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A Decision Support Tool for Assessing the Impact of Boat Wake Waves on Inland Waterways

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Abstract

The generation, propagation, attenuation and forces related to boat generated wake waves are currently being investigated due to increasing concerns regarding their impact on coastal and inland waterways. To ensure that these concerns are objectively addressed, a Decision Support Tool (DST) to assist in waterway management has been developed. The DST is based on standardised field measurements of boat wake waves, which have been specifically developed for this field of study, local wind wave energy calculations, and an assessment of the waterway's erosion potential. Importantly, the tool incorporates both individual and cumulative wave energy calculations and a field methodology for assessing the erosion potential of a selected site. An interactive spreadsheet has been developed to assist in applying the DST at selected sites. Field testing of the DST has assisted in refining and validating the assessment methods. The DST can be easily adapted to assess the impact of boat wake waves in a variety of waterways and can be expanded to include additional vessels. While there is currently a large demand for this type of decision support tool in coastal and inland waterways, no alternative comprehensive method currently exist.

1. INTRODUCTION

Over recent years community concern regarding the perceived impact of boat generated waves (or wake waves) on coastal and inland waterways has increased. At the same time, the popularity of recreational boating and watersports, such as wakeboarding, has grown dramatically. Determining whether boat wake waves are responsible for river bank damage has been difficult to assess due to the wide range of influencing factors and a paucity of data. In the absence of a comprehensive assessment methodology, common management strategies have been to enforce speed limits, restrict recreational or commercial boats movements, or limit wave heights generated in the waterway. In many situations, however, these solutions are neither effective nor based on adequate science, and a more comprehensive strategy, supported by field investigations, is required.

Attempts to create waterway management strategies to manage boat wakes have been problematic due to (1) the lack of standardised wave measurement criteria, (2) the different wave and shoreline monitoring techniques, (3) the diverse forms of boat wakes generated and (4) the wide range of shoreline types encountered. As such, the majority of boat wake investigations to date have focused on specific types of vessels, such as passenger ferries, located in high risk areas. These studies are typically undertaken in

reaction to a specific problem at a specific location and lack a standardised approach. This piecemeal approach results in a range of methodologies, monitoring techniques and management strategies being developed throughout the world, of which few are comparable.

Due to the gaps in current knowledge and the complexities inherent in assessing shoreline dynamics it is easy to understand the difficulty in establishing a standardised boating management criterion. Indeed, AMC (2003) suggests that due to the relatively new science of monitoring boat wake propagation, combined with the multitude of erosion parameters, a comprehensive boat wake management strategy is likely to be decades away. Nonetheless, several attempts have been made to manage boat wakes at individual sites and, as detailed in Table 1, these methodologies vary widely in scope and focus. Importantly, the previously proposed wave management criteria do not take into account the natural background wave energy, nor the condition of the bank.

Table 1 Previous Wake Wave Management Criteria

Wave Characteristic	Wave Management Criteria	Source
Maximum Wave Height (H_{\max})	28 cm from peak to trough measured 300 m from sailing line in deep water.	Stumbo <i>et al.</i> (1999).
Maximum Wave Height (H_{\max})	< 20 cm no action on bank stabilisation required. 20-30 cm requires monitoring. 30-40 cm requires bank engineering assessment and remediation.	Patterson Britton and Partners (2001).
Maximum Wave Height (H_{\max})	Based on wave height criteria: $H_h \leq 0.5 \sqrt{\frac{4.5}{T_h}}$ Where H_h is H_{\max} and T_h is mean wave period. (Equates to 0.75m for 2.0 second wave period.)	Parnell and Kofoed-Hansen (2001)
Wave Energy	< 2450 joules/m (150 lb/ft) in the highest significant wave of the wave train as measured 300m from sailing line in deep water.	Stumbo <i>et al.</i> (1999).
Wave Energy, Wave Period and Speed	Energy: $1962H_m^2T_m^2 < 60$ joules/m or <180 joules/m; Period: Comparison of boat length and energy in the form of $3.04\sqrt{L}$ Speed: Blanket Speed Limit of 5-6 knots	Australian Maritime College (2003)

To improve waterway management, this paper presents a comprehensive Decision Support Tool (DST) designed to assess the impact of boat wake waves along a stretch of inland waterway. The DST is based on standardised field assessment methods, comprehensive site assessment techniques and has been field validated. The DST discussed within this paper varies from previous methods as it attempts to include all of the major components associated with rapidly assessing a selected reach of a waterway within a single methodology. The primary aim of the DST is to quantitatively

determine the impact of a boat wake wave on a shoreline, and based on the susceptibility of a shoreline to erode, determine whether vessels should be restricted, managed or allowed. In brief, the DST compares the natural background wind-wave energy with the vessel generated wave energy, the operating frequency of the boats and the erosion potential of the bank. A short description of each step involved in applying the DST is provided below.

The first step of the DST is to determine the natural wind wave energy at the site using standard methods. The energy of the passing boat wave train is then determined based on previous field measurements. The third step involves assessing the potential for the bank to erode based on a series of weighted factors that incorporate physical and ecological features of the bank. Once these initial steps have been undertaken, the wake wave energy is compared to the average recurrence interval of the wind wave energy. This comparison is undertaken for both the maximum generated wake wave and the total wave energy generated from a typical day involving multiple boat passes. The comparison of these wake wave energies with the average recurrence interval of the wind wave energy provides an indication of the likely impact of the boat waves on the shoreline. These results are then compared with a 'bank erosion rating' to determine the most appropriate boating management strategy for the site.

An interactive spreadsheet has been developed to assist in applying the tool at individual sites. A methodology for selecting sites is also provided and, based on the management outcomes, the timeframes between reassessment of a site is prescribed. Important issues such as wave attenuation, operating versus maximum wave conditions and wave duration time limits have all been included within the methodology.

To test the applicability of the method, desktop and field assessments of a range of sites has been completed. Based on this development process, the DST is currently being adopted by the New South Wales' Maritime Authority for application on multiple sites.

This paper is divided into 8 sections with each section detailing an individual component of the DST. Following this brief overview, Section 3 discusses the standards developed in measuring wake waves and the specific field tests undertaken for the study. This section also details how this information was subsequently employed within the DST and interactive spreadsheet. Section 4 details the wind wave component of the DST and Section 5 outlines how the shoreline erosion potential is calculated. Based on this information, Section 6 details how the DST determines the appropriate management outcome for each waterway. Finally, Section 7 presents the tools

developed to easily apply the DST at various sites and discusses experiences gained from recent field applications.

2. BOAT WAKE WAVES

This section details the boat wake wave data obtained and subsequently employed within the DST. Particular emphasis is placed on the development of standardised methods developed to undertake the field measurements with the intention that further measurements undertaken by others can be incorporated within the DST. Other factors including wave attenuation, the frequency of boat movements and the individual wave energy versus the entire wave train energy are discussed.

As a boat travels through the water, it generates a series of waves. The height and period of these waves vary depending on boat speed and type. Once fully formed, the group of waves are termed a 'wave train'. In deep water the height of the waves within the wave train will attenuate with distance, though the period will remain relatively unchanged. The key descriptors of these waves are schematically displayed in Figure 1.

The energy within a boat wake wave may cause damage to a shoreline by initiating sediment transport. Damage may be caused by the effect of a single wave or the cumulative effect of several wave trains from many boats. Often the general public are concerned with waves of observably large amplitudes, however damage caused by a wave is a function of both the wave height and wave period. The preferred criteria for analysing the relative effects of waves is, therefore, wave energy; a function of both wave height and wave period (Equation 1). Within the DST, wave energy calculations have been used to calculate both the maximum wave generated by a single boat pass, and the cumulative energy of multiple waves over a specific time period.

$$E = \frac{\rho g^2 H^2 T^2}{16\pi} \quad (1)$$

Where, ρ is the water density, g is the gravitational constant, and π is a constant = 3.14. The total energy of the wave train is equal to the sum of the energy of each individual wave.

2.1 Standard Methods: Boat Wave Data

In deep water (depth/wavelength > 0.5), boat wakes from different boats should be comparable across different sites. To date, a range of measurement techniques have been employed to obtain boat wake data. While laboratory tests are commonly undertaken, the most scientifically sound means is via full-scale tests with a series of well spaced capacitance probes. Three wave staffs (or more) should be located away from the generated wave at: (i) the cusp locus point (approx 2 boat lengths); (ii) within 5 boat lengths from the sailing line and if feasible, (iii) at a sufficient distance to measure 75% attenuation of wave height (or approximately 10 boat lengths).

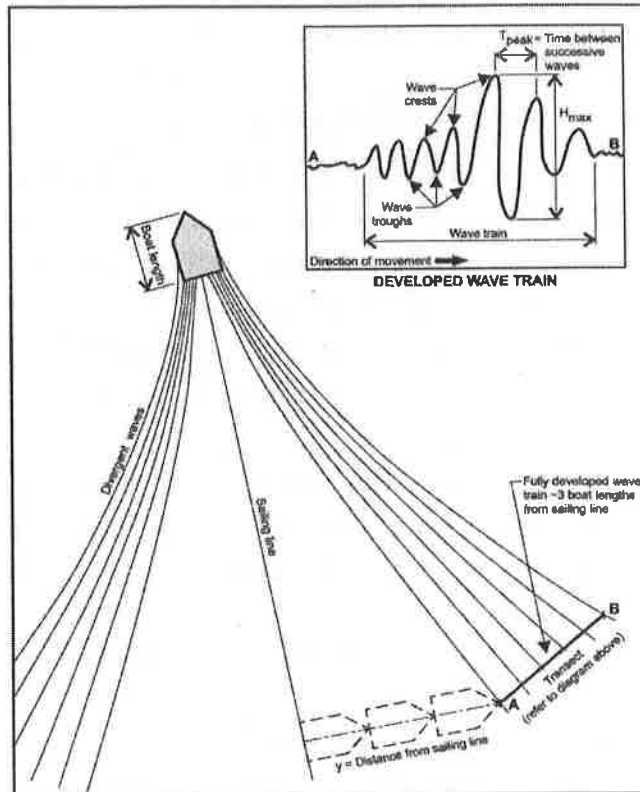


Figure 1. Schematic of Boat Wake Waves

The selected field site should have water deep enough to limit shallow water wave effects, have limited currents so that the probes remain vertical and unobstructed, and be sufficiently wide to reduce the restricted channel effect. The field tests should not be undertaken during windy conditions as wind waves may increase background noise and turbidity levels. Boats should be tested at a range of speeds including Sub-critical ($F_d < 1$), Critical ($F_d = 1$) and Super-critical ($F_d > 1$) Froude modes as well as trim and ballasting configurations. Boat speed should be calculated using appropriate methods considering the ambient currents. A calibrated radar gun is recommended to measure both the vessel speed and the distances between each wave staff. Particular attention should be given to wave reflection and a site should be chosen that absorbs the wave energy effectively. If wave reflection is apparent, especially from transverse waves generated at critical speeds, sufficient time should be taken between vessel tests to allow for the wave energy to dissipate. A typical field deployment schematic is given in Figure 2.

As part of this study, full scale field testing of several wakeboarding and waterski vessels was undertaken to determine the characteristic waves generated by different boats. The entire testing results are outlined in Glamore and Hudson (2005) and are based on the methodologies detailed above. During the tests 6 wakeboarding vessels and 5 waterski vessels were tested under 8 speed and towing conditions. Test runs included various ballasting configurations, with and without skiers, various speed levels, and turning/starting runs. Each test was repeated 6 times and wave heights were measured using purpose built submersible wave capacitance probes at 4 distances from the sailing line in a location without currents, fluctuations in water depth or significant background noise. Vessel speed and distances were calculated using a calibrated radar gun.

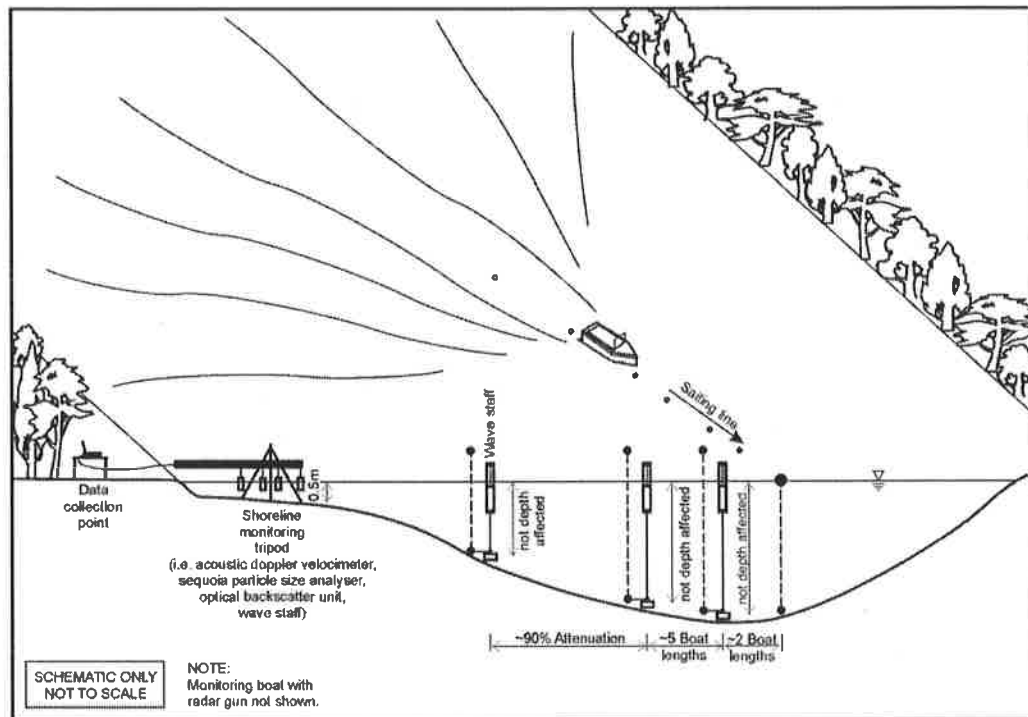


Figure 2. Schematic of Wake Wave Field Testing Protocols

Based on the field results, the differences between wakeboarding vessels and waterski vessels are most pronounced at their operating conditions (i.e. the speed for towing skiers; 30 knots for waterski boats and 19 knots for wakeboarding boats). The maximum waves produced through the vessel testing were measured 22 m from the sailing line and are detailed in Table 2.

Table 2 Wave of Operating Conditions

Boat	Velocity (knots)	Velocity (m/s)	H _{max} (m)	T _{peak} (s)	Boat Length L _w (m)	F _L	Energy H _{max}
Waterski	30	15.42	0.12	1.50	6.1	2.0	62
Wakeboard	19	9.76	0.25	1.57	6.1	1.3	293

The maximum waves recorded during field tests at all speeds are given in Table 3.

Table 3 Maximum Wave as predicted by the length based Froude Number (F_L)

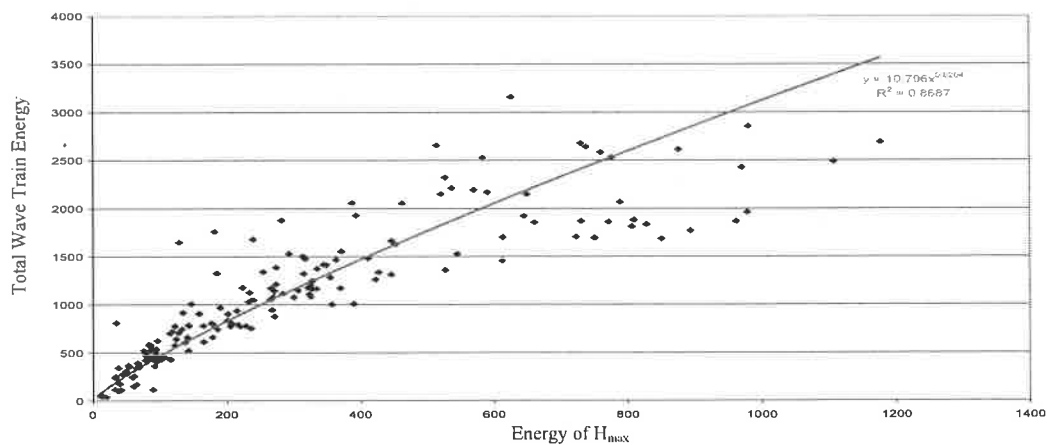
Boat	Velocity (knots)	Velocity (m/s)	H _{max} (m)	T _{peak} (s)	Boat Length L _w (m)	F _L	Energy H _{max}
Waterski	8	4.11	0.35	1.73	6.1	0.5	701
Wakeboard	8	4.11	0.33	1.86	6.1	0.5	700

Based on the wave energy calculations, it is clear that the maximum wave energy is not produced when the boats are at operating conditions, but rather at the slower velocities of 8 knots; the velocity at which the maximum wave is produced, as predicted by the length-based Froude number.

2.2 Wave Train Energy

Using the field experiment data, the energy of the entire wave train (not just the individual wave) was calculated for each boat pass. A good correlation ($r^2 = 0.88$) has been found between the total energy of the wave train and the energy of the maximum wave (Figure 3), as calculated by Equation 2. A power relationship was fitted to the data ($r^2 = 0.87$) and can be used to estimate the total energy of the wave train where the characteristics of the maximum wave are known:

$$E_{Tot} = 10.8E_{Hmax}^{0.82} \quad (2)$$

**Figure 3. Relationship of Energy of Maximum Wave Versus Energy of Entire Wave Train**

2.3 Wave Attenuation

A wave train generated by a boat initially appears as an accumulation of super-imposed waves. As the waves travel away from the sailing line, the wave train develops until all of the waves can be individually characterised by wave height and wave period, at which point the wave train may be considered fully developed. This occurs within 2-5 boat lengths from the sailing line. After the wave train becomes fully developed, the wave period remains constant while the wave height decreases in proportion to distance from the sailing line.

While it is important to calculate the maximum energy that may be inflicted on a shoreline by boat waves, attenuation of wake waves prior to impacting the shoreline should also be calculated to determine if boats may be managed within the available channel width or if width limitations should apply. If attenuation reduces the wave energy sufficiently to make boating more acceptable in a waterway, the distance away from the shore that the boats must travel should be specified in a boating management plan.

Attenuation of divergent waves may be calculated using the formula:

$$H = \gamma y^{\frac{1}{3}} \quad (3)$$

Where,

H = wave height (m)

γ = variable dependent on the vessel type and velocity

y = lateral distance from the sailing line (m)

Manipulation of Equation 3 results in Equation 3a.

$$\frac{H_y}{H_0} = y^{\frac{1}{3}} \quad (3a)$$

Where,

H_y = wave height y metres from the sailing line(m)

H_0 = wave height when generated (m)

Maximum wave heights have been measured at a distance 22 m from the sailing line. According to Equation 3a, the wave height at 22 m from the sailing line is 36% of the original wave height. Therefore, to calculate H_y at any distance from the sailing line, H_0 must first be back-calculated from the known wave height 22 m from the sailing line and multiplied by $y^{-1/3}$. If the wave train is not fully developed (i.e. is still within 22 m

of the sailing line), it is considered more appropriate to use the maximum wave statistics rather than attenuated values.

Attenuated wave heights should be calculated at a distance equal to half of the channel width. This represents the maximum attenuation possible at a site.

2.4 Frequency of Boat Movements

Erosion may be caused by the impact of a single wave or by the cumulative energy of many waves over a period of time. Consequently, a method of comparing the cumulative energy of many boat passes with the cumulative energy of wind waves over the same period must be defined. For every boat passing, the energy of the entire wave train will impact the shoreline. The cumulative effect of boats passing is, therefore, the product of the number of boats passing and the energy of the total wave train. Since it is assumed that most of the boat usage will occur over the daylight hours (8 - 12 hours), this period is used to compare cumulative energies.

If boats are already in use at a site, available data on boat use frequency on the peak day of the week should be used. If no data is available, a boat management survey should be conducted to determine the number of boat passes in a day. Surveys should be conducted on the same day of 5 consecutive weeks. The day should be chosen according to the heaviest use, but then averaged over the total number of weeks of surveys. This should prevent both damping of the frequency by averaging with very low use days such as weekdays, and exaggeration of likely boat use by surveying on highly trafficked public holidays.

If boats are not already in use at a site, projections should be made as to the likely number of boat passes on the peak day of the week. Alternatively, if boats are not already onsite, then this variable could be altered within the DST to determine the allowable number of boats on a particular stretch of a river.

2.5 Boat Wake Wave Data: Application within the DST

The vessel related data presented above is employed within the boat wake wave components (Stage 1) of the DST. During the development of the DST, the maximum wave was extracted from boat wake wave field data and the associated energy calculated. Then the energy of the maximum wave was interpolated to the energy of the entire wave train. The energy of the entire wave train can then be multiplied by the number of boat passes over a specific time period to give the cumulative boat wake

wave energy over a specific duration (8 - 12 hours). Within the interactive spreadsheet, users are given the option to select from a range of vessels and also to select whether the vessel of concern is to be tested at its operational speed or its maximum wave producing speed. Users also input the number of boats over the specified time period and the width of the river (for wave attenuation calculations). All calculations are then undertaken automatically, without the user having to have a high level understanding of the background data.

3. WIND WAVES

The natural wind-wave environment along a stretch of a river is one of the shaping factors of the waterway. Wind waves are generated by wind blowing across a fetch. The size of the waves may be limited by either the duration of the wind blowing or the length of the fetch. It is assumed that, in the absence of large floods, a waterway subjected to a certain wind-wave climate will establish equilibrium with that environment over time. For this reason, the natural wind wave climate should be assessed for each site and then compared with the energy of boat wake waves. Where the energy of the boat wake waves is of similar magnitude to the energy of the natural wind wave environment, it is unlikely that the boat wake waves will cause significant damage. If, however, boat wake wave energy greatly exceeds the wind wave energy of the site, erosion is anticipated. This section describes the method used to calculate wind wave energy at a site.

It is important to note that the factors that determine whether a wave will erode a river bank are complex and not fully understood. The erosion potential depends on many factors including, but not limited to, both the maximum wave energy of a single wave and the long-term impact of several waves over a period of time. For this reason, the wind wave energy of a location is characterised in two ways. First, the maximum fetch-limited wave energy is determined based on different wind speeds. Second, the cumulative wind wave energy for an extended duration is calculated to determine cumulative energy effects. Eight to twelve hours has been selected as an appropriate duration for calculating cumulative energy as it approximates the daylight hours during which boats are likely to be travelling.

In order of preference, the following types of wind data would be used to predict wind waves at a site in Australia:

- Site wind data (specifically collected for the study)
- Local airport data

- Regional wind data based on 3 second design wind gust data outlined in Australian Standards AS1170.2:2002

Ideally, wind data would be specific to the location of interest, thereby capturing local wind effects. In most cases, wind data of this nature will not be available in sufficiently long record sets to analyse for annual recurrence intervals. If local wind data is available, a wind rose should be made from the data to show percent occurrences of different wind speed intervals for the site.

Wind data is readily available at most locations in Australia in the form of wind roses at local airports. Data is presented as percent occurrence for different wind speed intervals and is typically divided into 16 wind directions. It is expected that this will be the primary source of wind data used for wave hindcasting. This data is typically in the form of 10 minute duration winds at $z = 10$ m height. Care should be taken in defining the wind speed intervals for presenting the data to ensure that low frequency high speed data is not neglected in the analysis. For example, the final bin may simply be >35 km/hour, however without including more detail regarding this data, a very conservative picture of the wind wave climate may be drawn.

If there is no local wind data available, regional 3 second gust design wind data for Australia can be found in AS1170.2:2002. This can be converted to a site wind speed for the 8 cardinal wind directions at the reference height of 10 m using the following equation:

$$V_{\text{sit},\beta} = V_R M_d (M_{z,\text{cat}} M_s M_t) \quad (4)$$

Where, V_R = regional 3 s gust wind speed (m/s) for annual exceedance probability of $1/R$; M_d = wind directional multipliers for the 8 cardinal directions; $M_{z,\text{cat}}$ = terrain/height multiplier; M_s = shielding multiplier, M_t = topographic multiplier.

Wind wave generation in deep water is governed by the wind speed, wind fetch and wind duration. If the development of the wave is hindered by the length of the fetch, the wind waves are termed fetch-limited, whereas if development is hindered by the duration of the wind, the waves are duration-limited. The Coastal Engineering Manual (2003) outlines relevant methods for predicting wind waves for a selected site and relevant equations are utilized within the DST and detailed below.

The following steps are used to calculate the maximum fetch-limited wind waves at a site. These values are used to compare the single maximum energy wind waves at a site with the maximum boat wake waves.

1. Determine the fetch length in 16 compass directions to the point of interest (i.e. the distance over water for which the waves can develop). This will most likely be completed using aerial photographs or topographic maps. Where available, GIS applications can be used for these calculations.
2. Using the fetch length for each direction and the matrix of wind speeds for the location, calculate the time ($t_{x,u}$) in seconds for the waves to become fetch limited using Equation 5. The wind speed used is the upper limit of each interval.

$$t_{x,u} = 77.23 \frac{X^{2/3}}{u^{1/3} g^{1/3}} \quad (5)$$

Where, X = fetch length (m); u = wind velocity (m/s); g = acceleration due to gravity (9.81 m/s^2).

3. If the time, $t_{x,u}$, is less than the wind duration, the wave is duration limited. For comparison, the waves can be converted to fetch limited waves by increasing the wind duration to the time for the waves to become fetch limited $t_{x,u}$. To calculate the wind speed at varying durations, the wind speed is first converted to a one hour wind speed u_{3600} before being converted to the wind speed u_i for the appropriate duration using the following equations:

If $1 < t_i < 3600$,

$$\frac{u_i}{u_{3600}} = 1.277 + 0.296 \tanh\left(0.9 \log \frac{45}{t_i}\right) \quad (6)$$

If $t_i > 3600$,

$$\frac{u_i}{u_{3600}} = -0.15 \log t_i + 1.5334 \quad (7)$$

Wave growth with fetch can then be calculated using the following equations:

$$H_{m,0} = 4.13 \times 10^{-2} \left(\frac{u_*^2}{g}\right) \left(\frac{gX}{u_*^2}\right)^{\frac{1}{2}} \quad (8)$$

$$T_p = 0.651 \left(\frac{u_*}{g}\right) \left(\frac{gX}{u_*^2}\right)^{\frac{1}{3}} \quad (9)$$

Where, $H_{m,0}$ = energy-based significant wave height; T_p = wave period (s); u_* = friction velocity = $(u^2 C_D)^{1/2}$; and C_D = drag coefficient = $0.001(1.1 + 0.035u)$.

Based on the percentage of time the wind has been blowing in a certain direction at a certain speed, these calculations generate a matrix of wind waves that occur for a percentage of time.

While the above steps (Equation 5-9) detail how to determine the height and period of a wind wave at a specific site, they do not include a duration or time period over which this event will occur. The steps used to calculate the cumulative waves generated at a site over a period of time (12 hours) are the same as above with the following minor modifications.

- Equations 6 & 7 are used to convert the 10 minute wind speeds to 8 - 12 hour duration wind speeds.
- Wave growth with fetch is calculated according to Equations 8 & 9 using the duration adjusted wind speeds.
- The number of waves calculated over 8 - 12 hours is calculated by dividing the duration by the wave period.

The output of these calculations is a matrix of wind waves that occur for a percentage of time based on the percentage of time the wind has been blowing in a certain direction at a certain speed. For each wind speed, the energy associated with the wave generated is calculated. Wind wave energy generated over 8-12 hours duration is simply the product of the energy of a single wave and the number of waves generated over the duration.

The Average Recurrence Interval (ARI) provides the likelihood of a wave occurring within the selected time period. In this methodology, the ARI represents the probability of a wave occurring at a site based on the available wind data. Calculating the wind wave ARI's for both individual waves and waves over a period of time is important for comparing these waves against boat generated waves.

Using the record length of the wind data, the ARI of the wind wave energies can then be approximated using the following steps:

1. Sort the wind wave energies from least to greatest, where the greatest is rank 1.
2. Calculate the cumulative percent occurrence for each of the records.

3. Convert the cumulative percent occurrence to an approximate ARI by dividing the cumulative percent occurrence rank 1 record by the cumulative percent occurrence for each record (i) and then multiplying it by the record length (n).

$$ARI_i = \frac{\text{Cumulative}\%_1}{\text{Cumulative}\%_i} n \quad (10)$$

These steps are completed for the energy of the single short-duration maximum fetch-limited waves and the cumulative energy of the 8 - 12 hour duration wind waves, thereby generating two sets of ARI's, which can be compared to the wake wave data.

4. CALCULATING SHORELINE EROSION POTENTIAL

Once the boat wake waves and the wind waves likely to be encountered onsite have been calculated, the bank erosion potential should be assessed. The bank erosion potential is calculated using a number of key criteria that are then summarized to form an erosion potential rating for the site. Sites with highly negative erosion potentials have a low resistance to erosion, whereas sites with strongly positive erosion potentials are well protected from bank erosion.

To determine which variables should be included within the methodology, a detailed literature review was completed. From the literature, key factors in the stability of river banks include river type, vegetation coverage and extent, erosion descriptors, adjacent land use and channel features. A full list of the categories, indicators and weightings used within the DST is provided in Table 4. A detailed description of the 22 indicators, including several that were chosen specifically for this study, and why they were selected for the DST is available in Glamore and Badenhop (2006).

For each of the 22 indicators a number of options are provided to assist in determining a score for that indicator. In general, indicators that reflect positively on the erosion resistance score positively, whereas indicators that detract from the erosion resistance score negatively. For instance, when determining the indicator 'wave zone cover' a user must select between <10% cover, 10 – 30% cover, 30 – 60% cover or >60% cover. Each of these options has a score associated with it ranging from -1 for <10% cover, to +2 for >60% cover. Based on the importance of each indicator, a weighting factor is then applied (i.e. Extreme, High, Moderate or Low importance, with corresponding weightings of 4, 3, 2 and 1) so that the final score for the indicator is the score multiplied by the weighting. The erosion potential indicator for the entire site is the sum of all 22 weighted scores.

Table 4 Erosion Potential Indicators Used in DST

Category	Indicator	Weighting	Indicator Options
River Type	Valley Setting	High	Confined, Partially Confined, Laterally Unconfined, Completely Armoured, Partially Armoured
	Stage variability	Moderate	Tidal, Natural, Regulated
Vegetation	Longitudinal continuity of bank vegetation over stretch	High	<10%, 10-30%, 30-60%, >60%
	Verge cover (10 m from top of bank)	Moderate	<10%, 10-30%, 30-60%, >60%
	Upper Bank Cover	High	<10%, 10-30%, 30-60%, >60%
	Wave Zone Cover	High	<10%, 10-30%, 30-60%, >60%
	Native canopy species regeneration (< 1 m tall)	Low	None, Scattered, Abundant
	Native understorey regeneration	Low	None, Scattered, Abundant
	Dominant Wave Zone Cover	High	Bare (vertical slope), Bare (1:3 slope), Bare (<1:7 slope), Rocks, Tree Roots, Mangroves, Grasses, Reeds
Channel Features	Bank Slope*	High	Near-Vertical, 1:3, 1:5, 1:7
	Bank Height	Moderate	<1 m, 1-3 m, >3 m
	Channel width	High	<36 m, 36 -120 m, >120 m
Erosion	Bank Sediment Type	Moderate	Bedrock/Boulders/Armour, Cohesive, Non-Cohesive, Complex
	Lateral Stability	Moderate	High, Moderate, Low (based on evidence of channel migration)
	Sinuosity	Moderate	<1:3, >1:3
	Erosion above the wave zone	Moderate	Absent, <10%, 10-30%, >30%
	Slumping	Moderate	Absent, <10%, 10-30%, >30%
	Undercutting in the wave zone	Extreme	Absent, <10%, 10-30%, >30%
Land use	Desnagging	Low	None, Conducted in Last Year
	Excavation	High	Present, Absent
	Extraction	Low	None, Water, Sediment
	Stock access	Extreme	Present, Absent

*Note that the bank slope indicator is dependent on the sediment type.

The final erosion potential rating determines the site's Erosion Potential Category, as summarised in Table 5. The highest possible score for a Confined valley setting (as selected in the Valley Setting Indicator) is 67 points, whilst the lowest possible score in a Confined setting is -24. The highest possible score for a Laterally Unconfined valley setting is 58 points, while the worst is -90.

The area to be assessed will be predetermined by the overall extent of the waterway feasible for recreational boating. As shown in Figure 4, this length is then divided into 500 m stretches on each side of the river, of which 30% are randomly selected. Each stretch is then divided into three sections and a 10 m wide transect at the midpoint of each section assessed. The erosion potential of the three transects should be averaged

for each stretch. Along the entire testing area, the lowest scoring stretch (i.e. that with the lowest final rating) is taken as the final score. Onsite assessments should be made at low tide and not during floods, as it is important that the banks can actually be observed during the assessment process.

Table 5 Final Erosion Potential Categories

Indicator Rating Score*	Erosion Category
≥ 40	Highly Resistant
20 to 40	Moderately Resistant
20 to 0	Mildly Resistant
0 to -25	Moderately Erosive
-25 to -97	Highly Erosive

*Note that the Indicator Rating Score is the summation of all 22 weighted scores for each transect.

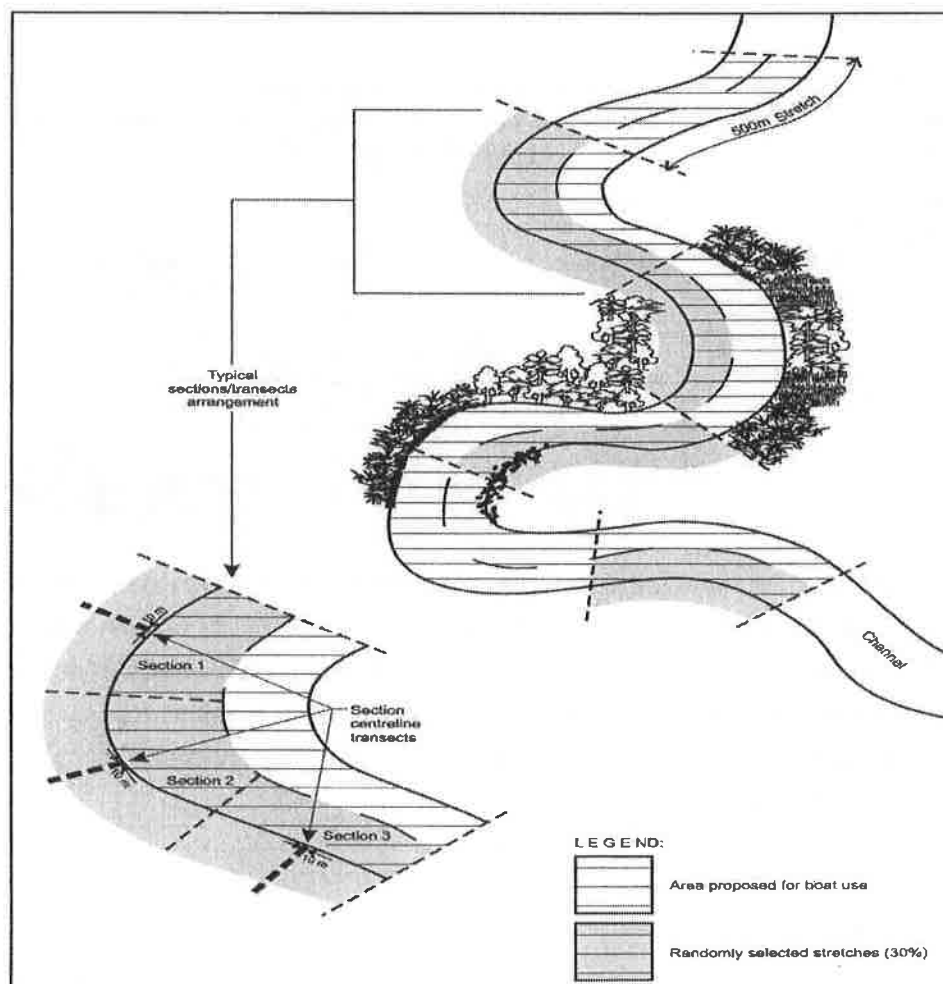


Figure 4. Schematic of Field Assessment Selection Process

5. DETERMINING MANAGEMENT OUTCOMES

The above sections have outlined relevant methods for determining the boat wake wave energy, for calculating wind wave energy, developing Average Recurrence Intervals (ARI), and for assessing the onsite erosion potential. Once this information has been gathered then the data is fed into a series of matrices that determine the management outcome.

The first matrix (Table 6) compares the ARI of the wind wave energy against the boat wave energy for both a single maximum boat wave train and an extended duration period (8 - 12 hour). The aim of this assessment is to determine the equivalent ARI of the boat wake wave energy (i.e. to establish if the boats wake wave energy is the equivalent of a 2-year wind wave event or a 20-year wind wave event). For instance, if the single maximum boat wave energy is equivalent to a 3-year ARI maximum wind wave AND the longer duration boat wave energy is comparable to the energy of a 3-year ARI wind wave, then the site would fall within a Category C rating.

Table 6 Comparison of ARI for Wind and Boat Waves

Equivalent ARI for maximum boat wake wave energy	Equivalent ARI of boat wake wave energy over an extended period (typically 8 - 12 hours)					
	<1	1-2	2-5	5-10	10-20	>20
<1	A	A	B	C	C	C
1-2	A	B	B	C	C	D
2-5	A	B	C	C	D	D
5-10	B	B	C	C	D	D
10-20	B	C	C	D	D	E
>20	B	C	C	D	E	E

Based on the outcome from Table 6, which compares the boat wave data against the wind wave data, an assessment is then made against the calculated site Erosion Potential (Table 7). As shown in Table 7, a site with a 'C' ARI Rating (as determined from Table 6) can either gain one of three management outcomes (Permit, Monitor, Assess) based on the erosion potential calculated for the site. The final management outcome is then applied to this entire stretch of the river.

Table 7 Final Management Outcome

ARI Rating	Erosion Potential				
	Highly Resistant	Moderately Resistant	Mildly Resistant	Moderately Erosive	Highly Erosive
A	ALLOW	ALLOW	ALLOW	MANAGE/MONITOR	MANAGE/RESTRICT
B	ALLOW	ALLOW	MANAGE/MONITOR	MANAGE/MONITOR	MANAGE/RESTRICT
C	ALLOW	MANAGE/MONITOR	MANAGE/MONITOR	MANAGE/RESTRICT	MANAGE/RESTRICT
D	MANAGE/MONITOR	MANAGE/MONITOR	MANAGE/MONITOR	MANAGE/RESTRICT	MANAGE/RESTRICT
E	MANAGE/MONITOR	MANAGE/RESTRICT	MANAGE/RESTRICT	MANAGE/RESTRICT	MANAGE/RESTRICT

Depending on the management outcome determined above, a varying reassessment period would apply. A site with a 'Monitor' management outcome should be assessed every 2 years, whereas the 'Permit' option allows reassessment every 5 years. If warranted, the DST could also be used to assess the impact of wave attenuation and, in certain scenarios, may result in an alternative management outcome.

6. USING THE DST

For ease of use and understanding, the equations and methods presented above have been incorporated within a user-friendly interactive spreadsheet. The interface is divided into five main categories: Introduction, Boat Wake Waves, Wind Waves, Shoreline Erosion Potential and Management Outcome. The spreadsheet is coded to only allow the user access to the key areas for data input, yet can be easily adapted to include additional components. A depiction of each primary assessment stage within the DST spreadsheet is provided in Figure 5.

In addition, a DST User's Manual has been developed to assist in using the interactive spreadsheet and to provide additional resources (i.e. field sheets, onsite checklists, representative photos with marked guidelines, etc) for the field assessment. A theoretical manual has also been developed (Glamore and Badenhop, 2007) to present the science behind the selected methodologies and to discuss the rationale for the erosion potential indicators.

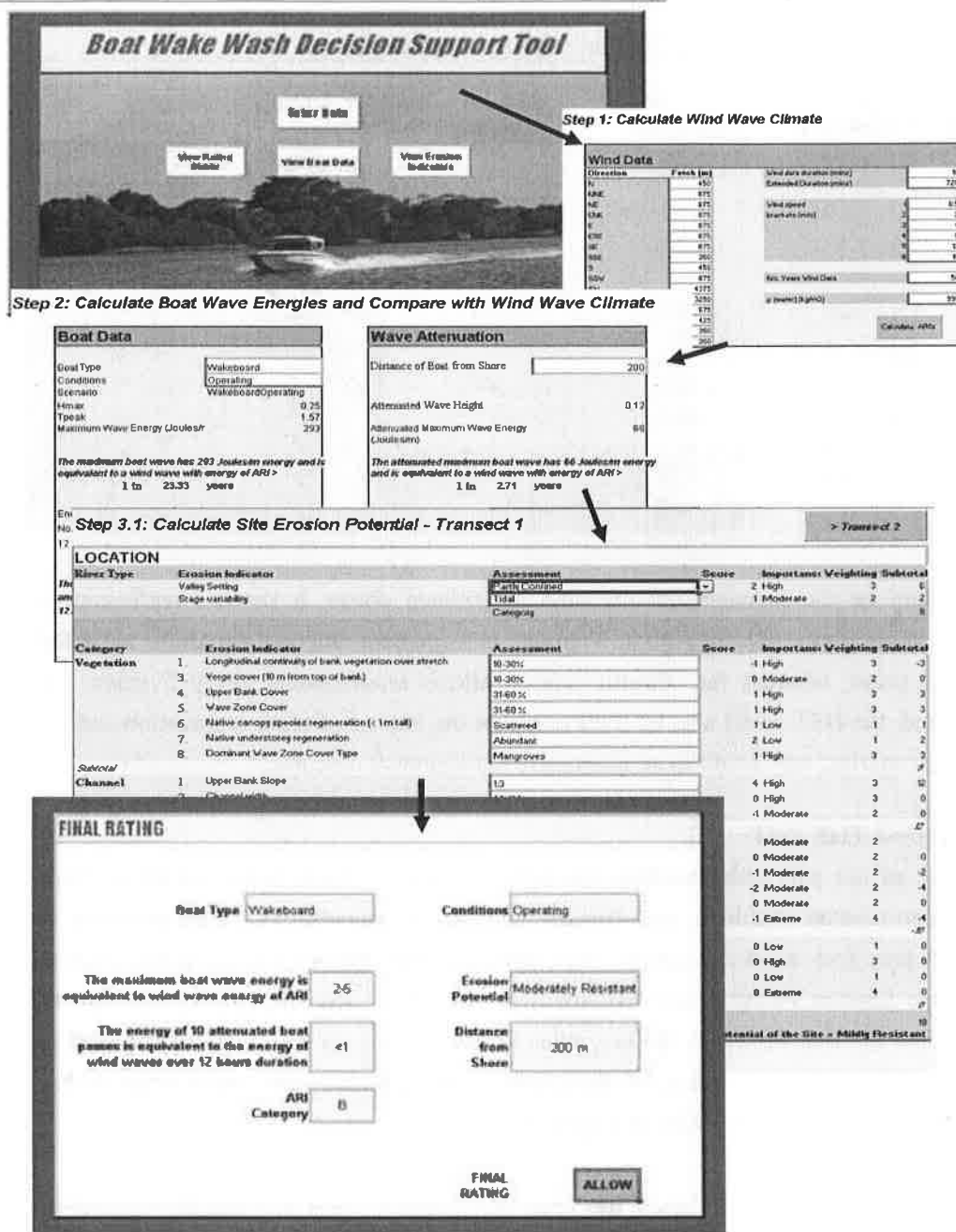


Figure 5. Images of the Assessment Stages Within the DST Spreadsheet

7. SUMMARY

A Decision Support Tool has been developed to determine if vessels should be permitted on a waterway based on whether the boat wake waves are likely to cause erosion at a selected site. The tool is structured around three major components: (i) determining the wave energy (from both a single wave train and multiple wave trains over a period of time) for selected boats based previously measured field data, (ii) calculating the average ARI recurrence interval for wind waves (for both maximum and

cumulative energy) at the selected site, and (iii) assessing a series of shoreline stretches of the waterway to determine the erosion potential. A decision matrix is then used to compare the energy from the boat wake waves relative to the local wind wave energy. The outcome from this matrix is then used against a matrix of erosion potential indicators for the site and a final management outcome is determined. Field protocols, resources (User and Theory Manuals, Onsite field spreadsheets and checklists, etc) and an interactive spreadsheet have been developed to assist in the decision making process.

8. ACKNOWLEDGEMENTS

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