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THE UNIVERSITY OF NEW SOUTH WALES

Water Research Laboratory
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1. Introduction

Over recent years community concern regarding the perceived impact of boat generated waves (or wake waves) on inland waterways has increased. At the same time, the popularity of recreational boating continues to increase and watersports, such as wakeboarding, have grown dramatically. Determining whether a boat wake wave is actually responsible for river bank damage has been difficult to quantify due to the wide range of influencing factors and a paucity of data. Indeed, due to a lack of an accepted bank assessment methodology a common management strategy has been to enforce speed limits and restrict recreational boats movements or activities. In many situations, however, this is not an effective long-term solution and a more comprehensive strategy, supported by field investigations, is required.

To overcome these concerns and improve waterway management the Water Research Laboratory (WRL) at the University of New South Wales have developed a standard methodology that assesses the erosion susceptibility of a reach of a river and determines whether a selected vessel should be permitted to operate within the waterway. The outcome of this study is a comprehensive decision support methodology (or system) which is presented within this report.

The methodology detailed within this report includes all of the major criteria associated with assessing a selected reach of a river. The method focuses on assessing the susceptibility of a river bank to erode due to a wake wave or series of wake waves. The tool is broken down into several components emphasizing the energy of the wake wave generated from the passing vessel, the naturally occurring wind energy at this same site, the erosion potential of the bank and the number of boat passes. While this provides an indication of the current physical state of the river bank, the tool has not been designed to assess the ecological health of the river.

In brief, the outlined methodology compares the natural wind-wave energy with the likely vessel generated wave energy, the operating frequency of boats and the erosion potential of the bank. The method first determines the natural wind energy at the site using standard methods. The energy of the passing boat wave is then determined based on previous field experiments conducted by WRL. The third step involves assessing the potential for the bank to erode based on a series of weighted factors that incorporate physical (including vegetation) 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 energy provides an indication of the likely impact of the boat waves on the shoreline. These results are then compared with the bank erosion index to determine the impact of the boat wake wave on the shoreline. The end result is one of three management categories: Permit, Permit with Monitoring and Restrict (labelled 'Allow', 'Manage/Monitor', 'Manage/Restrict' in the attached spreadsheet).

An interactive spreadsheet has been developed to assist in using the tool at any specific site. 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 assist in understanding and further developing the methodology a range of sites were assessed using both desktop methods and field investigations prior to development of the existing version. Throughout the report assumptions and limitations are detailed.

1.1 Report Outline

Following this brief introduction, Section 2 describes the methodology used for calculating wind waves in the local environment based on available wind data. Available data describing recreational boat wake waves is outlined in Section 3. Determining the bank erosion potential of a site is investigated in Section 4. This section includes a literature review on the various components that are important to bank stability and different methods of assessing river condition. Using this information, the indicators within the Decision Support System are determined in Section 4.2. Section 5 explains how the determination of wind waves, boat wake waves and site erosion potential are combined in the Decision Support System. Conclusions and recommendations for further research are summarised in Section 6.

2. Wind Waves

The natural wind wave environment along a reach of a river is one of the shaping factors of the waterway. Wind waves are generated by wind blowing across a stretch of water. The available length of water for the wind to blow across is called the '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 a waterway subjected to a certain wind-wave environment will establish equilibrium with that environment. For this reason, the natural wind wave climate should be assessed for each site. The energy of wind waves can then be 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 additional damage. If, however, boat wake wave energy greatly exceeds the prevailing wind wave energy of the site, accelerated erosion is more likely to result. This section describes the method used to calculate wind wave energy at a site.

It is important to note that the factors which 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 combined impact of several waves over a longer duration. For this reason, the wind wave energy of a location is characterised in two ways. Firstly, the maximum fetch-limited wave energy is determined based on different wind speeds. Secondly, 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.

2.1 Wind Data

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

1. Site wind data (specifically collected for the study)
2. Local airport data
3. Regional wind data based on design 3 second gust data outlined in Australian Standards AS1170.2:2002.

Ideally, wind data would be site 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 per cent occurrences of different wind speed intervals for the site.

Wind data is readily available at most locations in the form of wind roses at local airports. This data is in the form of per cent occurrence for different wind speed 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 in the form of 10 minute duration winds at 10 m height above ground. Care needs to be taken in defining the intervals for presenting the data to ensure that low frequency, high wind strength data is not neglected in the analysis. For example, the final category 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 data 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:

$$V_{sit,\beta} = V_R M_d (M_{Z,cat} M_s M_t) \tag{2.1}$$

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
$M_{z,cat}$ = terrain/height multiplier
M_s = shielding multiplier
M_t = topographic multiplier

2.2 Wave Hindcasting

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 current industry standard for coastal engineering works is the US Army Corps of Engineers Coastal Engineering Manual (CEM), (2003) which outlines a method for predicting wind waves for a selected site. The methodology presented within this report utilises equations outlined in the CEM manual.

2.2.1 Single Short Duration Maximum Fetch-Limited Waves

The following steps are used to calculate the maximum fetch-limited 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 at the location 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, a GIS system 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 2.2. The wind speed used is the upper limit of each interval.

$$t_{x,u} = 77.23 \frac{X^{2/3}}{u^{1/3} g^{1/3}} \tag{2.2}$$

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. To maximise the waves generated by the wind, 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 firstly 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:

$$\frac{u_i}{u_{3600}} = 1.277 + 0.296 \tanh\left(0.9 \log \frac{45}{t_i}\right) \quad (1<t_i<3600) \quad (2.3)$$

$$\frac{u_i}{u_{3600}} = -0.15 \log t_i + 1.5334 \quad (t_i>3600) \quad (2.4)$$

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

$$H_{m,0} = 4.13 \times 10^{-2} \left(\frac{u_*^2}{g}\right)\left(\frac{gX}{u_*^2}\right)^{\frac{1}{2}} \quad (2.5)$$

$$T_p = 0.651 \left(\frac{u_*}{g}\right)\left(\frac{gX}{u_*^2}\right)^{\frac{1}{3}} \quad (2.6)$$

Where,

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

The product of these calculations is a matrix of wind waves that occur for a percentage of time based on the percentage of time the wind is observed to blow for a certain combination of direction and speed.

2.2.2 Extended Duration Wind Waves

While the above section details how to determine the height and period of a wind wave at a specific site, it does not include a duration or time period over which this event is assumed to be occurring. The steps used to calculate the cumulative waves generated at a site over a period of time (say 8 - 12 hours) are the same as those in Section 2.2.1 with the following minor modifications:

1. Equations 3 and 4 are used to convert the 10 minute wind speeds to 8 - 12 hour duration wind speeds.
2. Wave growth with fetch is then calculated according to Equations 5 and 6 using the duration adjusted wind speeds.
3. 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 second 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.

2.3 Wind Wave Energy

Wave energy (E) is a function of both wave height and wave period, and can be calculated according to the following equation:

$$E = \frac{pg^2H^2T^2}{16\pi} \tag{2.7}$$

Where,

ρ = water density kg/m^3

π = a constant

= ~3.141

For each wind speed, the energy associated with the wave generated can now be 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.

2.4 Average Recurrence Interval

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 (further discussed in Section 3).

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

$$ARI_i = \frac{Cumulative\ \%_1}{Cumulative\ \%_i} n \tag{2.8}$$

This needs to be 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.

2.5 Assumptions and Limitations

- The accuracy of the assessment will be limited by the relevance of the available wind data to the site under consideration.
- It is assumed that formulae used for wave hindcasting and converting between winds of various durations are able to adequately predict waves caused by winds of certain durations blowing over certain fetches.
- It is assumed that the coarser resolution of wind intervals provided in wind roses is adequate for the assessment of the local wind-wave climate.

In summary, the natural wind wave environment of a site may be characterised by using local wind data to hindcast the waves generated. The energy of these waves may then be calculated from the wave height and wave period prior to determining the annual recurrence intervals of different wave energies. Similarly, the cumulative wind wave energy generated over a specific duration may be calculated. The output of these calculations is:

1. A list of ARI's of wind wave energy for single fetch-limited waves.
2. A list of ARI's of cumulative 8 - 12 hour duration wind wave energies.

This information is subsequently used in comparison to boat wake wave data in Section 5 to assist in formulating the appropriate site management strategy.

3. Boat Wake Waves

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 (decrease) with distance, while the period (i.e. time interval between successive waves) will remain relatively unchanged. The key descriptors of these waves are schematically displayed in Figure 1. More detailed information about wave theory can be found in Glamore and Hudson (2005).

The energy within a boat wake wave may cause damage to a shoreline by initiating the movement of sediments that form the river bank. Damage may result from the effect of a single wave or the cumulative effects of several wave trains caused by the passing of many boats. Often the general public are concerned about waves with 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. Within this report the calculation of boat wake waves has incorporated the energy of the maximum wave caused by a boat, and the cumulative energy of multiple waves caused by boats over a specific time period.

To enable comparison of boat waves with wind waves, the maximum wave is firstly extracted from field data of boat waves and the associated energy calculated. Secondly, the energy of the maximum wave is extrapolated 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). These two different datasets may then be compared to wind wave energy according to the methodology outlined in Section 5.

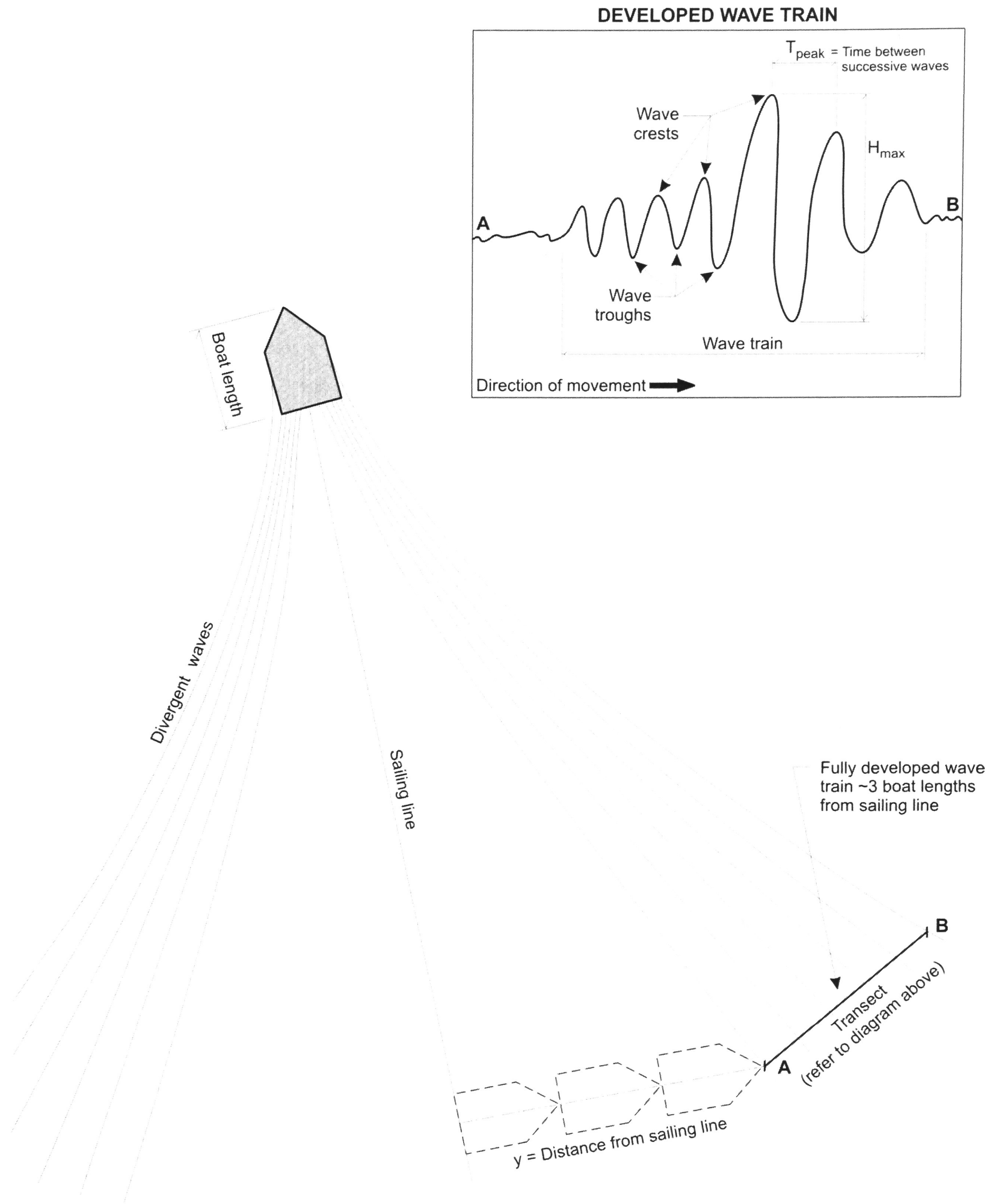


Figure 1: Schematic of Boat Waves

3.1 Boat Wake Wave Data

WRL completed full scale field testing of several wakeboarding and waterski vessels in 2005 to determine the characteristic waves generated by the different boats. The testing results are outlined in Glamore and Hudson (2005). Differences between wakeboarding vessels and waterski vessels are most pronounced at their operating conditions (30 knots for a waterski boat and 19 knots for wakeboarding boats).

The maximum waves produced by testing of the boats at operating conditions were measured 22 m from the sailing line and are found in Table 1.

Table 1: 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

Source: Glamore and Hudson (2005)

The maximum waves recorded during field tests at all speeds are given in Table 2.

Table 2: 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

Source: Glamore and Hudson (2005)

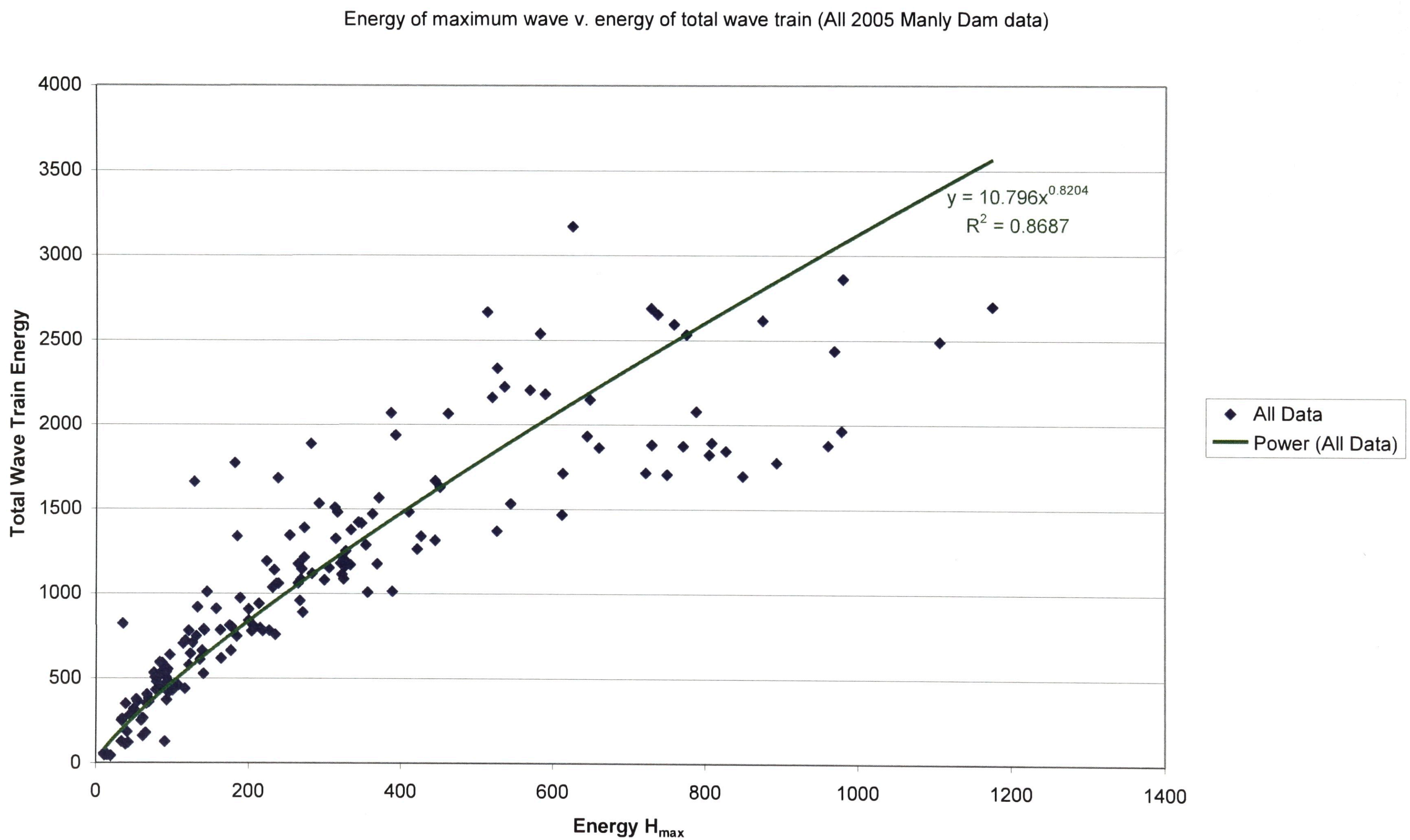
Wave energy calculations were discussed in Section 2.3. From these calculations, it is clear that the maximum wave energy is not produced when the boats are at operating conditions, but rather at the slower velocities of 8 knots; the velocity at which the maximum wave is produced as predicted by the length-based Froude number.

3.2 Wave Train Energy

In the 2005 study, 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 2) as calculated by Equation 2.7. 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:

$$E_{Tot} = 10.8 E_{Hmax}^{0.82} \quad (3.1)$$

Figure 2: Relationship Between Maximum Wave Energy and Wave Train Energy



Source: Glamore and Hudson (2005)

3.3 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 of the boat, the waves spread out 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:

$$H = \gamma y^{-\frac{1}{3}} \tag{3.2}$$

Where,

H = wave height (m)

γ = variable dependent on the vessel type and velocity

y = lateral distance from the sailing line (m)

Rearrangement of Equation 3.2 results in Equation 3.2a.

$$\frac{H_y}{H_0} = y^{-\frac{1}{3}} \tag{3.2a}$$

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 (Section 3.1). According to Equation 3.2a, 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 firstly 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.

3.4 Frequency of Boat Movements

Erosion may be caused both by the impact of a single wave and 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. It is assumed that most of the boat usage will occur over the daylight hours (between 8 - 12 hours) and thus, this duration is suggested 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 (e.g. Saturday), but then averaged over the total number of weeks of surveys. This should prevent both underestimating the frequency by averaging with very low use days such as weekdays, and exaggeration of likely boat use by surveying on a key public holiday such as Boxing Day or Easter Monday.

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 varied to determine the allowable number of boats on a particular stretch of a river.

3.5 Assumptions and Limitations

- Boat wake wave data is limited to the data collected by the Water Research Laboratory in 2005 (Glamore and Hudson, 2005), as no other data has been found that uses a standardised analysis criteria and is relevant to recreational vessels in inland waterways (much of the international literature focuses on large ships and ferries).
- Energy of the maximum wave can be related to energy of the total wave train.
- Wave heights measured at 22 m from the sailing line by Glamore and Hudson (2005) are representative of the maximum wave for the type of boats measured.
- Energy of the total wave train is an appropriate indicator of the erosive potential of the waves.
- Increases in wave height prior to breaking are negligible for waves with periods less than 3 seconds (MacFarlane and Cox, 2003).

4. Bank Erosion Potential

Defining the erosion potential of a section of river bank is complex, due to the interaction of many different processes caused by a wide range of variables. A literature review has been completed to determine the key factors concerning the erosion potential of river banks due to wave attack.

4.1 Literature Review

From the literature, key factors in the stability of river banks include vegetation, stock access, sediment type and channel equilibrium. Bank instability may also be caused by bed lowering, which in turn, may be caused by factors such as desnagging, sand and gravel extraction, and construction of dams and weirs. Many different methods for assessing river condition have been devised and their applicability for the assessment of erosion potential is described below.

4.1.1 Vegetation

Vegetation effects on bank erosion are complex. ASCE (1998) found that vegetation may have either positive or negative effects on mass failure of banks, but generally decreases soil erodibility. While the weight of a large tree on a bank could be considered to increase the potential for bank failure, the extra strength provided by the root system and the actual strengthening effect of the mass is likely to outweigh the negative effect of the surcharge (Rutherford *et al.*, 1999).

Vegetation zonation (Figure 3) from the water's edge to the top of the bank plays an important role in bank stabilisation. Bank stability against wave erosion is best provided by a combination of reeds, shrubs and trees. Trees and shrubs are not as effective at stabilising banks in the absence of reeds (Frankenberg *et al.*, 1996). In particular, vegetation at the toe of the bank is very important (Raine and Gardiner, 1995). Species with a "dense network of fibrous roots" are generally more effective at stabilising banks, however, trees with woody roots may enhance drainage and overall stability (Thorne, 1990 in Raine and Gardiner, 1995).

Vegetation at the average low water level is particularly important to prevent undercutting of the root zone (Thorne, 1990 in Raine and Gardiner, 1995). The density of the vegetation is likewise important, as the presence of one tree may simply promote turbulence and increased bank attack, whereas erosion will be reduced if other trees are within the wake zone of that tree. On high steep banks, stability is greatest when reeds grow from below the waterline all the way over the top of the bank (Frankenberg *et al.*, 1996).

Experimental work has shown that different types of vegetation are more resistant to wave attack than others. Coops *et al.* (1996) demonstrated that while 10 cm waves did not wash out either of two helophyte species, 23 cm waves damaged stands of *Scirpus lacustris* leading to erosion, but not *Phragmites australis*. The greatest changes to bank shape occurred within a few days of changing the wave regime. Effects of wave attack on vegetated slopes were compared with bare slopes which were 2-3 times more likely to fail. On unplanted slopes, considerable slope adjustment was seen even under 10 cm waves, and the slope was likely to be gentler than the vegetated slope (Coops *et al.*, 1996). Frankenberg and Tilleard (1991) claim that under regulated flow regimes, *Phragmites australis* is the only Australian native species that can effectively stabilise river bank, and is certainly the most useful for stabilising bigger rivers

(Frankenberg, 1992). In streams which change stage quickly and have small continuous flow variation, other rushes (*Juncus* spp.) and sedges (*Carex, Cyperus, Eleocharus*) are the most useful (Frankenberg, 1992). Experimental work by Cox and Dorairaj (2002) found that seedlings were more easily removed than fully grown plants by waves, and transplanted clumps of *Phragmites* could resist attack by 0.3 m waves even on a steep slope of 1:3.

Prosser (1999) showed that River Red Gum roots provide 25 kPa cohesion at the soil surface compared to typical soil cohesion of 15 kPa. Soil loosening processes were able to be prevented by just 50% grass cover on unstable banks. Brooks (1998) found that bank cohesion was more influenced by vegetation than silt and clay content and that different vegetation types may have more influence on stability than vegetation density with ground and mid-storey species perhaps more important than tree species. Similarly, Brisbane City Council (2003) noted that grasses and sedges are able to withstand higher shear stresses than trees.

Stock grazing damages the vegetation zonation of the banks, reducing the ability of the banks to withstand erosive forces. In particular, *Phragmites australis* will not persist if there is continued grazing (Frankenberg *et al.*, 1996).

It should also be noted that while vegetation on the bank is generally protective of the bank, vegetation in the stream may cause growth of sediment features within the channel, increasing velocities at the bank and enhancing erosion.

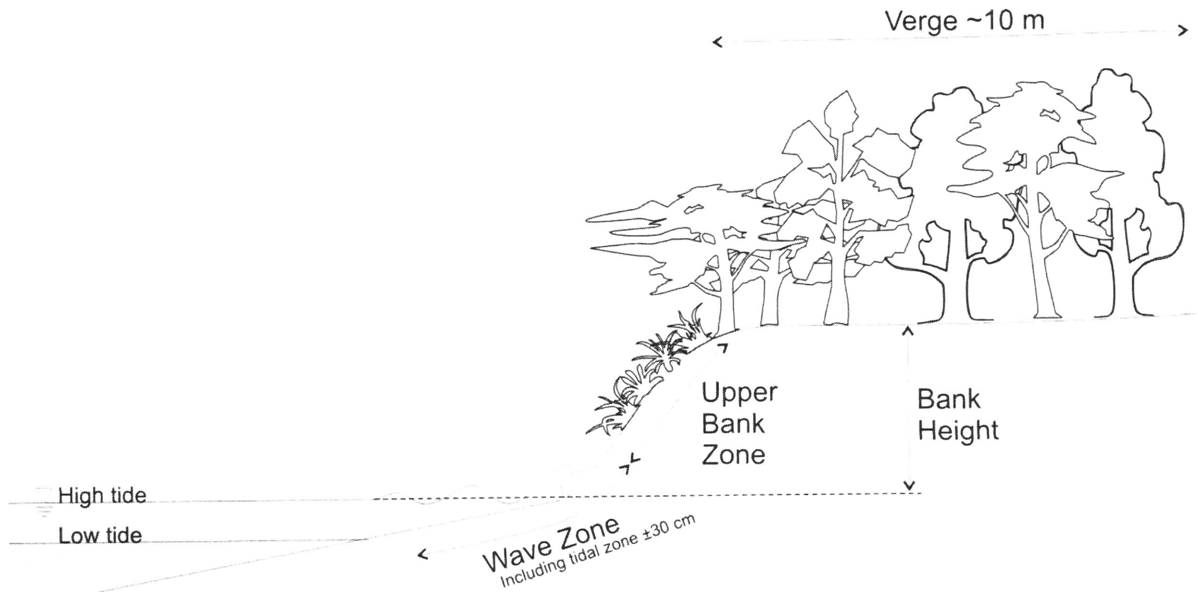


Figure 3: Vegetation Zonation

4.1.2 Channel Width

The channel width of a river in equilibrium is a reflection of the characteristics of the river including flow regimes and vegetation. If a river channel is too narrow, higher velocities during flooding may cause scouring or overbank flow, whereas deposition may occur within the channel if it is too wide. Growth of sandbars and rapids may lead to increased erosion of banks. Hey and Thorne (1986) in Raine and Gardiner (1995) recommend the use of the following empirical equations for the calculation of equilibrium channel width, W (m), based on the dominant discharge Q_b (m^3/s). The dominant, or bankfull discharge just fills the channel without overflowing and generally occurs every 1 in 18 months.

Table 3: Channel Width of Equilibrium Conditions (Hey and Thorne, 1986)

Equation	Vegetation Type	Description
W = 4.33 Qb0.5	I	Grassy banks with no trees or bushes
W = 3.33 Qb0.5	II	1-5% tree/shrub cover
W = 2.73 Qb0.5	III	5-50% tree/shrub cover
W = 2.34 Qb0.5	IV	Greater than 50% tree/shrub cover or incised into flood plain

However, the ASCE Task Committee on Hydraulics, Bank Mechanics and Modelling of River Width Adjustment (ASCE 1998) state that many rivers cannot be considered to have equilibrium channel widths due to variation in precipitation, frequency of flood events, and various external factors. This appears to be particularly true of rivers in semi-arid and arid areas, but may also occur due to climate change, changes in valley slope and vegetation succession. While equilibrium calculations cannot be used to predict rates of change or intermediate widths, they may still be useful for some applications. Brierley and Fryirs (2005) maintain the view that rivers are "in a state of perpetual adjustment, rather than oscillating around an equilibrium form".

ASCE (1998) state that the key processes causing change to channel width are erosion and deposition from river action and mass bank failure. Erosion processes are related to either the grain size and distribution and cohesive forces, and erosive resistance is related to soil moisture conditions. Bank failure may be caused by positive pore pressures due to rapid drawdown, and slaking may be caused by rapid immersion of a dry bank. ASCE (1998) postulate that adjustment is under "basal endpoint control", that is, sediments from mass wasting of the bank fall to the toe of the slope, and continued erosion of the bank is dependent on the continued removal of this sediment from the toe by fluvial activity. On this basis, banks can be categorised into those where removal is impeded, unimpeded or in excess.

Catastrophic changes to channel width have often been linked with high flood variability, however, Brooks (1998) has discounted this theory stating that high flood variability alone cannot be responsible. Consequently, other factors, such as vegetation, have a strong influence on channel width.

Channel meander greatly influences the stability of banks. The inside bend of a meander is likely to continue to accrete sediments, especially if they have been pioneered by vegetation. Consequently, erosion of the outside bend is promoted due to increased flow velocities caused by the reduced width of the channel. Erosion of the outside bend of the river may be reduced or even stopped by removal of vegetation on the inside bend (Raine and Gardiner, 1995). However, the presence of reeds and exclusion of stock on the outside meander of a river will not prevent erosion associated with meander movement and toe undercutting (Frankenberg *et al.*, 1996). Rivers that naturally meander, such as those with gravel beds, may have active erosion along half of their banks (Brierley and Fryirs, 2005).

The ability of a river to erode its banks and bed depends of the energy of the river and its sediment transport regime. Changes to discharge, slope and sediment supply may change the river from aggradational to degradational. The ability of the river to resist erosion is influenced by the roughness factors such as the alignment and shape of the river, vegetation, and bedrock outcrops.

4.1.3 Sediment

Sediment composition affects the erosion resistance of banks in alluvial rivers. Sands and gravels are more likely to be eroded than banks with a higher proportion of silts or clays (Brierley and Fryirs, 2005). Bank slope also varies according to sediment composition, with cohesive materials forming steeper banks than sandy sediments.

The sediment regime of a river affects its ability to adjust form, that is whether it deposits, transports or erodes sediments due to the energy and channel capacity of the river. It is dependent on the volume of water flowing on a slope and the sediment availability. The resistance of the channel due to shape, vegetation, and bedrock outcrops affects the distribution of energy on the channel and the resultant erosion.

Bedload dominated streams carry more than 11% of sediment along the bed and transport sediments larger than 62 μm, with sand being the most easily carried. They generally have high width:depth ratios (> 40) and have low sinuosity. In contrast, rivers with dominantly suspended loads generally have cohesive banks, meander and have channels with low width: depth ratios (<10) (Brierley and Fryirs, 2005).

4.1.4 Boat Wave Effects

Erosion caused by boat wash is likely to be in the form of a shallow slide (sediment moves along a shallow slide plane parallel to the bank) or cantilever failure (undercutting leaves overhanging blocks of sediment which topple out). As boat wave energy is generally concentrated at or near the water surface, an undercut may develop on the upper bank (Thorne *et al.*, 1997). For this reason, reed beds and emergent aquatic macrophytes (Rutherford *et al.*, 1999) are particularly effective against erosion caused by boats. Bonham (1980) in Rutherford *et al.* (1999) demonstrated that two thirds of the wave energy from recreational vessels could be absorbed by a 2 m wide reed bed. Removal of vegetation by wave attack appears to be influenced by both the wave height and the cumulative energy dissipated onto a bank (Cox and Dorairaj, 2002).

It is important to note that erosion may actually be more severe when wind waves are large due to the combined effect of wind waves and boat wash waves (Cranfield University, 1999).

4.1.5 Restricted Channel Effects

A vessel with a large underwater cross-section relative to the cross-section of the channel may cause a blockage effect whereby water surges in front of the vessel and draws down as it passes, causing damaging erosion. This can also be caused by a vessel travelling too close to the bank. The cross-sectional area of the craft and river should be calculated. If the vessel area is less than 3-4 % of the river cross-sectional area, effects are unlikely (MacFarlane and Cox, 2003).

4.1.6 River Condition Assessment Methods

Many different approaches have been used internationally to describe river health, using a range of indicators and analysis complexity. While the aim of this analysis is not to determine overall river health, it is recognised that a healthy river is likely to be more resistant to erosion caused by boat wake waves. In particular, some river condition assessment methodologies consider attributes such as bank stability and vegetation profiles which directly influence the erosion potential of a site. Those Australian methodologies considered most relevant are summarised in the following sections, with analysis of the components that are relevant for assessment of erosion potential.

Rivercare (Raine and Gardiner, 1995)

Raine and Gardiner (1995) describe guidelines for management of rivers in *Rivercare* for the Land and Water Resources Research and Development Corporation. Raine and Gardiner (1995) defined river types for management purposes based on a matrix of river condition in terms of sediment equilibrium (balance of sediment inflow and outflow) and percentage of natural bank vegetation cover. The assessment process is qualitative and based on comparing a site with photographs of other rivers resulting in nine possible ratings for a river. To stabilise a river, they recommend analysis of the channel width and alignment to determine what equilibrium condition the river is moving towards.

This analysis can be completed quickly and simply, however it is very subjective and does not have enough complexity to deal with the issues of erosion. The concept of determining the equilibrium channel width may be a useful component to consider further.

Rapid Appraisal of Riparian Conditions (Jansen *et al.*, 2004)

The Rapid Appraisal of Riparian Condition (RARC) was designed by Jansen *et al.* (2004) for Land & Water Australia to determine "the degree to which human-altered ecosystems diverge from local semi-natural ecosystems in their ability to support a community of organisms and perform ecological functions". The RARC has been tested on rivers in south-eastern Australia and is designed for riparian zones that are naturally dominated by trees. Jansen *et al.* (2004) acknowledges that their approach is similar to the Index of Stream Condition (Ladson *et al.*, 1999). The sub-indices and indicators used in RARC are found in Table 4.

Jansen *et al.* (2004) recommend assessment of approximately 500 m lengths of river, with 200 m as a minimum. Both sides of the river should be assessed on small rivers, while only one might be necessary on a larger river. Transects of the riparian zone along the side of the river should be at least 40 m wide for rivers narrower than 10 m, and four times the channel width for larger rivers, unless the riparian zone is clearly smaller due to valley confinement.

Table 4: Rating Categories for RARC

Sub-Index	Indicator	Useful for Erosion Potential
Habitat	Longitudinal continuity of riparian vegetation (≥ 5 m wide)	✓
	Width of riparian vegetation (dependant on channel width)	✓
	Proximity to nearest patch of intact native vegetation > 10 ha	×
Cover	Canopy (> 5 m tall)	✓
	Understorey (1-5 m tall)	✓
	Ground (< 1 m tall)	✓
	Number of layers	✓
Natives	Canopy (> 5 m tall)	×
	Understorey (1-5 m tall)	×
	Ground (< 1 m tall)	×
Debris	Leaf litter	×
	Native leaf litter	×
	Standing dead trees (> 20 cm dbh)	×
	Hollow-bearing trees	×
	Fallen logs (> 10 cm diameter)	×
Features	Native canopy species regeneration (< 1 m tall)	✓
	Native understorey regeneration	✓
	Large native tussock grasses	✓
	Reeds	✓

The indicators most likely to be useful for determining erosion potential are those related to the zonation, continuity and regeneration of vegetation and specific vegetation types.

Rapid Riparian Assessment Method (Taylor *et al.*, 2005)

The Rapid Riparian Assessment (RRA) Method was developed for the assessment of urban streams, recognising that other available assessment methods (e.g. River Styles) were not able to differentiate between the relative condition of urban streams, pronouncing them all in 'poor' condition. The assessment categories considered are summarised in Table 5. The variables are scored to indicate how the attribute contributes to river health from a lowest possible score of -10 (severely detrimental) to a highest possible score of 10 (extremely positive). Individual reaches are rated as excellent, good, fair, poor, very poor or severely degraded depending on the total score from the attribute assessment. The method has been trialled in the Ku-ring-gai Council area.

Table 5: Categories used in Rapid Riparian Assessment

Category	Attribute	Useful for Erosion Potential
Site Features	• Land use	?
	• Extraction	✓
	• Excavation	✓
	• Litter	×
	• Sewer line	×
	• Odours	×
	• Turbidity	×
Channel Features	• Shape (incl. natural or modified)	✓
	• Pool and riffle sequences	×
	• Meanders	✓
	• Large woody debris	×
Depositional Features	• Benches	?
	• Islands	?
	• Channel bars	?
Erosional Features	• Bedrock exposure	?
	• Undercutting	✓
	• Bank slumps	✓
	• Knick points	×
	• Gully/rill erosion	×
Riparian Vegetation	• Buffer width	✓
Vegetation Structure Assessment	• Vegetation structure and weed assessment	✓

Source: Taylor *et al.* (2005)

Using the RRA method, reaches are determined using longitudinal connectivity, buffer depth and land use to determine reach boundaries on a 1:10 000 scale topographical map. One sample point is assessed for each reach less than 600 m, two sample points for 600 - 2500 m reaches and three for reaches longer than 2500 m.

Attributes considered in the RRA that may be useful for erosion potential are those related to man-made intervention (extraction and excavation), which alter the natural equilibrium of the channel, the shape including modifications, erosional features, meanders and vegetation factors. In RRA, the presence of meanders in an alluvial channel is considered positive, however, the presence of meanders increases the susceptibility of the bank to erosion. Of the erosional features, gully/rill development may be considered to be accounted for by the vegetation features, as this will not occur if the banks are vegetated (Rutherford *et al.*, 1999).

Index of Stream Condition (Ladson *et al.*, 1999)

The Index of Stream Condition (ISC) was developed in conjunction with the Victorian Department of Primary Industries to assess current river condition (primarily rural) in comparison with the assumed 'natural' condition prior to European settlement. The Index includes terms of flow regimes, channel condition, riparian condition, water quality and invertebrates present. It has already been used to survey 950 reaches in Victoria in 1999 and again in 2004.

"The ISC combines information on five key aspects of river health. These components, or sub-indices, measure changes in hydrology, water quality, streamside zone (vegetation), physical form (bed and bank condition and instream habitat) and aquatic life. The Index was developed using information that could be easily understood, collected at the regional scale and fed directly into regional planning exercises. In addition, the methodology had to be accurate, easy to use, cost effective, based on good science and able to be undertaken by CMA staff, Waterwatchers and others associated with natural resource management" (DSE, 2005).

A detailed reference manual has been developed for the ISC in addition to a comprehensive field manual. The field manual includes reference photos to be used by field staff for assessing bank stability, bed stability and woody vegetation and instream physical habitat, and schematics for estimating vegetation cover, in addition to field sheets to complete.

The area for assessment using the ISC is a reach – an area of the river that is approximately homogenous in terms of each of the subindexes and generally longer than 5 km.

The indicators used for the Index of Stream Condition are outlined in Table 6. The indicators included which may be useful for analysing erosion potential are those considering vegetation, bank stability and the hydrology of flows. The vegetation indicators are very similar to those in RARC. The use of the photos to assess bank stability may not be the most appropriate method due to the subjective nature of the assessment. The change in flows impacts the equilibrium dimension of the channel, however, it may be complex to include in the assessment of erosion potential.

Table 6: Sub-Indexes and Indicators Used in Index of Stream Condition

Sub-Index	Indicators	Useful for Erosion Potential
Hydrology	Low flows	?
	High flows	?
	Zero flows	?
	Seasonality	?
	Variability	?
Water Quality	Total phosphorous	×
	Turbidity	×
	Salinity (EC)	×
	pH	×
Streamside Zone	Width	✓
	Longitudinal variability	✓
	Understorey diversity	✓
	Recruitment	✓
	Large trees	✓
	Tree canopy	✓
	Litter	×
	Logs	×
Physical Form	Bank stability	✓
	Large wood	×
	Fish passage	×
Aquatic Life	AUSRIVAS (habitat)	×
	SIGNAL (pollution)	×

River Styles (Brierley *et al.*, 2002)

The River Styles framework has been used by NSW Department of Land and Water Conservation (now the Department of Natural Resources) for all geomorphic assessments of rivers in New South Wales. It differs from the other assessment methods as it is based on defining the geomorphology of a river within the context of the altered catchment in order to determine the processes involved in the river functions. A River Style is defined as "a river reach with a near-uniform assemblage of geomorphic units" (Brierley and Fryers, 2000 in Brierley *et al.*, 2002). The framework (as shown in Figure 4) follows the following four stages:

1. Determining River Styles throughout a catchment
2. Assessing the geomorphic condition of each River Style
3. Determining the potential for the river to recover
4. Creating targets for river rehabilitation.

This process has been used to define 21 river styles in coastal catchments in New South Wales. Significantly, the River Styles framework recognises that the inherent stability of a river varies between styles and therefore "some stream systems are more sensitive to physical and biological disturbance than others" (Brierley *et al.*, 2002). For example, "alluvial rivers on sandy substrates with minimal vegetation protection are perhaps the most sensitive variant of river morphology to change" (Brierley and Fryirs, 2005), however, rivers with cohesive or bedrock banks and/or bed, armouring, dense bank vegetation, large quantities of woody debris are more resistant to changes. Using the River Styles method, controls on erosion or deposition are determined to understand the character of the river.

Whereas the Index of Stream Condition and RARC compare the condition of the river to its perceived natural state (pre-European), River Styles classifies a river as in 'good condition' if the reach has adjusted to the current catchment conditions, is "self-maintaining" and is functioning within its range of natural variability. Rivers that are still adjusting to a new equilibrium or are changing rapidly might be considered "moderate" or "poor".

The concept of River Styles is a useful starting point for the assessment of erosion potential as it puts the assessment of the river in context of the river type. Additionally, for the assessment of erosion potential, the primary concern is not to determine the state of 'naturalness' of a particular waterway, rather it is to assess whether the river may be eroded by boat wake wash. In this instance, it is more relevant to determine whether the river is 'self-maintaining' and in equilibrium with the current conditions.

Valley confinement is of key importance to the geomorphology of the rivers. Only completely self-adjusting alluvial rivers are not controlled by valley confinement. Stage, stream power, and shear stresses are all higher in narrow valleys than wide valleys for the same flow.

No particular reach length is recommended for assessment using the River Styles method, rather it is recommended that resolution reflects the intended use of the data.

The complexity of the River Styles methodology is too great to be used in totality for a rapid assessment of erosion potential. Should an authority have the expenditure, the use of this method could be very valuable in determining the natural adjustment ability of a river type. However, a river that is resilient to natural adjustment due to the low energy of the river at that point may not be resilient to wave attack, as the energy of the wave may be greater than the natural energy conditions of the river.

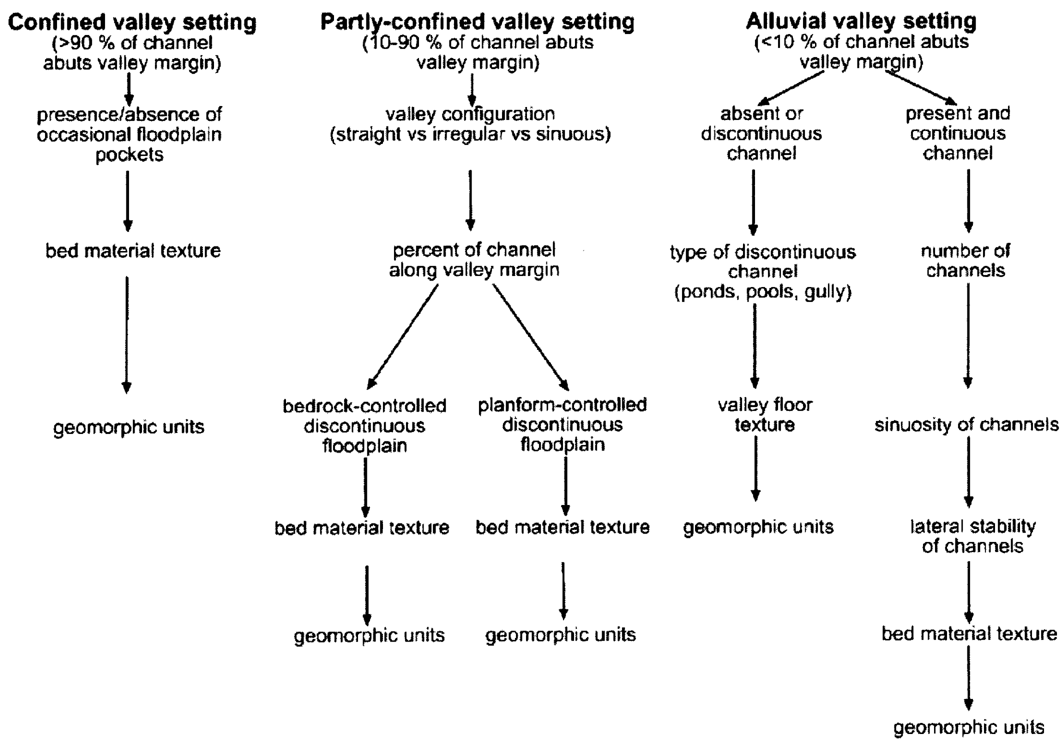


Figure 4: River Styles Framework

4.2 Erosion Potential Assessment Methodology

4.2.1 Erosion Potential Indicators

From the literature review, and some basic testing of river scenarios, the important indicators to include in the assessment of erosion potential were determined. Following both desktop and field testing of the Decision Support System the indictors were refined and are as in Appendix A. The assessment method used as the source or inspiration for the indicator is acknowledged next to each indicator. Each indicator was given a rating of High, Moderate or Low importance, with corresponding weightings of 3, 2 and 1. It is important to note that the indicators were chosen and weighted based on their relevance to river bank erosion by boat wash, NOT to assess the overall health of a river. Each erosion indicator is scored according to set rating intervals at a transect, and multiplied by the weighting of the indicator. In general, those indicators which reflect positively on the erosion resistance of the river score positively, whereas those indicators which detract from erosion resistance score negatively. Of course, these ratings are in part subjective.

Valley Setting

Valley setting is the most important indicator of the erosion potential of a site. A site that is either confined within a valley such that the floodplain is virtually non-existent or completely armoured will not be affected by the vegetation cover of the banks. In these situations, only bank slope, channel width, bank sediment type, erosion of the banks and excavation need to be rated, and the site instantly receives the maximum score for vegetation parameters. A confined valley does not have any floodplain, whereas a partially confined valley has pockets of discontinuous floodplain and the channel may change position. A laterally unconfined valley has a continuous floodplain.

Stage Variability

Stage variability is considered moderately important as it reflects the range of conditions with which the site is in equilibrium. A tidal estuary is better able to resist wave attack as the water levels are regularly changing and therefore wave attack will not concentrate on one area of the bank, whereas a highly regulated river may receive all of the wave energy at one height on the bank, causing fretting at that location. A non-tidal river is likely to have natural variability that is less than a tidal river, but more than a highly regulated river. Note that although a tidal river will be either natural or regulated, it is given the rating of 'tidal' as that best reflects the stage variability of the site.

Longitudinal Continuity of Bank Vegetation Over Stretch

Longitudinal continuity of bank vegetation helps to account for variability between transects assessed and is considered highly important. Armoured or rock banks are considered to contribute to vegetation over the entire stretch (rather than being considered bare banks). Rather than general vegetation continuity, it was determined through testing that longitudinal continuity of bank vegetation was a better indicator, as a well forested area with completely bare banks would otherwise still be likely to score highly in longitudinal continuity. <10%, 10-30%, 31-60% and >60% were selected as intervals for observations, as small percentages, such as 2% vegetation cover, cannot really be considered to improve the bank stability more than no vegetation at all. Additionally the longitudinal continuity of bank vegetation is divided into Verge, Upper Bank and Wave Zone Cover.

Verge Cover

Rather than rating the percentage of canopy, understorey and ground cover as is done in RARC, it was considered more appropriate for the assessment of erosion potential to rate the percentage cover of the different areas of riparian zone. The different zones are portrayed in Figure 3. The verge is the top of the bank and is generally only gently sloping. In this zone, vegetation is generally taller and many trees may be present. While vegetation in this zone will not directly protect the river bank against wave attack, it may add to the overall stability of the bank, especially tree roots, and is therefore considered moderately important. It is important that this cover specifically contains trees and shrubs. During testing of the DSS, many transects were assessed with verges that were completely vegetated, but only with grass. This indicator has therefore refined to clarify that the verge cover assessed is trees and shrubs. To ensure that a reasonable width of riparian vegetation is included for stability, this parameter should include vegetation within 10 m of the verge. Therefore, a single line of trees on the verge of the bank may only be considered to cover 50% of the verge.

Upper Bank Cover

The upper bank extends from above the top of the waterline or top of the high tide mark to the verge and is generally indicated by a change in slope. During the review process this was slightly modified to recognise that travelling waves will break onto the lower ~30 cm of the bank, and therefore this section should be included with the aquatic zone in a zone labelled the wave zone.

Wave Zone Cover

The wave zone incorporates both the aquatic zone and the lower ~30 cm of the bank. The aquatic zone is from the edge of the bank into the river to a depth of approximately 2 m where emergent macrophytes may still be able to survive. In tidal estuaries, the aquatic zone may be defined as the area between low tide and high tide. This zone is highly important as aquatic vegetation may dissipate wave energy prior to the waves impacting the banks. If the dominant wave zone cover type is either rocks, or bare with slope less than 1:7, this indicator is not given a negative value even if the cover is absent.

Native Canopy Species Regeneration and Native Understorey Regeneration

Vegetation regeneration indicators reflect the likely future resistance of the bank to wave attack, or self-healing ability. As they may not currently protect the bank against erosion but have potential to do so in the future, these factors are considered to be of low importance. During testing of the DSS, it was questioned whether it was important that the vegetation regenerating was native or whether other species such as lantana may also fulfil the role required. However, for sustainability of bank stability it is important that regeneration is not of a monoculture of weed species which may be wiped out with one disease or predator. It also seems important that a healthy diversity of canopy and understorey species are maintained.

Dominant Wave Zone Cover Type

The dominant type of cover at the height of the wave zone is highly important as different vegetation or slopes have varying ability to dissipate energy and resist shear stress. The literature indicates that reeds and vegetation that forms a dense root mat have the most value in erosion resistance. Limited literature is available to differentiate between vegetation types, however grasses also appear to have high erosion resistance due to the dense root mats produced. Mangroves are likely to have greater energy dissipation ability than ordinary trees due to their exposed root systems (pneumatophores), however, trees and tree roots are better than bare banks. During the review process, in addition to the previous values of Bare Banks, Trees/Tree roots, Mangroves, Grasses and reeds, the following choices were added: Bare (Vertical slope), Bare (1:3 - 1:6), Bare (≤1:7 slope) and Rock. During field testing of the DSS, many sites were seen that were gently sloping beaches that did not seem to be in any danger of eroding, while those sites with a very steep slope were much more likely to be attacked by waves. These additional rating options give the user more flexibility in rating the wave zone.

Upper Bank Slope

Bank slope is highly important if the river is not confined or bedrock, or if the vegetation is less than excellent. Where vegetation parameters at a site receive a score less than 30/38, this factor is taken into account. Steeper banks are more readily able to be eroded due to higher downslope gravitational forces. The stability of the slope is also dependant on the bank sediment, and this indicator is therefore now rated according to a matrix with bank sediment. Note that the slope of this region has been more carefully differentiated from the slope of the wave zone, which could be confused when viewed at low tide.

Channel Width

Channel width is rated highly important in the assessment of erosion potential as greater attenuation of waves may be achieved prior to reaching the shore. A very small channel width may lead to blockage effects. The rating intervals are based on significant distances for wave development. Waves are considered to be fully developed approximately 2-5 boat lengths away from the sailing line. As recreational vessels are commonly approximately 6 m in length, the first width interval (36 m) was chosen such that a boat travelling in the centre of a river would be three boat lengths away from the shoreline. A 36 m wide river may provide 62% attenuation at the shoreline as the waves travels 18 m from the sailing line. Similarly, 75% attenuation may be possible in a 120 m wide channel if the boat is sailing in the centre of the river.

Bank Sediment Type

Bank sediment type is rated as moderately important if the vegetation parameters at a site receive a score less than 30/38. This indicator does not receive a separate rating but is rated according to a matrix with Upper Bank Slope.

Lateral Stability

Lateral instability, demonstrated by the presence of billabongs, prior channels or identified through aerial photos, is an indicator of historically high rates of natural erosion. It is considered moderately important as it demonstrates that the site is likely to be eroded.

Sinuosity

Sinuosity is quantified as the channel length of the river divided by the valley length. Similarly to lateral instability, the sinuosity of a river is considered moderately important as it indicates the river is likely to have high rates of natural erosion. A river is considered meandering if sinuosity is greater than 1.3. Meandering rivers are likely to be eroding on the outside of their bends.

Bank Height

During testing of the DSS, it was observed that the bank height has a considerable effect on the stability of the bank, if the bank is near vertical. The ability of tree roots to stabilise a bank is limited to the rooting depth of the tree, which is seldom greater than 2 m (Rutherford et al., 1999). Higher banks are only considered negative if the bank is not rock and if the bank is vertical.

Erosion above the Wave Zone

During initial test phases of the DSS this indicator was labelled 'erosion at the toe of the bank'. However, in practice, this was found to be difficult to differentiate from undercutting, and therefore this indicator has been altered as a means of defining erosion that is above the wave zone but does not look like slumping. This is rated as moderately important as it is not directly attributable to boat waves.

Slumping
Bank slumping is the mass failure of the banks due to erosion of the banks or high pore water pressures in the bank. This is rated as moderately important as it indicates weakness in the banks, but is not likely to be directly attributable to the same erosional processes caused by boats.

Undercutting within the Wave Zone
Undercutting describes the removal of sediment from the base of the bank resulting in an overhanging bank which may then fail and fall into the river. As the type of erosion most likely to be caused by wave action, this indicator is rated extremely important. This parameter encompasses any erosion occurring specifically in the wave zone.

Desnagging
Desnagging refers to the removal of logs and fallen vegetation from the river channel. This may cause instability due to changes in hydraulics. This is considered of low importance, and is scored based on whether it has or has not occurred in the past year.

Excavation
Excavation of the banks is likely to cause general instability of the banks and change the dynamics of flow in the river. While this does not occur often, it is rated highly important when it does. This is scored on only a presence/absence basis.

Extraction
Extraction of sediment and water changes the hydraulics of a river leading to instability. As for desnagging this is considered of low importance, however, the removal of sediment through dredging is likely to be more damaging and destabilising than water extraction.

Stock Access
Stock access to the banks of the river is highly damaging due to animals trampling on the banks and feeding on vegetation. Many studies have shown stock access to be one of the greatest causes of erosion. For this reason, stock access is considered highly important. It is scored on a simple presence/absence basis, but the presence of stock access scores -3 multiplied by the highest weighting.

Other
Other indicators considered for addition in the assessment included:

- Sediment transport regime – bedload, suspended load or mixed load
- Number of layers – the number of vegetation layers (canopy, understorey and ground)
- In-stream vegetation growing – this may cause erosion of banks due to channel restriction
- Equilibrium channel width – used to determine if the channel is likely to be widening or narrowing
- Exposed roots – indicating erosion
- Channel structural variability – complexity may increase erosional resistance.

Each of these indicators was considered to be either implied by other indicators, or the effects could not be well defined for inclusion into a simple assessment.

4.2.2 Assessment Area

The area to be assessed will be predetermined by the overall extent of the waterway feasible for recreational boating. This length should then be divided into 500 m stretches on each side of the river, of which ~30% may be randomly selected. Each stretch should then be divided into three sections and a 10 m wide transect at the midpoint of each section assessed. A schematic of this process is shown in Figure 5.

The erosion potential of the three transects should be averaged for each stretch. Along the entire area the lowest scoring of the stretches (i.e. that with the lowest final rating) is to be taken as the final score.

To ensure the worst stretches along a river are not missed in this process, prior to completing the erosion potential assessment of a stretch, it is beneficial to do a quick visual survey of the whole river and document any lengths of severe erosion greater than 20 m. These sections may require additional analysis and incorporation into the management outcome.

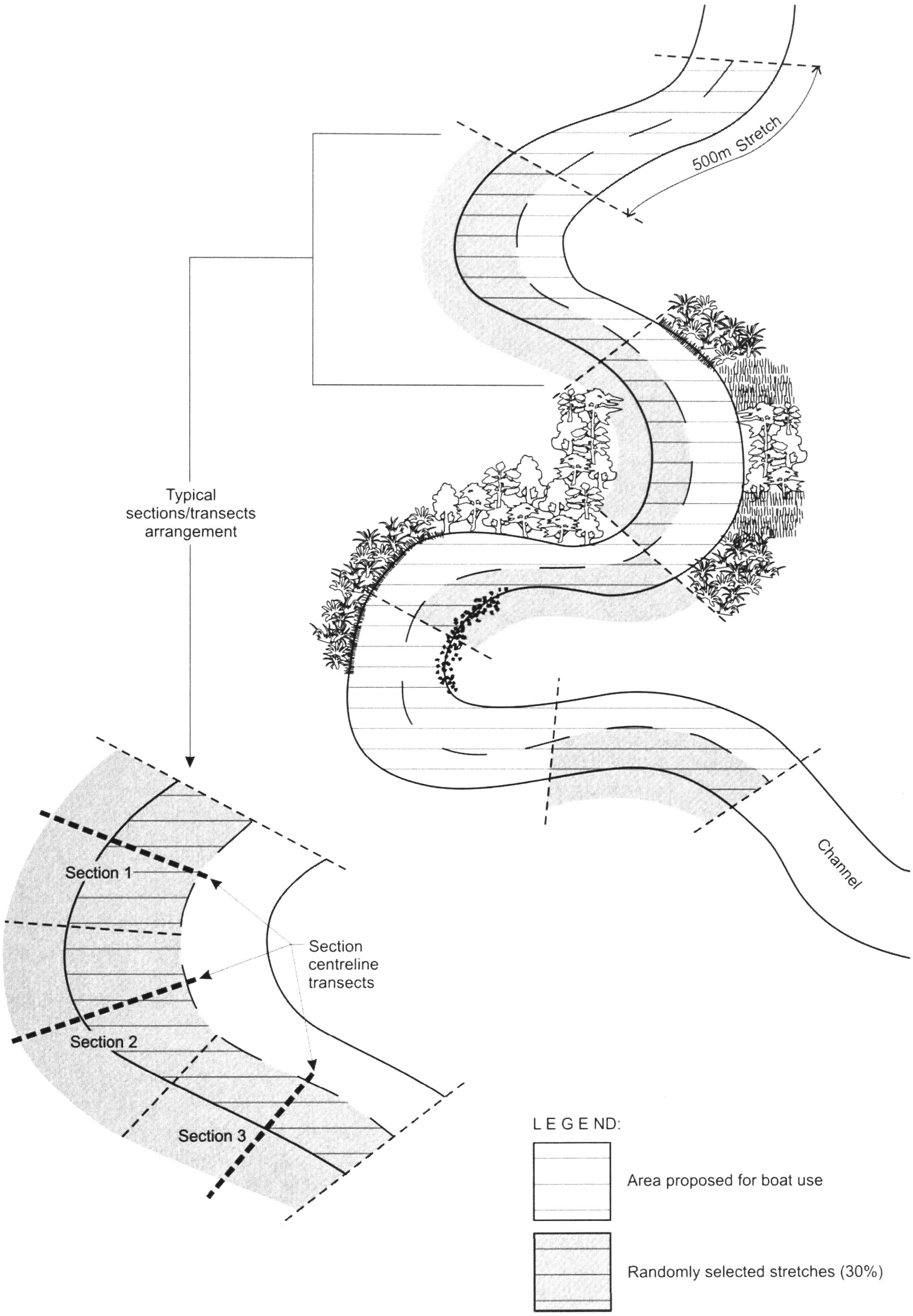


Figure 5: Erosion Potential Assessment Area

4.2.3 Assessment Timing

Assessments should be made at low to mid-low tide, or mean water level, not during floods. It is important that the banks can actually be observed during the assessment process. Using the assessment system along tidal rivers, the bank profile was seen to change slope at the top of the high tide along many transects.

4.2.4 Scoring

The final erosion potential score of the site is the sum of the scores for each indicator, with the exception of a few special cases:

1. Where the valley setting is confined and the bank sediment is bedrock, it is assumed that many of the indicators, such as vegetation, assume negligible importance. The score is the sum of ratings for bank slope, channel width, bank sediment type, erosion of the banks and excavation, and the site instantly receives the maximum score for vegetation parameters.
2. Where the vegetation is in excellent condition and receives a subtotal score greater than 30, it is assumed that the bank sediment type and bank slope are insignificant, and therefore these indicators simply score zero where they may have otherwise scored negatively if the bank was vertical or consisted of non-cohesive sediments.

The final erosion potential score of the site determines the erosion category of the site, as summarised in Table 7.

Table 7: Erosion Categories

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

The highest possible score is for a Confined valley setting and is equal to 70 points, while the lowest possible score is for a laterally unconfined valley and is −97.

4.2.5 Assumptions and Limitations

- The accuracy of the assessment is limited by the available data.
- The relative importance and weighting of the different indicators has been chosen based on literature review and basic testing using photographs. Extensive field work may indicate that some adjustment of specific weightings are more appropriate, or that additional indicators should be included to adequately represent the site.
- The complexity level of the analysis is designed to allow assessment by a wide range of users in a short period of time. Assessment requiring high levels of fluvial geomorphology analysis was not considered appropriate.

5. Decision Support System Methodology

The information and methods outlined above have been incorporated into a single decision support system. The system has been developed within a Microsoft EXCEL spreadsheet format to allow easy manipulation of the variables and due to the general familiarity of EXCEL by most potential users. Further, to allow for widespread use of the system many of the complex formulae presented above have been incorporated within the spreadsheet and do not require hands-on processing. This section outlines the step-by-step process required to use the system and thus determine whether vessels should be permitted on a selected stretch of a waterway. A flow chart of the process is given in Figure 6.

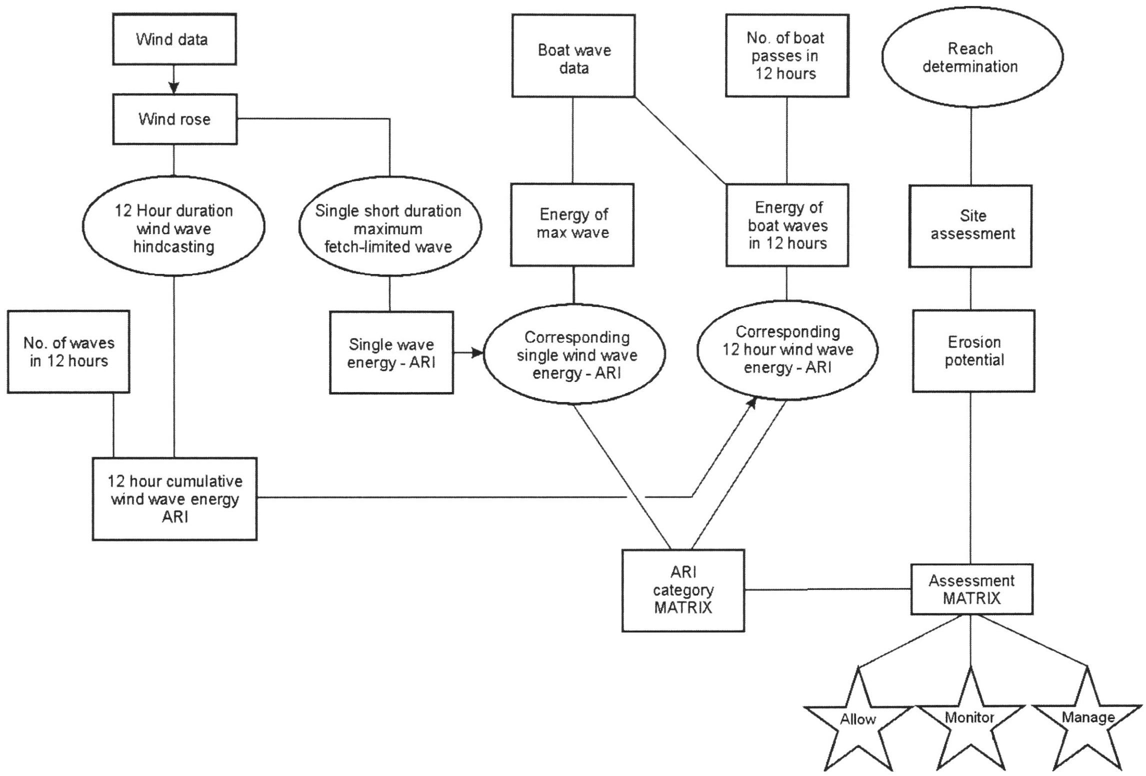


Figure 6: Flow Diagram of Decision Support System

5.1 Data Required

The data required for use of this Decision Support System is summarised in Table 8.

Table 8: Data Required for Assessment using the Decision Support System

Assessment Component	Data required
Wind Waves	Fetch length from topographic maps, aerial photographs or GIS.
	Wind rose or local wind data
Boat Wake Waves	Distance of boat from shoreline
	Boat movement frequency
Bank erosion potential	Topographic map / aerial photographs
	Regulation and extraction information
	Site assessment field trip

5.2 User Procedure

The Decision Support System methodology is summarised as a flow chart in Figure 6. The key features of the system are that it considers both the effect of the maximum boat wave and the effect of cumulative boat waves over time compared with the natural wind wave environment on a specific section of river. Assessment of the erosion potential due to boat wake waves will be determined in several manners.

1. The effect of the maximum wave in the wave train, recognising that just one wave may cause erosion.
2. The effect of the whole wave train of several boats passing over a period of time, recognising the cumulative effects of energy on a bank.

The steps to complete the rating of a site are as follows:

A. Calculate wind-wave energy annual recurrence intervals (ARI's).

1. Divide the area to be assessed into 500 m stretches and randomly select 30% of these stretches.
2. For each stretch, calculate the fetch lengths of the 16 compass directions.
3. Using the local wind rose, complete wave hindcasting for both the fetch-limited single wave and extended 12 hour duration waves for each wind speed in each direction.
4. Calculate the wind wave energy of the fetch-limited waves and determine the corresponding ARI's of the fetch-limited energy of a single wave.
5. Calculate the total wind wave energy at the site over 12 hours and determine the ARI's of the total wind wave energy for each adjusted wind speed and direction.

B. Calculate Equivalent Boat Wave ARI's

1. Calculate the energy of the maximum boat wake wave. Compare the energy to the calculated energy of single wind waves and determine the equivalent wind wave energy ARI of the boat wake wave.
2. Calculate the energy of boat waves over a 12 hour duration. Compare the energy to the calculated energy of wind waves over a 12 hour duration and determine the equivalent wind wave energy ARI of the boat wake waves.

3. Calculate the energy of the maximum boat wake wave **attenuated at the shoreline**. Compare the energy to the calculated energy of single wind waves and determine the equivalent wind wave energy ARI of the boat wake wave.
4. Calculate the energy of boat waves **attenuated at the shoreline** over an extended duration (8 - 12 hours). Compare the energy to the calculated energy of wind waves over an extended duration and determine the equivalent wind wave energy ARI of the boat wake waves.
5. Compare the two equivalent ARI's, with and without attenuation to the rating system in Table 9 to determine the boat wake wave category from A to E.

Table 9: Comparison of ARI for Wind and Boat Waves

	Equivalent ARI of Boat Wake Wave Energy over an extended period (typically 8 - 12 hours)					
Equivalent ARI for Maximum Boat Wave Energy	**<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

C. Calculate the erosion potential of the site

1. Divide each of the stretches located in Step A1 into three sections, and choose the middle transect of each of the section.
2. Conduct a site assessment of each of the transects using the Erosion Potential rating system. Average the results of each of the transects in a section to determine an Erosion Potential score for each of the sections

D. Determine site rating for each section

1. Compare the ARI category with and without attenuation to the erosion potential category to determine the final rating as shown in Table 10. If the final ratings with and without wave attenuation are different, the critical distance from the shoreline for boat travel should be noted and included in a boating management plan.

2. Compare the final ratings of each of the transects. The rating for the entire assessment area is the lowest of values from all of the sections, i.e. (i.e. if all of the sections are rated 'Allow', except for one which is rated 'Manage/Restrict' the final rating for the site will be 'Manage/Restrict'.

Table 10: Final Rating Matrix

	Erosion Potential				
ARI Rating	**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

5.3 Decision Support System Spreadsheet Package

The decision support system methodology has been formulated into a spreadsheet package for ease of use. Upon opening the spreadsheet, the user is welcomed by a front page giving the option to Enter Data, View Rating Matrix, View Boat Data or View Erosion Potential Indicators (Figure 7). The three View tabs may allow addition of boat data or adjustment to the weighting of different criteria or rating of different scenarios. Following the Enter Data button, the user should only fill in cells coloured white. The first step (Figure 8) is to enter wind parameters such as fetch length and wind data in the form of % occurrence of different intervals. From this information wind waves are hindcast and the wind wave energy is sorted into Average Recurrence Intervals (ARI's). Step 2 (Figure 9) requires the choice of boat type, number of boat passes and distance of the sailing line from the shore. Only data for wakeboarding and waterski vessels (Section 3.1) is currently available, however, the database can be easily extended as additional data becomes available. The program calculates the energy of the maximum boat wave and total boat waves over an extended duration (8 – 12 hours), then finds the ARI of the equivalent wind wave energy.

Step 3 is to calculate the erosion potential of the three transects of the stretch being assessed. For the calculation of Erosion Potential, the rating of each indicator is selected from a drop-down box. Where the selection of one indicator negates the necessity of another indicator, that indicator is automatically greyed out. Upon completion of the page, the user may select the Determine Rating button which takes the user to the final rating page where the final rating is displayed. If the fully developed wave causes the score to be 'Manage/Monitor' or 'Manage/Restrict', yet the attenuated wave rates 'Allow', or 'Manage/Monitor' respectively, a warning will appear on the final rating screen: "Warning! Boat Distance from the shore must be maintained!". A rating must be completed for each section of the river to be analysed.

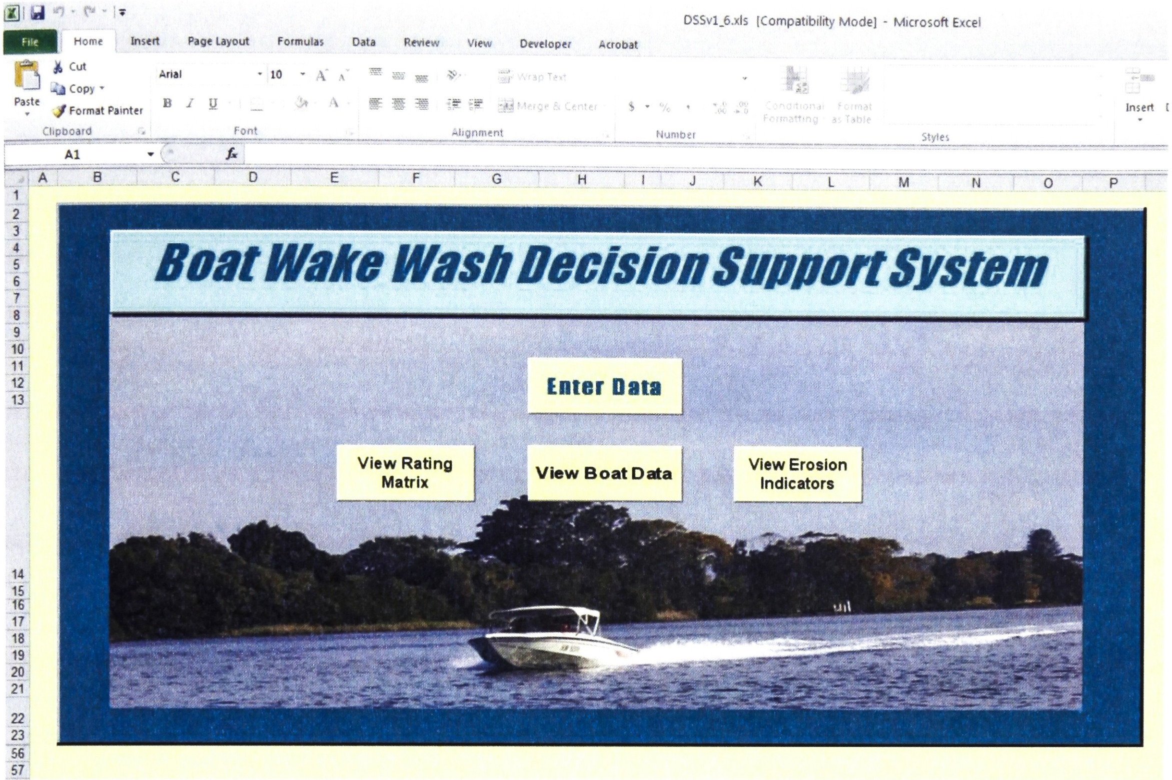


Figure 7: DSS Spreadsheet Front Page

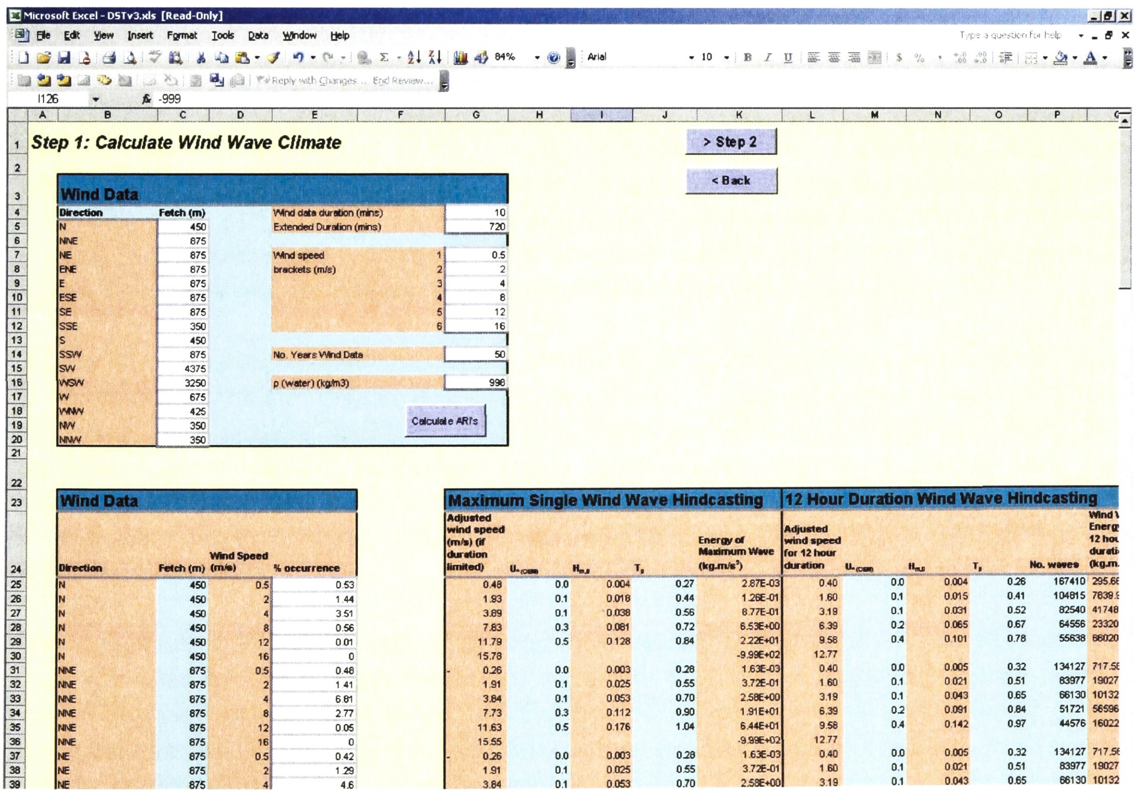


Figure 8: Step 1: Wind Wave Calculations

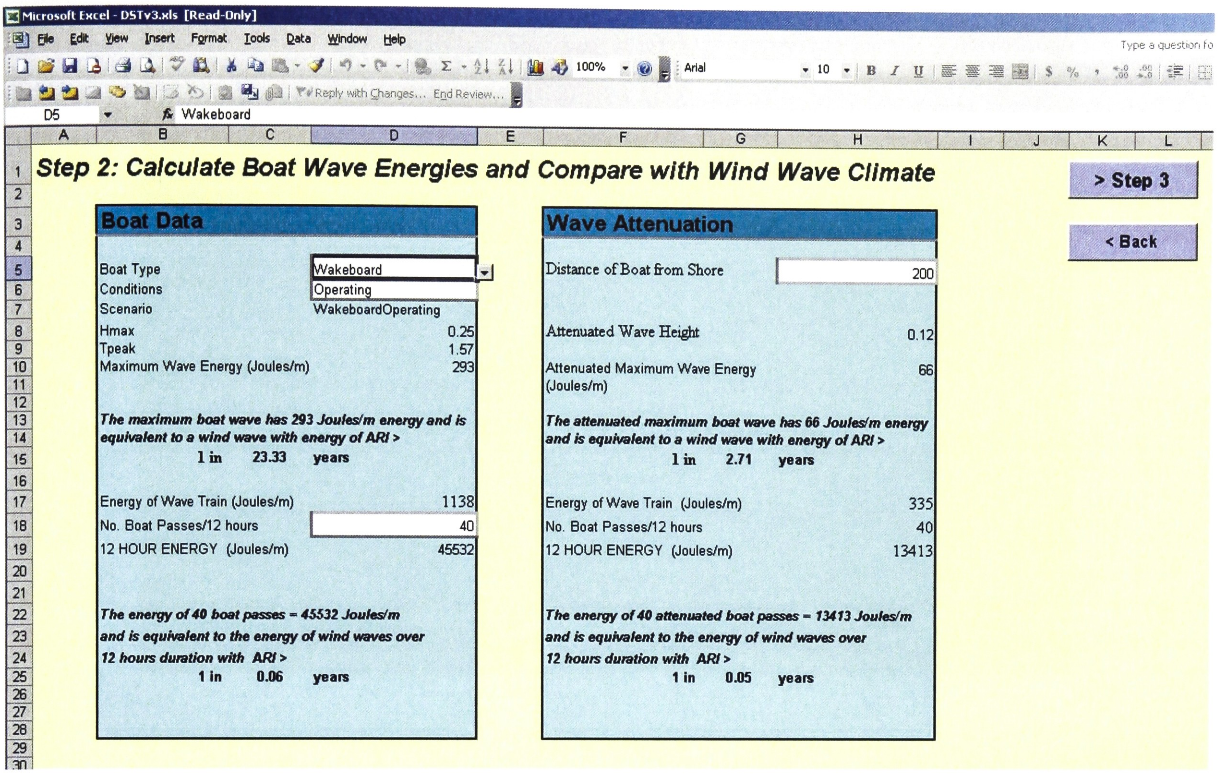


Figure 9: Step 2: Boat Calculations

5.4 DSS River Assessment

The DSS methodology and spreadsheet package were initially desktop tested on several sites to determine the appropriateness of the indicator and rating system. Following desktop testing field testing was implemented on one river with slight adjustments being made prior to further testing of another river. During this final field exercise the updated and refined DSS was applied across all sites. Nonetheless, the variety of sites and high erosion potential at several sites provided several new observations that were subsequently adopted within the DSS.

Figures 10 to 14 provide examples of the five types of shoreline erosion potential ratings. Figure 10 shows sites that are "Highly Resistant" to erosion. These sites are characterised by natural armouring (rock ledges), artificial armouring (retaining walls or breakwaters) or by sites with prolific and dense aquatic vegetation and a gentle slope. Figure 11 depicts sites that were classified as "Moderately Resistant" to erosion. These sites tended to have a gentle slope and some aquatic vegetation but lacked dense vegetative growth or had a near-vertical but well vegetated bank slope.

Sites classified as "Mildly Resistant" to erosion are given in Figure 12. These sites are similar to those classified as "Moderately Resistant" except in that they typically have some form of mild erosion apparent onsite either through slumping, lack of vegetation or undercutting. In contrast, sites classified as "Moderately Erosive" have larger eroding sections (typically >50%) and were actively eroding (Figure 13). In many cases these sites where most vulnerable to erosion at the high tide where the bank slope changed from gentle to near-vertical. Finally, "Highly Erosive" sites, as shown in Figure 14, are actively eroding, lack cohesion, typically have more than one mechanism of erosion and can be severely impacted by boat wake waves.

Figure 10: Erosion Potential: Highly Resistant

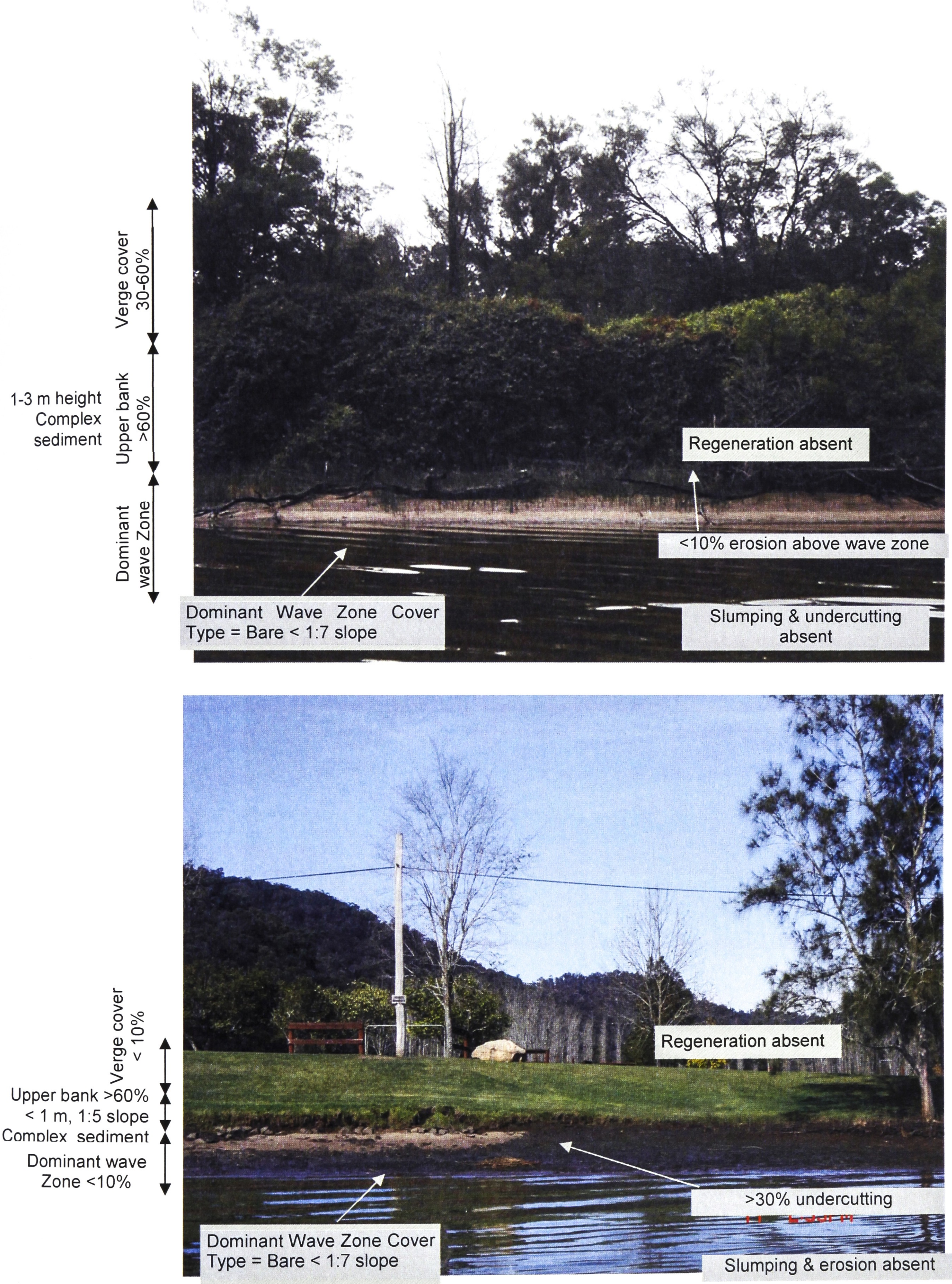


Figure 11: Erosion Potential: Moderately Resistant

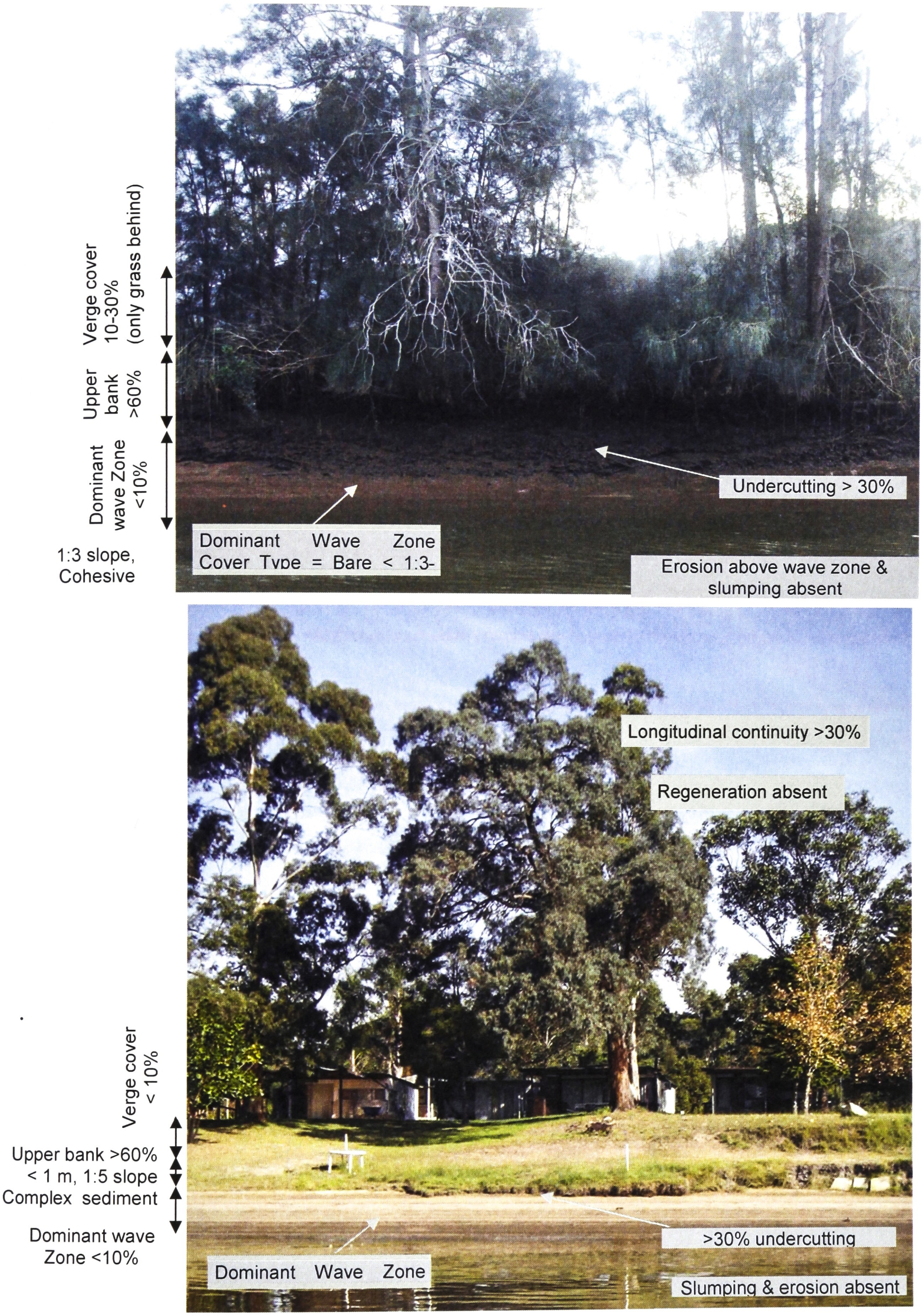


Figure 12: Erosion Potential: Mildly Resistant

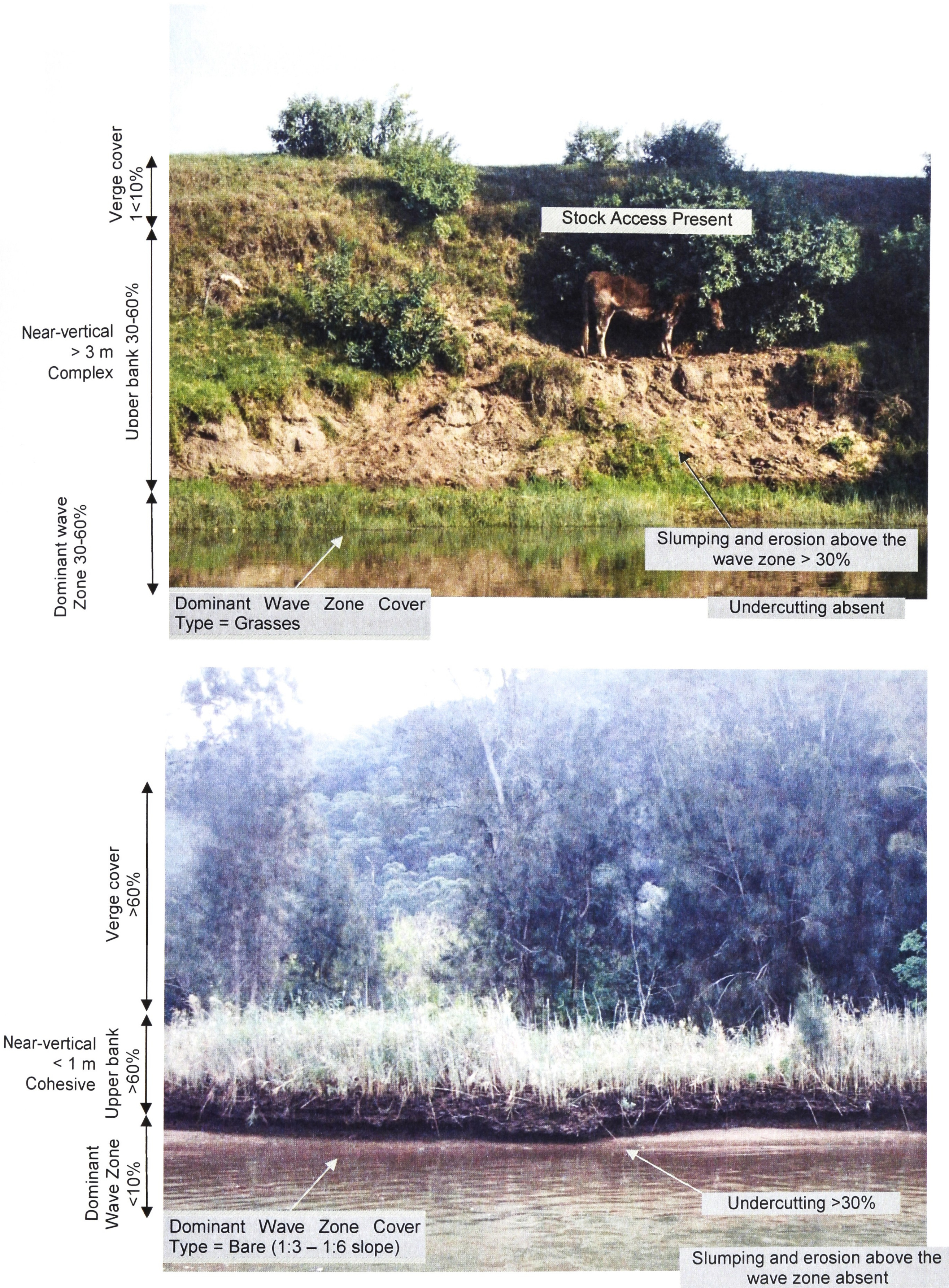


Figure 13: Erosion Potential: Moderately Erosive

Figure 14: Erosion Potential: Highly Erosive

6. Conclusions and Recommendations

Due to community concern regarding boat wake waves and the increased popularity of recreational boating, waterway managers need a standard method to assess the potential impact of boating on a stretch of river. To this end, this study has produced a comprehensive decision support methodology (or system) including all of the major criteria associated with assessing a selected reach of a river.

The steps used to assess a site are summarised below:

1. Determine the natural wind wave energy at the site using standard methods.
2. The energy of the passing boat wave is then determined based on previous field experiments conducted by WRL.
3. The wake wave energy is compared to the average recurrence interval of the wind wave energy for both the maximum generated wake wave and the cumulative wave energy generated from a typical day involving multiple boat passes.
4. An erosion potential assessment incorporating physical and biological features of the bank is undertaken using standard weighted indicators.
5. The results of the boat wake wave and wind comparison are then evaluated in a matrix against the bank erosion potential category to determine the impact of the boat wake wave on the shoreline. The end result is one of three management categories: Permit, Permit with Monitoring and Restrict ('Allow', 'Manage/Monitor', 'Manage/Restrict').

An interactive spreadsheet and a methodology for selecting sites have been developed to assist in using the system at individual sites.

To assist in understanding the methodology a range of sites were assessed using both desktop methods and field investigations prior to development of the existing version. Throughout the report assumptions and limitations are detailed.

The results of these assessments are used to firstly categorise the average recurrence interval (ARI) energy of boat wake waves relative to the wind wave environment and finally to determine an appropriate management action by comparing the ARI category to the erosion potential of the site.

Advantages of the methodology and spreadsheet package are summarised below:

- Easy-to-use.
- Uses energy as the criteria to assess boat waves, thus including wave period and wave height.
- Considers both the energy of the maximum boat wake wave and the cumulative energy of multiple boat passes.
- Can compare the maximum wave against operating conditions.
- Includes wave attenuation in wide rivers.
- Considers the natural wind wave environment of the site.
- Uses a range of comprehensive erosion potential indicators specific to boat wave erosion to assess a site.
- Considers both the overall river setting and specific sites.
- It is not excessively conservative, but does not ignore the range of potential impacts.
- Easy to modify/improve as further experience and knowledge is gained.

Key assumptions and limitations of the methodology are as follows:

- The analysis assumes that the river is in equilibrium with the wind wave environment.
- While the methodology provides an indication of the current state of the river bank, the system has not been designed to assess the ecological health of the river.
- Currently only wakeboarding and waterski boats are included, however the methodology may easily incorporate a range of boats if adequate field data becomes available.

6.1 Implementation

The management outcomes generated by the Decision Support System need to be assessed in relation to other environmental, economic and social concerns. A recommendation by the system to restrict boating (or a certain type of vessel) may have economic or social values which outweigh the environmental concerns. Nonetheless, the system provides a scientific and quantitative means of assessing the physical environmental concerns and can be used by waterway managers without bias. It is recommended that the Decision Support Tool is used to assist in formulating boating management plans and helps to support bank erosion studies.

Once applied, the three management outcomes (Permit, Permit with Monitoring and Restrict) have different reassessment periods and implications. The permit (or 'Allow') outcome occurs when the site has a low erosion potential and little difference between wind and wake wave energies. In these circumstances the vessel in question should be permitted without restrictions. It is advised that this rating is applied for no more than 5 years, after which the site is reassessed to determine if the boat wake waves have increased the erosion potential.

If the permit with monitoring outcome (or 'Manage/Monitor' option in the EXCEL spreadsheet) is prescribed, then the vessel in question should be allowed on site, although speed and location restrictions may be applied. This is relevant when the vessel's speed, number of boat passes or the site's erosion potential rating can be managed to reduce the overall impact on a certain stretch of a river. If this management outcome is prescribed and boats are already on the waterway then the site should be reassessed every 2 years. If boats are currently restricted from the waterway then the site should be assessed at 6 month intervals for the first two years and at two year intervals afterwards.

The restrict boating outcome (or 'Manage/Restrict' option in the EXCEL spreadsheet) is given to sites where strong erosion is likely to occur from a passing vessel. If a site is given this outcome then a range of restoration options should be considered prior to permitting vessels on the waterway. Importantly, if a site is given this outcome then the Decision Support System could be used to determine if reducing the boat numbers or implementing speed restrictions would improve its rating. The system can also be used to determine the bank restoration techniques that would be most appropriate (i.e. provide the most positive benefit or points in the EXCEL spreadsheet) to the site. If this management option is prescribed then the site should be reassessed every 2 years.

6.2 Areas for Future Research

Throughout the development of the DSS care has been taken to apply previously accepted scientifically established and/or published methods. In several areas these methods are available and have been duly noted. However, in many areas published methods are not currently available and further research is required. A description of the most relevant research gaps is given below.

Maximum wave energy (threshold versus linear relationship): Within the DSS it is assumed that there is a linear relationship between wave energy and erosion (i.e. as wave energy increases, erosion increases). However, some researchers have proposed that the relationship can be better described as a step function with waves over a certain height or wave period initiating erosion, whereas waves under this threshold do limited damage.

To determine if shorelines tend to be threshold dominated or more linear in nature a series of flume based studies would be undertaken. The shorelines could be of varying slope, soil types and vegetated states. The shorelines would then be subjected to waves of a similar nature to wind and boat waves and erosion could be assessed via a series of erosion measurement techniques (including digital video and erosion pegs). The outcome of these studies would have a major impact on the way in which the DSS predicts the erosion potential at a site and would be used in refining the classification ratings.

Maximum versus cumulative wind energy: One of the most important aspects of the DSS is that it incorporates both maximum individual waves and cumulative wave energy into the rating process. In its current form, the DSS has a matrix table where the ARI rating of the maximum waves is compared with the ARI rating of the cumulative waves and a resultant category is provided. Presently the ratings within this table are based on a common sense approach with extreme values given an extreme rating and mild values given a lesser rating.

To provide some scientific evidence that may assist in quantifying these ratings it is recommended that additional testing be undertaken. First, to quantify the maximum wave energy rating the above mentioned flume tests should be undertaken. Second, a similar study should be undertaken to assess the influence of *cumulative* wave energy on bank erosion. This study would be based on a similar methodology as the above mentioned study but would focus on comparing long term impacts of smaller waves.

Relative importance of vegetation cover: Within the erosion potential indicators of the DSS there has been estimates made as to the erosion capacity of certain types of vegetation. Based on these estimates a value has been prescribed to each form of vegetation (i.e. reeds are given a rating of 3, mangroves a rating of 1 and trees and tree roots a rating of 0). While there is some qualitative information available to verify this rating, additional data is required to determine the actual rating or weighting that should be applied to each type of vegetation. This information could be obtained from laboratory tests but may be better obtained from field measurements under controlled conditions.

Verification of other parameters: In addition to the vegetation cover parameters other parameters also require verification. Parameters of greatest importance include bank height, upper bank slope and bank cover. Laboratory experiments could be devised for each of these parameters in order to develop better quantitative methods for assigning ratings and weightings.

7. Acknowledgements

The authors wish to acknowledge the assistance of Dr Mark Taylor at Macquarie University who assisted in refining the bank erosion indicators.

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APPENDIX A: Erosion Potential Indicators

Appendix A: Erosion Potential Indictors

Category	Indicator	Importance	Rating Options and Scores
River Type	Valley Setting	High	Confined = 4 Partly Confined = 2 Laterally Unconfined = 1 Completely armoured = 4 Partially armoured = 2
	Stage variability	Moderate	Tidal = 1 Natural = 0 Regulated = -1
Vegetation	Longitudinal continuity of bank vegetation over stretch	High	<10 % = -2 10-30 % = -1 31-60 % = 1 > 60 % = 2
	Verge cover (10 m from top of bank)	Moderate	<10 % = -1 10-30 % = 0 31-60 % = 1 > 60 % = 2
	Upper Bank Cover	High	<10 % = -1 10-30 % = 0 31-60 % = 1 > 60 % = 2
	Wave Zone Cover	High	<10 % = -1 10-30 % = 0 31-60 % = 1 > 60 % = 2
	Native canopy species regeneration (< 1 m tall)	Low	None = 0 Scattered = 1 Abundant = 2

<table>
<tr><th>Category</th><th>Indicator</th><th>Importance</th><th>Rating Options and Scores</th></tr>
<tr><td>Vegetation
(continued)</td><td>Native understorey regeneration</td><td>Low</td><td>None = 0
Scattered = 1
Abundant = 2</td></tr>
<tr><td></td><td>Dominant Wave Zone Cover Type</td><td>High</td><td>Bare (Vertical slope) = -4
Bare (1:3 - 1:6) = -2
Bare (≤1:7 slope) = 3
Rock = 4
Trees/Tree roots = 0
Mangroves = 1
Grasses = 2
Reeds = 3</td></tr>
<tr><td>Channel Features</td><td>Bank Slope</td><td>High</td><td>
<table>
<tr><th></th><th colspan="4">Upper Bank Slope</th></tr>
<tr><th>Bank Sediment</th><th>Near-Vertical</th><th>1:3</th><th>1:5</th><th>≤ 1:7</th></tr>
<tr><td>Bedrock/Boulders/Cobbles/Armouring</td><td>4</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td>Cohesive</td><td>-2</td><td>0</td><td>1</td><td>3</td></tr>
<tr><td>Complex</td><td>-3</td><td>-2</td><td>-1</td><td>2</td></tr>
<tr><td>Non-Cohesive</td><td>-4</td><td>-3</td><td>-2</td><td>1</td></tr>
</table>
</td></tr>
<tr><td></td><td>Channel width</td><td>High</td><td><36 = -2
36-120 = 0
>120 = 2</td></tr>
<tr><td></td><td>Bank Height</td><td>Moderate</td><td>If Bank Slope Is Near Vertical
> 3 m = -3
1-3 m = -1
< 1 m = 0</td></tr>
<tr><td>Erosion</td><td>Bank Sediment Type</td><td>Moderate</td><td>See Bank Slope</td></tr>
</table>

Category	Indicator	Importance	Rating Options and Scores
	Lateral Stability	Moderate	High (no evidence of channel migration) = 0 Moderate (some evidence of channel migration) = -1 Low (lots of evidence of channel migration) = -2
Erosion *(continued)*	Sinuosity	Moderate	< 1.3 = 0 >1.3 = -1
	Erosion above the Wave Zone	Moderate	Absent = 0 < 10 % banks = -1 10-30 % banks = -2 > 30 % banks = -3
	Slumping	Moderate	Absent = 0 < 10 % banks = -1 10-30 % banks = -2 > 30 % banks = -3
	Undercutting in the Wave Zone	Extreme	Absent = 0 < 10 % banks = -1 10-30 % banks = -2 > 30 % banks = -3
Land use	Desnagging	Low	None = 0 Conducted in last previous year = -1
	Excavation	High	Present = -1 Absent = 0
	Extraction	Low	None = 0 Water = -1 Sediment = -2
	Stock access	Extreme	Absent = 0 Present = -3

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