The development of vessel wave wake criteria for the Noosa and Brisbane Rivers in Southeast Queensland

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Abstract

Several rivers in Queensland, Australia, are experiencing bank erosion problems. Public concern compelled the relevant authorities to commission a series of inter-related studies to determine the extent of the erosion, its probable causes and a means of quantifying the erosion potential of vessel wash.

Sections of the Noosa River are in pristine condition, suffering little or no anthropogenic impact. However, one reach of the river is used by recreational and small commercial vessels as a transit route between two large lakes and is often traversed at high speed. The Brisbane River is also used for recreational boating, but the river has undergone significant change since European settlement almost 200 years ago.

The Australian Maritime College (AMC) conducted field tests to measure the wave wakes of a variety of craft that frequent these rivers. The wakes were analysed for certain maximum values such as wave height, wave period and wave energy, as well as total wake trace energy. Previous experiments attempting to correlate erosion thresholds against wake parameters were re-analysed and applied to the Noosa and Brisbane Rivers. Vessel operating criteria were developed for each river in terms of the energy of the maximum wave, maximum permitted waterline length (which can characterise wave period) and vessel speed. It is proposed that multiple criteria provides a better indicator of erosion potential than traditional single indicators such as wave height.

Keywords: vessel wash, wake, recreational boating, erosion, wave height, wave period, wave energy.
1 Introduction

Sheltered waterways are being subjected to increasing pressure from recreational activities, including recreational boating, as well as public transport and marine tourism. There are three primary causes of this pressure. Firstly, the continuing urbanisation of the environment and the premium placed on waterfront land; secondly, the growth in leisure time, combined with low-cost, mass-produced, high-speed recreational craft, and thirdly, a growth in tourism.

Marine regulating authorities are required to respond to these changes to protect the environment. It is recommended that vessel operating guidelines, where required, should be developed using sound scientific justification.

1.1 Southeast Queensland study

The Noosa and Brisbane Rivers in Southeast Queensland both experience anthropogenic pressures, but react differently due to their different usage patterns. Whilst vessel wash can be identified as the primary cause of bank erosion on the pristine Noosa River, vessel wash is only a small component of the erosive influences present on the heavily modified Brisbane River. The aim of the study undertaken was to determine the extent of vessel wash and derive vessel operating criteria that would reduce wash impacts on both rivers (with greater focus on the Noosa River).

1.2 Issues encountered

The issues encountered by this study and previous studies were wide-ranging. They were complicated by the possible contamination of genuine vessel wash concerns with amenity issues, such as over-emphasising bank erosion problems as a means of addressing vessel noise.

Factors influencing the study included bank erosion, loss of riparian vegetation, falling trees, turbidity, land use issues affecting bank stability, extractive industries (gravel dredging), altered flows and commercial fishing.

2 Description of Noosa and Brisbane Rivers

Whilst there are some similarities between the two rivers investigated in the study, the relatively untouched condition of the Noosa River cannot be compared with almost two centuries of development in and around the Brisbane River.

2.1 Noosa River

The section of river experiencing erosion is located between two shallow lakes, Lake Cootharaba and Lake Cooroibah. The river is of reasonably consistent depth and cross-section, with mid-river depths predominantly between 7 to 11 metres. The banks are generally steep, with slopes ranging from 2 in 1 to 5 in 1 (EPA [1]), and characterised for much of the reach by steep soil and clay banks that shoal quickly. Beach profiles are found in the lower reaches of the river.
Riparian vegetation in the form of Melaleuca forests, Casuarina forests and mangroves stabilises the banks and much of the surrounding land is barely above mean water level. The river experiences diurnal tidal flows of up to 0.5 m/s (EPA [1]), though the tidal range is barely a few hundred millimetres.

Although the river has been used for transport for over a century, it remains essentially in its natural state. One section is used for cattle grazing and recreational camping, which has led to bank degradation. The major sources of boat wash are from recreational vessels and small tourist vessels that pass between the two lakes.

2.2 Brisbane River

The Brisbane River is a meandering river system that rises in the hinterlands to the west of the city of Brisbane and opens into Moreton Bay at the Port of Brisbane. It has one significant tributary, the Bremer River.

Following European settlement of Brisbane, the river was progressively altered, mainly by dredging and through gravel extraction. With the lower reaches of the river opened to deep draught shipping, the banks were exposed to tidal conditions that led to bank instability, Macfarlane and Cox [2].

Anthropogenic activities such as removal of riparian vegetation, cattle grazing, bank armouring, riverside development and dumping of waste (industrial waste and sewage) have irreparably damaged the river environment. The river is also subjected to significant flood events.

Recreational boating is relatively new to the river. The section of river investigated is popular in summer months for water-skiing, but there are few commercial users of the upper reaches of the river.

3 Wash evaluation proposal

After visiting the sites and conducting community consultations, a report was prepared detailing what could be offered in way of assessment and possible solutions. One major drawback was the lack of any similar project elsewhere, coupled with the extremely limited number of studies attempting to link bank erosion with vessel wash in any quantitative manner. There have been studies undertaken on vessel wash (though typically focussing on larger vessels) and studies on bank erosion from incident waves (though typically a continuous incident wave field), but almost nothing linking the two. Those that were available tended to be site specific or comprised of data that had been heavily manipulated. The reasons for this are quite simple – vessel wash is the domain of naval architects, who care little of what happens to waves once they radiate into the far field, and bank erosion is a civil engineering concern, hence the emphasis on regular wave patterns.

The proposal comprised a three-part approach. Firstly, measurements of vessel wash were made on-site using a range of craft normally frequenting these rivers. Secondly, this wash data would be compared with that of existing bank erosion studies in an attempt at picking trends. Thirdly, a set of operating criteria
would be proposed. The final answer was termed an “80%” solution, defined as a cost-effective means of getting to within 20% of the ultimate answer, then monitoring and modifying the recommended vessel operating criteria over time to account for that remaining 20%. In comparison, a comprehensive series of studies into vessel wash and subsequent erosion would have cost considerably more, placing it well beyond the financial capacity available.

4 Wash testing procedure

It would have been possible to conduct the wash testing at almost any site having similar bathymetry – vessel wash in itself is not influenced by shoreline type. The option also existed to conduct scale model or CFD testing, but these alternative assessment methods were discounted for several reasons, including the lack of availability of models representative of those vessels operating upon these rivers (both physical and virtual ship models) and the resources required to satisfactorily validate existing CFD models. Field-testing remains the most cost-effective and realistic means of gathering data. It also serves to re-assure the general public that something is being done to address the problem.

The most important factor for successful full-scale wash testing is consistency. Wash is a dynamic phenomenon from which we seek to take a static slice over time. Lack of test consistency remains the greatest cause of data scatter.

4.1 External influences

Vessel waves are influenced by a variety of factors. If steps are not taken to properly account for these influences, substantial errors can be generated in the data collected.

4.1.1 Depth

Deep-water wave wakes are relatively stable, predictable and comparable. Once the water depth shoals or the vessel speed increases such that the depth Froude number is greater than unity, the entire wave pattern and the way in which it propagates alters. Similarly, if the generated waves begin to feel the bottom (when the water depth is less than half the deep water wavelength), wave propagation also changes.

A water depth along the sailing line greater than the vessel’s waterline length will minimise depth influences, with the leading divergent wave having a depth Froude number of about 0.75. Also, the maximum wave, defined as the highest wave in the wave train, will not generally be depth-affected if the water depth is greater than half the vessel’s waterline length (with the depth Froude number of the maximum wave about 0.63). Only the long-period, low height leading waves will be depth-affected, Macfarlane [6].

4.1.2 Distance off

The lateral distance between the vessel sailing line and the measurement point (distance off) must remain consistent, requiring the course to be properly laid out
and marked. Wake waves attenuate in height as they propagate and calculation of the rate of decay needs accurate measurements.

For river testing, a minimum distance from the sailing line to the shore of one-quarter of the river width is recommended since vessels operating on rivers, particularly at speed, are most likely to navigate the mid-half of the river. It is also recommended that measurements are made not closer than one boatlength from the sailing line (preferably at least two to three boatlengths), to avoid the localised interaction between a vessel’s transverse and divergent wave systems that cannot be properly measured with a single wave probe, Macfarlane [6].

When comparing vessel wash results alone (excluding any shore influence), the distance off is made a function of the vessel waterline length, not an absolute value. Evaluation at a fixed distance favours the shorter vessels as their waves will have attenuated in height more than those of the longer vessels.

4.1.3 Speed
To achieve a steady state wash, the vessel must travel at a consistent speed for several boatlengths. There can be no acceleration or deceleration, particularly prior to reaching the measurement point as those waves passing the measurement point were generated some time prior to the vessel passing. Acceleration and deceleration can generate a large wash, but they are not steady-state conditions and are therefore difficult to define and measure practically.

4.1.4 Course
A straight course should be maintained for some distance prior to reaching the measurement point. Wash is focussed on the inside of a curved course and diffracted on the outside. It is recognised that this does not model the real world, as many recreational boating activities involve manoeuvring. However, measurement of manoeuvring and the resulting wave patterns can be extremely complex due to the large number of variables involved.

4.1.5 External influences
External contamination from incident wind waves, incidental boat wash, reflections and currents must be minimised. The wash from small vessels, particularly the long period, leading waves, is often difficult to distinguish if background noise is high.

5 Vessel wash and erosion
It has become standard practice to characterise vessel wash in terms of a small number of parameters, though there is still debate over which parameters are the most indicative of the potential for wash-induced damage, Macfarlane [6].

von Krusenstierna [3], drawing from several independent wash studies, argues that it is reasonable to expect that the erosive components of a vessel’s wash may be contained within a small segment of the overall wave train. This argument has been developed further by assuming that a small segment of the overall wave train can characterise the overall erosion potential, rather than
contain the erosive components. This is important for the statistical prediction of vessel wash parameters, as it makes the collection, analysis and subsequent application of statistical wash data simpler and hence more practical.

5.1 Wash measures

There has been a significant shift in recent years in what is considered an indicative measure of wash and therefore erosion potential. The growth in the high-speed ferry industry has driven much of the research, but the environmental science lags well behind the development of this form of transport. In the recent past, the most common indicator used was wash height, usually taken as the height of the highest wave (measured crest to trough or trough to crest), in the belief that the reduction in wave height alone was sufficient to protect the environment. This gave rise to “low-wash” ferries, usually of catamaran form, with their parameters optimised for minimum wave height.

It is now accepted that this is only part of the story, as other wash parameters such as period and energy are also important. Unfortunately, the wash height criterion has become commonplace and is still a major focus for the marine industry and maritime regulators.

5.1.1 Wave height

Vessels generate two wave systems, divergent waves (commonly termed bow waves) that propagate at an angle to the sailing line and transverse waves (loosely termed stern waves) that propagate along the sailing line. Usually, the divergent waves are the dominant waves. The divergent packets usually contain the highest and most energetic waves and attenuate in height slower than transverse waves, so are more apparent further from the vessel. For high-speed vessels operating in shallow water, or high-speed vessels operating at very high length Froude numbers, transverse waves are not generated.

However, vessels operating in a bounded waterway such as a river can generate a significant transverse wave train. In open water, the energy of the transverse waves is dissipated by the lateral spreading of the wave, but a bounded waterway limits this. The transverse wave train can be energetic and, in a meandering river, can come ashore long after the vessel has passed.

Whilst it is common to measure the height of the maximum wave, it is often not a reasonable indicator of overall erosion potential. Most high speed vessel wakes degenerate into several wave packets in the far field, with decreasing wave periods, and it is not uncommon to find the highest wave in one of the latter packets, with a correspondingly short wave period.

It would appear that attempts to reduce wash height through certain vessel design measures, notably increasing vessel length, may have transferred wash energy away from wave height and into another form, Macfarlane [6].

5.1.2 Wave period

This is taken as the time separation of the same point on two successive waves, usually taken between zero crossing points. The longest wave periods are always...
found at the beginning of a wave trace, as the long-period waves travel the fastest.

Sheltered waterways are sensitive to long-period waves, as they do not usually occur naturally in such an environment, where wind-generated waves predominate. Wind waves grow faster in height than period as wind speed fetch increases, so sheltered shorelines have natural armouring mechanisms against wave height, provided the period remains low. Such a wave climate often produces shoreline change, but not necessarily nett erosion.

The introduction of vessel wash with periods several hundred percent longer than normally experienced can lead quickly to erosion.

5.1.3 Wave energy and power
Wave energy and power can be calculated for individual waves, or summed over a wave packet. The equation for the energy per metre crest length of a deep-water wave is given by:

\[ E = \frac{\rho g^2 H^2 T^2}{16\pi} \]  

where
- \( E \) = energy per metre of crest length (J/m)
- \( \rho \) = the density of water (kg/m³)
- \( g \) = acceleration due to gravity (m/s²)
- \( H \) = wave height (m)
- \( T \) = wave period (s)

For seawater, eqn (1) reduces to

\[ E = 1962H^2T^2 \]  

Deep-water waves propagate as a packet at a speed half that of the individual waves in the packet. The power of any wave, being the rate of transfer of energy through a vertical plane, will vary according to the packet (group) velocity and not that of the individual wave (phase velocity). Wave power is a \( H^2T \) relationship, which has the effect of penalizing height and not period.

5.2 Shoreline types
During the evaluation of the Noosa and Brisbane Rivers there was considerable discussion regarding shoreline types and how data from other studies could be applied.

Any wash and erosion assessment that also attempts to account for a substantial number of shoreline characteristics will almost certainly fail, for the simple reason that the number of possible combinations of vessel wash, water depth and shoreline types is practically infinite.

After concluding the Noosa and Brisbane River studies and following subsequent consultations with coastal engineers it is proposed that there may be only two or three primary sheltered waters shoreline types for which erosion criteria need to be developed – compacted (and often sheer) soil banks supported by riparian vegetation (the Noosa River model), muddy sands with a beach-like
profile (the Brisbane River model) and sandy muds or sand with a beach-like profile.

6 Wash criteria development

Many wash criteria that have been developed in the past have tended to be specific to particular vessels or routes. This limits the portability of the criteria. To make any wash criteria relatively universal, it must follow some basic rules, Macfarlane & Renilson [7]. Firstly, it must be simple to apply; any criterion that requires wash trials for individual vessels is only suitable for site-specific, vessel specific applications. Secondly, assessment must require the minimum amount of vessel data, such as length and displacement, as complex input data may not be easy to gather. Thirdly, it must not be over-simplistic, possibly ignoring scientific principles and unfairly penalising some vessels, blanket speed limits are an example of this.

Recreational boating is a relatively unregulated mode of transport compared to other transport modes. Regulation is often difficult or beyond the financial means of regulatory bodies. This was recognised very early in the Noosa/Brisbane River study and every attempt was made to simplify the criteria.

6.1 Single or multiple criteria?

An evaluation of wash studies completed prior to the Noosa/Brisbane River study concluded that a single wash criterion was only valid in certain instances, mainly involving low-speed vessels operating on a particular route. Wherever there were vessels of varying types and lengths, and travelling at different speeds, a single wash criterion was unable to successfully control erosion.

As discussed, vessels travelling at high speeds (length Froude number greater than 0.5) produce long-period waves, with periods that can be considerably longer than a sheltered waterway would experience naturally. These waves are never the highest waves in a high-speed wash, but can be highly energetic in addition to exhibiting other long-period wave characteristics such as shoaling and run-up.

Of the four most common wash measures (maximum wave height, period of the maximum wave and energy and power of the maximum wave) some combination of these was considered the most appropriate, most importantly because all of these wash measures could be derived easily, either through field trials or statistically from a wash database.

It is debatable whether wave energy is a better measure than wave power. The EPA report (EPA [1]) preceding the wash study consistently referred to the Noosa River as being a low energy environment, leading to the decision to adopt energy as a preferred criterion. Wave energy is a function of the square of both the wave height and period, whereas wave power varies only linearly with period, a measure that weights against height and in favour of period. Sheltered waterways occasionally experience considerable changes in natural wave height due to wind but the period of wind waves varies to a much lesser degree. The
sensitivity of sheltered waterways to long-period waves produced by high-speed vessels suggested that the favouring of wave period in the wave power calculation was possibly not justified. More recent unpublished work shows that wave energy is a more consistent indicator of erosion potential, though wave power is still better than simplistic measures such as wave height.

6.2 The link between wash period and vessel size.

It has been demonstrated that the maximum wave height of a high-speed vessel travelling in deep water is primarily a function of displacement to length ratio and the corresponding period is primarily a function of the vessel’s waterline length (Macfarlane and Renilson [4], Cox [5]). Vessel form has only a small influence on the wash of high-speed vessels, which is contrary to the common belief that low-wash vessels must be of a multihull type, such as a catamaran.

Moreover, an analysis of the deep-water wash characteristics of a number of vessels revealed that the period of the waves in the leading packet decayed according to a simple relationship. The waves in a deep-water wash trace were assigned a “wave number” (not to be confused with the term wavenumber used in coastal engineering), starting with the first wave that usually rose from the still water level. It is possible to have wave numbers with half values, depending on whether the wave is measured between up-crossings or down-crossings on the wave trace. The period of the divergent waves in a deep-water trace can be approximated by:

\[ T_n = T_1 n^{-0.6} \]  

where \( T_n \) is the period of the \( n^{th} \) wave and \( T_1 \) is the period of the first wave. The exponent in eqn (3) is a statistical average. Further analysis also shows that the period of the first divergent wave, hence the first wave, in a deep-water wash trace, can be linked to a vessel’s waterline length (L) by the empirical equation:

\[ T_1 = \sqrt{\frac{22\pi L}{3g}} \]  

6.3 Re-analysis of the Gordon River data

The Gordon River in Tasmania is a sheltered river traversed by cruise vessels conducting wilderness tours. Concerns over vessel-generated erosion led to several wash studies and on-going erosion monitoring spanning approximately 20 years. A considerable amount of data has been generated linking erosion rates to wash parameters. The Gordon River data was collected from controlled, full-scale wash tests on several river cruise vessels, comparing the measured wash parameters to the measured erosion.

Unfortunately much of the data has been manipulated in the search for suitable statistical relationships and the raw data has not been made available. To make the data applicable to the Noosa and Brisbane Rivers, a method of extracting useful data was developed. In the original Gordon River study, the wave periods reported were the average of the wave periods in the divergent
wave packet of each test run, losing the absolute relationship between the maximum wave values of height ($H_m$), period, energy and the subsequent erosion measured. The method developed for the Noosa and Brisbane Rivers was an attempt to estimate the period of the first wave given the relationships in eqns (3) and (4), but resulted in a weighting of wave packet period results, the packets with more waves receiving a longer first wave period.

![Figure 1: Wave numbering.](image)

Erosion was measured on the Gordon River using erosion pins. In re-analysing each individual test run, the value $H_mT_1^2$ was plotted against $T_1$ in a log-log graph and the corresponding erosion value marked against each data point. This is presented as figure 2. The value $H_mT_1^2$ has no particular physical validity, except that it represents the energy per unit wave height of a deep-water wave. It is believed that this parameter may have some validity when assessing small craft waves; these waves do not generally shoal before breaking and break when the water depth approximately equals the wave height, so the parameter is an indication of the energy in the total water depth just as the wave breaks. Further work conducted since the preparation of the Noosa and Brisbane Rivers report has shown this parameter to be highly effective in correlating wash and subsequent erosion. This work also clearly demonstrated that there are wave energy/power thresholds below which erosion is insignificant and that these thresholds can be characterised by simple vessel wash parameters such as maximum wave values.

From figure 2, arbitrary limits of the value $H_mT_1^2$ were chosen for each river. The erosion data was roughly grouped into three sections. The Noosa River limit was chosen as the point where the measured erosion values began to increase, reflecting the Noosa River’s low-energy environment. Conversely, the Brisbane River limit was chosen as the bottom of the mid-section, where the erosion values began to increase dramatically.
These chosen limits of $H_mT_1^2$ were then converted to energy values by multiplying with a fundamental wave height value, taken as the Gordon River Criterion wash height limit of 75mm at a lateral distance of 50 metres, then corrected for period by using the statistical relationship that the period of the highest wave in a deep water divergent packet is approximately 60% of $T_1$. The wave height values were corrected from the shoreline back to the wave measurement probe using accepted wave decay relationships.

To fulfill the desire for multiple criteria, the corresponding $T_1$ value for each $H_mT_1^2$ limit was converted to a vessel waterline length limit using eqns (3) & (4).

### 6.4 Developed criteria

For each river, three criteria were developed, the first two to be applied jointly and the third used as a more traditional option.

#### 6.4.1 Noosa River criteria

**Energy criterion:** The energy per metre crest length of the maximum wave is to be less than 60J/m, ie,

$$1962H_m^2T_m^2 \leq 60J/m$$

Where $H_m =$ height of the maximum wave in metres

$T_m =$ period of the maximum wave in seconds measured approximately 23 metres from the sailing line.

**Period-based waterline criterion:** A vessel capable of satisfying the energy criterion at any speed (in knots) greater than $3.04\sqrt{L}$ should have a static waterline length 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.

**Blanket speed limit:** If a blanket speed limit is preferred, a recommended value of 5 knots along the entire river would limit boat wash energy to the levels present before the introduction of high-speed craft.

#### 6.4.2 Brisbane River criteria

**Energy criterion:** The energy per metre crest length of the maximum wave is to be less than 180J/m, ie,

$$1962H_m^2T_m^2 \leq 180J/m$$

measured approximately 23 metres from the sailing line.

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

**Blanket speed limit:** If a blanket speed limit is preferred, a recommended value of 6 knots along the entire river would limit boat wash energy to the levels present before the introduction of high-speed craft.
6.5 Example of results

Full-scale test results are presented for the River Ranger, a 4.6 metre centre-console patrol vessel.

Figure 2: Gordon River erosion data.
Figure 3 is a plot of maximum wave height as a function of vessel speed, demonstrating the high wave height at the pre-planing condition and the gradual reduction in height as speed increases. Figure 4 shows that, when travelling at high speeds, the period of the maximum wave remains approximately constant. Figure 5 is a plot of energy of the maximum wave as a function of vessel speed, comparing the measured energy with the Noosa and Brisbane River energy criteria. As with height, the energy of the maximum wave reduces at high speeds. If energy is used as a criterion for wash, it can give a false impression that erosion potential may also reduce with increasing vessel speed. This justifies the application of multiple criteria.
Figure 5: Energy of the maximum wave as a function of vessel speed – River Ranger.

7 Criteria application

It is recognised that the application of wash criteria requiring specific vessel information can be troublesome, making its application to recreational boating difficult. The benefit of the proposed criteria is that they rely only on simple wash parameters such as the height and period of the maximum wave, and not more complicated measures such as total wash energy. The maximum wave values can be derived statistically from only vessel length and displacement, while the complimentary criterion of wave period of the longest wave has been reduced to a function of waterline length only.

The practical application of the derived wash criteria will almost certainly result in the imposition of the blanket speed limits, as both river systems have a considerable amount of recreational traffic and/or commercial traffic that is not speed-dependent for its operational viability. However, the criteria allow for vessels seeking exemptions from any blanket speed limit to be assessed by statistical means and be licenced to operate accordingly.

8 Conclusions

Recreational and commercial vessels such as those operating on the Noosa and Brisbane Rivers introduce wave climates never before experienced by sheltered waterways. In particular, long-period waves can quickly lead to environmental degradation, though some very sheltered waterways can be adversely affected by any introduced wave climate.

The imposition of vessel operating criteria based on several known erosion indicators such as wave energy and wave period, derived from simple vessel
parameters, gives regulatory authorities the means to control the boating traffic and its associated environmental impacts. In broad terms, the high-speed operation of anything other than small craft on these sheltered waterways is unsustainable.

References


