis of an incident wave field acting over a long timeframe. In the case of the wave wake of a passing vessel, the waves generated are discrete events and so do not necessarily lend themselves to description on a statistical time basis. It is felt that wave energy may be a better measure for such discrete events.

The Noosa and Maroochy River studies introduced another derived parameter – wave energy per unit wave height, or a $HT^2$ relationship when reduced to its principal variables, Macfarlane and Cox (2004). This parameter has shown empirically to display the most promising correlation between incident waves and erosion. Short period waves of less than 2 seconds period, such as the maximum waves generated by small craft and sheltered waterway wind waves themselves, do not shoal to any appreciable degree before they break. Moreover, a wave breaks when the water depth approximately equals the wave height, so its energy is concentrated into a depth of water equal to the wave height. Consequently, it is believed that energy per unit wave height is a measure of the energy content in a short-period wave just at the time of breaking, and therefore the energy being dissipated onto the shoreline. It is agreed that this explanation has not been tested and serves only as a possible explanation of the empirical strength of the $HT^2$ relationship with erosion rates.

## 8. BANK EROSION STUDIES

In Australia there have been several significant studies that have attempted to measure bank erosion from vessel wave wake. The first were academic collaborations on the Gordon River in the early 1990s (von Krusenstierna 1990, Nanson et. al., 1994) and the second is an on-going study on the Gordon River conducted by Bradbury (refer Bradbury *et al*, 1995). There was a desktop study of the Swan River (Pattiarachi 1990), but its analysis technique was rudimentary and the results inconclusive.

Von Krusenstierna attempted to measure erosion using erosion pins set into sandy banks, from which commercial vessels were subsequently banned. The waves of a passing vessel were measured and the resultant erosion was measured. Unfortunately the wave wake data was analysed and averaged in such a way as to make it almost unrecognisable. However, it was demonstrated that there was a threshold of wave wake values below which the rate of erosion was regarded as less significant, and such thresholds were evident for all of the wave wake measures recorded. In the Noosa River study, this manipulated data was recovered somewhat and threshold wave energy and period values were extracted. At the time they appeared reasonable, but there was no comparative data available.

From the mid 1990s further experiments were conducted on cohesive muddy banks lining the Gordon River reaches remaining open to commercial traffic. Although of cumulative concern, the amount of erosion per vessel pass was expected to be less than 0.1 mm and therefore undetectable by measurement of erosion pins in the field. Instrumental measurement of the turbidity (degree of suspension of solid material) resulting from sediment suspension in normally very clear water was therefore used as a proxy for erosion. Since the land manager had a pressing need for a criterion to distinguish appropriately ‘low wake energy’ vessels the suggestion from early (and limited) data of an initial threshold to sediment movement at a wave height of 75 mm was used to define the maximum acceptable wave. Subsequent work demonstrated this to be overly simplistic and that wave period was also an effective influence. That point was most graphically demonstrated by the extreme turbidity caused by the low but long waves generated by small planing craft. However limiting wave height and period independently was found overly restrictive in that it excluded many of the wave wake events that did not cause any erosion.

Four graphs from one of several sites used in the on-going study are presented, showing turbidity near the river bank (measured at two different water depths) against the maximum wave parameters of height (Figure 5), period (Figure 6), energy (Figure 7) and power (Figure 8). A fifth graph, Figure 9, shows turbidity against the derived parameter of $HT^2$ (energy per unit wave height). From these graphs, several salient features become apparent:

- All graphs define very definite threshold values below which turbidity is essentially zero (ie. within the range of instrumental and background noise).
- Wave height is a relatively poor indicator of erosion potential. One wave height value of 178mm shows zero turbidity, yet the second-highest recorded turbidity event occurs for another wave at this same height.
- There is close correlation between wave period and turbidity.
- There is similarly close correlation between both wave energy and power with turbidity.
- The derived parameter $HT^2$ exhibits the tightest grouping of all data points.

## 9. OPERATING CRITERIA

### 9.1 SINGLE OR MULTIPLE CRITERIA?

The historical application of a single operating criterion, most notably a limit on the height of the maximum wave, has been demonstrated to be at best unreliable and at worst incorrect. For example, a single criterion of wave height was adopted for vessel operations on Sydney Harbour yet there have been reports of significant foreshore damage (Kogoy, 1998). Moreover, attempts to remedy the lop-sided nature of a single parameter criterion by expanding into a wave energy or wave power form may be inefficient in containing all erosive components of vessel wave wake, so that some vessel types might still be over-restricted when limits are based upon experimentally determined thresholds to erosion.

On the other hand, where limits have been determined by desktop (or otherwise incomplete) studies they have not always been appropriate for all relevant vessel types. For instance, some high-speed vessels, particularly those claimed to possess “wave wake reducing characteristics” (which are more strictly often only wave *height* reducing characteristics by way of high length-displacement ratio) have the potential to satisfy an apparently reasonable energy criterion but still cause erosion. Prime examples of this are the various “low-wave wake” ferries operating in Sydney and Brisbane, Australia. Such vessels have been found capable of generating wave periods considerably in excess of the existing waterway wave climate (up to 4-5 times longer), but with low accompanying height when travelling at high speed. The possibility of this is illustrated graphically in Figure 4, where the most commonly applied wave wake parameters of energy, power and wave height reduce gradually at high speeds.

An energy criterion may be reasonably defined for commercial vessels operating at any speed. However, if commercial vessels are forced to operate at low speed then it is possible that smaller, high-speed recreational craft may meet the energy criterion yet still create an erosive wave wake, since aspects of geomorphic response may be linked more to wave period than height.

The particular sensitivity of sheltered waterways to incident wave period led to the belief that multiple criteria were the key to any operating limits. High-speed, deep water wave period was shown to remain essentially constant whereas other parameters decreased steadily as speed increased well into the high-speed range. The other benefit of including a period-based criterion was the strong correlation at high speed between the period of the maximum wave and a vessel’s waterline length. This was an important part of the criterion simplification process necessary for eventual application in practical situations.

### 9.2 CRITERIA DEVELOPMENT

From an analysis of the original Gordon River erosion studies (von Krusenstierna, 1990) two criteria were derived both for the Noosa and Brisbane Rivers, to be applied jointly; an energy criterion and a wave period criterion. The data plot used to derive the energy criterion could also be used to derive a period criterion. By then using the relationship between wave period and waterline length, as discussed in Section 4, the period criterion simply became an upper limit of waterline length.

The wave wake data presented in von Krusenstierna had been collected by a group dominated by geographers. The data was presented in a modified statistical form, using parameters such as significant wave height and period, with the raw data being discarded. Unfortunately this data format is incompatible with present day wave wake analysis, but there was sufficient information available to recover certain values in the form of the maximum wave height, $H_m$, and a statistical derivation of the period of the leading wave, $T_1$.

When $H_mT_1^2$ was plotted against $T_1$ as a log-log graph (Figure 10), the Gordon River erosion data tended to clump into three distinct groups – low erosion, moderate erosion and substantial erosion. The derived values of $H_mT_1^2$ and corresponding $T_1$ values were converted into energy and waterline length limits as follows:

- ○ $T_1$ was related to vessel static waterline length using statistical values derived from ship model wave wake testing, knowing that there was reasonable predictability in the relationship for the deep water, high-speed condition. The empirical relationship used was:

$$T_1 = \sqrt{\frac{22\pi L}{3g}} \qquad \text{(Equation 2)}$$

- $H_m T_1^2$ was converted to energy by multiplying by a "fundamental wave height", which was one that was derived from field work and used for many years as the operating criterion for the Gordon River, corrected for the different lateral distance to the measurement point.

The threshold energy and period values for the upper bound of the "low erosion" group became the Noosa River criteria, the Noosa River being a very sheltered river with sensitive banks. The lower bound of the "moderate erosion" group became the Brisbane River criteria, the upper Brisbane River being a more energetic environment.

Using the "low erosion" grouping does not imply "zero" erosion, as there are some events in this grouping where modest erosion was recorded. Further discussion of a possible "zero" threshold is presented in Section 11.

## 10. DERIVED CRITERIA

In numerical terms the criteria for each river are:

***Noosa River***
(a) *Energy Criterion*

The energy per metre of crest length of the maximum wave is to be less than 60 J/m, i.e.,

$$1962 H_m^2 T_m^2 \leq 60 \text{ J/m} \qquad \text{(Equation 3)}$$

measured at a point approximately 23 metres abreast of the sailing line.

(b) *Period-Based Waterline Length Criterion*

A vessel capable of satisfying the energy criterion at any speed (in knots) greater than $3.04\sqrt{L}$ (i.e., a length Froude number >0.5) should also have a static waterline length (L) less than 5.2 metres. Vessels longer than 5.2 metres waterline length should be restricted to those speeds less than $3.04\sqrt{L}$ that satisfy the energy criterion.

***Brisbane River***
(a) *Energy Criterion*

The energy per metre of crest length of the maximum wave is to be less than 180 J/m, i.e.,

$$1962 H_m^2 T_m^2 \leq 180 \text{ J/m} \qquad \text{(Equation 4)}$$

measured at a point approximately 23 metres abreast of the sailing line.

(b) *Period-Based Waterline Length Criterion*

A vessel capable of satisfying the energy criterion at any speed (in knots) greater than $3.04\sqrt{L}$ shall also have a static waterline length (L) less than 9.0 metres. Vessels longer than 9.0 metres waterline length shall be restricted to those speeds less than $3.04\sqrt{L}$ that satisfy the energy criterion.

It is noted that the energy threshold for the Brisbane River is three times that of the Noosa River. In coastal engineering terms, energy states tend to jump in orders of magnitude, not in incremental percentages. In many respects the push by designers to improve the wave wake characteristics of their vessels by a nominal modest percentage is likely to be somewhat inconsequential in erosion terms. Generally, a design either will or will not work – small changes to design parameters like hull spacing, waterline beam, draught, etc are unlikely to turn an erosive design into an acceptable one. These double criteria highlight the design dilemma – lengthening the hull to reduce the displacement-length ratio and hence wave height will only increase the wave period. This has been the legacy of the "low wave wake" catamaran designs.

## 11. COMPARISON BETWEEN BANK EROSION STUDIES

It is useful to compare the operating limits derived during the Noosa River study (using the original Gordon River erosion data of von Krusenstierna, 1990) with those obtained from the ongoing Gordon River studies.

The threshold (practically zero turbidity) values for energy, power and period of the maximum wave at one Gordon River site (Figures 7, 8 and 6) are:

| | |
|---|---|
| Energy | 30 J/m |
| Power | 10 W/m |
| Period | 1.1 to 1.2 seconds |

When this threshold energy value of 30J/m is transposed from the 50 metre lateral distance measurement used on the Gordon River to the 23 metre distance used on the Noosa River using a $-^1/_3$ wave decay exponent, the threshold energy becomes 50J/m. This is comparable to the 60J/m applied to the Noosa River. It must be remembered that the Noosa River energy criterion was based on a "low erosion" data grouping and not a "zero threshold" recorded in the later Gordon River studies. It is also worth noting that to completely avoid erosion the criteria must be matched to the most erosion susceptible site under conditions where erosion is most likely to occur. Although the Gordon results presented indicate a threshold of 30 J/m, the selected test site was deliberately chosen to allow testing of the widest range of vessel speeds because it was considered to be relatively robust and capable of repeated wave impacts without unnecessary bank degradation. Work at more sensitive sites has concentrated simply upon defining the threshold to erosion and a generalised limit as low as 10 J/m at the measurement point may be more appropriate. This would translate to approximately 16J/m under the Noosa River test conditions.

When comparing wave periods, the Noosa criterion of a maximum waterline length of 5.2 metres corresponds to a period of the maximum wave at high speeds of about 1.4 to 1.5 seconds, taken by reviewing the vessel wave wake data and comparing the recorded periods with the recorded waterline lengths. This period is slightly longer than the 1.1 to 1.2 seconds threshold recorded in the Gordon data, but the variation may again be explained by the difference between “low erosion” and “zero threshold”.

In conclusion, it appears that two independent studies separated by over a decade, using different equipment, vessels, measurement techniques and analyses, have derived very similar relationships between bank erosion and high-speed, small craft wave wake.

## 12. WATERWAY TYPES

As noted, unless the overall numbers of parameters are reduced and those chosen are simplified, it would be impossible to derive any useful erosion criteria. From discussions with coastal engineers, it is believed that there may only need to be as few as two, but probably three, bank types studied. All are natural depositional landforms. Artificial shorelines are more diverse and should be engineered to withstand an appropriate wave climate, although that has not always been the case.

The first is typical of very sheltered waterways that may experience little or no tidal range and do not have a beach structure since the energy climate is not wave dominated. These low-lying banks tend to be characterised by cohesive muds and substantial sediment trapping riparian or saltmarsh vegetation (usually not mangroves). The sediments are fine enough to be transported in suspension by currents and these deposits may represent the accumulation of sediment over extensive (geomorphological) time-scales. Once such natural features are disturbed by erosion the damage is effectively permanent.

The second is characterised by some resemblance to a beach, usually consists of fine sand and muddy sediment (so-called muddy sands) but may not have formed entirely (or at all) in response to wave driven processes. Cohesive soil banks may lie at the head of the beach, such that the beach represents an adjustment of the bank which has been exposed to wind wave, tidal and flood influences. These banks can withstand some wave action, but they often do not have the support of riparian vegetation. The upper bank structure can be severely weakened if the riparian vegetation is removed due to anthropogenic intervention such as land development (such as the Brisbane and Parramatta Rivers), cattle grazing (such as along the Patterson River in NSW, and many others) and tidal influx (Brisbane River).

The third possible bank type is what we would regard as a sandy beach, with fine to coarse grained sand (sandy muds or clean sand) that extend well above and below the mean waterline. These beaches are normally found in open areas in bays and at estuary mouths where there is a substantial wind wave climate and/or strong tidal flows. It is this third bank type which may be surplus to the study requirements, as they are somewhat dynamic by nature and are already reasonably understood by current coastal engineering science. Energetics are typically such that true beaches are not susceptible to wave wake from small craft although some may be affected by larger, high-speed ferries.

For small craft operating in sheltered waterways, only the first two bank types are considered to be of prime importance.

## 13. EVENTUAL APPLICATIONS

Any pragmatic observation would suggest that widespread application of the double criteria of wave wake energy and period limits will never happen. At best it would be limited to specific instances, such as locations with sensitive banks and commercial vessel operations.

If it were to be implemented, the simplest way to make it work would be as follows:

- Designate boating areas according to their threshold wave wake limits. This could be as simple as dividing waterways into zones, such as A,B,C,D, each with particular wave wake threshold values that suit the perceived erosion potential.
- For each licenced vessel, generate a table of relevant operating speeds for each zone using vessel waterline length and displacement. The table could be generated using any validated prediction tool, such as the AMC’s wave wake database, which can generate maximum wave height and corresponding period given simple input data (L, displacement, y and speed).
- Each vessel owner would simply have to operate their vessel according to the zone they were in, using the tabulated data.

As an example, Table 2 shows a typical speed limit table that could be fixed to the dashboard of the hypothetical vessel “*Minnow*”.

If builders of small craft were forced to "register" their designs, where various design parameters are verified and recorded, the information would be readily available. The displacement in particular would have to be at some specific loading, which might be the registered capacity of the vessel (according to existing registration requirements). Provided this information was accurate, the means would then exist for regulatory bodies to provide vessel owners with simplified operating guidelines.

## 14. CONCLUSIONS

Although limited, there has been sufficient work undertaken to demonstrate the erosive components of deep water wave wake from small craft. Small recreational craft wave wake is easier to analyse as the accompanying wave periods are low and the wave wake behaves as deep water wave wake in all but the shallowest of water. Threshold erosion values of a number of wave wake parameters have been derived, along with their relative ranking in terms of erosion influence.

The salient conclusions reached are:

- For the deep water condition, there is a clear relationship between vessel waterline length and the period of the maximum wave.
- Wave height alone is a poor indicator of erosion potential
- Derived wave wake parameters such as energy, power and energy per unit wave height (which is applicable to short period, small craft wave wake), are better measures of erosion potential
- A single operating criterion may either not encompass all erosive wave wake components or be overly restrictive for at least some vessel types.
- Multiple operating criteria such as a combination of wave energy and period limits appear to offer the best solution.
- Simplified operating criteria have been derived for several rivers and, with existing knowledge, can be applied to all small recreational vessels.

We have dispelled some of the myths regarding wave wake and erosion and outlined a method by which erosive effects might be reasonably controlled.

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| Fetch (m) | 5m/s | 10m/s | 20m/s |
|---|---|---|---|
| 100 | 26mm / 0.5s | 62 / 0.7 | 144 / 0.9 |
| 500 | 59 / 0.8 | 137 / 1.1 | 321 / 1.5 |
| 1000 | 83 / 1.0 | 194 / 1.4 | 452 / 1.9 |
| 10000 | 250 / 2.0 | 586 / 2.8 | 1304 / 3.8 |

**Table 1** Hindcast Wind Waves (wave height in mm / wave period in seconds)

**Vessel Name** : Minnow
**Registration No.** : ABC123

| ZONE | Slow Speed | High Speed | Speeds to Avoid |
|---|---|---|---|
| **A** | Up to 4 knots | Do not operate | Over 4 knots |
| **B** | Up to 5 knots | Over 18 knots | 5 to 18 knots |
| **C** | Up to 6 knots | Over 14 knots | 6 to 14 knots |
| **D** | Open Speed | Open Speed | Nil |

**Table 2** Example table of speed restrictions

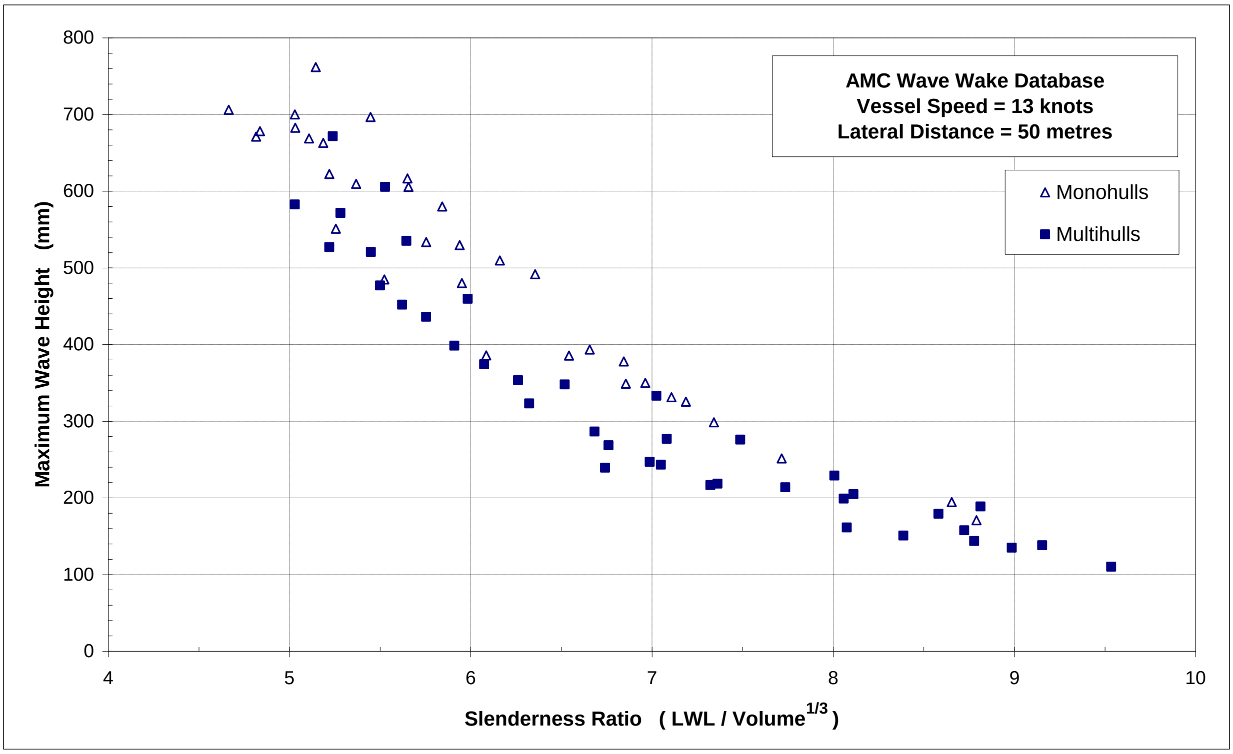


Figure 1

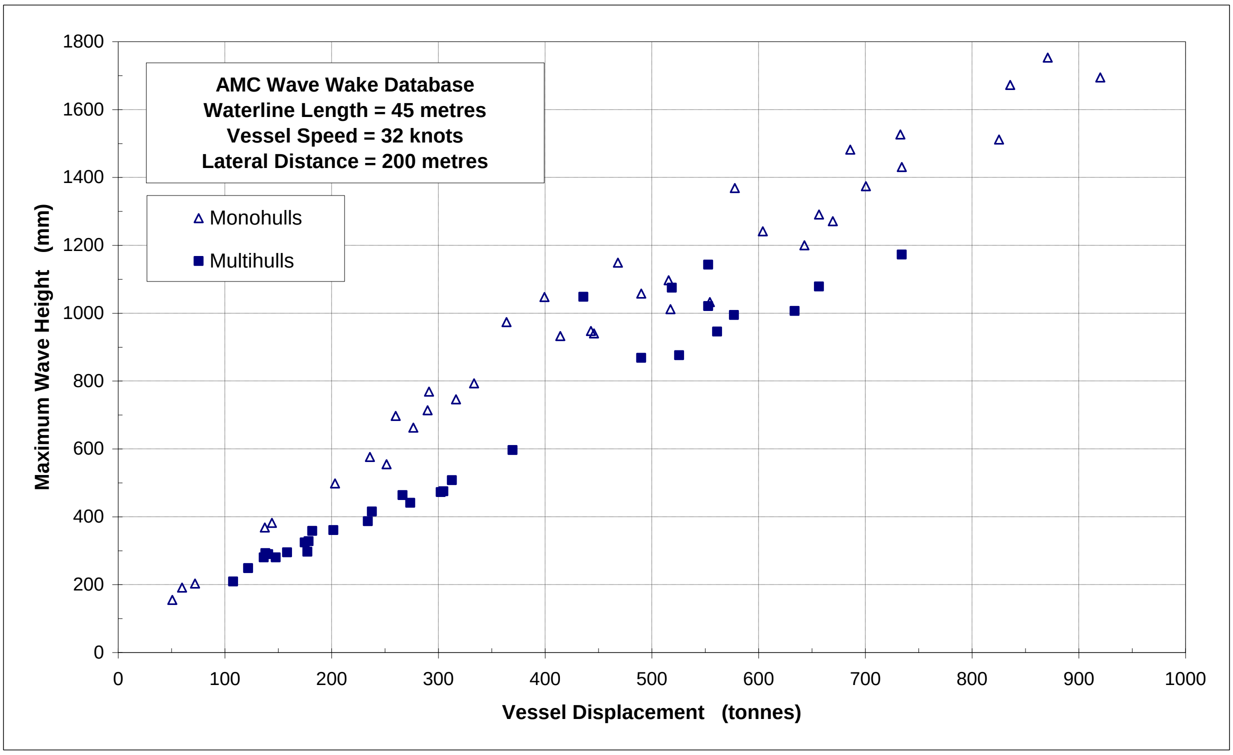


Figure 2

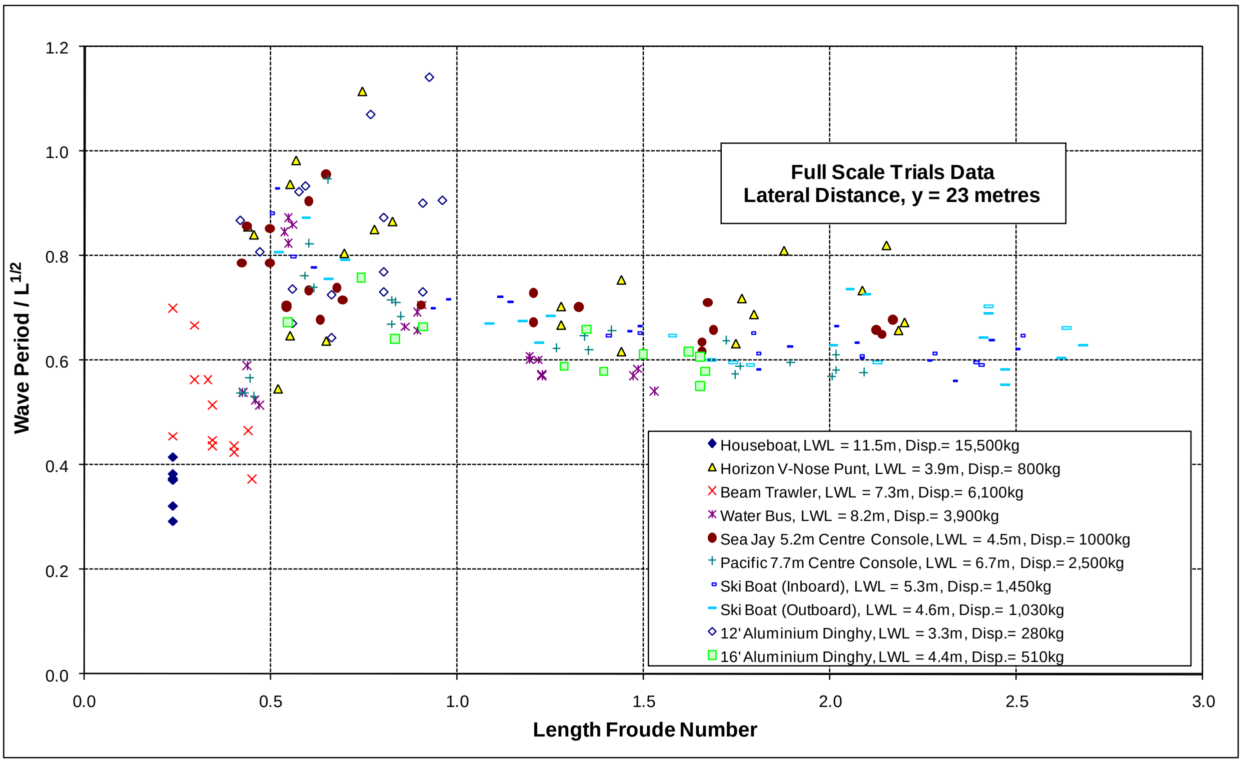


Figure 3

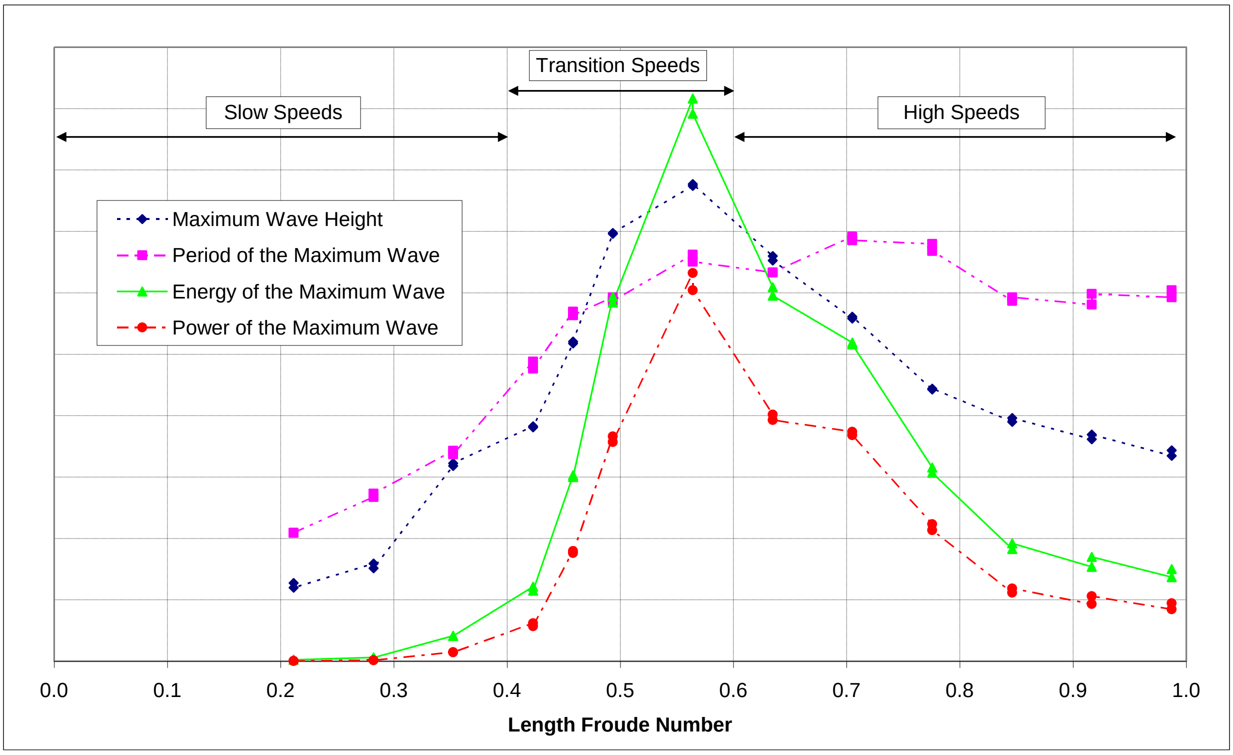


Figure 4

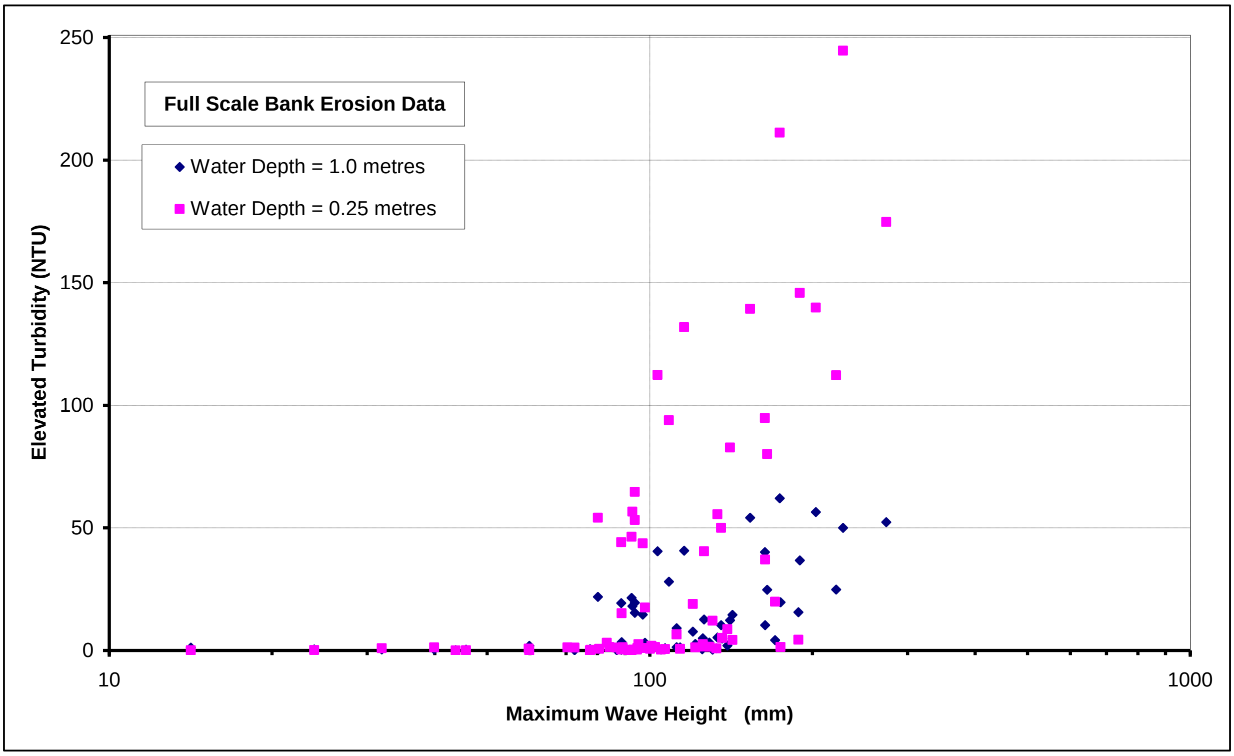
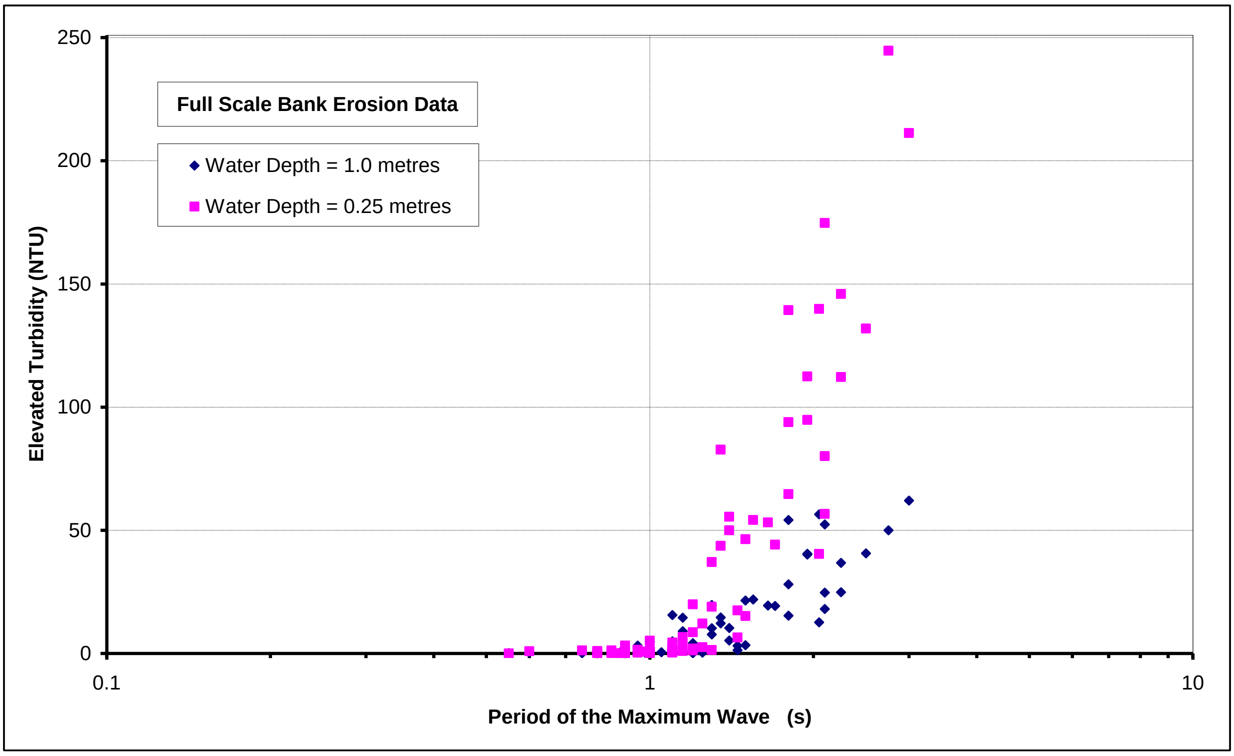


Figure 5



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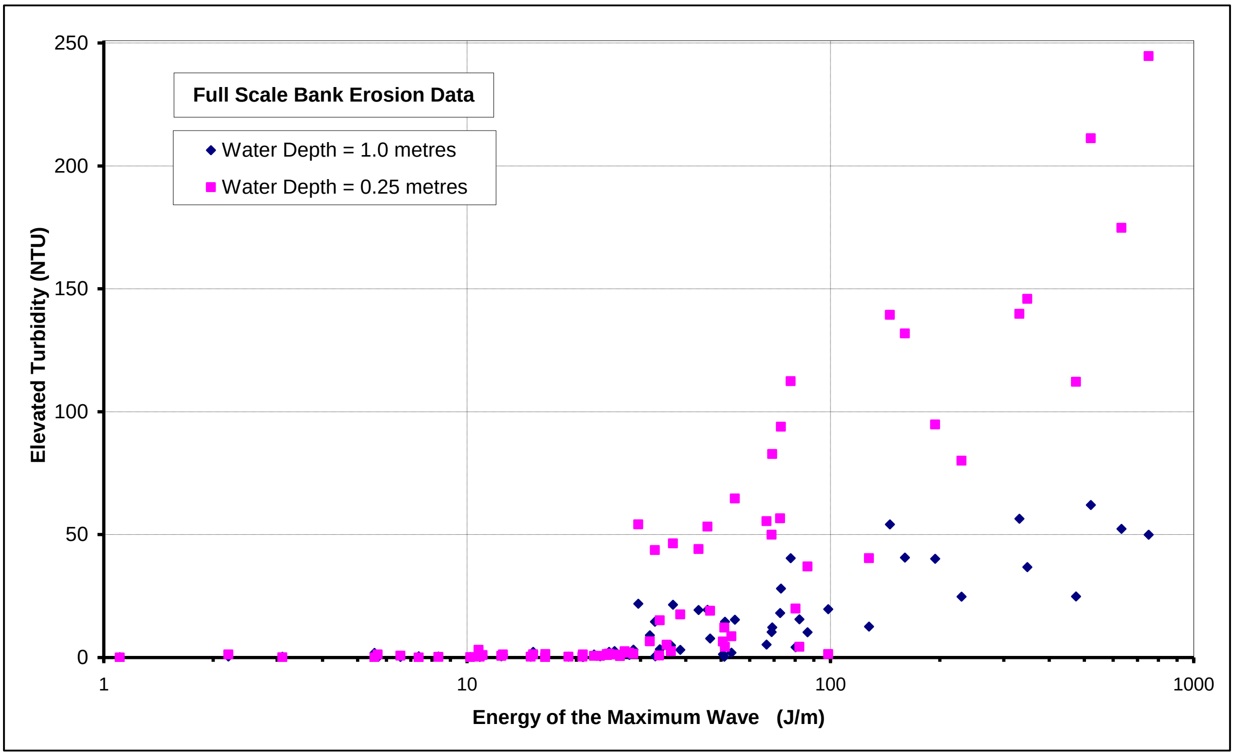

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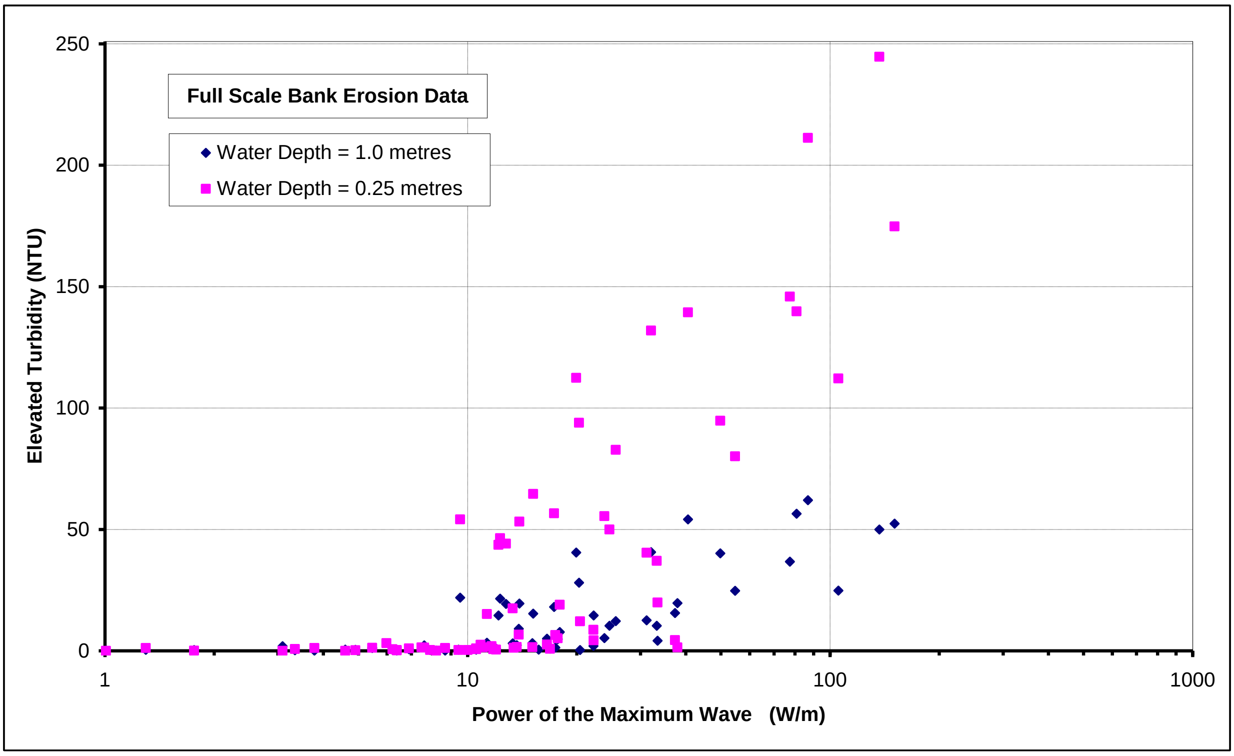

Figure 8

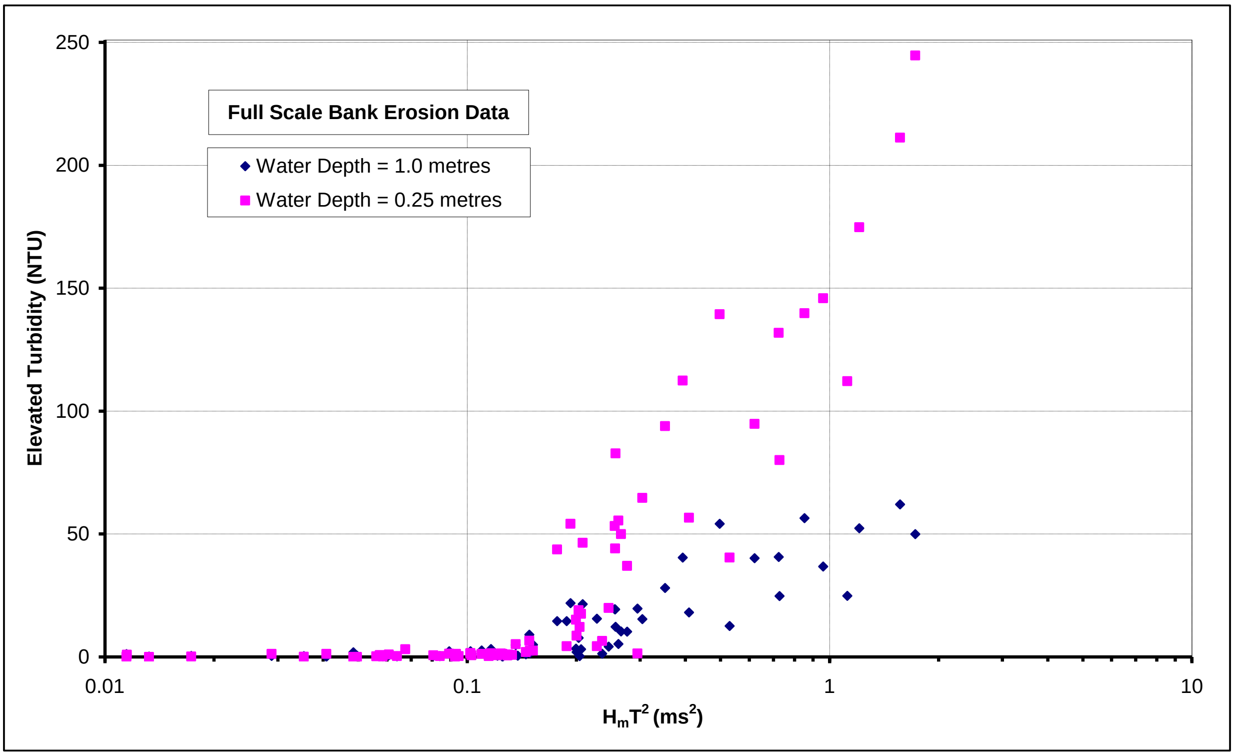

Figure 9

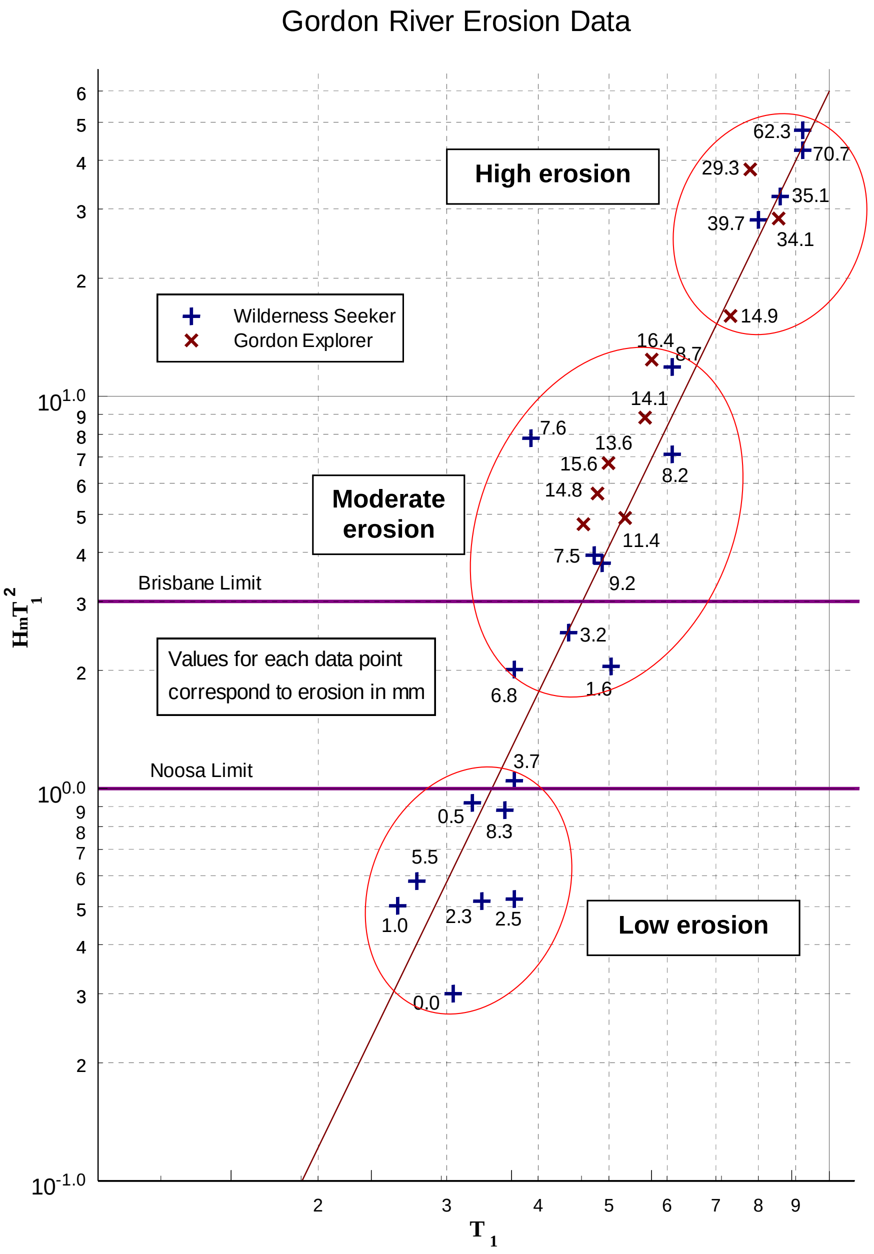
Gordon River Erosion Data
High erosion
Moderate erosion
Low erosion
Wilderness Seeker
Gordon Explorer
Brisbane Limit
Noosa Limit
Values for each data point correspond to erosion in mm
62.3
70.7
29.3
35.1
39.7
34.1
14.9
16.4
8.7
14.1
7.6
13.6
15.6
8.2
14.8
11.4
7.5
9.2
3.2
6.8
1.6
3.7
0.5
8.3
5.5
1.0
2.3
2.5
0.0
$10^{1.0}$
$10^{0.0}$
$10^{-1.0}$
$H_mT_1^2$
$T_1$
2
3
4
5
6
7
8
9

Figure 10