Water Research Laboratory

Riverbank Vulnerability Assessment using a Decision Support System: Lower Hawkesbury River (Wisemans Ferry to Spencer)

WRL Technical Report 2014/04
June 2014

by
W C Glamore, I R Coghlan and J E Ruprecht

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THE UNIVERSITY OF NEW SOUTH WALES

Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

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Client Address	PO Box 37 Hornsby NSW 1630
Client Contact	Ms Ana Rubio
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Water Research Laboratory
110 King Street, Manly Vale, NSW, 2093, Australia
Tel: +61 (2) 8071 9800 Fax: +61 (2) 9949 4188
ABN: 57 195 873 179
www.wrl.unsw.edu.au
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Executive Summary

Human activities pose a potential threat to estuarine habitats in the lower Hawkesbury River, particularly on riverbank sections comprised of soft, erodible materials. This report provides a detailed riverbank vulnerability assessment of a 29 km section of the Hawkesbury River, New South Wales.

This project was primarily undertaken to provide a new baseline for evidence-based management of riverbank erosion for Hornsby Shire Council. A Decision Support System (DSS) designed by the Water Research Laboratory (WRL) (Glamore and Badenhop, 2006; 2007), was used to objectively assess and rank the susceptibility of the riverbanks in the study area to erode based on a variety of environmental factors. Specifically, the DSS was used to assess:

- The current condition of the riverbanks using a robust and repeatable ranking system;
- The effect of natural wind waves and boat wake waves and other contributing causes to riverbank erosion along key reaches of the Hawkesbury River;
- The vulnerability of the riverbanks to erosion; and
- Potential management actions that can best address erosion at key sites.

The Hawkesbury River study area (between Wisemans Ferry and Spencer) was initially divided into fifty-eight (58) sections along the river, the majority being 500 m in length. A field campaign was undertaken to assess the erosion potential at three representative transects on the left and right riverbanks within each riverbank section (348 sites in total). Wind data was then used from Richmond RAAF Base (the closest long-term wind data set) to determine site specific wind wave conditions at each section.

In assessing riverbank erosion potential (i.e. the current condition), key criteria and importance weightings were combined to form an erosion potential rating for each site. These criteria include river type, vegetation coverage and extent, erosion descriptors, adjacent land use and channel features. Erosion potential was assessed at mid – low tide and high tide to accurately observe the wave zone throughout the entire tidal cycle.

During the field assessment it was noted that the riverbank erosion potential is significantly reduced at the top of high tide. At the majority of locations, the wave zone at mid – low tide interfaces with a gently sloping tidal beach. However, at high tide the wave zone interfaces with the bottom level of the vegetation or bedrock/armouring. Such vegetation/bedrock/armouring is more resistant to erosion when compared to a sloping beach. This indicated that the riverbanks in the study area are generally less vulnerable to erosion at high tide than at mid - low tide.

An erosion potential score and associated erosion potential category were assessed for each site. Sites with highly negative erosion potential scores have a low resistance to erosion, whereas sites with highly positive erosion potential scores have a high resistance to erosion. All five erosion potential categories in the DSS ('Highly Resistant', 'Moderately Resistant', 'Mildly Resistant', 'Moderately Erosive' and 'Highly Erosive') were observed in the study area. However, the majority of the region is considered 'Highly Resilient' to erosion throughout the tidal range. At mid – low tide, 50 percent of all transects observed were 'Highly Resistant' to erosion, whereas at high tide, this rating increased to approximately 80 percent. Conversely, only 1 percent of all transects observed were 'Highly Erosive' at mid – low tide. Figures ES-1 and ES-2 and Tables ES-1 and ES-2 display the distribution of the erosion potential categories across the entire study area for mid - low tide and high tide conditions, respectively.

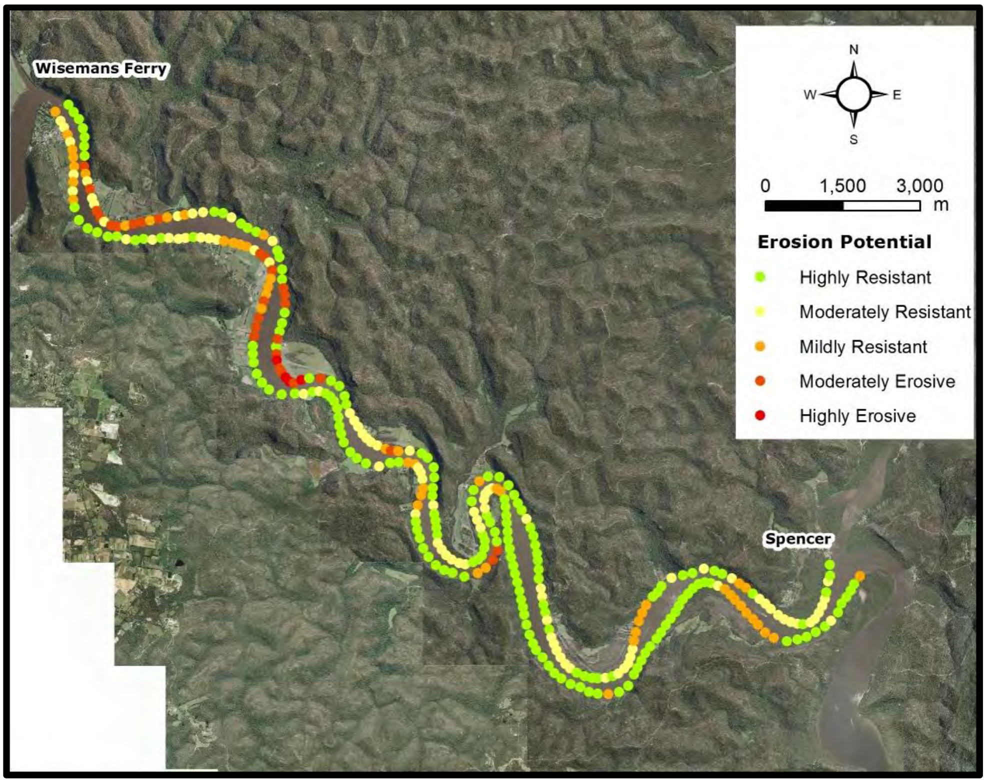

Figure ES-1: Erosion Potential for Each Transect (Mid - Low Tide Conditions)

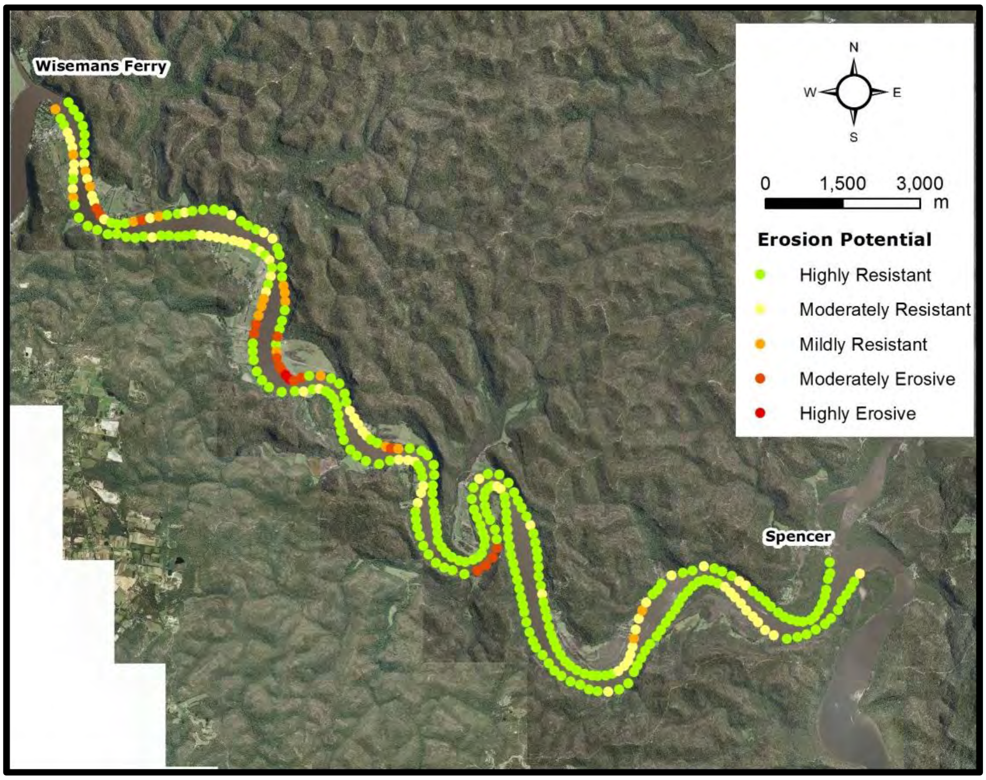

Figure ES-2: Erosion Potential for Each Transect (High Tide Conditions)

Table ES-1: Erosion Potential of the Hawkesbury River Study Area (Mid – Low Tide Conditions)

Erosion Potential (Mid – Low Tide Conditions)	Number of Occurrences (Individual Transects)	Number of Occurrences (Bank Stretch Average)
Highly Resistant	177	64
Moderately Resistant	88	24
Mildly Resistant	51	23
Moderately Erosive	28	5
Highly Erosive	4	0
Total	**348**	**116**

Table ES-2: Erosion Potential of the Hawkesbury River Study Area (High Tide Conditions)

Erosion Potential (High Tide Conditions)	Number of Occurrences (Individual Transects)	Number of Occurrences (Bank Stretch Average)
Highly Resistant	276	83
Moderately Resistant	46	23
Mildly Resistant	14	6
Moderately Erosive	11	4
Highly Erosive	1	0
Total	**348**	**116**

The DSS was used to assess the natural wind wave climate for each site, with fetch lengths determined from the middle of each stretch. Based on the length of the wind record from Richmond RAAF Base, the average recurrence interval (ARI) of the wind wave energy was calculated for both the maximum wind wave and for an extended duration of wind waves of eight hours.

Waves generated by passing boats on the Hawkesbury River were also considered with the DSS. While broad information about boat use between Wisemans Ferry and Spencer exists, detailed boat pass counts are unavailable. In the absence of this information, WRL developed a range of daily boat pass numbers estimated for the waterway. For typical conditions, it was expected that boating numbers between Wisemans Ferry and Spencer varied between 10 and 150 boat passes per day (10 to 150 boat passes for an 8 hour duration). By definition, a return journey by one boat which passes a riverbank section is counted as 2 boat passes.

The riverbank erosion potential, wind waves and boat waves at each stretch were then assessed within the DSS matrices to produce a final management recommendation either 'Allow', 'Monitor' or 'Manage'. For all but one scenario tested, only the 'Allow' (approximately 75% of stretches) and 'Monitor' (approximately 25% of stretches) management recommendations were observed between Wisemans Ferry and Spencer (see Table ES-3). This suggests that under existing conditions the entire study area is suitable for boating numbers of 50 boat passes per day. This equates to approximately 6 boat passes per hour over an 8 hour operating day. For one scenario tested (wakeboard 'operating' conditions, 150 boat passes), one riverbank stretch recorded the 'Manage' recommendation. This represents less than 1% of the total stretches assessed. As an example, Figure ES-3 displays the DSS management recommendations for this particular boat pass scenario.

Table ES-3: Number of Stretches Determined in each DSS Management Category (Mid – Low Tide)

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	50 Passes	150 Passes	10 Passes	50 Passes	150 Passes
Allow	88	88	79	90	90	90
Monitor	28	28	36	26	26	26
Manage	0	0	1	0	0	0

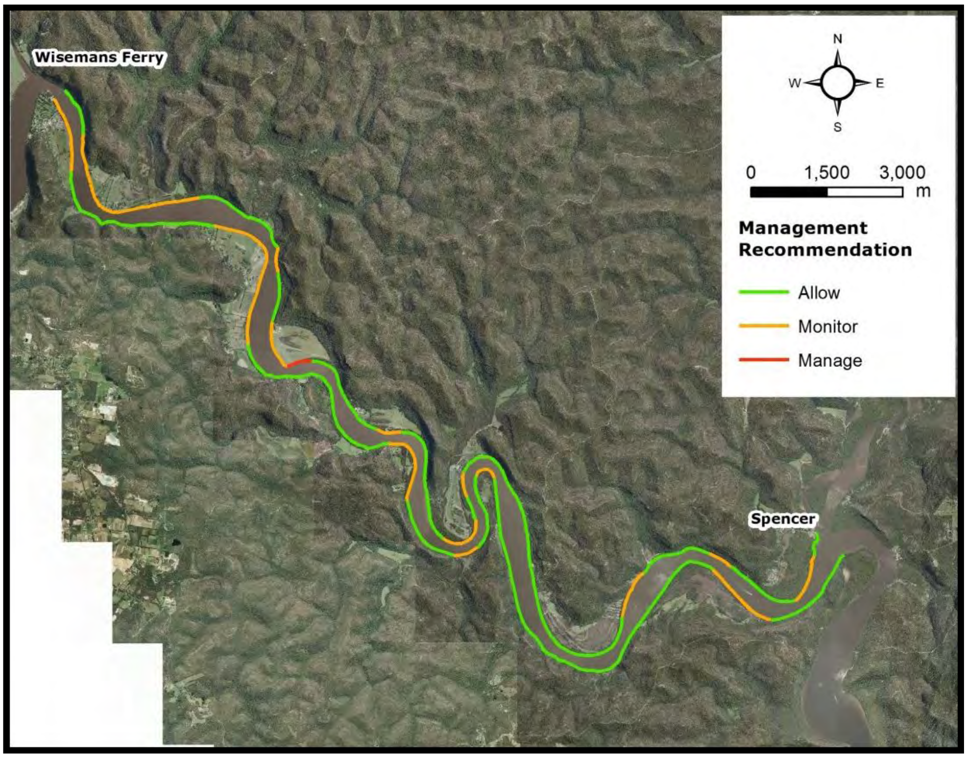

Figure ES-3: Example DSS Management Recommendations – Wakeboard Operating - 150 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

RECOMMENDATIONS

Five recommendations are suggested to reduce riverbank vulnerability and improve boating management in the study area as follows:

Recommendation 1: Onsite management techniques should be implemented for the one stretch of the river prescribed a 'Manage' rating. This stretch of the river is privately owned and is associated with bed and breakfast accommodation known as "The Missions". It is recommended that stock be restricted and native riparian vegetation be planted in this stretch of the Hawkesbury River. Buoys should also be put in the water to prevent boats passing within 70 m of the riverbank.

Recommendation 2: The DSS results should be further analysed to determine the key factors contributing to high riverbank vulnerability for river stretches prescribed a 'Monitor' rating and appropriate onsite techniques implemented. Installation of fencing to prevent stock access, planting of native riparian vegetation and removal of lantana vegetation would reduce the erosion potential.

Recommendation 3: Due to the limited data available on boat usage patterns, an assessment of boating numbers on the waterway encompassing both busy, and normal, weekends and week days, should be undertaken to provide a more accurate picture of recreational boating within the study area. This data gathering, coupled with a survey of users, would help to establish preferred areas for recreational boating and potentially help focus further investigations to key areas of use.

Recommendation 4: A comprehensive monitoring program should be commissioned for future comparison against the objective baseline established in this investigation. Riverbank stretches classified as 'Monitor' and 'Manage' should be reassessed every two years and 'Allow' stretches reassessed every five years. It is also recommended that the DSS be applied across a greater extent of the shoreline managed by HSC. Berowra Creek and Porto Bay, which largely consist of soft, erodible materials, remain priority areas for further assessment.

Recommendation 5: Since local wind records are unavailable, the local wind conditions on the Hawkesbury River should be assessed with the deployment of local anemometers over an extended period to develop scaling factors applicable to the wind conditions at the Richmond RAAF Base. This will better approximate wind conditions on the river and result in a more accurate local wind wave estimate for comparison with boat wake waves.

KEY FINDINGS

- In broad terms, the vulnerability of the riverbanks in this stretch of the Hawkesbury River is comparatively low when compared to other rivers in NSW due to several reasons. Natural rock armouring is present along approximately 25% of the riverbanks in the study area. A significant extent of both the left and right riverbanks is managed by the NSW National Parks and Wildlife Service. As such, grazing hard hoofed stock is generally absent and native riparian vegetation, particularly mangroves, remains intact. The boat pass numbers are relatively low in this stretch of the Hawkesbury River, in part due to the absence of public boat ramps between Wisemans Ferry and Spencer. Finally, the lack of inappropriate development along the riverbanks is also a contributing factor to its low vulnerability.
- The majority of the region is considered 'Highly Resilient' to erosion throughout the tidal range. The riverbanks in the study area are generally less vulnerable to erosion at high tide than at mid - low tide.
- Under existing conditions the entire study area is suitable for boating numbers of 50 boat passes per day. This equates to approximately 6 boat passes per hour over an 8 hour operating day.
- Riverbank stretches classified as 'Monitor' and 'Manage' (approximately 25% of stretches) should be reassessed every two years and 'Allow' stretches (approximately 75% of stretches) reassessed every five years.
- The most vulnerable riverbank section in the study area, "The Missions", is privately owned and falls within the local government area of Gosford City Council. This finding supports observations by local commercial fishers consulted in a workshop by Hornsby Shire Council in 2008. Erosion problems have been known to exist in this part of the Hawkesbury River for at least 20 years. Several onsite management techniques which would improve the rating of the site from 'Manage' to 'Monitor' were outlined.

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1. Introduction

The Hawkesbury River is located to the north and west of Sydney in New South Wales. Hornsby Shire Council (HSC), Gosford City Council (GCC) and other government agencies are concerned that human activities may be a potential threat to estuarine habitats in the lower Hawkesbury River, particularly on riverbank sections comprised of soft, erodible materials.

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Australia (UNSW) was commissioned by the HSC to undertake a riverbank vulnerability assessment on an approximate 29 km long section of the Hawkesbury River between Wisemans Ferry and Spencer (the study area) (Figure 1-1). This study was funded by HSC and the NSW Office of Environment and Heritage (OEH). The study area was chosen by HSC, in consultation with WRL. Note that the riverbanks are defined based on looking downstream the river (i.e. the left bank is managed by GCC and the right bank is managed by HSC).

The NSW Department of Primary Industries (Astles et al., 2010) recently mapped the distribution of estuarine habitats on the lower Hawkesbury Estuary foreshore to better understand the potential threat to these habitats from human activity. An ecological risk assessment was undertaken on the river reach between Wisemans Ferry and Spencer (the focus of this WRL report). Astles et al. (2010) determined that a significant extent of the shoreline between Wisemans Ferry and Spencer was categorised as being comprised of soft materials, which are typically more vulnerable to shoreline erosion.

This project builds on the work by Astles et al. (2010) and provides a new baseline for evidence-based management of riverbank erosion. A Decision Support System (DSS) designed by WRL, was used to objectively assess and rank the susceptibility of the riverbanks in the study area to erode based on a variety of environmental factors. Specifically, the DSS was used to assess:

- The current condition of the riverbanks using a robust and repeatable ranking system;
- The effect of natural wind waves and boat wake waves and other contributing causes to riverbank erosion along key reaches of the Hawkesbury River;
- The vulnerability of the riverbanks to erosion; and
- Potential management actions that can best address erosion at key sites.

Many land- and water-based factors can contribute to the erosion of riverbanks. Land-based factors include clearing of native vegetation on riverbanks, grazing hard hoofed stock on riverbanks and inappropriate development on riverbanks. Water-based factors include periodic flooding of the Hawkesbury River (which both erodes and deposits material), tidal flows causing natural scour sites coupled with depositional sites and waves (generated by either the wind or boats) breaking against riverbanks. The focus of this study is on wave impacts on riverbanks, with consideration given to land-based factors which may influence the riverbank's ability to resist potential erosion.

The core of the DSS process is a field-based, riverbank erosion potential assessment. Key criteria and importance weightings are combined to form an erosion potential rating for the site. These criteria include river type, vegetation coverage and extent, erosion descriptors, adjacent land use and channel features (see example DSS field sheet in Appendix E). A fundamental assumption of the DSS is that it assumes that in an ideal environment, the riverbank has the potential to be in a dynamic equilibrium with the wind environment, and subsequently that boat wave energy exceeding the wind environment, depending on the relative magnitude and the riverbank vulnerability, has the potential to negatively impact the riverbank. For the purpose of informing specific management actions, the DSS highlights riverbank sections which may be negatively impacted by boat wave energy.

Due to the large amount of technical material generated as part of this riverbank vulnerability assessment, this report has been structured for conciseness. Significant tasks which do not form the core of the riverbank vulnerability assessment have been documented in appendices, rather than in the main body of the report. Specifically, literature relevant to this project, including geomorphology of the Hawkesbury River, the geology of its riverbanks and documented recreational boating activity, was reviewed by WRL and summarised in Appendix A. Readers unfamiliar with the background theory of wind waves and boat wake waves are directed to Appendix B. A detailed overview of the DSS methodology is included in Appendix C and readers are encouraged to consider this discussion if they are also unfamiliar with the DSS.

The main body of the report is divided into four sections. Following this introduction:

- Section 2 presents the methodology and details of the Hawkesbury River DSS assessment;
- Section 3 introduces the results of the DSS analysis, as determined for a range of different scenarios, including the riverbank erosion potential assessment; and
- Section 4 discusses the results and provides recommendations for further development and investigations on the Hawkesbury River including implementation options to minimise erosion at vulnerable areas.

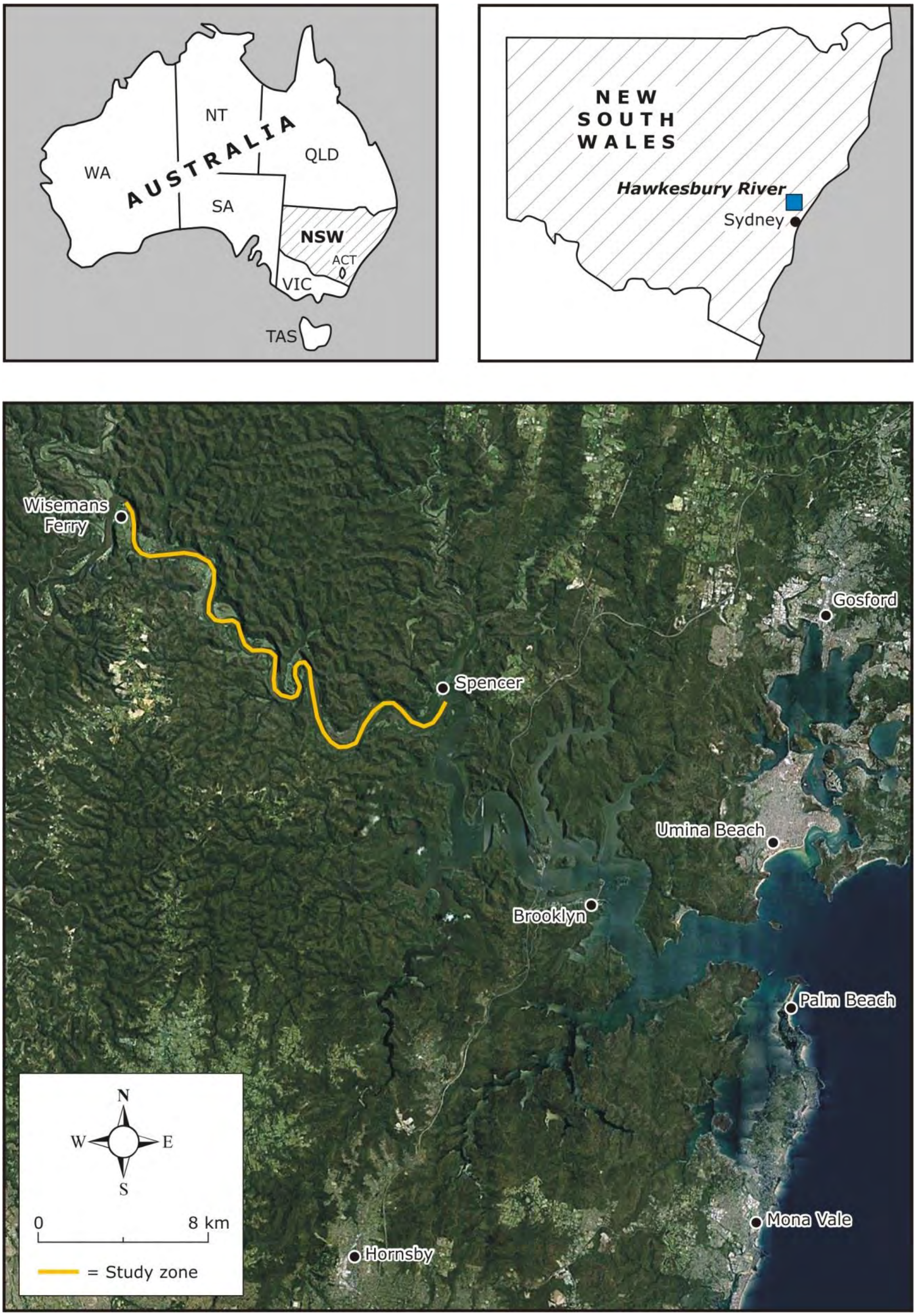

Figure 1-1: The Study Area

2. Assessment Methodology and Details

2.1 Preamble

This section discusses the specific aspects of the Decision Support System (DSS) and the methodology followed to apply the DSS to the selected region of the Hawkesbury River. Initially the site selection requirements are discussed (Section 2.2), followed by a detailed description of the field based riverbank assessment (Section 2.3). The wind data and locations used for assessment are presented (Section 2.4) along with the rationale behind the selection of boat numbers and conditions (Section 2.5).

2.2 Site Selection

Sites were selected using aerial photography and GIS mapping of the selected region of the Hawkesbury River. The river was first segmented into the required stretches. In order to incorporate complexities associated with riverine geometry the stretches were labelled as either inside bend, outside bend or straight. The majority of stretches were 500 m in length, however, shorter stretches were required in several locations to incorporate the different geomorphic zones. Overall, a total of fifty-eight (58) stretches were identified for survey (Figure 2-1). Finally, within each stretch three transects spaced along each bank (a total of 348 transects) were selected as per the DSS methodology (Appendix C).

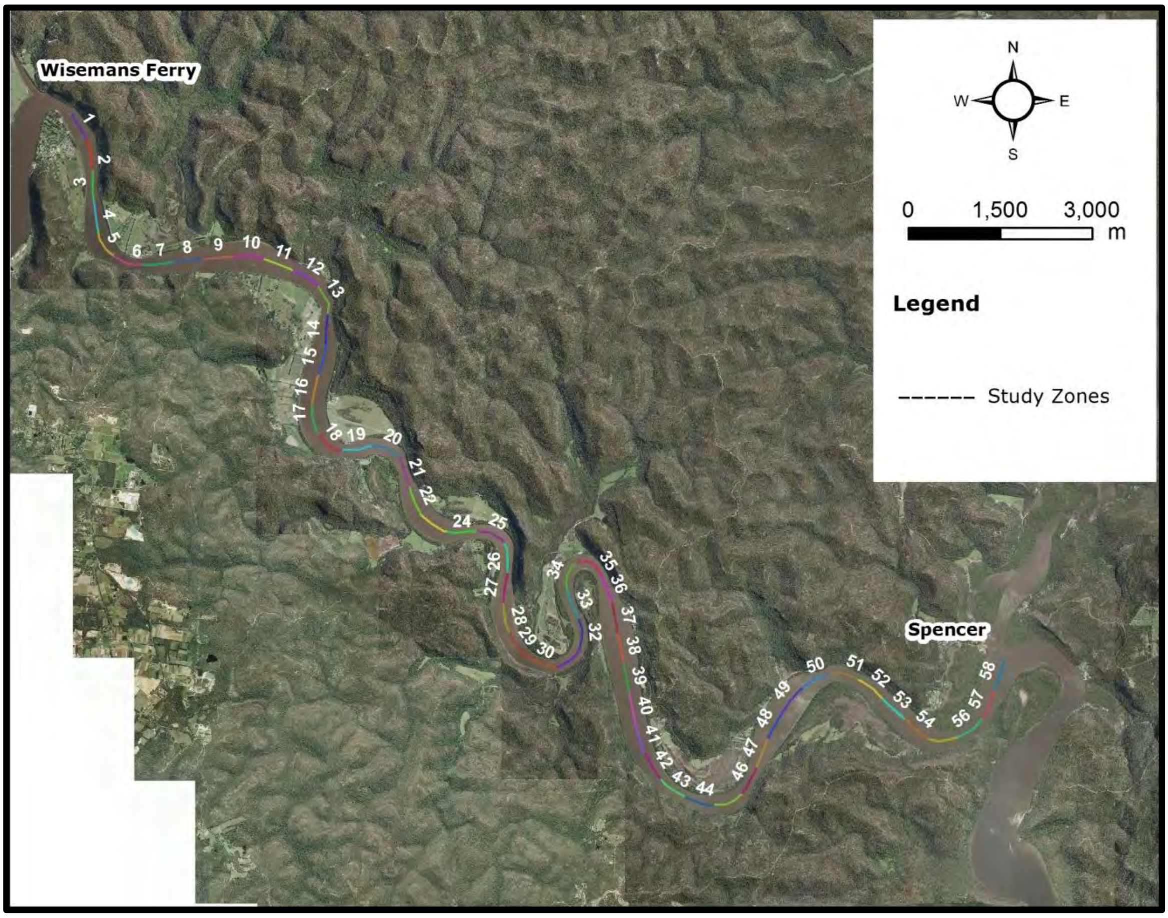

Figure 2-1: Numbered Stretches of the Hawkesbury River

2.3 Riverbank Erosion on the Hawkesbury River

Three transects on each bank of the 58 stretches were observed, totalling 348 site inspections. These sites were predetermined to eliminate bias and were identified in the field through a combination of aerial photography and GPS methods. HSC provided a boat and a driver for each day of the field assessment.

Four days were allocated for the field assessment in two separate campaigns (24 - 25 February, 2014 and 10 – 11 March 2014). Assessment dates were selected to incorporate low tides during the middle of the assessment period. Water levels on the Hawkesbury River are monitored at three locations (Figure 2-2): Spencer, Gunderman and Webbs Creek (Wisemans Ferry) by Manly Hydraulics Laboratory (MHL) on behalf of the NSW Office of Environment and Heritage (OEH). Figure 2-3 and Figure 2-4 display the water levels on these four survey days. Glamore and Badenhop (2006) state that tidal river assessments should be conducted at mid- to low tide to accurately assess the wave zone.

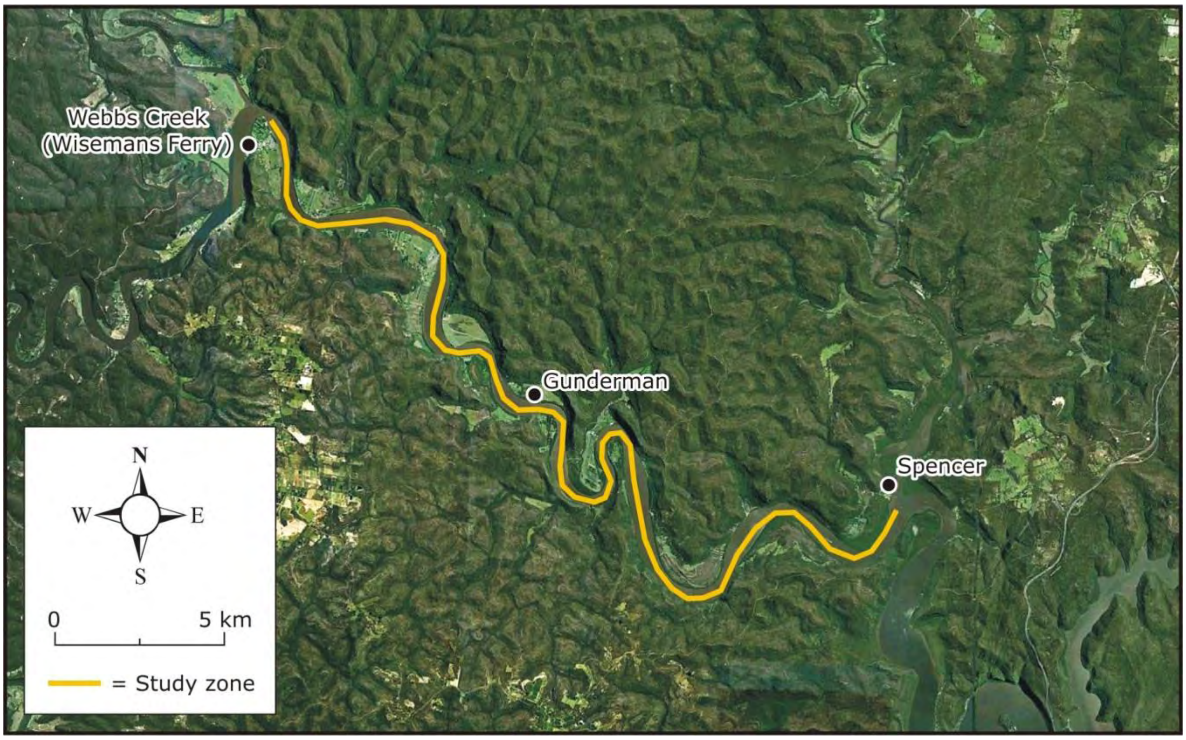

Figure 2-2: Location of Water Level Monitoring Stations

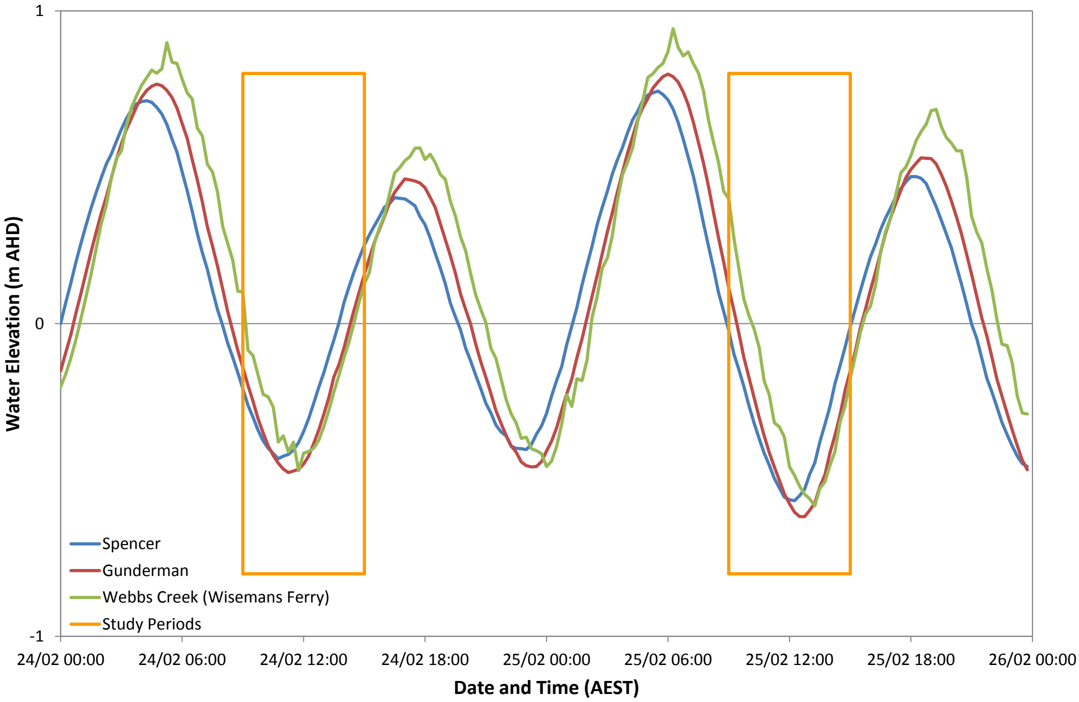

Figure 2-3: Water Levels on the Hawkesbury during Field Campaign 1 of 2 (Source: MHL-OEH)

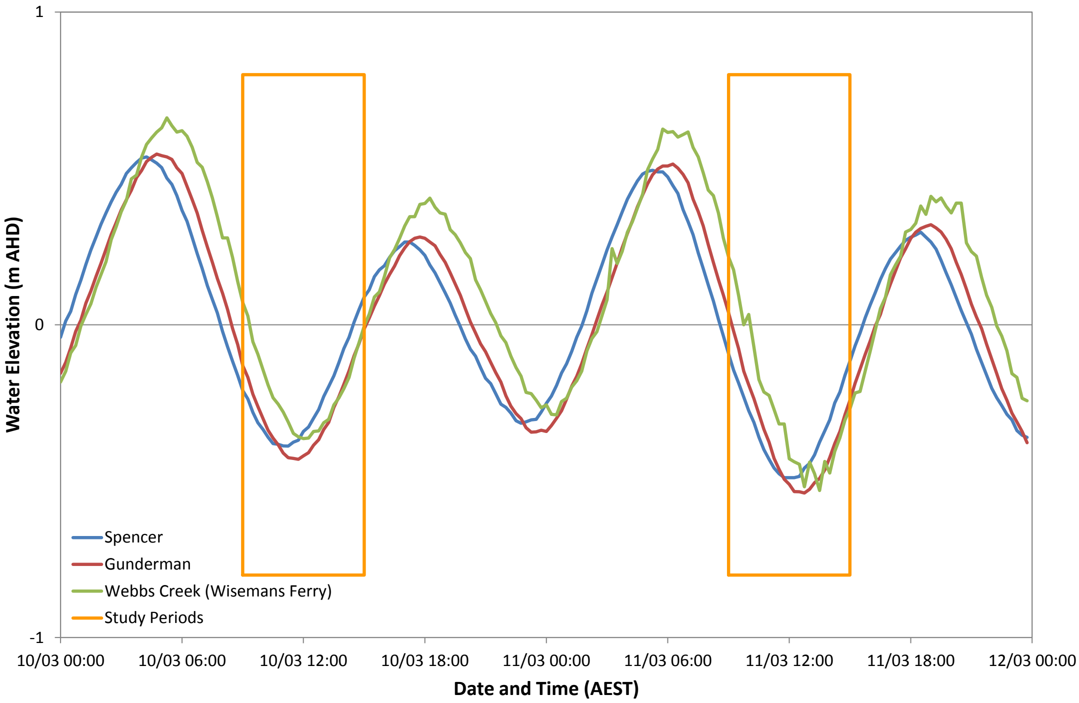

Figure 2-4: Water Levels on the Hawkesbury during Field Campaign 2 of 2 (Source: MHL-OEH)

2.3.1 Site Identification and Erosion Indicators

A combination of aerial photography and GPS co-ordinates were used to locate each preselected transect. Prior to the assessment, the exact transect extent was determined to ensure assessors were documenting the same riverbank locations. Two assessors completed the field work. Blind testing was undertaken as a quality assurance check to ensure the repeatability of the analysis. At each location a DSS field sheet was completed (see example DSS field sheet in Appendix E), a GPS waymark obtained and two photographs taken. The width of the river was measured with a laser rangefinder. Note that the erosion potential for each site is based only on its current condition when inspected in the field. That is, no assessment was made of the cause (i.e. flooding, tidal scour, wind waves or boat wake waves) of any erosion observed.

Several erosion indicators were constant for the entire 29 km study area, including:

- Stage variability was recorded as 'tidal' due to the nature of the river;
- The lateral stability was recorded as 'high' for all stretches due to the river's confined nature;
- Sinuosity (the channel length of the river divided by the valley length) was less than 1.3;
- HSC staff confirmed that no de-snagging had taken place in the river; and
- No major water extraction by the local farmers occurs in the study area.

2.4 Wind Waves on the Hawkesbury River

2.4.1 Baseline DSS Assessment

An accurate representation of the wind climate is highly important for the DSS analysis. Ideally wind data would be obtained from a local source as part of the investigation, however this was not possible. Glamore and Badenhop (2006) recommend the use of regional weather stations when local records are unavailable. As such, a weather station near the Hawkesbury River, located at the Richmond RAAF Base (Figure 2-5) was used for this study (Note: this weather station was moved slightly in October 1993). Data was obtained for both weather station positions, producing a combined dataset of 74 years (Appendix D). No scaling adjustments were undertaken to simulate local wind conditions on the river for the baseline DSS assessment.

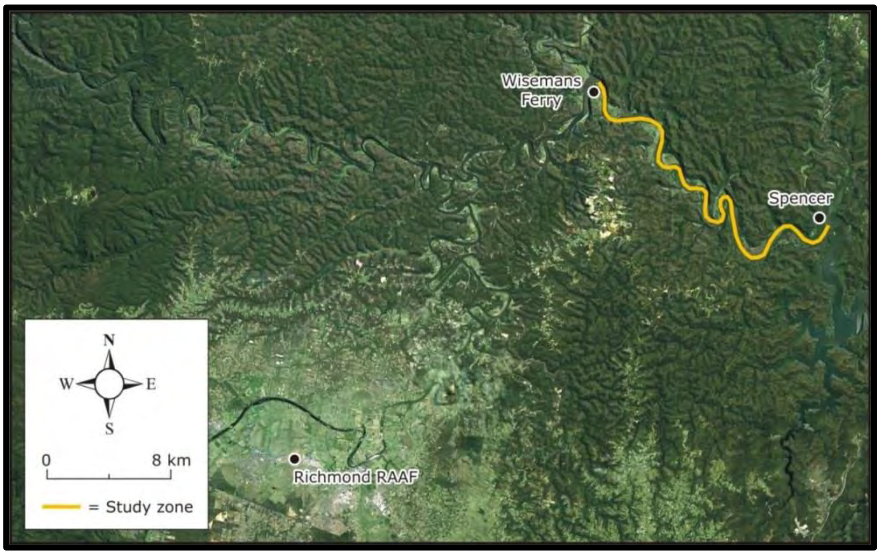

Figure 2-5: Location of the Wind Station with Respect to the Hawkesbury River Study Area

As per the DSS methodology (Appendix C), fetch lengths for each stretch were determined using the centre of the stretch as a reference point. Based on the length of the wind record, the average recurrence interval (ARI) of the wind wave energy was calculated for both the maximum wind wave and for an extended duration of wind waves of eight hours for all but two boat pass scenarios. Eight hours was selected for the extended duration wind analysis as it is a likely length of time for watersports on the river.

2.4.2 DSS Sensitivity Test (Adjusted Local Wind Conditions)

Sensitivity tests were also undertaken to examine the assumption that winds at Richmond RAAF Base are a reasonable approximation of conditions within the study area (Wisemans Ferry to Spencer). WRL re-assessed the wind wave energy with scaling factors developed to represent worst-case local wind conditions on the Hawkesbury River. These scaling factors were developed by comparing the extreme wind speeds (10 minute) at Richmond RAAF Base with those set out in the Australian Wind Standard - AS 1170.2 (2011).

Design wind velocities (0.2 second gust, 10 m elevation, Terrain Category 2) in AS 1170.2 are given for average recurrence intervals of 1 to 10,000 years. Site wind speeds (V_{sit}), are calculated according to Equation 2-1 using multipliers for direction (M_d), terrain ($M_{z,cat}$), shielding (M_s) and topography (M_t).

$$V_{sit} = V_r M_d (M_{z,cat} M_s M_t) \tag{2-1}$$

The Hawkesbury River falls within Region A2 (AS 1170.2, 2011) and corresponding wind speed multipliers were adopted. A Category 2 terrain multiplier is suggested for open terrain with well-scattered obstructions which is consistent with the topography of the riverbanks in the study area (AS1170.2:2011, S4.2.1). No further shielding or topography multipliers were applied. The site wind speeds (0.2 second) were adjusted to equivalent sustained 10 minute wind speeds using the approach set out in Figure II-2-1 of Part II of the USACE Coastal Engineering Manual (2006). Sustained (10 minute) wind speeds for ARI up to 10,000 years for all directions at Richmond RAAF base and AS 1170.2 are presented in Figure 2-6. Since the shortest ARI given in AS 1170.2 is 1 year, WRL extrapolated the Australian Wind Standard for more frequent wind events for application in the DSS. Since the AS 1170.2 wind speeds are approximately 25% faster than at Richmond RAAF Base for ARI 1 to 74 years, the AS 1170.2 values were extrapolated by multiplying the Richmond RAAF Base winds speeds less than 1 year ARI by 1.25 (Figure 2-7).

As discussed in Appendix A, Johnson (1994) found that wind directions on the Hawkesbury River between Wisemans Ferry and Spencer tend to be dictated by local topography. That is, the river valley channels the wind on the river. To account for wind channelling in the DSS sensitivity test, the extrapolated Australian Wind Standard speeds were applied along the longest fetch at each river stretch. **In comparison with the baseline DSS assessment, these worst-case local wind conditions have the effect of increasing the natural wind wave energy acting on each stretch of the river.**

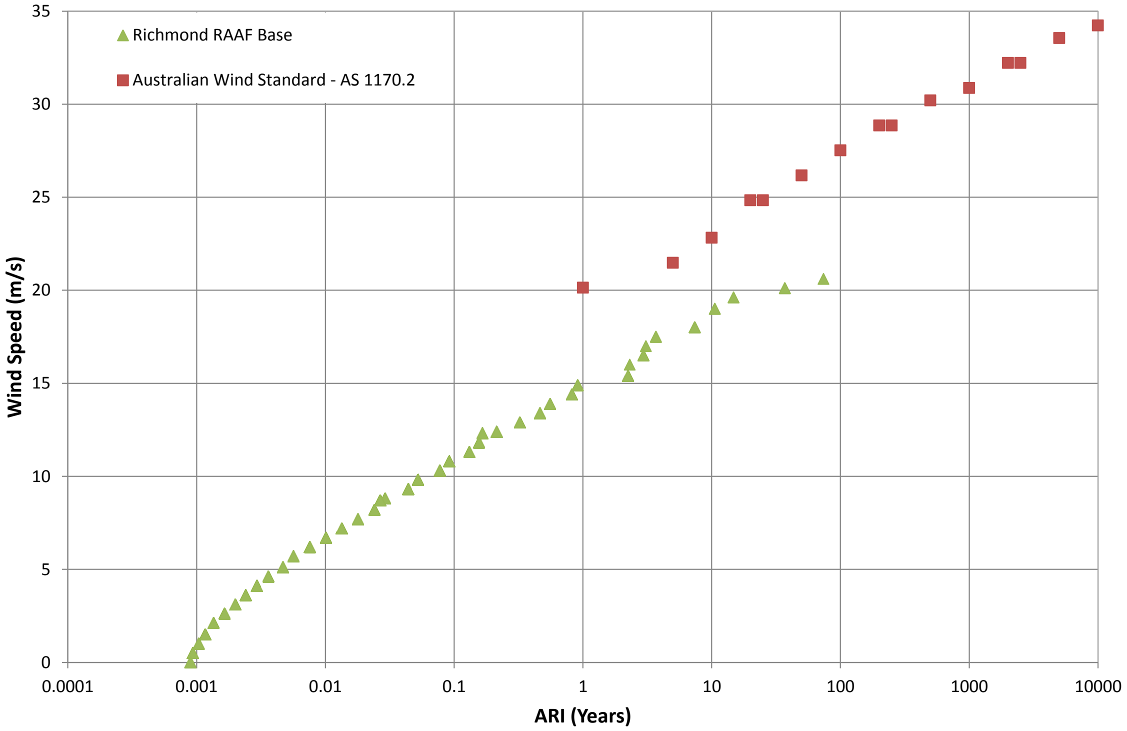

Figure 2-6: Sustained Wind Speeds (10 Minute) – All Directions - Richmond RAAF Base and AS 1170.2

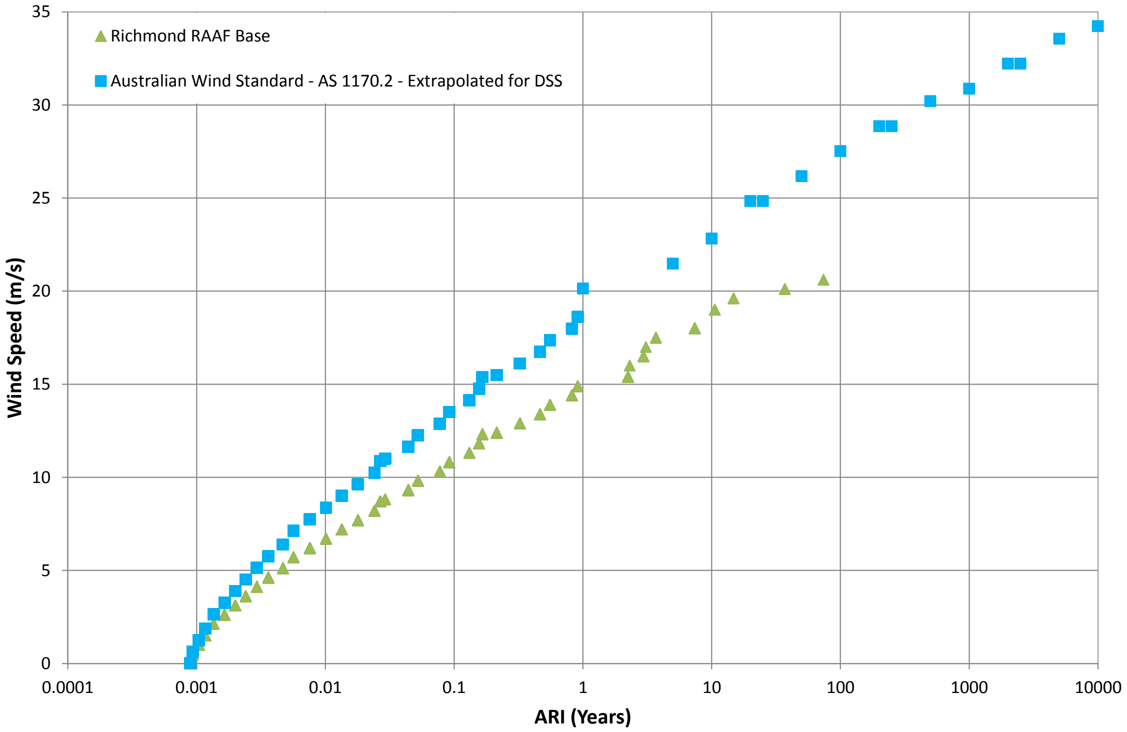

Figure 2-7: Sustained Wind Speeds (10 Minute) - All Directions - Richmond RAAF Base and AS 1170.2 (Extrapolated)

2.5 Wake Waves on the Hawkesbury River

2.5.1 Preamble

The wake wave data already incorporated into the DSS provides quality controlled direct measurements of wake waves from various boats at preselected speeds. A required input, however, is the number of boat passes in the selected time period (generally eight hours). Access to previous boat pass data on the Hawkesbury River was limited.

2.5.2 Previous Literature

On the 26th of January 1994 (Australia Day), Johnson (1994) undertook a boat pass count between Wisemans Ferry and Spencer at Laughtondale. The count was undertaken between 10:20 AM and 1:00 PM (2 hour, 40 minute duration) and 48 passing boats were identified (approximately 18 boat passes per hour). For the purpose of estimating yearly boat traffic at Laughtondale, Johnson (1994) assumed that daily boat pass counts varied from 20 (low usage), to 40 (moderate usage) to 80 (high usage). However, only one boat pass count on one day was undertaken at Laughtondale as part of Johnson's investigation. The author asserted that the boat pass data between Wisemans Ferry and Spencer was scarce, that the boat activity estimates were uncertain and that more boat pass count collection was required in the area.

As discussed in Section 2.1, Astles et al (2010) found that there was limited information on the number of recreational boats, their size, the number of hours of activity and where they go between Wisemans Ferry and Spencer. Astles et al. (2010) estimated the number of boats using the area between Wisemans Ferry and Spencer by counting the number of boats in aerial photos. The study found that there were 9 boats less than 7 m in length and 40 boats greater than 7 m in length (total 49 boats); however the authors asserted that this was an underestimate of boating activity. It was noted that there are 58 moorings located within the study area.

The HSC *Sustainable Water Based Recreation Facilities Plan* provides a summary of findings and directions for water-based recreation activities within the LGA. Based on Exercise, Recreation and Sport Statistics (ERASS) conducted annually within NSW, @leisure (2010) estimated that there were likely to be 1,800 residents within HSC who participate in power boating (water-skiing and wakeboarding). The authors also noted that the annual Bridge to Bridge Water Ski Classic race which runs over a weekend (two days) in November and through the river stretch between Wisemans Ferry and Spencer has had approximately 150-200 boats enter in recent years (at the time of writing). It was noted that during the peak of this competition in the mid-1980s, up to 430 boat entries were recorded.

A comprehensive overview of the entire lower estuary to estimate levels of investment in the recreational boating industry was undertaken for HSC by Rolyat Services (2013). The study found that there were 32 moored vessels and 158 berthed vessels between Wisemans Ferry and Spencer (total 190 vessels) based on a review of aerial photographs and site inspections. Note that vessels berthed at marinas and on private wharves and jetties, as well as those stored on hard stands in marinas and ashore in private premises were included in the count of berthed vessels. Rolyat Services (2013) asserted that berthed vessels are used more frequently than moored vessels due to their greater ease of access and convenience.

2.5.3 *Adopted Wake Waves*

While the data outlined in the previous section provides broad information about boat use between Wisemans Ferry and Spencer, detailed boat counts are unavailable. Specifically, the activity of moored and berthed vessels is unknown, as is the number and activity of vessels stored off-river and deployed from boat ramps. In the absence of this information, WRL has developed a range of daily boat pass numbers estimated for the waterway. These boat pass numbers developed are based on WRL's experience on the Hawkesbury River and results from detailed boat pass surveys from similar rivers (Table 2-1). The wave type selected for each of these boat pass numbers was "operating conditions" (Glamore and Badenhop, 2006). This describes the waves generated when a vessel is towing a rider at operational speed (typically 19 knots for wakeboarding and 30 knots for water skiing). Eight hours was selected as an appropriate duration for calculating cumulative energy as it approximates the hours during which boats are likely to be travelling on an average day.

Table 2-1: Adopted Daily Boat Passes for Typical Conditions

Scenario	Wave Type	No. Boat Passes (-)	Duration (hours)
Low – Wakeboard	Operating	10	8
Medium – Wakeboard	Operating	50	8
High - Wakeboard	Operating	150	8
Low – Waterski	Operating	10	8
Medium – Waterski	Operating	50	8
High – Waterski	Operating	150	8

A series of boat pass sensitivity tests were undertaken with a second set of boat pass scenarios likely to occur on public and school holidays (extreme) and during competitions (event) (Table 2-2). For these scenarios, a duration of twelve hours has been used as it is estimated this would only take place in summer when long daylight hours are maximised.

"Maximum wave" conditions (for an 8 hour duration) were also included in this second boat pass set. Maximum wave energy is not produced when vessels (both wakeboarding and water skiing) travel at "operating conditions", but rather at the slower velocity of approximately 8 knots. This velocity is related to typical vessel length and is predicted by the length based Froude-number discussed in Appendix B. These conditions are experienced when a boat is accelerating, or slowing down from operational speed.

Table 2-2: Adopted Daily Boat Passes for Holiday and Competition Conditions

Scenario	Wave Type	No. Boat Passes (-)	Duration (hours)
Maximum – Wakeboard	Maximum	50	8
Event – Wakeboard	Operating	500	12
Extreme - Wakeboard	Operating	1,000	12
Maximum - Waterski	Maximum	50	8
Event – Waterski	Operating	500	12
Extreme – Waterski	Operating	1,000	12

3. Decision Support System Results

3.1 Preamble

This section summarises the results produced by the DSS for the assessment of the Hawkesbury River. The erosion potential of the riverbanks is discussed in Section 3.2. Secondly, Section 3.3 presents the equivalent average recurrence interval (ARI) ratings for each boat pass scenario, as discussed in Section 2.5. The distribution of the erosion potential along the riverbanks is presented, with annotated images providing examples of the different erosive states in Appendix F. The management recommendations from the DSS, for both the mid – low tide baseline assessment and the sensitivity tests (high tide, holiday/competition conditions and adjusted local winds) are then presented in Section 3.4.

3.2 Riverbank Erosion Potential Assessment

The riverbank assessment was conducted at mid – low tide and high tide to accurately observe the wave zone. During the field assessment it was noted that the erosion potential is significantly reduced when conducted at the top of high tide. In most cases, the wave zone would alter from the gently sloping tidal beach, present at the majority of locations, to the bottom level of the vegetation or bedrock/armouring. This was shown to reduce riverbank susceptibility to wave attack. Figure 3-1 provides a representative transect in the study region showing the effect of water level on the erosion potential assessment between mid – low and high tide.

Figure 3-1: Effect of Water Level on Erosion Potential Assessment

Table 3-1 and Table 3-2, and Figure 3-2 and Figure 3-3, display the distribution of the erosion potential categories across the entire study area for mid - low tide and high tide conditions, respectively. All five erosion potential categories in the DSS were observed at transects in the study area of the Hawkesbury River. The 348 transects documented were averaged for the left and right bank of each stretch to produce a representative erosion potential for each bank of the stretches. Annotated field photos for each observed erosion potential category are provided in Appendix F. Note that the erosion potential for each site was based only on its current condition when inspected in the field. That is, no assessment was made of the cause (i.e. flooding, tidal scour, wind waves or boat wake waves) of any erosion observed.

A comparison between the mid – low tide and high tide assessments, highlights a substantial increase in the number of occurrences of 'highly resistant' sites. At mid – low tide, 50 percent of all transects observed were 'highly resistant' to erosion, whereas at high tide, this rating increased to approximately 80 percent. Consequently, the number of sites in the 'moderately erosive' or 'highly erosive' categories reduced from 32 occurrences at mid – low tide to 12 occurrences at high tide, a reduction of approximately 60 percent. As such, the majority of the study region is considered highly resilient to erosion throughout the tidal range.

Table 3-1: Erosion Potential of the Hawkesbury River Study Area (Mid – Low Tide Conditions)

Erosion Potential (Mid – Low Tide Conditions)	Number of Occurrences (Individual Transects)	Number of Occurrences (Bank Stretch Average)
Highly Resistant	177	64
Moderately Resistant	88	24
Mildly Resistant	51	23
Moderately Erosive	28	5
Highly Erosive	4	0
Total	**348**	**116**

Table 3-2: Erosion Potential of the Hawkesbury River Study Area (High Tide Conditions)

Erosion Potential (High Tide Conditions)	Number of Occurrences (Individual Transects)	Number of Occurrences (Bank Stretch Average)
Highly Resistant	276	83
Moderately Resistant	46	23
Mildly Resistant	14	6
Moderately Erosive	11	4
Highly Erosive	1	0
Total	**348**	**116**

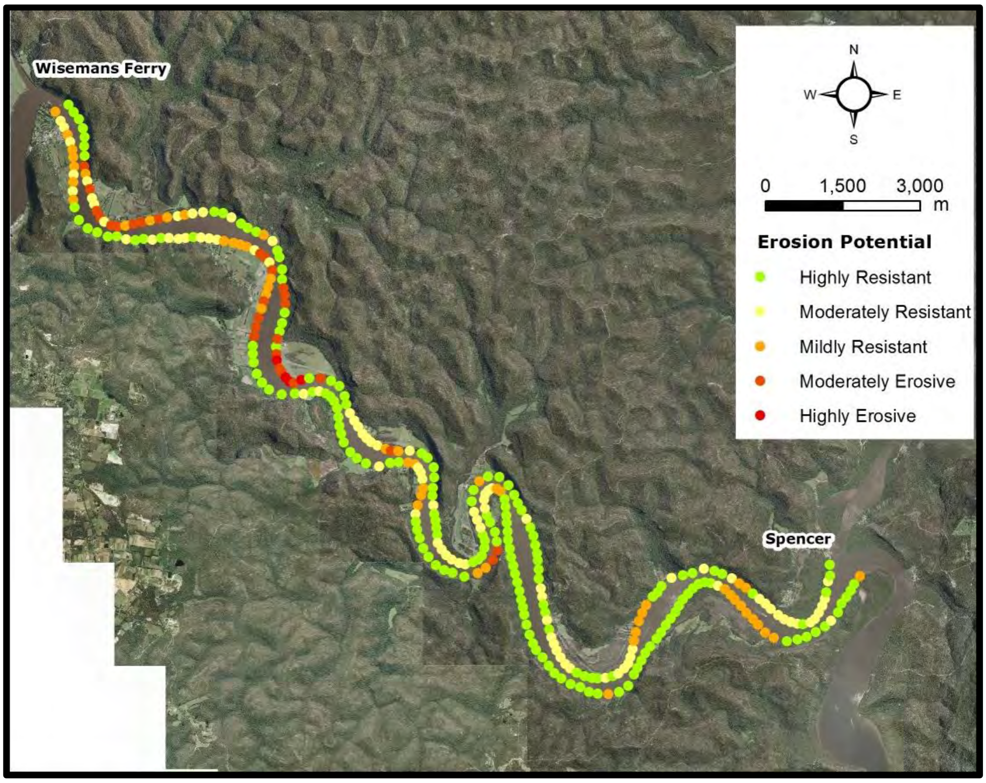

Figure 3-2: Erosion Potential for Each Transect (Mid - Low Tide Conditions)

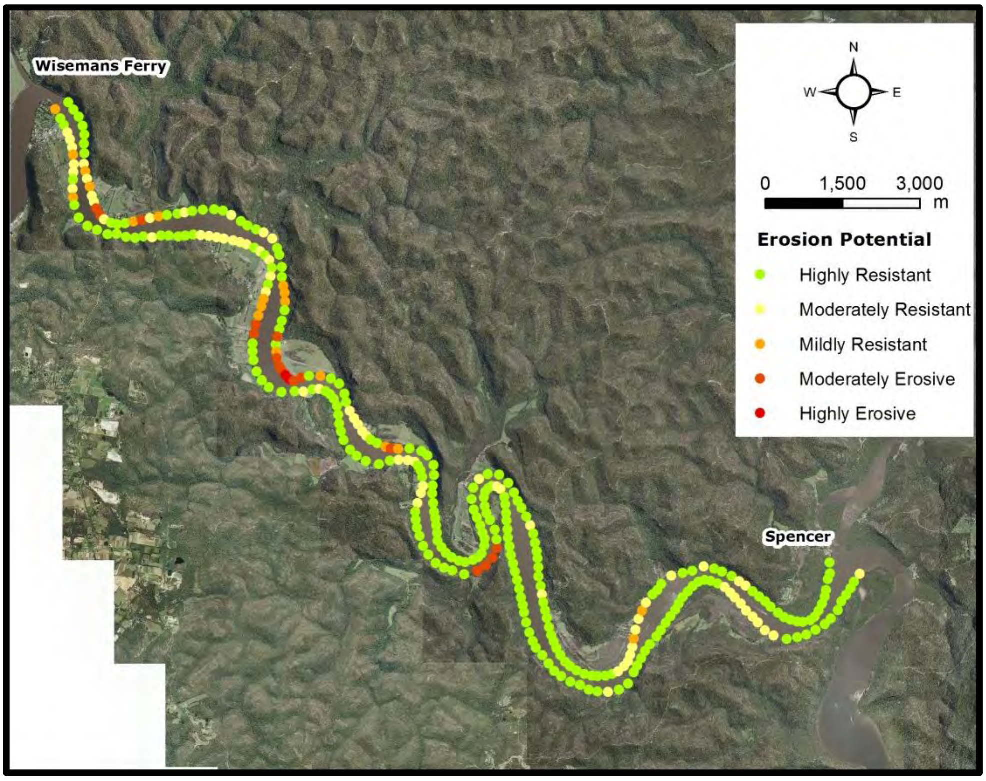

Figure 3-3: Erosion Potential for Each Transect (High Tide Conditions)

The erosion potential of the riverbank is a major influencing factor in the assessment. Substantial reaches of the study area are naturally armoured by large rock ledges or cliffs (Figure 3-4 and Figure 3-5), while other reaches have been artificially armoured (Figure 3-6). This armouring, whether it be natural or artificial, generally provides erosion potential ratings of 'Highly Resistant'.

Figure 3-4: Rock Cliffs (Stretch R6)

Figure 3-5: Significant Bedrock Protecting River Banks from Erosion (Stretch L38)

Figure 3-6: Armouring at Transect R13C and R7B

A range of factors influence the lower erosion potential scores (or higher ratings) observed in the DSS assessment of the Hawkesbury River. Many reaches are bounded by alluvial floodplains on one or both sides. The floodplains were typically observed to be open farmlands cleared of native riparian vegetation (Figure 3-7). At several sites there was also obvious uncontrolled stock access to the riverbanks (Figure 3-9). The combination of these factors in these reaches results in a high risk of bank destabilisation including erosion, slumping and undercutting (Figure 3-8 and Figure 3-10). All three indicators were observed along the study area and as such, these sites scored higher erosion potential ratings.

Figure 3-7: Erosion at Stretch L18 (Stock Access Present)

Figure 3-8: Significant Erosion, Slumping and Undercutting of Riverbanks where Stock Access is Present at Stretch L5

Figure 3-9: Stock Present on the Riverbanks (Stretch L20)

Figure 3-10: Significant Undercutting of Riverbanks where Stock Access is Present at Stretches L20 and R31

In addition to the site specific erosion potential, consideration must be given to potential processes dominated by riverine geometry. As such, each stretch of river was assigned one of three geometric zones: inside bank, outside bank or straight, to determine if there were related patterns to underlying processes. Figure 3-11 displays these classifications for comparison with the DSS erosion potential values displayed previously (Figure 3-2 and Figure 3-3). There is no obvious correlation between these geometric zones and the erosion potential values, confirming there are additional factors to consider in riverbank assessment other than just the riverine geometry.

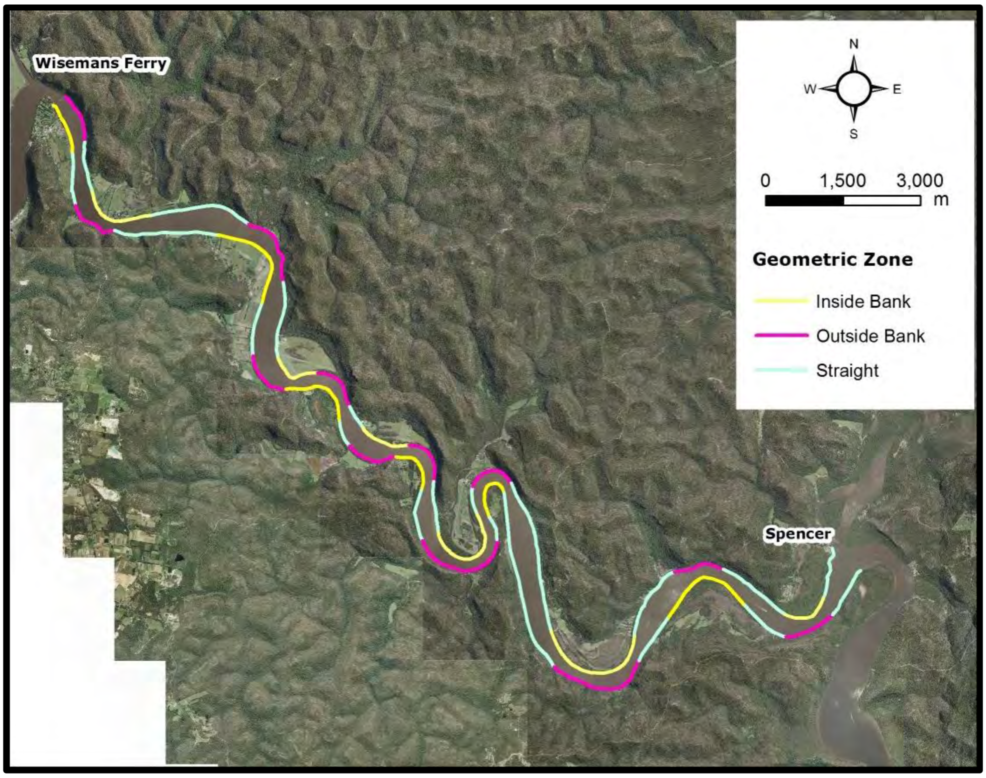

Figure 3-11: Geometric Zones along the Hawkesbury River Study Area

3.3 Equivalent Average Recurrence Interval (ARI)

The wind frequency data was applied to fetch lengths for all stretches of the Hawkesbury River (measured in the centre of each stretch) to determine the average recurrence interval of wind events on the river. These wind values were then compared with the energy of both the maximum boat wave and the cumulative wake waves over the entire day (Table C-2) to establish an ARI rating for each boat pass scenario for each location. This section presents the number and distribution of each occurrence interval for the different boat pass scenarios. A total of 116 ratings are produced, one for each riverbank for the 58 study stretches. Appendix G provides an applied example of the comparison between the wind and the wake wave data.

Table 3-3 and Table 3-4 provide a breakdown of the different ARI ratings for the twelve total boat pass scenarios, applying wakeboarding and waterski 'operating' conditions for five different boat passes, and the 'maximum wave' condition as produced for 50 boat passes for both vessel types. Figure 3-12 to Figure 3-17 display the distribution of the different ARI ratings along the study region for the 10, 50 and 150 boat pass scenarios for wakeboard and waterski vessels. Figures illustrating the ARI ratings of the more extreme boat pass scenarios have been omitted for brevity. The most observed rating is the 'B' category for all scenarios except the 1,000 boat pass scenarios.

As expected, with increasing boat numbers on the river, the equivalent ARI for the stretches typically becomes larger. 150, 500 and 1000 boat passes result in the 'D' category on some stretches, whilst the 500 and 1,000 boat passes are the only scenarios to result in 'E' ratings. The most observed rating for 1,000 boat passes is 'E'. The 'maximum wave' condition is the same for both wakeboard and waterski 'operating' scenarios and the results lie within the range produced by the wakeboard 'operating' scenario for 50 and 150 boat passes.

Table 3-3: Number of Stretches in Equivalent ARI Ratings for Each Wakeboard Boat Pass Scenario

Equivalent ARI Category	Operating Conditions					Maximum Wave
	10 Passes	50 Passes	150 Passes	500 Passes	1,000 Passes	50 Passes
A	3	3	3	3	1	0
B	113	113	83	22	7	106
C	0	0	27	65	33	9
D	0	0	3	18	35	1
E	0	0	0	8	40	0

Table 3-4: Number of Stretches in Equivalent ARI Ratings for Each Waterski Boat Pass Scenario

Equivalent ARI Category	Operating Conditions					Maximum Wave
	10 Passes	50 Passes	150 Passes	500 Passes	1,000 Passes	50 Passes
A	22	22	22	22	22	0
B	94	94	94	86	51	106
C	0	0	0	7	34	9
D	0	0	0	1	9	1
E	0	0	0	0	0	0

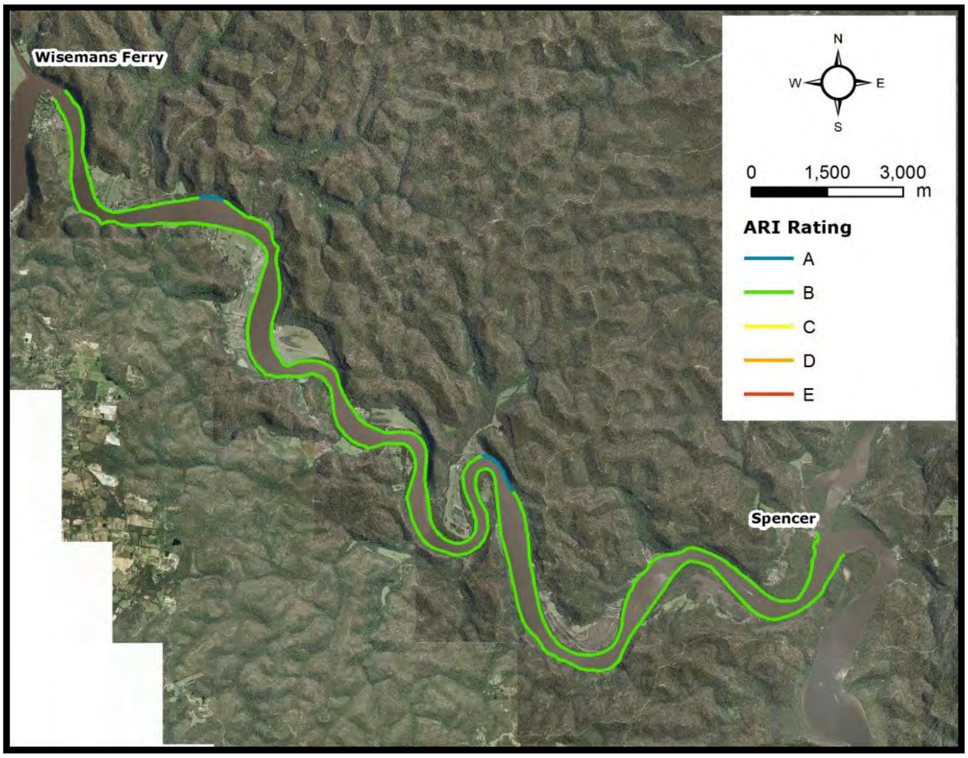

Figure 3-12: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Wakeboard Operating - 10 Boat Passes

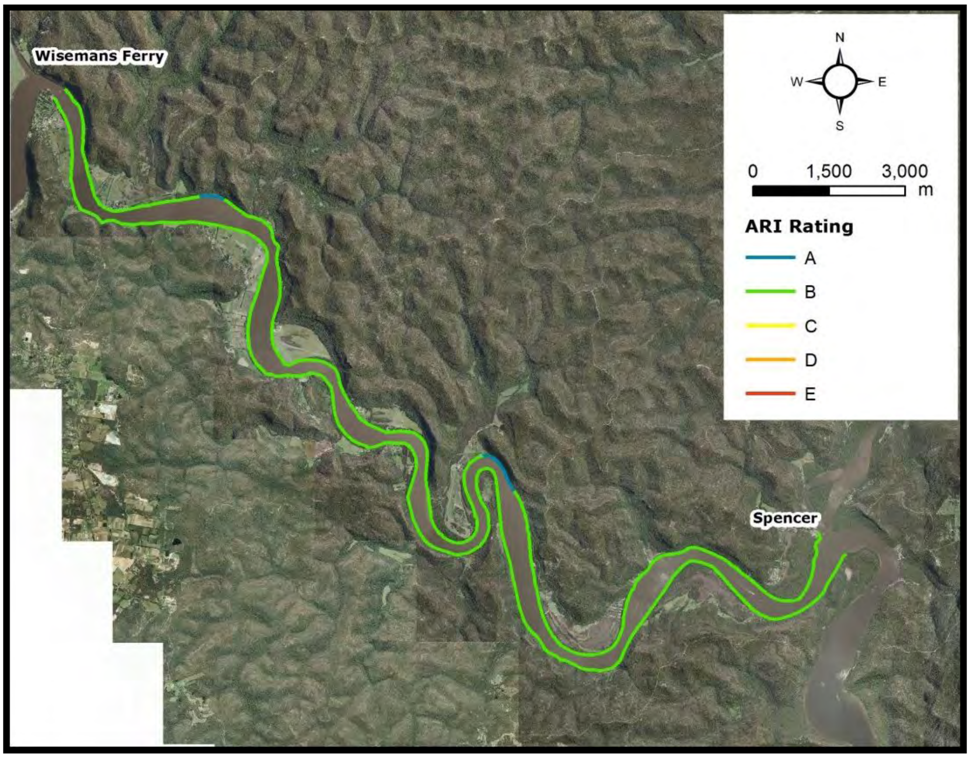

Figure 3-13: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Wakeboard Operating - 50 Boat Passes

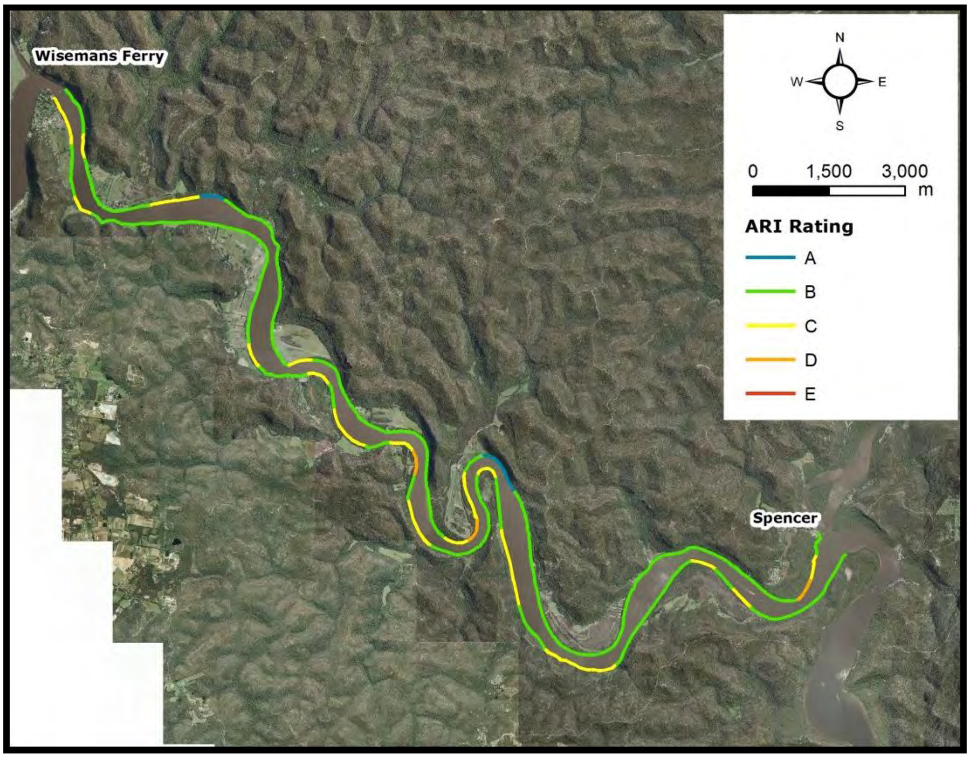

Figure 3-14: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Wakeboard Operating - 150 Boat Passes

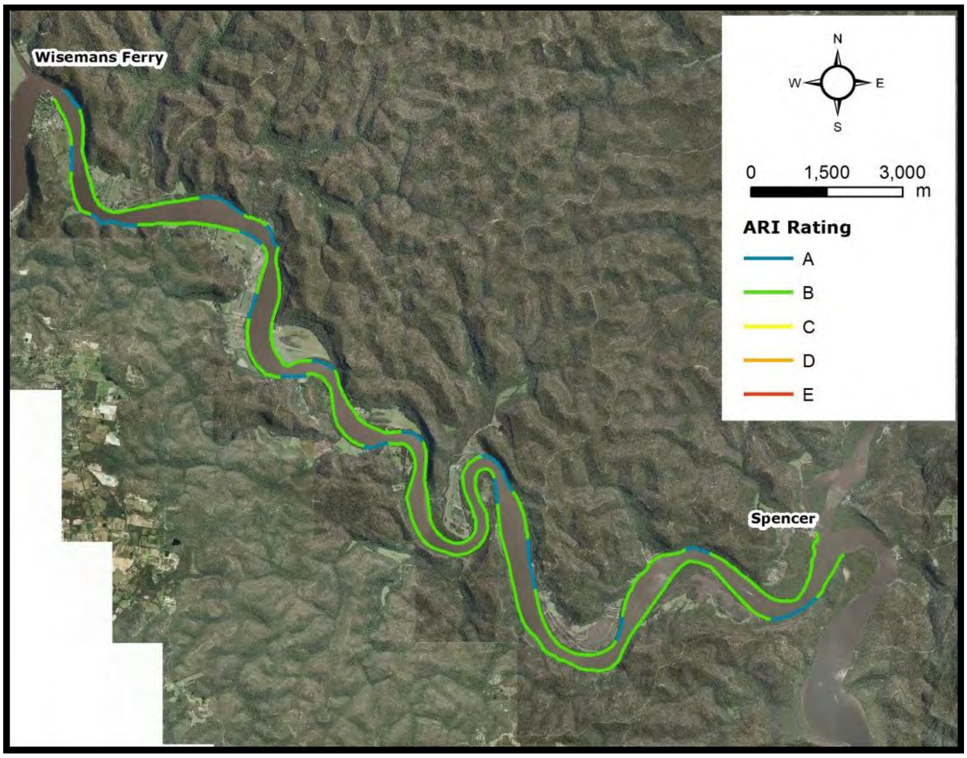

Figure 3-15: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Waterski Operating - 10 Boat Passes

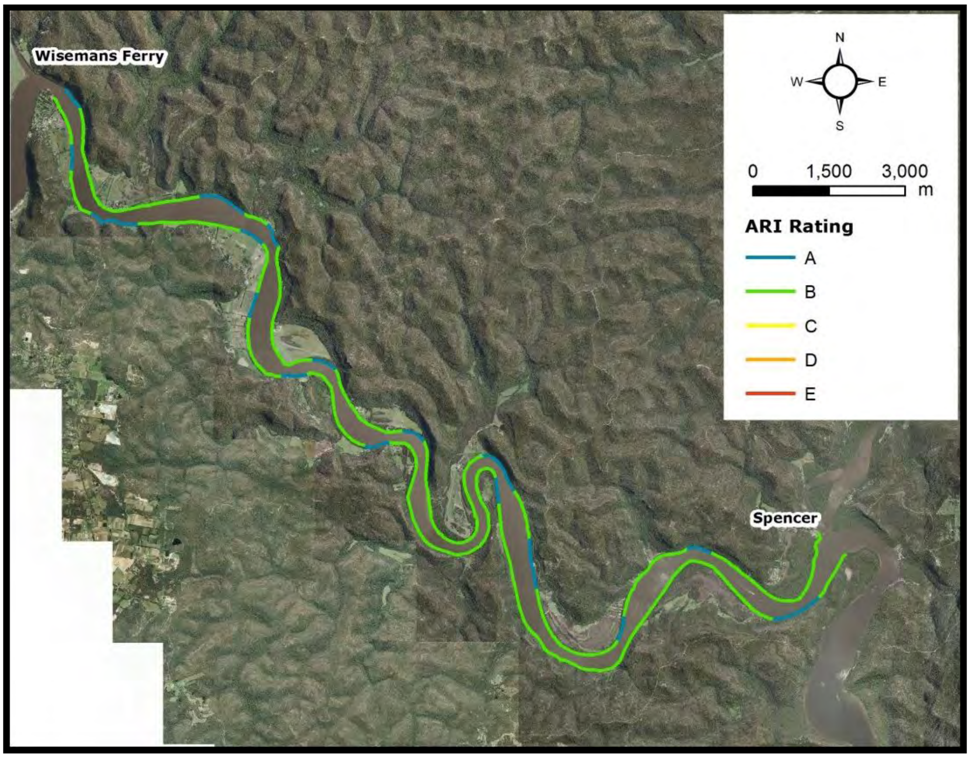

Figure 3-16: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Waterski Operating - 50 Boat Passes

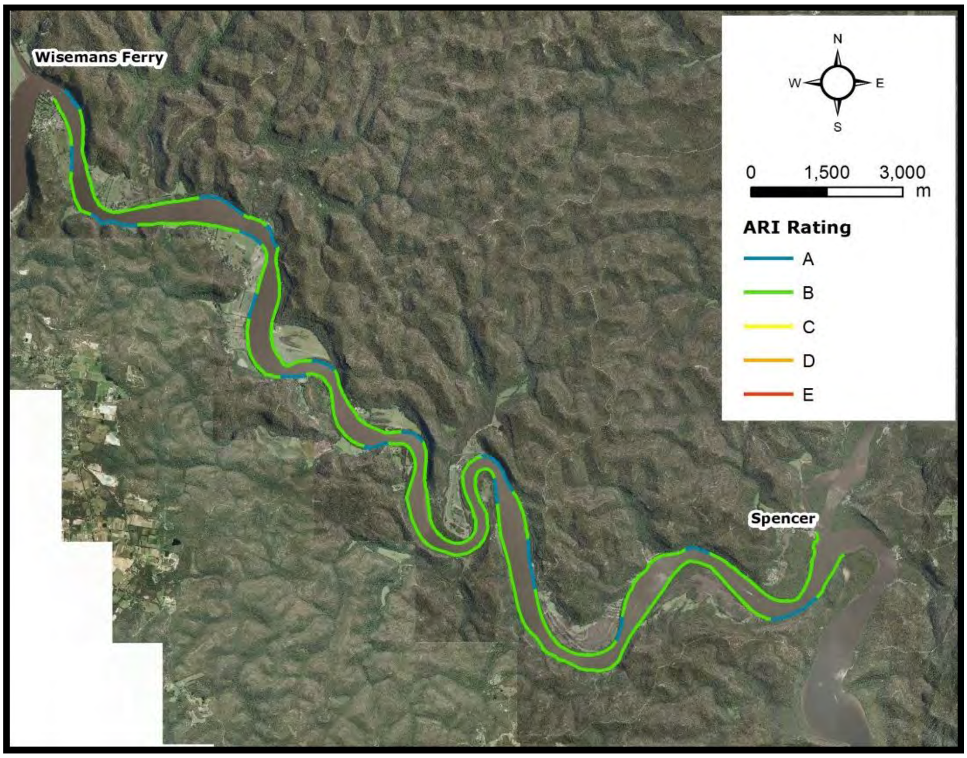

Figure 3-17: Equivalent Wind/Boat Wave Average Recurrence Interval Rating – Waterski Operating - 150 Boat Passes

3.4 DSS Management Recommendations

This section provides an overview of the management recommendations produced using the DSS. Results are presented for both the mid – low tide baseline assessment and the sensitivity tests (high tide, holiday/competition conditions and adjusted local winds), with each assessed under six different boat pass scenarios. Note that maps of DSS management recommendations for the three sensitivity tests have been included in Appendices H, I and J rather than in the main body of the report for brevity. A summary of the scenarios investigated include:

- Baseline DSS Assessment
    - Wakeboarding 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at mid – low tide, applying regional winds
    - Waterskiing 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at mid – low tide, applying regional winds

- Sensitivity Test for High Tide Conditions (Appendix H)
    - Wakeboarding 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at high tide, applying regional winds
    - Waterskiing 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at high tide, applying regional winds

- Sensitivity Test for Holiday and Competition Conditions (Appendix I)
    - Wakeboarding 'operating' conditions for 500 and 1,000 boat passes (12 hour duration) and 'maximum wave' condition for 50 boat passes (8 hour duration) at mid – low tide, applying regional winds
    - Waterskiing 'operating' conditions for 500 and 1,000 boat passes (12 hour duration) and 'maximum wave' condition for 50 boat passes (8 hour duration) at mid – low tide, applying regional winds

- Sensitivity Test with Adjusted Local Wind Conditions (Appendix J)
    - Wakeboarding 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at mid – low tide, applying adjusted local winds
    - Waterskiing 'operating' conditions for 10, 50 and 150 boat passes (8 hour duration) at mid – low tide, applying adjusted local winds.

For each riverbank stretch, one of three management recommendations was assigned: Permit ('Allow'), Permit with Monitoring ('Monitor') or Manage ('Manage'). The management rating is a function of the erosion potential and the relative magnitude of natural wind wave energy and boat wake wave energy (see Appendix C). 'Allow' sites have positive erosion potential scores and limited difference between the wind and wake energies. 'Monitor' sites have neutral erosion potential scores and moderate difference between the wind and wake energies. 'Manage' sites have negative erosion potential scores and significant difference between the wind and wake energies. The exception to this is sites with the worst case "Highly Erosive" erosion potential which are classified as 'Manage' sites regardless of wind and boat wake wave energies.

Riverbank vulnerability to erosion is influenced by several factors, including boat wake waves. The attenuation of the boat generated waves is incorporated into the DSS assessment of the Hawkesbury River through a 'distance of boat from shore' parameter. As the Hawkesbury River is relatively wide, implementing a 'distance off' requirement may reduce boating impacts on the riverbanks. This default assumption within the DSS is that the 'distance of boat from shore' is half the width of the river. However, in sections of the study area recreational boaters are likely to be closer to the riverbank than half the width of the river. As such, **WRL selected a 'distance off' value of 30 m as a conservative management criteria for all scenarios assessed.** This distance is consistent with boating management plans found elsewhere in NSW.

3.4.1 DSS Management Recommendations for Mid – Low Tide Conditions (Baseline Assessment)

Table 3-5 and Figure 3-18 to Figure 3-22 present the DSS management recommendations for the Hawkesbury River study area under mid – low tide conditions. It is evident that increasing boat numbers has an impact on the management recommendation along the river. For wakeboard 'operating' conditions, 8 additional locations recorded the 'Monitor' recommendation and 1 additional location recorded the 'Manage' recommendation, following an increase from 10 boat passes to 150 boat passes. However, the management recommendations were the same for waterskiing 'operating' conditions for all scenarios.

As expected, the stretches recording the 'Monitor' and 'Manage' recommendations are regularly associated with alluvial plains as opposed to the armoured sections found in the lower reaches or the steep bedrock riverbanks, scattered throughout the study area.

Table 3-5: Number of Stretches Determined in each DSS Management Category (Mid – Low Tide)

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	**50 Passes**	**150 Passes**	**10 Passes**	**50 Passes**	**150 Passes**
Allow	88	88	79	90	90	90
Monitor	28	28	36	26	26	26
Manage	0	0	1	0	0	0

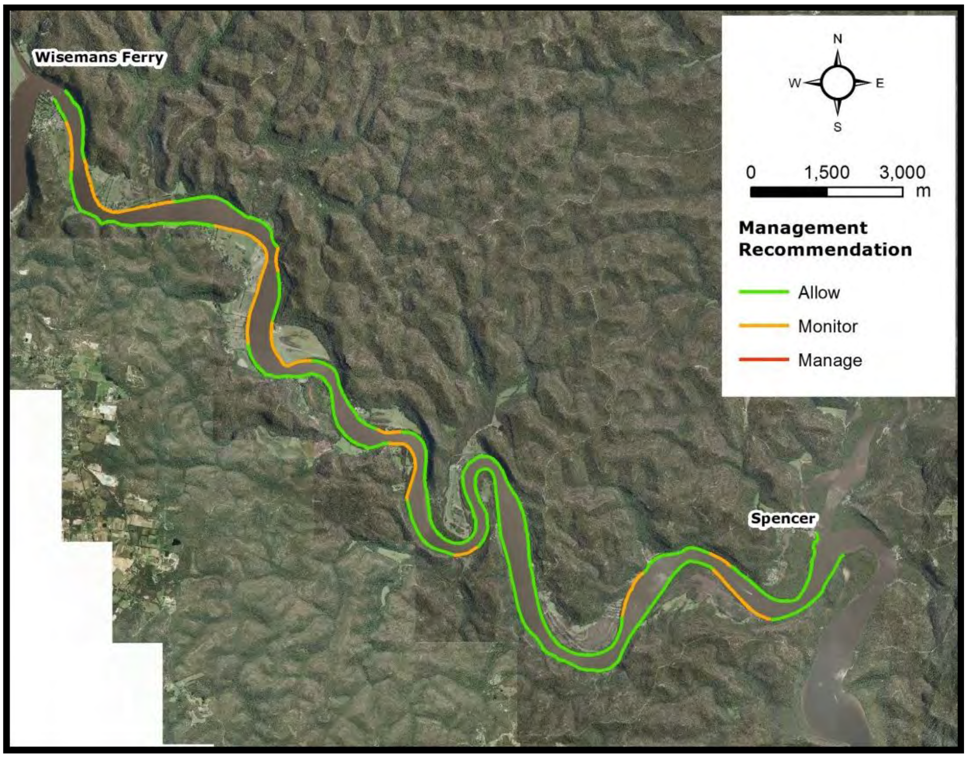

Figure 3-18: DSS Management Recommendations – Wakeboard Operating - 10 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

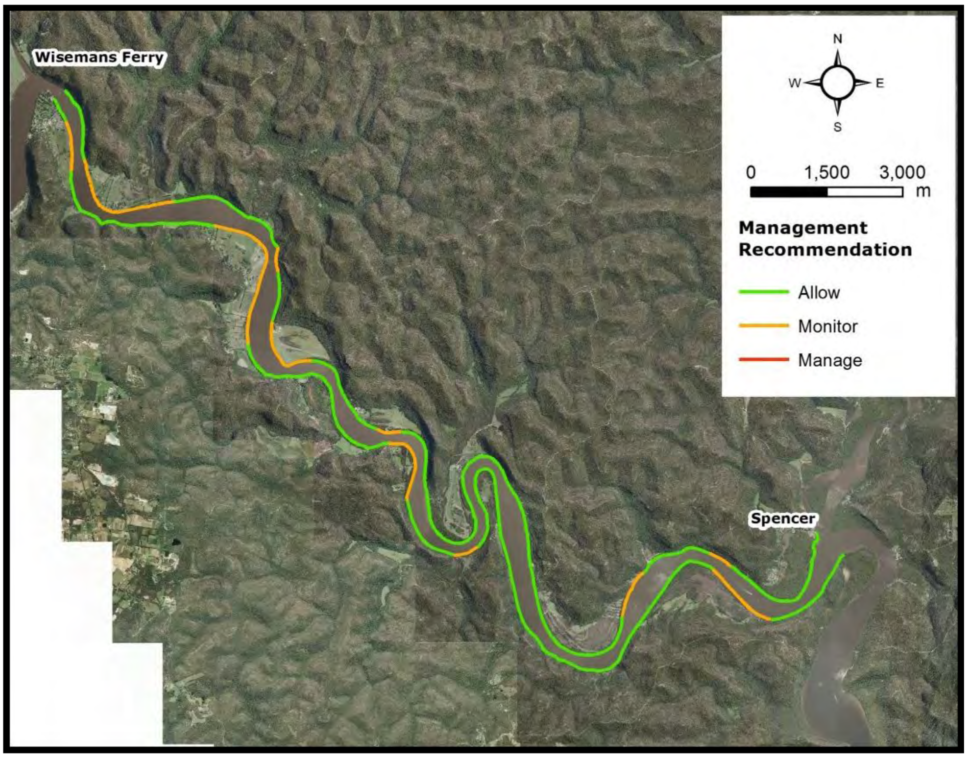

Figure 3-19: DSS Management Recommendations – Wakeboard Operating - 50 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

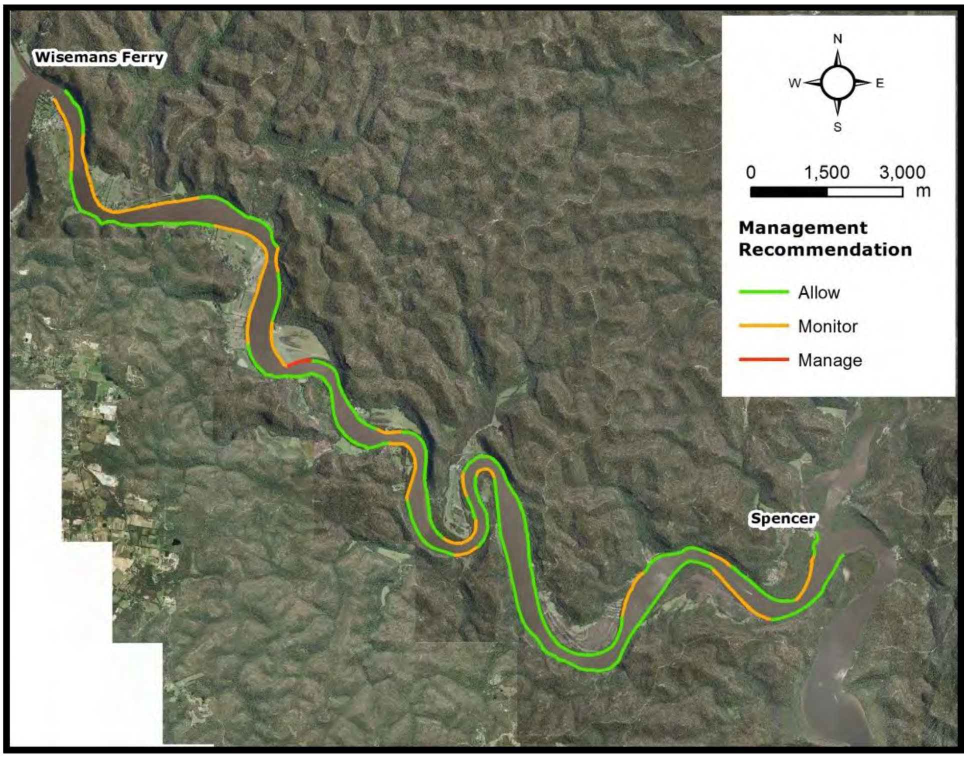

Figure 3-20: DSS Management Recommendations – Wakeboard Operating - 150 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

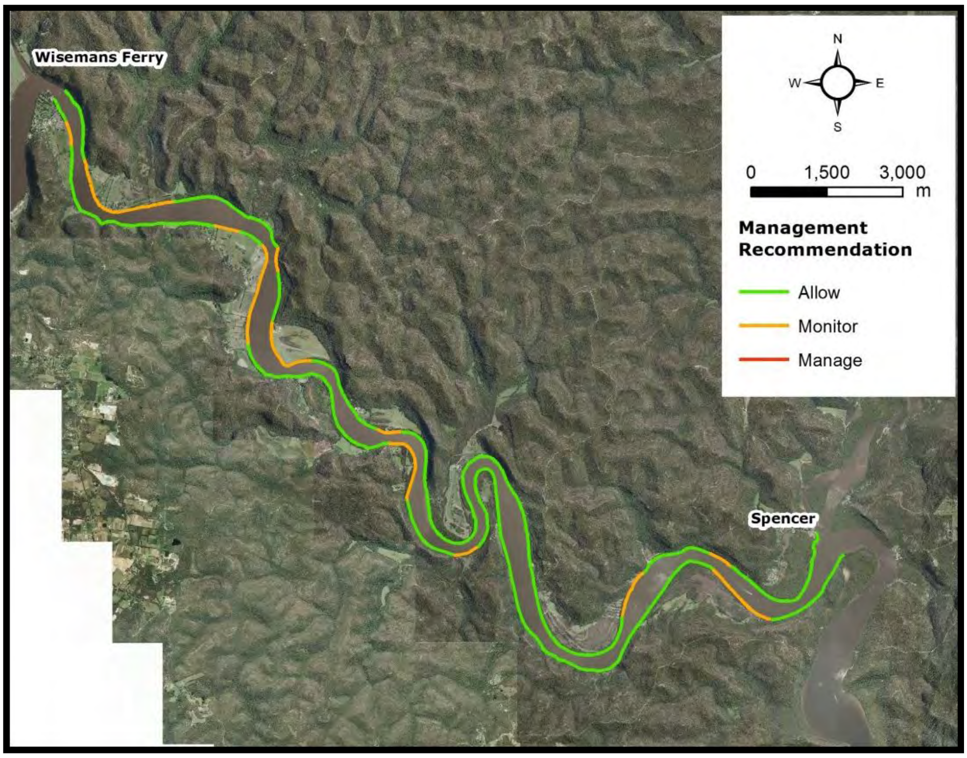

Figure 3-21: DSS Management Recommendations – Waterski Operating - 10 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

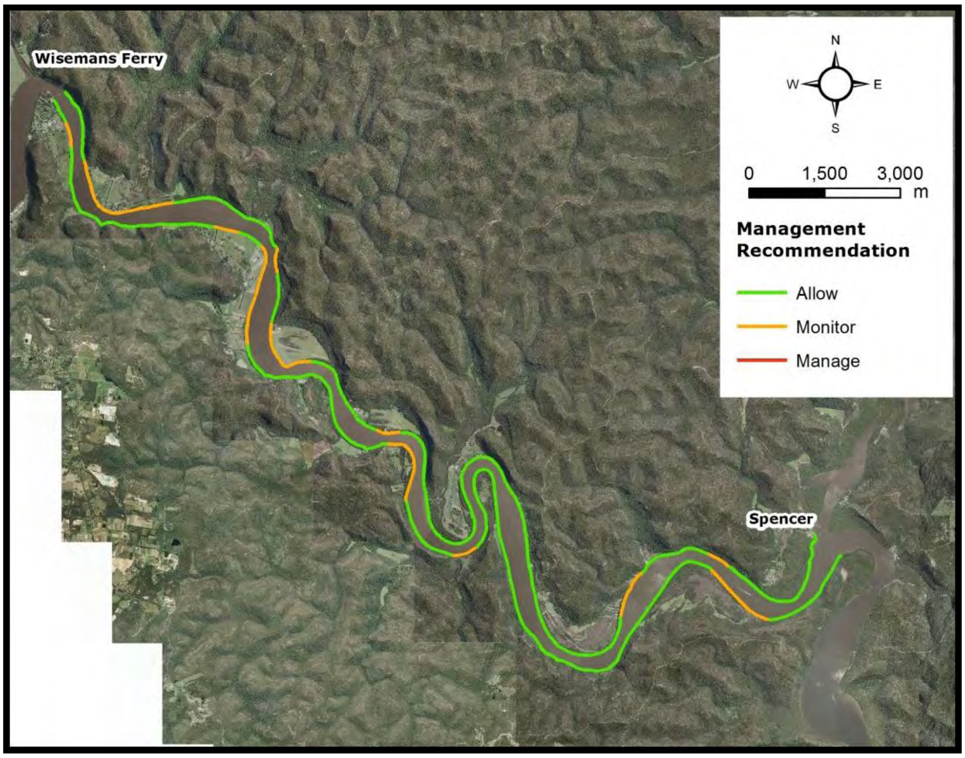

Figure 3-22: DSS Management Recommendations – Waterski Operating - 50 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

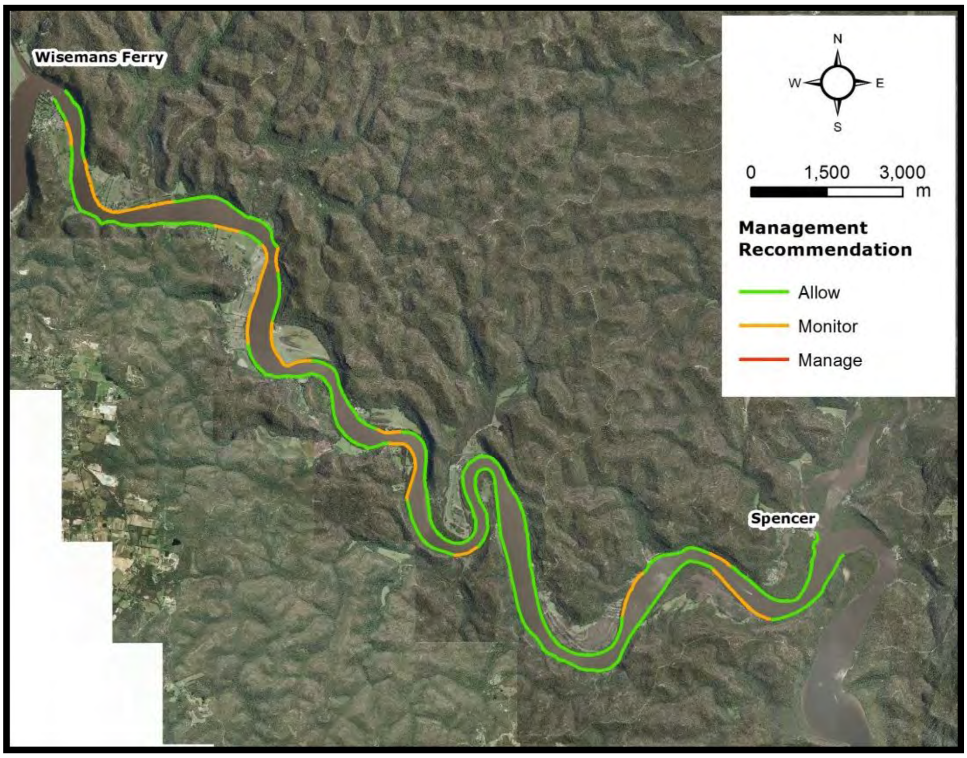

Figure 3-23: Figure 6 24: DSS Management Recommendations – Waterski Operating - 150 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

3.4.2 DSS Sensitivity Test for High Tide Conditions

The DSS management recommendations for the high tide assessment are provided in Table 3-6, while Appendix H provides the distribution of these recommendations along the waterway under different boat pass conditions. The observed decrease in the erosion potential of sites at high tide has consequences on the overall DSS management results. Table 3-7 provides a direct comparison between mid – low tide (Table 3-5) and high tide (Table 3-6) assessments. This data shows an increase in the number of reaches observed in the 'Allow' category and a decrease of a similar magnitude is observed in the 'Monitor' category for all scenarios. There was no change in the 'Manage' category for 150 boat passed under wakeboard 'operating' conditions. Based on these results it is evident that wave action at mid - low tide is more likely to cause riverbank erosion than at high tide.

Table 3-6: Number of Stretches Determined in each DSS Management Category (High Tide)

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	50 Passes	150 Passes	10 Passes	50 Passes	150 Passes
Allow	108	108	98	109	109	109
Monitor	8	8	17	7	7	7
Manage	0	0	1	0	0	0

Table 3-7: Comparison of DSS Management Recommendations for Varying Tidal Conditions

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	50 Passes	150 Passes	10 Passes	50 Passes	150 Passes
Allow	20	20	19	19	19	19
Monitor	-20	-20	-19	-19	-19	-19
Manage	0	0	0	0	0	0

The results from these sensitivity tests may be used to infer potential future impacts on shoreline vulnerability if mean sea level and/or tidal range increases with climate change. However, it is noted that this was not the primary purpose for undertaking these tests, that stationarity of bank vegetation and geometry cannot be assumed and that further investigation is outside the scope of this study.

3.4.3 DSS Sensitivity Test with Holiday and Competition Conditions (Mid – Low Tide Conditions)

Recreational boating on the Hawkesbury River increases during holiday periods and annual skiing competitions. These periods have been assessed using the DSS by increasing the number of boat passes and wake-generated conditions for wakeboarding and waterskiing boating activities. Six scenarios are investigated at mid – low tide, including 500 and 1,000 boat passes, as well as, the 'maximum wave' condition as recorded for 50 boat passes. The DSS management recommendations for the holiday and competition conditions are provided in Table 3-8, while Appendix I provides the distribution of these recommendations for the study region.

The results provided in Table 3-8 indicate a significant increase from baseline conditions in the number of sites that require monitoring and management for all scenarios. Higher counts were observed in all categories for wakeboard 'operating' conditions compared with waterski 'operating' conditions. 'Maximum wave' condition results lie between the results from the wakeboard 'operating' conditions with 50 and 150 boat passes. It should be noted the 'maximum wave' conditions occur when boats are accelerating and decelerating (i.e. when it is necessary to retrieve fallen wakeboarders or skiers).

Table 3-8: Number of Stretches Determined in each DSS Management Category (High Boat Passes)

Management Option	Wakeboard			Waterski		
	Operating Conditions – 8 Hour Duration		Maximum Wave – 12 Hour Duration	Operating Conditions – 8 Hour Duration		Maximum Wave – 12 Hour Duration
	500 Passes	1,000 Passes	50 Passes	500 Passes	1,000 Passes	50 Passes
Allow	53	27	85	87	75	85
Monitor	54	65	30	28	40	30
Manage	9	24	1	1	1	1

The results from these sensitivity tests may be used to infer potential future impacts on shoreline vulnerability if future boat use in the study area increases. However, as discussed previously, the available boat pass count information is very limited and that uncertainty remains as to the actual present recreational boat use between Wisemans Ferry and Spencer.

It is understood that the DSS management recommendations for the annual Bridge to Bridge Water Ski Classic race (see Section 2.5.2) are approximated by the waterski 'operating' conditions for 150 (Figure 3.23) and 500 (Figure F-4) boat passes. Options are provided in Section 4.3 for the one stretch of the river which for which WRL recommends management actions be implemented to prevent significant erosion from waterski vessels during the competition. This stretch of the river is privately owned and is associated with bed and breakfast accommodation known as "The Missions". This may be as simple as ensuring that boats be restricted from passing within 70 m of shoreline at this location.

3.4.4 DSS Sensitivity Test with Adjusted Local Wind Conditions (Mid – Low Tide Conditions)

As discussed in Section 2.4, it was not possible to obtain a local wind data source for use with the DSS, so data from a regional weather station at Richmond RAAF Base was acquired. To test the sensitivity of the baseline DSS management recommendations (Section 3.4.1) established on this wind climate, management recommendations were recalculated with increased natural wind wave energy. This approach combined the Australian Wind Standard (AS 1170.2) speeds with consideration of wind channelling observed by Johnson (1994). The DSS management recommendations for the local wind conditions sensitivity tests are provided in Table 3-9, while Appendix J provides the distribution of these recommendations along the waterway under different boat pass conditions at mid – low tide. Table 3-10 provides a direct comparison between the baseline DSS assessment based on offsite winds (Table 3-5) and the worst-case local wind conditions (Table 3-9).

Table 3-9: Number of Stretches Determined in each DSS Management Category (Adjusted Local Winds)

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	**50 Passes**	**150 Passes**	**10 Passes**	**50 Passes**	**150 Passes**
Allow	88	88	87	104	104	104
Monitor	28	28	29	12	12	12
Manage	0	0	0	0	0	0

Table 3-10: Comparison of DSS Management Recommendations for Varying Wind Conditions

Management Option	Wakeboard – Operating Conditions – 8 Hour Duration			Waterski – Operating Conditions – 8 Hour Duration		
	10 Passes	**50 Passes**	**150 Passes**	**10 Passes**	**50 Passes**	**150 Passes**
Allow	0	0	8	14	14	14
Monitor	0	0	-7	-14	-14	-14
Manage	0	0	-1	0	0	0

The increased natural wind wave energy associated with these sensitivity tests has minor consequences on the overall DSS management results. The data in Table 3-10 shows either no change or a reduction in the number of reaches observed in the 'Monitor' and 'Manage' categories for all scenarios. There is a corresponding increase in the 'Allow' category for scenarios where the number of reaches categorised as 'Monitor' or 'Manage' were reduced. This result is expected since, for a given boat pass scenario, the wave wake energy has a lower magnitude relative to the wind wave energy. For scenarios where there were no differences between the baseline and worst-case DSS management results, the reduction in equivalent wind wave ARI for boat wake energy was not sufficient to change the ARI rating and/or the management recommendation. At most, there was a 12% reduction in the number of reaches categorised as 'Monitor' and a 12% increase in reaches categorised as 'Allow'. The magnitude of these changes is considered minor which confirms the robustness of the baseline outcomes.

The results from these sensitivity tests may be used to infer potential future impacts on shoreline vulnerability if local wind speeds increase with climate change. However, it is noted that this was not the primary purpose for undertaking these tests and further investigation is outside the scope of this study.

4. Discussion and Recommendations

4.1 Preamble

This section discusses the results presented in Section 3.4, highlighting the management recommendations and aspects for further improvement. **In broad terms, the vulnerability of the riverbanks in this stretch of the Hawkesbury River is comparatively low when compared to other rivers in NSW.** Potential sources of error regarding boat pass and wind source numbers are discussed. A forensic examination was also undertaken on the one site that was prescribed a 'Manage' rating in the baseline DSS assessment. Management options to reduce the calculated rating at this site from "Manage' to 'Monitor' are outlined. Recommendations are provided regarding further investigations and management techniques for reducing riverbank erosion and improving boat wake management on the Hawkesbury River Estuary.

The relatively low vulnerability of riverbanks in the study area is due to several reasons. Natural rock armouring is present along approximately 25% of the riverbanks in the study area. A significant extent of both the left and right riverbanks is managed by the NSW National Parks and Wildlife Service. As such, grazing hard hoofed stock is generally absent and native riparian vegetation, particularly mangroves, remains intact. The boat pass numbers are relatively low in this stretch of the Hawkesbury River, in part due to the absence of public boat ramps between Wisemans Ferry and Spencer. Finally, the lack of inappropriate development along the riverbanks is also a contributing factor to its low vulnerability.

4.2 DSS Management Discussion

WRL recommends consideration of the six sets of management recommendations (low, medium and high boat pass scenarios for wakeboard and waterski vessels) generated by the baseline DSS assessment to inform final management recommendations. For these scenarios with mid-low tide conditions, excluding the 150 boat pass scenario for wakeboarding vessels, only the 'Allow' and 'Monitor' management recommendations are observed. This suggests that the entire study area is suitable for boating numbers of 50 boat passes per day operating, equating to 6 - 7 boat passes per hour over an 8 hour operating day. However, many of the stretches (between 22% and 31% for the six scenarios considered) were categorised with the 'Monitor' recommendation. Glamore and Badenhop (2006) recommend that when the 'Monitor' option is produced, the river reaches should be reassessed every two years to determine whether the condition trajectory is positive, negative or stable.

The results of the sensitivity test with high tide conditions indicate that wave action at high tide is less likely to cause riverbank erosion than at mid - low high tide. As such the suitability of 50 boat passes per day remains valid throughout the entire tidal cycle.

It is evident from observing the distribution of the different DSS management recommendations, that the **erosion potential of the riverbanks is the dominant factor affecting the outcomes** (i.e. compared with the boat pass numbers and the wind climate source). To this point, some likely controls on erosion potential were discussed in Section 3.2. However, the sensitivity test with holiday and competition conditions demonstrates that boat pass numbers alter the DSS management recommendations and a better understanding of boat pass numbers on the Hawkesbury River would assist the development of management strategies into the future.

The results of the sensitivity test with adjusted local wind conditions indicate that the wind climate source has a relatively minor impact on the DSS management recommendations. While it is a lower priority than recording boat pass numbers, the collection of wind data on the riverbanks of the study area with anemometers over an extended period would reduce the uncertainty associated with the DSS management recommendations.

4.3 Forensic Examination of Erosion Causes for 'Manage' Site

Baseline DSS management recommendations for mid – low tide conditions have been provided in Section 3.4.1. The DSS assessment has identified one location, stretch L19, as a 'Manage' site for the wakeboard 'operating' conditions, 150 boat passes scenario. This scenario recorded a 'category C' ARI rating and scored 'highly erosive' in the riverbank erosion potential assessment. While not part of the baseline DSS assessment, stretch L19 was also categorised as a 'Manage' site for the waterski 'operating' conditions, 500 boat passes scenario which approximates the upper bound of erosion potential associated with the annual Bridge to Bridge Water Ski Classic race. As such, a forensic examination was undertaken to determine the key factors producing low erosion potential scores.

WRL understands that this stretch of the riverbank is privately owned and is associated with bed and breakfast accommodation known as "The Missions". As it forms part of the left bank (looking downstream) of the study area, it falls within the local government area of Gosford City Council.

4.3.1 Site Characteristics

Stretch L19 (Figure 4-1) has the following site characteristics, including:

- The site is bounded by cleared alluvial floodplains containing complex bank sediments (clay overlying sand);
- The site is located on the upstream toe of an inside bend on the Hawkesbury River;
- The site has poor/limited verge cover;
- The site has poor/limited native riparian vegetation regeneration and wave zone cover; and
- Uncontrolled stock access observed at the site.

The combination of these characteristics has resulted in low erosion potential scores for this site. Composite bank material is particularly susceptible to erosion when native riparian bank vegetation is removed and stock access is permitted along the banks. As such, the exposed banks become inherently unstable and are more prone to erosion, slumping and undercutting.

In addition, riverine geometry is of particular importance to note at this site. The site is located on the upstream toe of an inside bend and this is likely to influence the erosion and undercutting of the banks during flooding of the Hawkesbury River. High flows down the river can result in eddy shedding around these bends causing extensive erosion of unprotected banks.

Figure 4-1: Forensic Examination of Stretch L19

It has been known that erosion problems exist in this part of the Hawkesbury River for at least 20 years. Johnson (1994) used this section of the river as an example location where the rate of erosion was particularly significant. Johnson (1994) indicated that a fence had been installed in this stretch of the Hawkesbury River in approximately 1989. At the time of the installation, the fence was located approximately 10 m from the edge of the riverbank. However, by 1994 the edge of the riverbank was almost co-linear with the fence (Figure 4-2). Based on this anecdote, this is an approximate linear erosion rate of 2 m/year. At the time of WRL's field work in 2014, this fence was no longer visible.

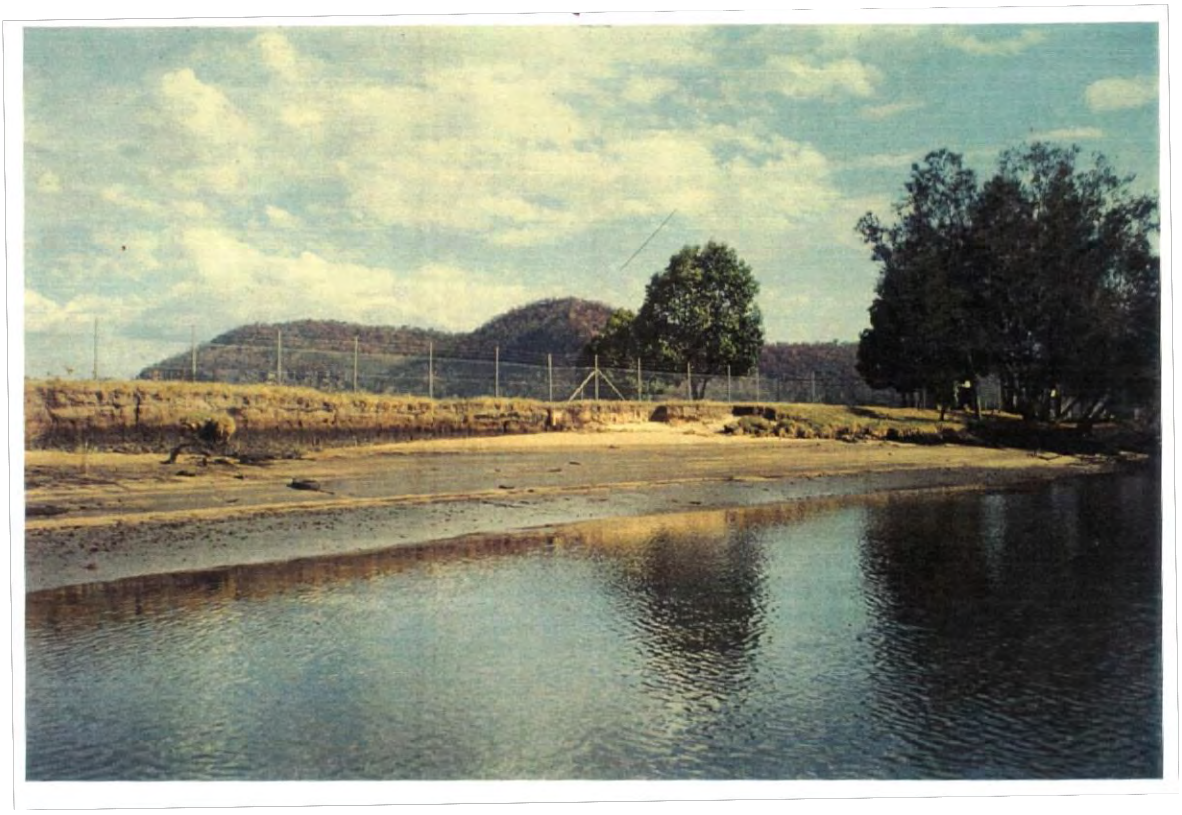

Figure 4-2: Fence Preventing Stock Access at Stretch L19 (Source: Johnson, 1994)

The finding that "The Missions" section of the Hawkesbury River is the most vulnerable section in the study area also supports observations by local commercial fishers consulted in a workshop by HSC in 2008 (HSC, 2008).

4.3.2 Management Recommendations

Several management options which may improve the rating of the site from 'Manage' to 'Monitor' were simulated for stretch L19 using the DSS. The process involved using the DSS to:

- Determine an appropriate boat management option for 150 wakeboard passes at the site;
- Assess the impact of removing stock access from the banks; and,
- Simulate native riparian vegetation regeneration at the site.

The following management options are prescribed by WRL to permit a monitoring recommendation ('Monitor') at Stretch L19 discussed above in Section 4.3.1, including:

- Boats should be restricted for up to 70 m from shoreline. HSC is encouraged to advise the NSW Roads and Maritime Services (RMS) to put out buoys to prevent boats entering the restricted zone.
- Farm access roads and stock should be restricted up to 50 m from the riverbanks through fencing. This will encourage the banks to consolidate and allow the verge and upper bank native vegetation cover to regenerate.
- Planting of native riparian vegetation is recommended to encourage site regeneration and to improve the longitudinal continuity of bank cover. This includes planting reeds and mangroves (where appropriate) in the wave zone and upper banks. Native trees should be planted on the verge.

It is also recommended that Gosford City Council (GCC) undertake a riverbank survey in this area of the river. This survey should be repeated every two years to quantify the rate of erosion and monitor the impact of implemented management actions. These repeat surveys could be done in parallel with reassessment via the DSS as recommended by Glamore and Badenhop (2006) for stretches when the 'Monitor' option is produced. This monitoring work would establish whether the riverbank condition trajectory is positive, negative or stable at this site.

4.4 Recommendations

The key recommendations resulting from this investigation are as follows:

Recommendation 1: Implement the management recommendations for the only stretch in the study (L19) area prescribed a 'Manage' rating for the baseline DSS assessment.

As discussed in Section 4.3.2, it is recommended that stock be restricted and native riparian vegetation be planted in this stretch of the Hawkesbury River. Buoys should also be put in the water to prevent boats passing within 70 m of the riverbank. This is particularly important during the annual Bridge to Bridge Water Ski Classic race.

Recommendation 2: Use the DSS to determine key factors contributing to high riverbank vulnerability and implement appropriate management techniques.

The DSS has be used as a management tool to determine the key factors producing low erosion potential scores at the only site with a 'Manage' rating. However, this process could be repeated for those sites with a lower 'Monitor' rating. In many cases, it is evident that both lantana and stock access are increasing the erosive potential of the riverbanks. Installation of fencing to prevent stock access and planting of native riparian vegetation would reduce the erosion potential. Additionally, removal of the extensive lantana vegetation, and establishment of native vegetation may also improve riverbank stability.

Recommendation 3: Develop a better understanding of boat usage patterns on the waterway.

As mentioned in Section 5, there is limited data available on boat pass numbers, including both boat numbers and user activity. An assessment of boating numbers encompassing both busy, and normal, weekends and week days, as recommended by Glamore and Badenhop (2006) would provide a more accurate picture of recreational boating within the study area. This data gathering, coupled with a survey of users, would help to establish preferred areas for recreational boating and potentially help focus further investigations to key areas of use.

Recommendation 4: Establish a monitoring program for reassessment in the future and apply the DSS across a greater extent of the shoreline managed by HSC.

A comprehensive and established monitoring program will provide an objective baseline for future comparison and management of the Hawkesbury River between Wisemans Ferry and Spencer. Glamore and Badenhop (2006) recommended reassessment of 'Monitor' sections every two years, and 'Allow' sections every five years. Following this entire assessment, a partial assessment, potentially 30% of randomly selected stretches, as recommended by Glamore and Badenhop (2006), would provide an overview of the river. This assessment could be coupled with improved boat statistics (Recommendation 3) at the more frequented sections of the river.

Additionally, expanding the DSS application to include the shorelines of Berowra Creek and Porto Bay which also consist of soft materials to a large extent (Astles et al., 2010), will provide a better understanding of additional riverbank conditions managed by HSC. This understanding will lead to better riverbank and boating management outcomes in priority areas besides Wisemans Ferry to Spencer.

Recommendation 5: Assess the local wind conditions on the Hawkesbury River over an extended period to develop scaling factors applicable to the existing wind record.

The baseline DSS assessment has used wind data from the regional Richmond RAAF Base as an approximation of conditions on the Hawkesbury River as it is the best available data. However, through the use of local anemometers over an extended period it is possible to develop scaling factors applicable to the wind conditions at the Richmond RAAF Base. This assessment of comparative winds between the study area (Wisemans Ferry to Spencer) and Richmond RAAF Base would build on the preliminary wind work of Johnson (1994). Subsequently, this will better approximate wind conditions on the river and result in a more accurate local wind wave estimate for comparison with boat wake waves.

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Appendix A – Literature Review

A-1 Estuarine Habitat Mapping and Geomorphic Characterisation of the Lower Hawkesbury Estuary River and Pittwater Estuaries (Astles et al., 2010)

The NSW Department of Primary Industries (Astles et al., 2010) recently mapped the distribution of estuarine habitats on the lower Hawkesbury Estuary foreshore to better understand the potential threat to these habitats from human activity. The river reach between Wisemans Ferry and Spencer (the focus of this WRL report) was defined as the "riverine channel" of the estuary and a subsequent risk assessment was undertaken on this reach. The purpose of the risk assessment was to determine which habitats were at intolerable levels of risk from various human activities and then to identify issues that need to be addressed if these risks are to be reduced. The risk assessment undertaken by Astles et al. (2010) focused on the ecological value of estuarine habitats and excluded human orientated values such as economic worth and social amenity. Eight human activities were assessed within this reach as follows:

- recreational fishing (excluding activities associated with boating);
- commercial fishing;
- aquatic recreation;
- foreshore development;
- stormwater/catchment run-off;
- sewage treatment;
- dredging and sedimentation; and
- commercial vessels.

The following features were mapped within the lower Hawkesbury Estuary as part of the study:

- estuarine macrophytes, including:
  - mangrove;
  - seagrass; and
  - saltmarsh.
- foreshore habitats (see Table A-1);
- rocky reef, including:
  - subtidal; and
  - intertidal.
- marinas/wharves/jetties;
- intertidal mudflats;
- sandflats, including:
  - subtidal; and
  - Intertidal.
- deep (>5 m) subtidal soft sediments;
- water depth;
- riverside settlement;
- oyster leases;
- navigation aids, mooring and boat ramps; and
- no wash zones.

The entire foreshore of the lower Hawkesbury Estuary was divided into segments and classified according to the 11 categories defined in Table A-1.

Table A-1: Intertidal Foreshore Mapping Categories (Astles et al., 2010)

Substratum/Habitat	Definition
Artificial rock wall	Typically vertical to 45°, consolidated/structured sandstone blocks, mixed rock, concrete, etc., or unconsolidated rock fill.
Natural Horizontal hard	Flat or sloped solid rock > 15 m long & 2 m wide. Can have deep crevices and rockpools.
Natural Vertical hard	Solid vertical rock > 15 m long & 2 m wide; can have deep crevices.
Natural soft	Natural mangrove foreshore, with muddy sediments. Muddy sediments, no large stands of mangroves, but may have or 1 – 2 small trees. Sandy sediments with no obvious vegetation, very few rocks.
Mixed natural hard	Solid rock and rocks ranging from small pebbles to large boulders. Rocks ranging from small pebbles to large boulders with no solid rock.
Mixed natural hard + natural soft	Sand/mud interspersed with rock.
Riverine vegetation	Dense brackish riverine riparian vegetation other than mangroves
Artificial rock wall + natural soft	
Artificial rock wall + natural rock	
Artificial rock wall + natural hard & soft	
Artificial rock wall + mangroves	

Table A-2 summarises the distribution of foreshore categories between Wisemans Ferry and Spencer by length (km and %). Astles et al. (2010) denoted 79% of the riverbank foreshore in this reach as "natural soft" or "riverine vegetation" (i.e. comprised of soft materials which are susceptible to erosion) largely by desktop techniques rather than field examination. For the same "riverine channel" reach, no seagrass beds were found, however, 250.31 hectares of mangroves and 107.15 hectares of saltmarsh were identified and mapped within the area.

Table A-2: Distribution of Intertidal Foreshore Mapping Categories: Wisemans Ferry to Spencer (Astles et al., 2010)

Substratum/Habitat	Length	
	(km)	(%)
Artificial rock wall	1.020	1.6
Natural Horizontal hard	1.990	3.0
Natural Vertical hard	0.806	1.2
Natural soft	51.736	79.1
Mixed natural hard	9.072	13.9
Mixed natural hard + natural soft	0.111	0.2
Riverine vegetation	0.049	0.1
Artificial rock wall + natural soft	0.355	0.5
Artificial rock wall + natural rock	0.049	0.1
Artificial rock wall + natural hard & soft	0.000	0.0
Artificial rock wall + mangroves	0.221	0.3
Total	**65.409**	**100.0**

During WRL's fieldwork program for this riverbank vulnerability assessment (see Section 5.4), the classification denoted by Astles et al. (2010) at each of the 348 site inspections of the riverbank between Wisemans Ferry and Spencer was reviewed in the field. While the categories had been assigned largely by desktop techniques rather than field examination, WRL confirmed that classifications by Astles et al. (2010) were correct for approximately 90% of the site inspections. For the remaining 10% of sites, where WRL's "on water" assessment according to Table A-1 differed from that of Astles et al. (2010), there was no observable trend in the differences between the categories assigned.

Soft riverbanks are typically more vulnerable to shoreline erosion. This erosion may have serious implications for the sustainability and biodiversity of aquatic and riparian ecosystems. As indicated in Table A-2, a significant extent of the shoreline between Wisemans Ferry and Spencer (jointly managed by HSC and GCC) was categorised as being comprised of soft materials. The extent of soft riverbanks within the "riverine channel" reach, as determined by Astles et al. (2010), is reproduced in Figure A-1.

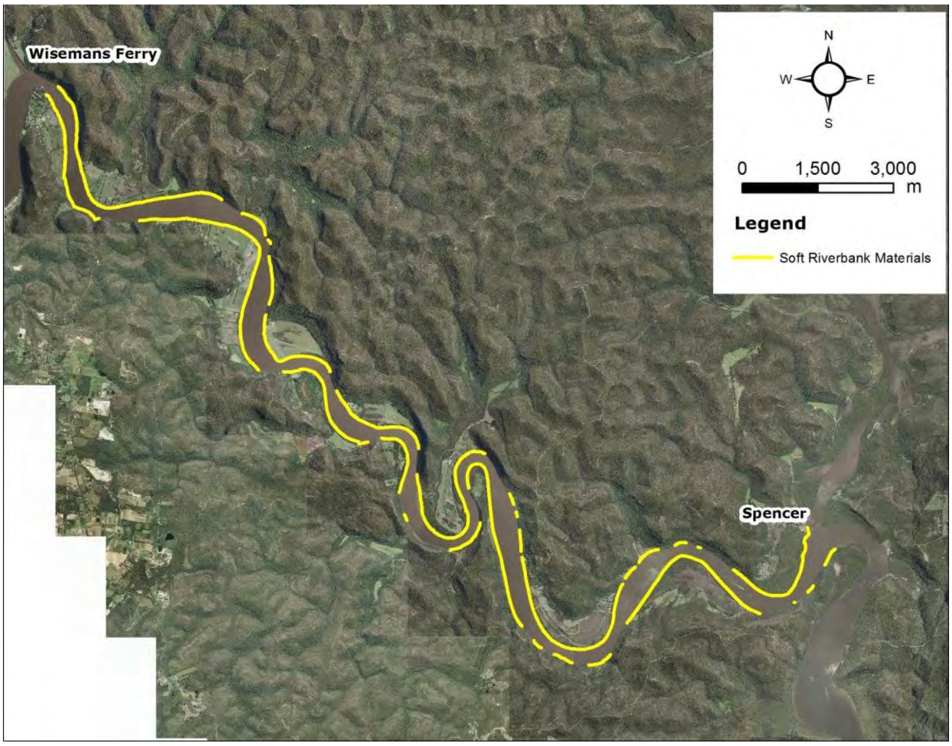


Figure A-1: Riverbanks Comprised of Soft Materials in the Hawkesbury River Estuary Study Area (adapted from Astles et al., 2010)

Examples of hard surface foreshore classes found in the lower Hawkesbury Estuary are illustrated Figure A-2.

Figure A-2: Examples of Hard Surface Foreshore Classes in the Lower Hawkesbury Estuary. Natural Vertical Hard (A), Natural Horizontal Hard (B), Artificial Rock Walls (C and D) (Astles et al., 2010)

Of the eight human activities assessed by Astles et al. (2010) as part of the ecological risk assessment, two activities between Wisemans Ferry and Spencer are relevant to this WRL report on shoreline erosion: aquatic recreation and commercial vessels. Aquatic recreation comprised boating (including launching and retrieving boats), waste disposal, foreshore picnicking and walking, swimming, aquatic competitions (i.e. water ski races) and moorings. Commercial vessels comprised public and private ferries, water taxis and commercial cruise vessels.

Astles et al. (2010) concluded that the risk level for mangroves and saltmarsh between Wisemans Ferry and Spencer from aquatic recreation was tolerable. While the risk level for saltmarsh was determined to be acceptable, it remains a priority habitat because its cover declined significantly between the 1940s and the 2000s (Williams and Thiebuad, 2007). However, it was also asserted that information on recreational boating (non-fishing) was a key knowledge gap within the risk assessment.

"There is little information on the number of recreational boats (non-fishing), where they go and how many people they carry in this area. Recreational boats are able to go virtually anywhere in the [riverine channel], depending upon their size, and so can potentially interact with all types of estuarine habitats. Information is needed on the magnitude of activity (e.g. number of boats, number of people per boat, number of hours of recreational activity that is boat-based), location and size of boats (smaller day boats compared to larger overnight boats) participating in

recreational activities. Such information should be collected to ensure differences in activity between seasons, week days and weekends and school and non-school holiday periods can be assessed." – Excerpt from Astles et al. (2010)

Due to the paucity of information regarding aquatic recreation, and specifically recreational boat activities, the number of boats using the area between Wisemans Ferry and Spencer was estimated by counting the number of boats in aerial photos. Counted boats were categorised as being less than 7 m in length (assumed as day boating activity) or greater than 7 m in length (assumed as overnight boating activity). These aerial photos were a composite of several photos taken at different times of the day and dates. Astles et al. (2010) asserted that this was an underestimate of boating activity in the area but that no other data source was readily available.

Other than two continuously operating ferry vessels, the number of water taxis, and commercial cruise ships operating in the "riverine channel" was unknown. As such, Astles et al. (2010) concluded that the ecological threat from commercial vessels was unknown between Wisemans Ferry and Spencer.

One of the recommendations of Astles et al. (2010) was that that the condition of habitats that had intolerable levels of risk should be quantified and analysed for any signs of degradation. It was asserted that quantifying both the condition of a habitat and the stressors potential affecting it was needed to gain a more accurate assessment of the extent of habitat degradation and its possible causes.

A-2 The Effect of Boat Wash on Bank Erosion on Berowra Creek and the Hawkesbury River between Wiseman's Ferry and Brooklyn (Johnson, 1994)

This study investigated the impact of boat waves on bank erosion in Berowra Creek and the Hawkesbury River between Wisemans Ferry and Brooklyn. Wind wave and boat wake measurements at nine sites in the study area between January and April 1994. **These measurements indicated that wind directions on the river tend to be dictated by the local topography.** The boat measurements showed that few boats in the study area produce waves greater than 0.3 m and those which do are usually large, semi-planing and full displacement hull boats. **Johnson (1994) concluded that boat waves in the area exert significant energy on river banks, usually of the same order of magnitude as wind waves but in some instances, much higher**.

A classification map containing observations of the bank types in the study area and also the condition of the banks with respect to erosion, was developed by Johnson (1994) on 6 August 1994. Observations were made during low tide and this classification map is reproduced in Figure A-3. The bank type is indicated by colour and the bank condition by lines. Figure A-4 provides a good indication of the historical erosion problems along the study stretch and can be compared with the results of WRL's current study.

Measurements of wind and boat wave characteristics were undertaken to estimate and compare wind and boat wave power acting at the study sites. Wave hindcasting methods were used to predict the likely wind wave characteristics. Boat pass rates and boat wave characteristics were used to estimate the likely boat wave conditions. Annual wave power due to wind and boat waves were calculated and compared at each site.

Johnson (1994) asserted that long-term wind data is required to determine the nature and frequency of wind-waves. There were no wind measurement sites on the Hawkesbury River and no long-term local wind data existed for the study. Johnson's study considered long-term regional wind data available at Sydney Airport and Penrith.

Two anemometers were installed on the river at Muskoka, near Gunderman (approximately 11 km upstream of Spencer), and Melvy's Wharf, opposite Bar Point (approximately 8.5 km downstream of Spencer), to measure the site wind speed and direction. Two measurement campaigns from January to March 1994 were conducted during wind wave events to provide data for checking the wind-wave predicting technique. Half-hourly wind speed and direction data was measured continuously by the anemometers.

Wind roses were prepared for the sites (Figure A-5). The wind speeds and directions from these sites were compared to the wind at Penrith on the same days, to give an indication of the relevance of using offsite data. The wind rose for Muskoka showed that the most probable direction for the strongest winds was from the south-east. On the equivalent wind rose for Penrith, there was an even distribution of strong easterly, south-easterly and southerly winds. Assuming that the same wind system was being measured in the two locations, **the data indicated that the river valley channels the wind on the river**. This was consistent with personal observations by the author of winds acting on the River.

Exceedance plots were produced for the Muskoka wind data and also Penrith data for the same time period. The data is provided in Figure A-6. Penrith was shown to have generally higher velocities for a given exceedance. Johnson (1994) explained that this may indicate that winds undergo some decrease in velocity when they reach the river, due to valley effects. However, this assumed that the same wind event was being measured at both locations.

Similar observations were expected for the Melvy's Wharf site. Observations by Johnson (1994) at the site indicated that the longest fetch lengths occur over the south and the east. During the monitoring period, significantly sized wind-waves were acting on the shoreline due to winds from the south-east. However, the wind rose for Melvy's Wharf indicated that southerly winds dominated and the highest wind speed class was 3 to 6 m/s, indicating low velocity local breezes rather than major wind events. Johnson (1994) explained this phenomenon by the south-easterly winds interacting with the hillside and being directed towards the anemometer at the northern end of the curved shoreline. **This suggested a dominance of localised breezes probably due to the wind interaction of the hill behind the site. This is an important consideration when using offsite wind data to generate wind-wave energies for a channelised river bank erosion assessment.**

The results of the wind analysis undertaken by Johnson (1994) showed that that **wind direction on the river was determined by the topography of the area** (as confirmed at Muskoka), with possible reductions in velocity resulting. The data also indicated that there may be a relationship between the wind occurring at Penrith and that measured at Muskoka, although due to a lack of data and no significant major wind events occurring during the measurement period, this relationship could not be determined. The Melvy's Wharf wind data was considered unrepresentative of the wind acting on the water in that region and was not included in the study.

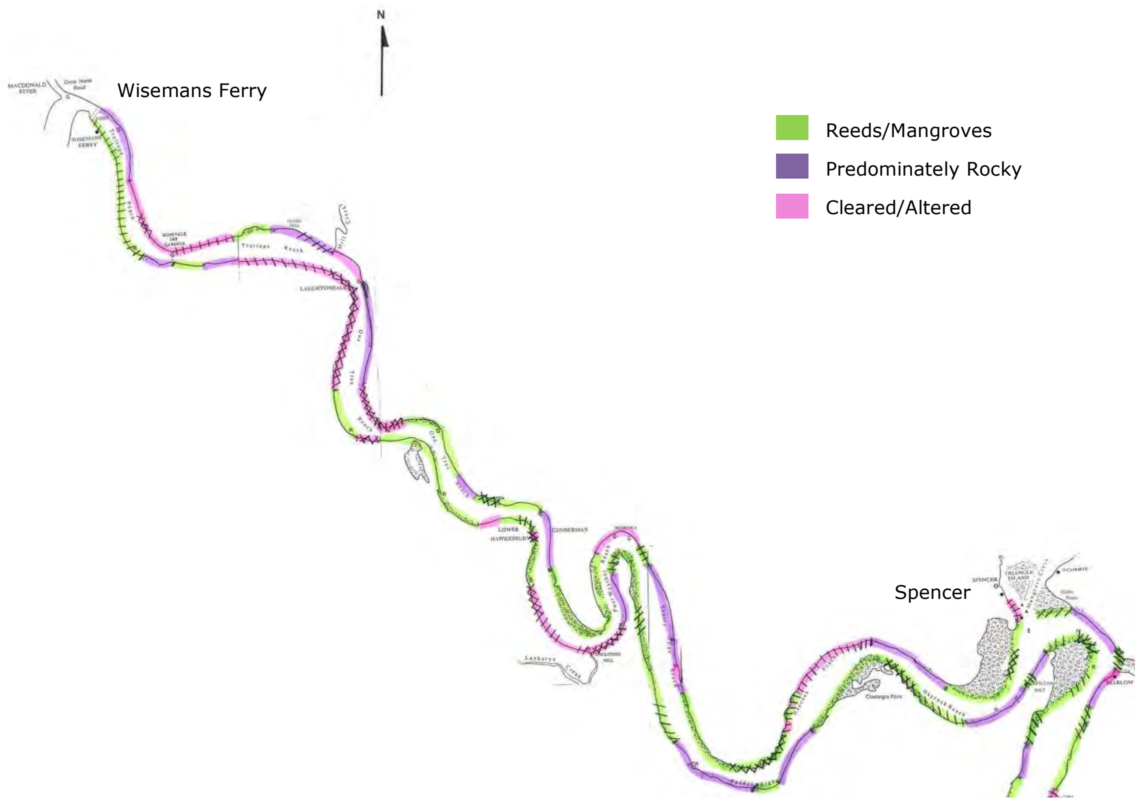


Figure A-3: Bank Type and Conditions as mapped by Johnson (1994)

Figure A-4: Eroded River Bank along Stretch L18, (A) by Johnson (1994) and (B) by WRL (2014)

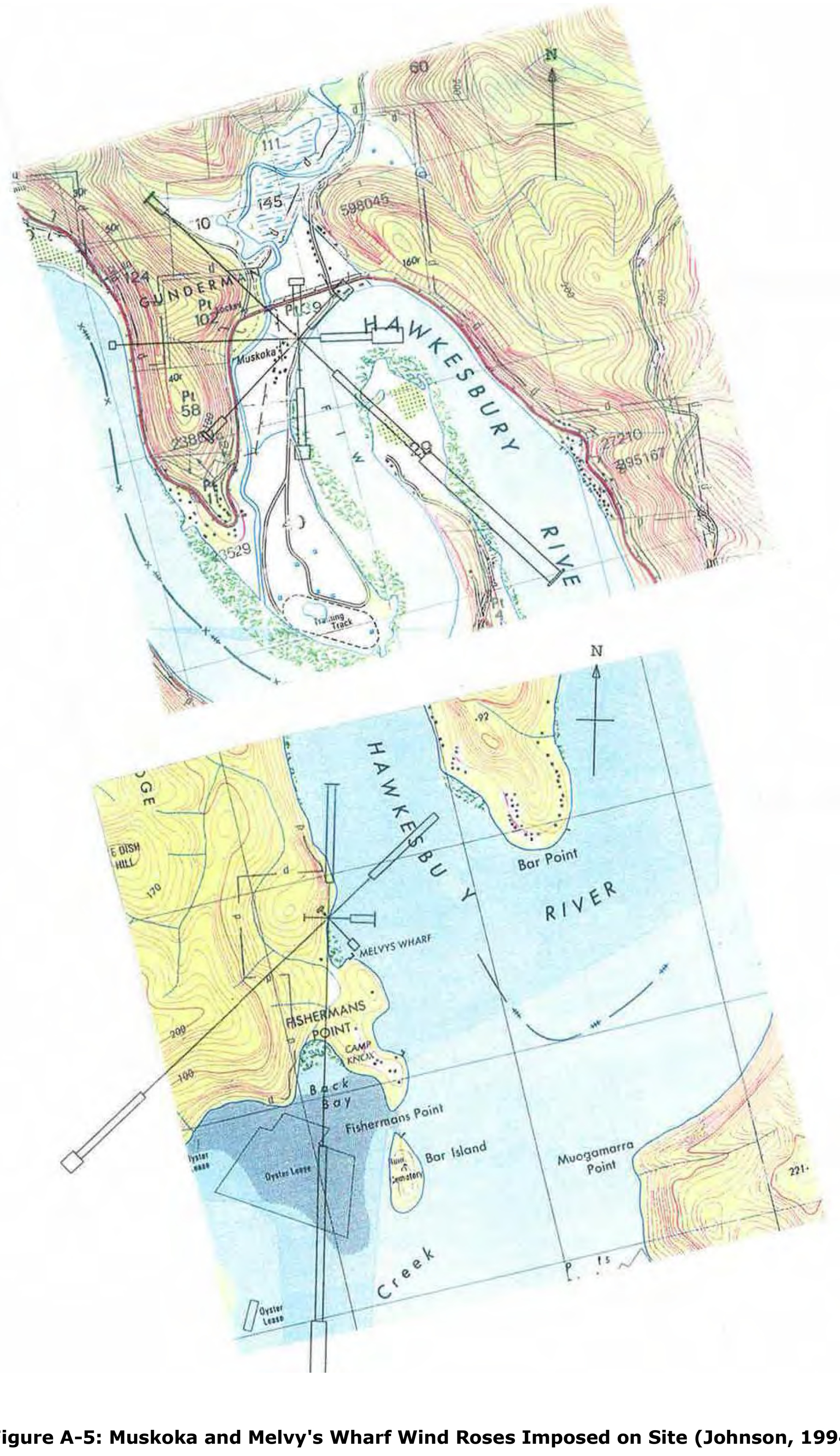


Figure A-5: Muskoka and Melvy's Wharf Wind Roses Imposed on Site (Johnson, 1994)

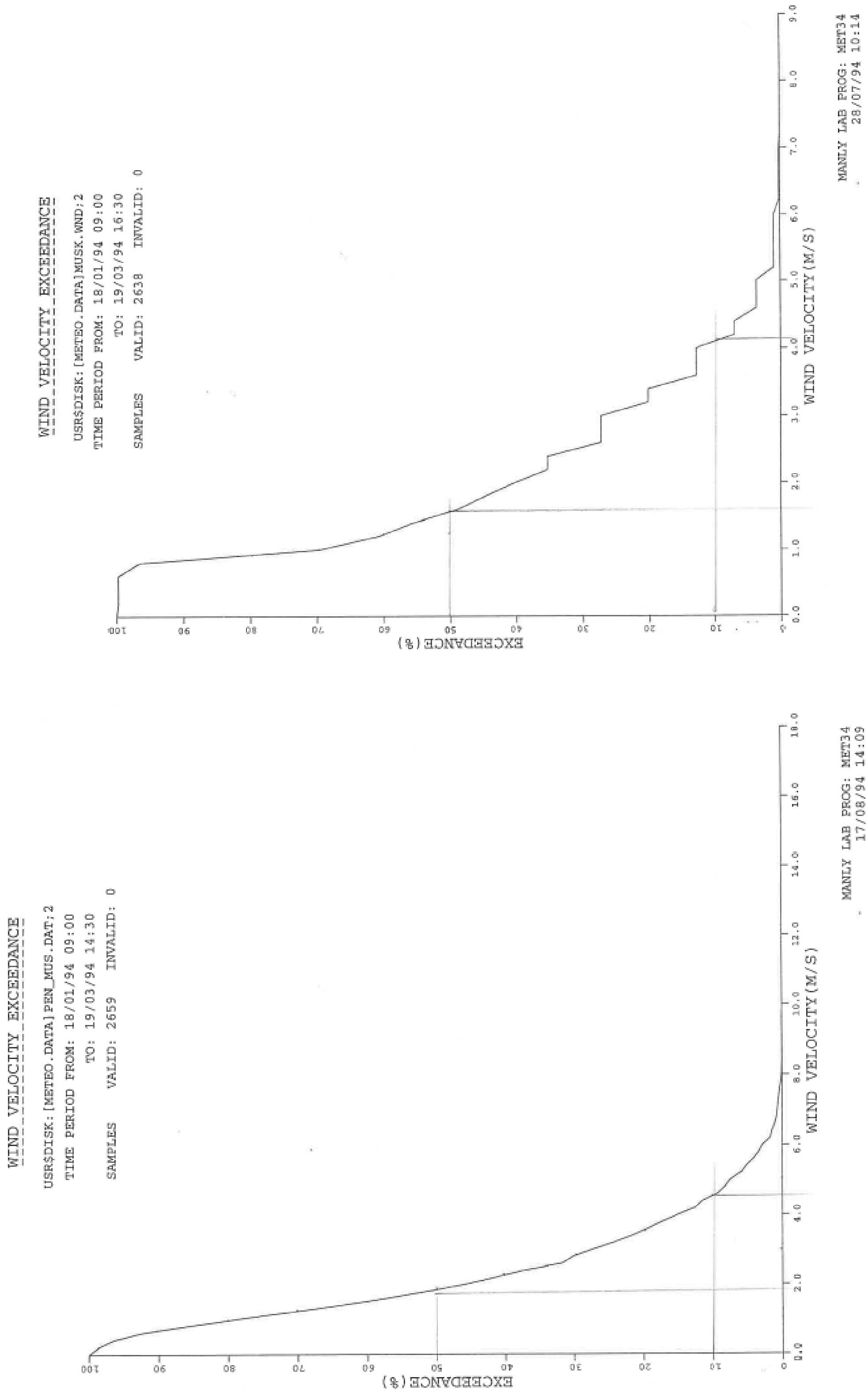


Figure A-6: Exceedance Plots for Muskoka and Penrith - Muskoka (Johnson, 1994)

A-3 Hawkesbury River Hydraulic and Sediment Transport Processes - Channel Geometry, Morphological Changes and Bank Erosion (NSW Public Works, 1987)

The NSW Public Works Department commissioned a study in 1986 to examine long term changes in the Hawkesbury River. This study investigated channel geometry, bank erosion and morphological changes in the Hawkesbury River using historical hydrosurveys, aerial photogrammetry and bank erosion inventory. The study area included the Hawkesbury/Nepean River system from Penrith downstream to Brooklyn. However, photogrammetric data was only available for the upper reaches of the Hawkesbury River from Wisemans Ferry to Penrith. As such, limited relevant information was available for the work being undertaken between Wisemans Ferry and Spencer in WRL's study.

Appendix B – Wave Theory

B.1 Preamble

Wave theory is a large and complex discipline which ranges in scale from micro-sized waves to tsunamis. Furthermore, even first-order wave theory can contain intricate and advanced calculations. This review of basic wave theory focuses primarily on the theory directly applicable to this study. Only the most pertinent equations have been provided and the majority of the mathematics has been withheld from the text. Fundamental wave components are provided in Section B.2, with wind wave generation and propagation detailed in Section B.3 and boat wake wave generation and propagation discussed in Section B.4.

B.2 Fundamental Wave Components

The primary components characterising individual waves are wave period and wave height. The wave period (T) is defined as the time it takes for two successive wave crests or troughs to pass a given point. The vertical distance between a wave trough and crest is the wave height (H) (Figure B-1). Other useful variables include wavelength (L), the distance between consecutive wave crests or troughs, and celerity (C), the speed of the wave defined as the quotient of the wave length and wave period ($C = L/T$).

The wave components listed above can be used to describe either a single wave or a series of waves within a group, commonly referred to as a wave train. Throughout international literature for boat wake waves, both the largest wave height recorded within the wave train (H_{max}) and the wave with the largest period in the train (T_{peak}) are used to characterise the wave train. This difference is important, as sometimes the wave with the maximum height may not have the longest period (or vice versa) (Glamore and Hudson, 2005).

The energy within a wave is calculated using the wave height and period, as shown in Equation B-1. To calculate the total energy of waves within a wave train the individual wave energies are summed (Maynord, 2001). When measured under similar conditions, the total wave energy can be used to compare waves from multiple sources.

$$E = \frac{\rho g^2 H^2 T^2}{16\pi} \qquad \text{(B-1)}$$

where

E = wave energy (per unit width of wave crest) (J/m)
ρ = water density (kg/m^3)
g = gravitational constant (m/s^2)
H = wave height (m)
T = wave period (s)
π = constant (≈ 3.14)

Water depth (d) can have a significant influence on wave characteristics. As water depth decreases towards the shoreline, shoaling processes reshape the wave, potentially causing wave breaking. This shape is largely a function of water depth and wavelength, as waves begin to 'feel' the bottom when the ratio of depth/wavelength (d/L_w) is less than 0.5. For this type of assessment, waves can only be compared when the waves maintain a linear, sinusoidal wave shape (Parnell and Kofoed-Hansen, 2001).

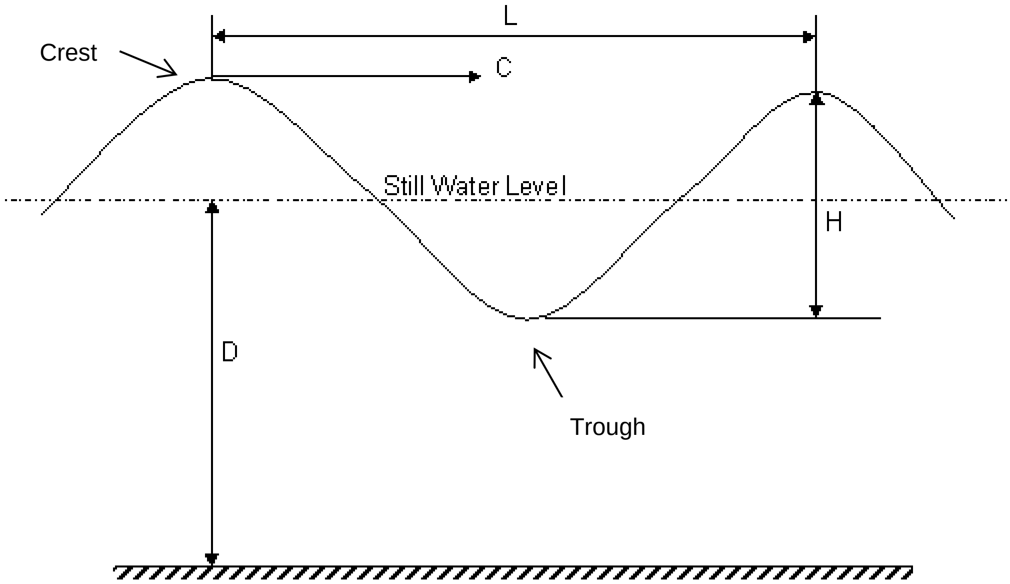


Figure B-1: Wave Characteristics

B.3 Wind Wave Generation and Propagation

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, within the DSS 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 riverbank 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 hours has been selected as an appropriate duration for calculating cumulative energy as it approximates the hours during which boats are likely to be travelling on an average day. However, when considering the possible extreme case for the Hawkesbury River, 1000 boat passes per day, a duration of twelve hours has been used as it is estimated this would only take place in summer when long daylight hours are maximised.

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), (2006) which outlines a method for predicting wind waves for a selected site. The methodology used within the DSS utilises equations outlined in CEM.

B.3.1 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 compass directions at the location of interest (i.e. the distance over water for which the waves can develop).

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 B-2. The wind speed used is the upper limit of each interval.

$$t_{x,u} = 77.23\frac{X^{2/3}}{u^{1/3}g^{1/3}} \qquad \text{(B-2)}$$

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:

$$\frac{u_i}{u_{3600}} = 1.277 + 0.296\tanh\left(0.9\log\frac{45}{t_i}\right) \qquad (1<t_i<3600) \qquad \text{(B-3)}$$

$$\frac{u_i}{u_{3600}} = -0.15\log t_i + 1.5334 \qquad (t_i>3600) \qquad \text{(B-4)}$$

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

$$H_{m,0} = 4.13\times10^{-2}\left(\frac{u_*^2}{g}\right)\left(\frac{gX}{u_*^2}\right)^{\frac{1}{2}} \qquad \text{(B-5)}$$

$$T_p = 0.651\left(\frac{u_*}{g}\right)\left(\frac{gX}{u_*^2}\right)^{\frac{1}{3}} \qquad \text{(B-6)}$$

where

$H_{m,0}$	= energy-based significant wave height (m)
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.

B.3.2 Extended Duration Wind Waves

While the previous 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 an extended duration (8 - 12 hours) are the same as those in Section B.3.1 with the following minor modifications:

1. Equations B-3 and B-4 are used to convert the 10 minute wind speeds to 8 hour duration wind speeds;
2. Wave growth with fetch is then calculated according to Equations B-5 and B-6 using the duration adjusted wind speeds; and
3. The number of waves calculated over the extended duration 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.

B.3.3 Wind Wave Energy

Wave energy (E) is a function of both wave height and wave period, and can be calculated according to Equation B-1. For each wind speed, the energy associated with the wave generated can now be calculated. Wind wave energy generated over the extended duration is simply the product of the energy of a single wave and the number of waves generated over the duration.

B.3.4 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.

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; and

3. Assign an approximate ARI for the greatest wind energy equal to the record length (n).
4. Calculate an approximate ARI for each of the remaining records (i) by dividing the record length (n) by the cumulative per cent occurrence for the previous energy record (i-1), then multiplying it by the total number of wind observations including calms (w_{obs}) plus 1. This is equivalent to the record length (n) divided by the rank of each energy record ($rank_i$).

$$ARI_i = \frac{n}{(Cumulative\ \%_{i-1} \times w_{obs})+1} = \frac{n}{rank_i} \quad \text{(B-1)}$$

This needs to be completed for the energy of the single short-duration maximum fetch-limited waves and the cumulative energy of the extended duration wind waves, thereby generating two sets of values.

B.4 Wake Wave Generation and Propagation

Every vessel that moves through the water generates wake waves. Most boats generate at least two sets of waves; divergent waves which move out from the bow at an angle and transverse waves that move out from the stern (Macfarlane and Cox, 2003). The height and period of the waves in the wave train are largely associated with factors relating to the vessel and its operation including hull design, displacement, trim, loading, speed, method of propulsion, course, rate of change in course, etc. Other than at critical speeds, the energy of transverse waves from recreational vessels is negligible (Macfarlane and Cox, 2003). The propagation of divergent waves is a function of the hull form (Prismatic Coefficient), angle of entry, vessel speed, and speed-length ratio, and can take up to 5 boat lengths to fully develop (Maynord, 2001).

Boat speed has a significant influence on whether a boat is in displacement or planing mode (Figure B-2). When in displacement, or sub-critical, mode (i.e. lower speeds) short-crested divergent waves and transverse waves are present. When travelling in planing, or super-critical, mode (i.e. faster speeds) the divergent waves become long-crested and transverse waves fade away.

Johnson (1958) proposed the use of Froude numbers which relate the length of a vessel to boat velocity. These numbers can be used to indicate the conditions under which maximum wave height and length are produced. The length-based Froude number (F_L) defines that each vessel of a specific length will generate its maximum wave length when F_L is between 0.39 and 0.50 (Johnson, 1958) as calculated by:

$$F_L = v_s/\sqrt{gL_w} \quad \text{(B-2)}$$

where

v_s = vessel speed (m/s)
L_w = vessel length at the water line (m)
g = gravitational constant (m^2/s)

The maximum wave height is produced when a boat is travelling at the same speed as the propagating wave train and is calculated using the depth-based Froude number (F_d) (Johnson, 1958). This wave height occurs when F_d = 1:

$$F_d = v_s/\sqrt{gh} \quad \text{(B-3)}$$

where

h = water depth (m)

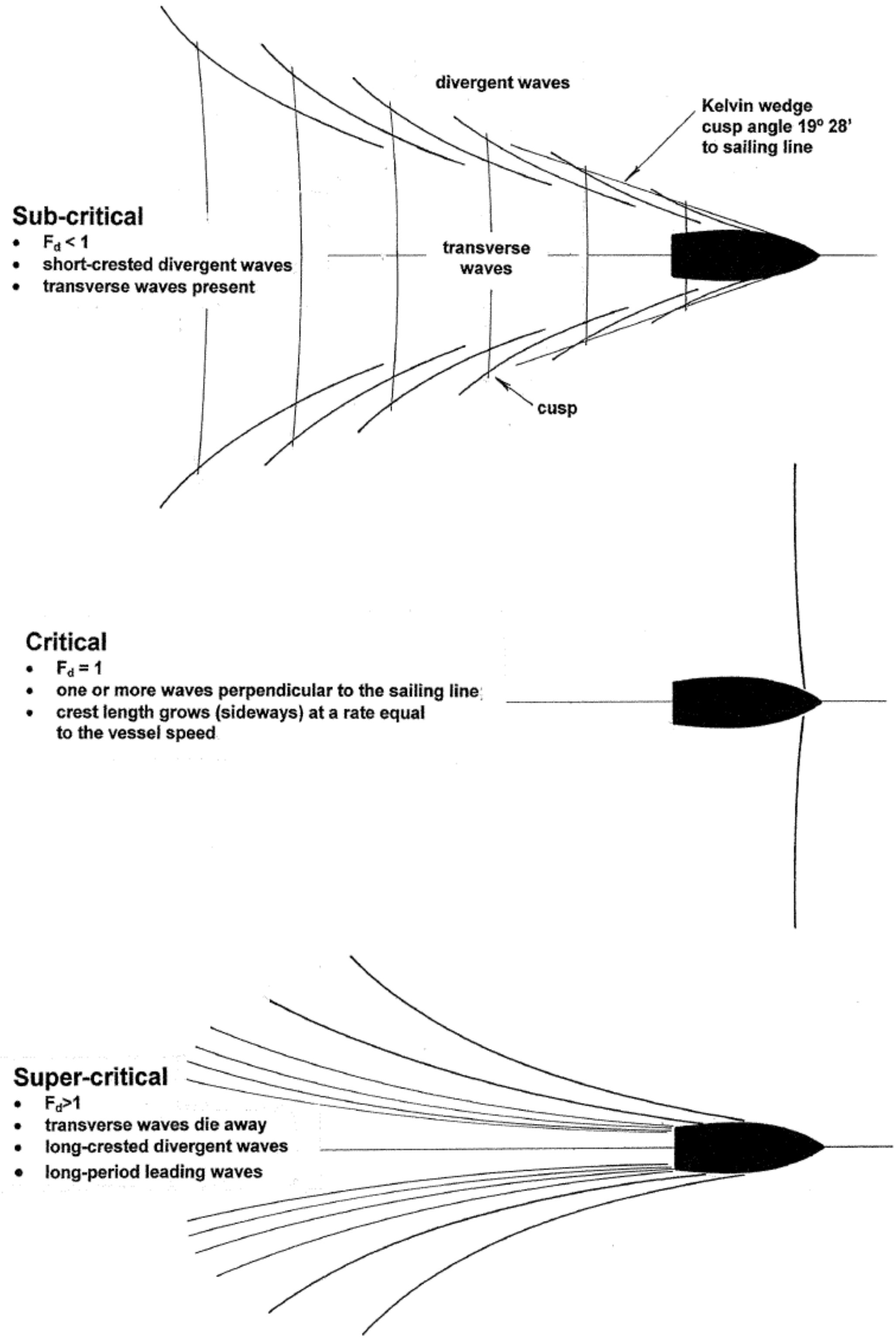


Figure B-2: Wake Wave Patterns (Source: Macfarlane and Cox, 2003)

The aforementioned Froude numbers can be used to determine when a theoretical vessel travelling at a given speed and depth would produce its maximum wave condition (Maynord, 2005). For instance, the majority of vessels used for waterskiing and wakeboarding have a length of approximately 6.0 m, which equates to a maximum transverse wavelength ($F_L = 0.5$) at a speed of ~ 7.5 knots (Glamore and Hudson, 2005). Furthermore, in water with an average depth of 10 m, these vessels would have to travel faster than 20 knots to maintain super-critical divergent wave patterns ($F_D > 1.0$) (Glamore and Hudson, 2005).

While this information is useful in gaining a fundamental understanding of the wave conditions based on vessel length, speed and water depth, it is important to note that a very small change in displacement (loading) or trim can have a major impact on wake height. Stumbo et al. (1999) indicated that a change in dynamic trim of as little as one degree can double the wash energy of a given vessel at a given speed. This is important because the vast majority of wakeboarding vessels have the capacity to alter loading and trim to optimise wake generation through ballasting (Glamore, 2011).

Once the boat waves are generated, the resultant wave train is influenced by a range of environmental factors including wind, water depth, riverbed characteristics, natural waves, tidal currents and other vessels. In a typical wave train, the wave height of the divergent waves attenuates due to diffraction as shown in Equation B-4 (Macfarlane and Cox, 2003). In contrast, as the wave train moves away from the vessel the waves disperse and the wave period increases. This spreading of the wave train continues for 2 - 5 boat lengths, after which the wave period remains relatively unchanged in deep water.

$$H = \gamma y^{-1/3} \tag{B-4}$$

where

H = wave height (m)

γ = variable dependent on the vessel and its speed

y = lateral distance from the sailing line (m)

If the wave travels into shallow water where it 'feels' the bottom the wave will cease dispersing and become depth-limited. Within a wave train, waves with a longer wave period will become depth-limited prior to waves with a shorter wave period. If the wave continues to propagate into shallower waters, the wave height will increase while the wavelength and phase velocity decrease until the wave shoals and break (Glamore and Hudson, 2005). The impact of the breaking wave on the riverbank is an important component of the DSS used and discussed in Appendix C.

Appendix C – The Decision Support System (DSS) Methodology

C.1 Preamble

The need for a comprehensive, field tested methodology to determine the vulnerability of a riverbank to erode due to boat waves has been highlighted in several studies and via comparative techniques on waterways in Australia and around the world (e.g. Cowell, 1996; Johnston, 1996; Glamore and Hudson, 2005). The DSS developed by Glamore and Badenhop (2006; 2007) provides a standard methodology for assessing the erosional vulnerability of a riverbank, providing recommendations on the likely impact of recreational boat wake waves along a waterway using an evidence-based approach.

This section describes the DSS methodology. Specifics of the DSS application to the study area are found in Section 2 of the main body of the report and the results of the study in Section 3, with accompanying discussion and recommendations in Section 4.

To accurately assess the range of processes involved, the DSS comprises several components. It combines the energy of the wake wave generated from the passing vessel and number of boat passes, the background wind energy and the erosive potential of the riverbank (Figure C-1). The DSS incorporates wake data from several types of boats operating at a range of speeds as measured in controlled field conditions. The wake wave energy is compared to the average recurrence interval (ARI) of the wind wave energy onsite. This comparison is undertaken for both the maximum generated wake wave and the total wave energy generated from a selected day involving multiple boat passes.

The DSS addresses previous inadequacies (e.g. Cowell, 1996; Johnston, 1996) by comparing wind wave energy with wake waves in a comprehensive manner. Previous comparison methods either addressed the energy of the maximum wave, or the cumulative energy of a series of waves. In the DSS, the probable impact of boat wake waves is assessed using both the energy of the maximum wave and the cumulative energy of multiple waves over a specified time period. The inclusion of both of these mechanisms is important as boat wake waves may cause damage to a riverbank via a solitary wave or the cumulative effect of multiple wake waves over an extended period of time.

Within the DSS, the wind/boat wave assessment is combined with a field assessment of bank erosion potential, specific to each location, to produce a management recommendation. The end result is one of three management categories: Permit ('Allow'), Permit with Monitoring ('Monitor') and Manage ('Manage'). These outcomes are discussed in more detail in Section C.6.

Results from the DSS can be used to quantitatively assess riverbank sections or provide overall waterway management. It has been trialled at various locations in NSW to ensure that it provides robust and scientific results (WRL, 2007). These trials allowed for calibration and adaptation of the DSS to a wider range of conditions. **A fundamental assumption of the DSS is that it assumes that in an ideal environment, the riverbank has the potential to be in a dynamic equilibrium with the wind environment, and subsequently that boat wave energy exceeding the wind environment, depending on the relative magnitude and the riverbank vulnerability, has the potential to negatively impact the riverbank.**

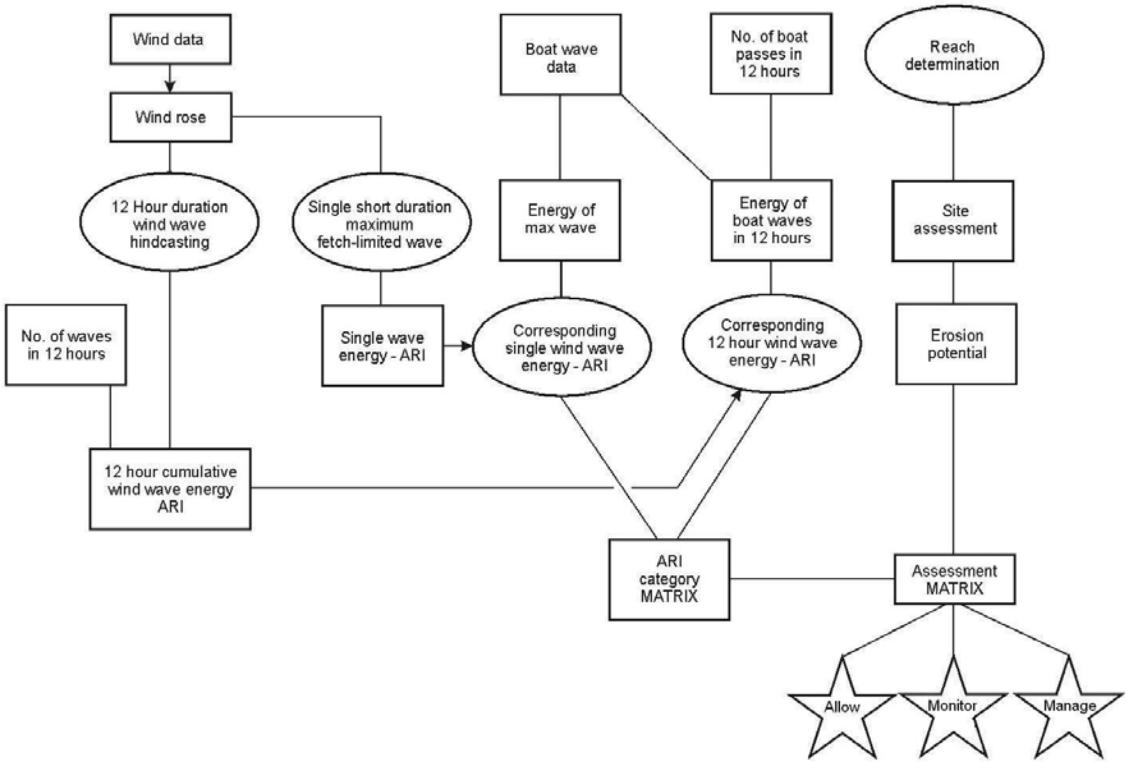


Figure C-1: Flow Diagram of the Decision Support System

C.2 Site Selection

The study area must be determined prior to undertaking any aspects of the field assessment. The entire study area is initially divided into stretches. These sections should generally be no greater than 500 m. As part of the process each riverbank is identified by one of the following geomorphic conditions: straight; inner-bank; or outer-bank. The length of each section should be chosen to ensure continuity in geomorphic condition. The DSS recommends at least 30 % (randomly chosen) of the stretches be observed to gain an adequate understanding of the state of the river. Each of the stretches selected for analysis is then divided into three sections and a 10 m wide transect at the midpoint of each section is assessed (Figure C-2). The erosion potential of the three transects is averaged for each stretch. Note that for this study 100 % of all stretches selected were assessed.

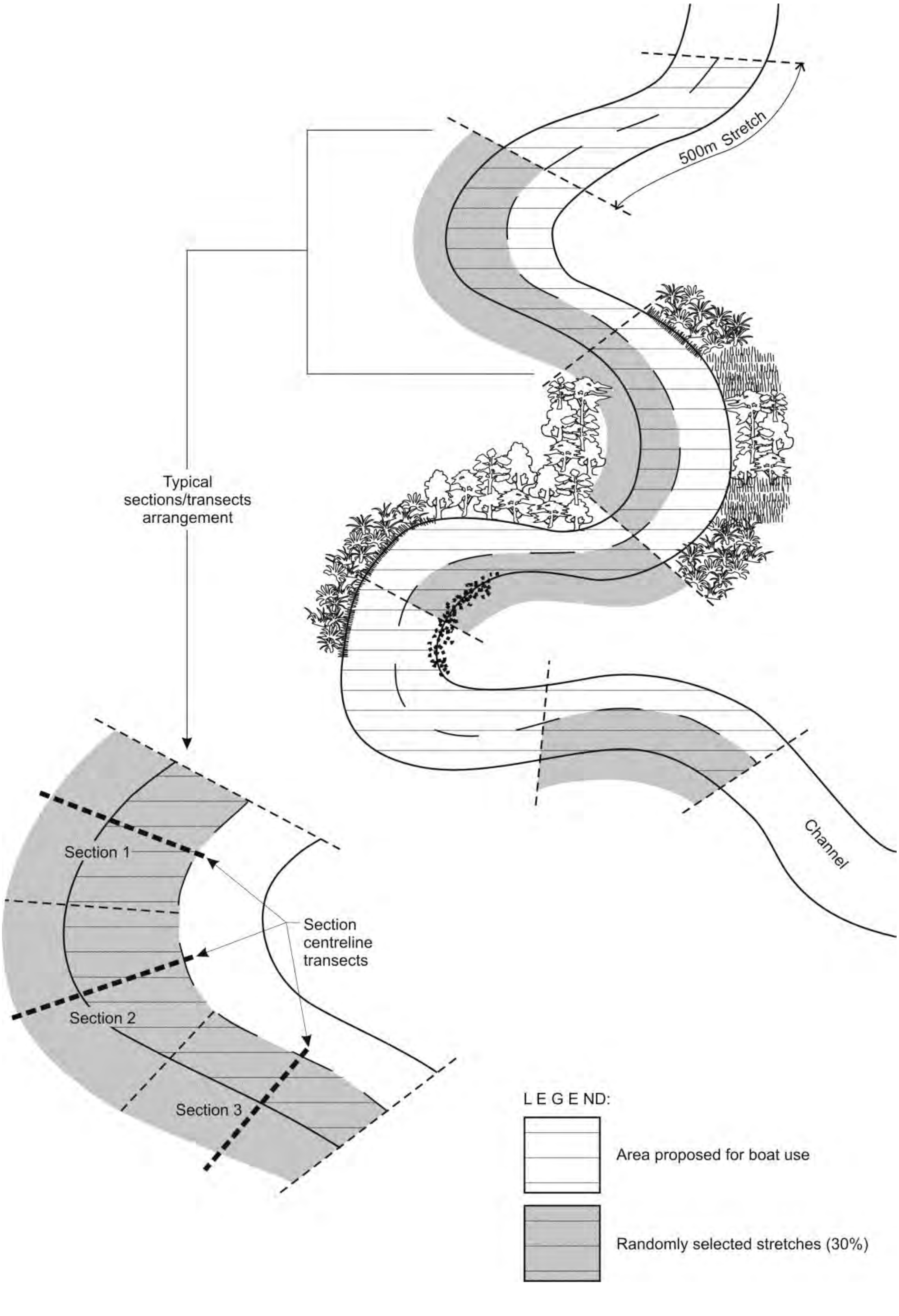


Figure C-2: Transect Locations

C.3 Wind Waves

The natural wind-wave environment is a shaping factor of any waterway. Wind waves are generated by wind blowing across a distance of water, also known as a 'fetch'. The size of the waves may be limited by the duration of the wind or the length of the fetch. It is assumed that in an ideal environment, a waterway subjected to a particular wind-wave climate has the potential to establish a dynamic equilibrium with that wind environment. In the DSS the natural wind wave climate is assessed for each site, with fetch lengths determined from the middle of each stretch. The natural energy of the wind waves can then be compared with the energy of boat wake waves.

The Average Recurrence Interval (ARI) of the wind waves is used for this comparison. The 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. It is important to note that the factors determining whether a wave will erode a riverbank are complex and not fully understood. Erosion depends on many aspects including, but not limited to, the maximum energy of a single wave and the combined impact of many waves over a longer duration. Subsequently, the wind wave energy of a location is characterised in two ways in the DSS. 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 hour periods are recommended as an appropriate duration for calculating cumulative energy as it approximates the daylight hours during which boats are likely to be travelling. A more detailed example of wind wave calculations is provided in Appendix G.

C.4 Wake Waves

To enable comparison of boat waves with wind waves, the maximum wave is first extracted from collected field data of boat waves and the associated energy calculated. The wave energies included in the DSS are from controlled field tests on a range of vessels (Glamore and Badenhop, 2006). The wave characteristics can be selected for waterski or wakeboarding vessels performing under a range of conditions, including operational conditions, maximum wave generated and 4 knots. Subsequently, the maximum likely wave and the wave produced when travelling under the selected conditions are calculated. This information is then combined with the number of boat passes on the river in a given period. The user is also required to enter the minimum boat distance from shore.

The energy of the maximum wave is extrapolated to the energy of the entire wave train. The wave attenuation equation is applied to determine the likely energy of the wave when it reaches the riverbank. The energy of the entire wave train can then be multiplied by the number of boat passes over a specific time period to calculate the cumulative boat wake wave energy at the riverbank over the specified duration (8 - 12 hours). These two datasets are then compared to the previously calculated wind wave energy.

C.5 Riverbank Erosion

A detailed literature review on bank erosion was conducted to inform the development of the DSS. Key factors in the riverbank stability were found to include vegetation, stock access, sediment type and channel equilibrium. Additionally, bank instability may be caused by factors producing bed lowering, such as de-snagging, sand and gravel extraction, and construction of dams and weirs. Several different methods for assessing river condition were discussed and considered; their applicability for erosion potential assessment is detailed in Glamore and Badenhop (2006).

The bank erosion potential assessment included in the DSS estimates the susceptibility of riverbanks to erode due to boat wake waves. Key criteria and importance weightings are combined to form an erosion potential rating for the site. These criteria include river type, vegetation coverage and extent, erosion descriptors, adjacent land use and channel features. A full list and detailed description of the categories, indicators and weightings used within the DSS can be found in Glamore and Badenhop (2006).

The erosion potential is assessed at three transects along both banks of the river for each stretch (Assessment Sheet – Appendix E). A score is given for each transect (Table C-1) and these scores are averaged to obtain a final erosion potential category for the stretch of riverbank. Sites with highly negative erosion potential scores have a low resistance to erosion, whereas sites with strongly positive erosion potential scores should be well protected from bank erosion. Appendix F provides some examples of riverbanks in each of the erosion potential categories for the Hawkesbury River study.

Table C-1: Erosion Potential Categories

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

C.6 Final Decision Support System Recommendations

Following the calculation of the boat wake wave energy, the wind wave energy and the erosion potential of the sites, the data is fed into a series of matrices determining the management recommendation. A rating must be completed for each stretch of the river to be analysed.

The first matrix (Table C-2) 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 hours). The aim of this assessment is to determine the equivalent ARI of the boat wake wave energy. The outcome from Table C-2 is then compared to the calculated erosion potential for each stretch (Table C-3). The lower and upper bound recurrence intervals for each Wind ARI Rating Category are also shown in Table C-4 in readily understandable time intervals. An example of the wave comparison calculations are provided in Appendix G.

Depending on the management recommendation determined in Table C-3 varying general recommendations and suggestions for reassessment periods are provided. The permit (or 'Allow') recommendation occurs when the site has a low erosion potential and there is limited difference between wind and wake wave energies. In these circumstances the vessel in question should be permitted to operate. It is advised that after five years the site be reassessed to determine if the boat wake waves have increased the erosion potential (Glamore and Badenhop, 2006).

Table C-2: Equivalent Wind ARI Rating

Equivalent Wind Wave ARI for Maximum Boat Wave Energy	Equivalent Wind Wave ARI of Boat Pass Scenario for Extended Duration					
	$<9.58\times10^{-3}$ years	9.58×10^{-3} – 1.92×10^{-2} years	1.92×10^{-2} - 3.83×10^{-2} years	3.83×10^{-2} - 1.53×10^{-1} years	1.53×10^{-1} - 3.07×10^{-1} years	$>3.07\times10^{-1}$ years
$<9.58\times10^{-3}$ years	A	A	B	C	C	C
9.58×10^{-3} – 1.92×10^{-2} years	A	B	B	C	C	D
1.92×10^{-2} - 3.83×10^{-2} years	A	B	C	C	D	D
3.83×10^{-2} - 1.53×10^{-1} years	B	B	C	C	D	D
1.53×10^{-1} - 3.07×10^{-1} years	B	C	C	D	D	E
$>3.07\times10^{-1}$ years	B	C	C	D	E	E

Table C-3: Final Management Recommendation

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

Table C-4: Lower and Upper Bound Recurrence Intervals for Wind ARI Rating Categories

ARI	Lower Bound Recurrence Interval	Upper Bound Recurrence Interval
$<9.58\times10^{-}3$ years		exceeded 2 times per week
9.58×10^{-3} – 1.92×10^{-2} years	exceeded 2 times per week	exceeded 1 time per week
1.92×10^{-2} - 3.83×10^{-2} years	exceeded 1 time per week	exceeded 1 time every 2 weeks
3.83×10^{-2} - 1.53×10^{-1} years	exceeded 1 time every 2 weeks	exceeded 1 time every 8 weeks
1.53×10^{-1} - $3.07\times10^{-}1$ years	exceeded 1 time every 8 weeks	exceeded 1 time every 16 weeks
$>3.07\times10^{-1}$ years	exceeded 1 time every 16 weeks	

If the permit with monitoring recommendation (or 'Monitor') is prescribed then the vessel in question should be allowed on site, although monitoring is recommended and some erosion may still occur. If the 'Monitor' recommendation is prescribed and boats are already on the waterway then the site should be reassessed every two years. If boats are currently restricted from the waterway then the site should be assessed at six month intervals for the first two years and at two year intervals thereafter (Glamore and Badenhop, 2006).

The manage boating recommendation (or 'Manage') is given to sites where significant erosion is likely to occur from passing vessels. A range of restoration options should be considered for such sites. The DSS can be used to determine if reducing the boat numbers or implementing speed restrictions would improve its rating. The DSS can also be used to determine which of the characteristics investigated in the erosion potential assessment are having the most negative influence on the site and these can be prioritised for bank restoration works. A site classified as 'Manage' should be reassessed every two years (Glamore and Badenhop, 2006).

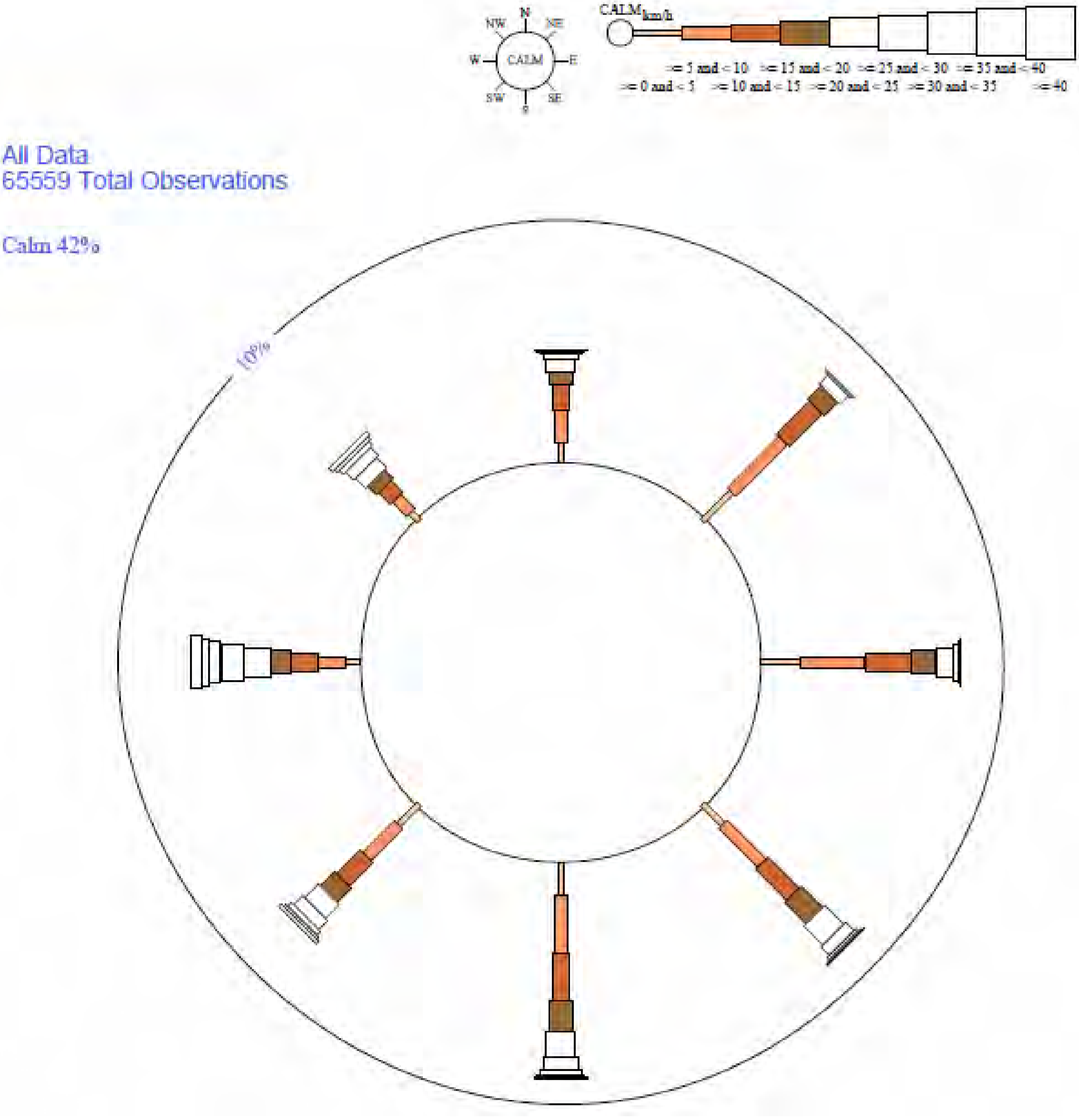
If the fully developed wave causes the score to be 'Monitor' or 'Manage' yet the attenuated wave rates 'Allow' or 'Monitor' the distance maintained from shore is critical to the management recommendation. Subsequently sites where this occurs are presented as '*Allow' or '*Monitor'. Note that due to the conservative assumption that boats travelled at a distance of 30 m from the riverbank, no sites were categorised as '*Allow' or '*Monitor' in this assessment.

Appendix D - Wind Roses and Frequency Data

Rose of Wind direction versus Wind speed in km/h (01 Dec 1939 to 20 Oct 1993)
RICHMOND RAAF

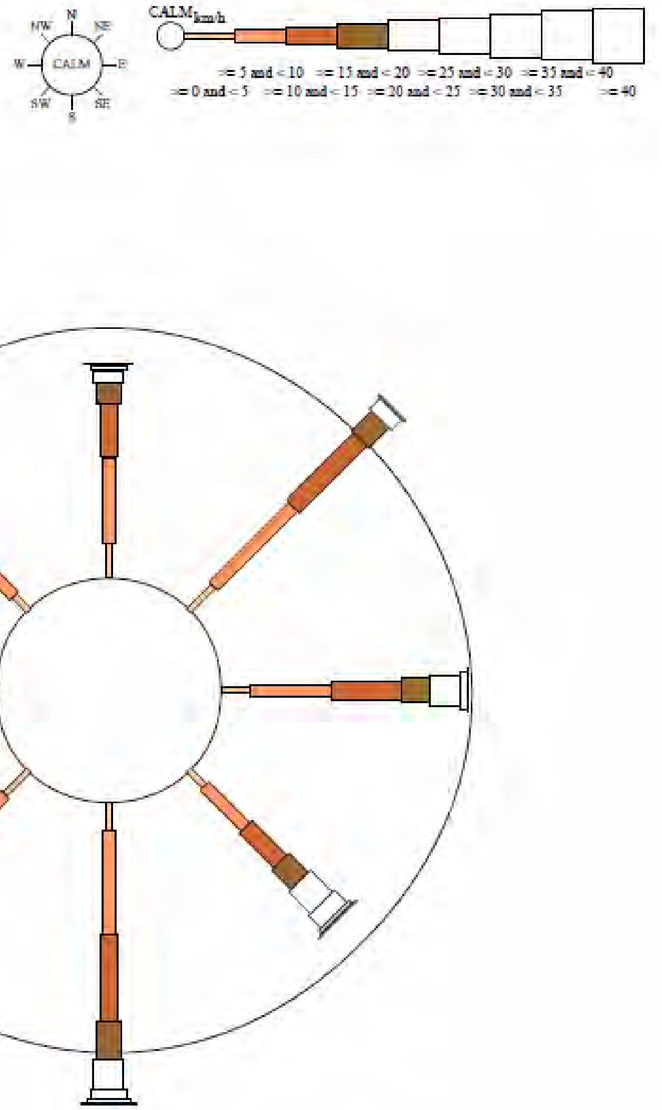
Site No: 067033 • Opened Jan 1928 • Closed Oct 1994 • Latitude: -33.6022° • Longitude: 150.7794° • Elevation 19m

An asterisk (*) indicates that calm is less than 0.5%.
Other important info about this analysis is available in the accompanying notes.



Rose of Wind direction versus Wind speed in km/h (21 Oct 1993 to 30 Apr 2014)
RICHMOND RAAF
Site No: 067105 • Opened Sep 1993 • Still Open • Latitude: -33.6004° • Longitude: 150.7761° • Elevation 19m

An asterisk (*) indicates that calm is less than 0.5%.
Other important info about this analysis is available in the accompanying notes.



Frequency Analysis of Wind direction versus Wind speed in km/h (01 Dec 1939 to 20 Oct 1993)

Custom times selected, refer to attached note for details

RICHMOND RAAF

Site Number 067033 • Opened Jan 1928 • Closed Oct 1994 • Latitude: -33.6022° • Longitude: 150.7794° • Elevation 19m

Values are frequency totals.
Other important info about this analysis is available in the accompanying notes.

All Data **65559 Total Observations**

Wind speed in km/h	Wind direction									
	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Calm**	**ALL**
>= 0 and < 5	556	1142	1099	798	922	810	417	326		**33903**
>= 5 and < 10	907	2013	1778	1521	1585	1243	774	555		**10377**
>= 10 and < 15	665	1297	1270	1231	1343	920	710	457		**7896**
>= 15 and < 20	377	529	692	830	826	559	577	332		**4724**
>= 20 and < 25	320	337	498	745	740	542	737	398		**4320**
>= 25 and < 30	173	58	125	322	347	348	641	308		**2324**
>= 30 and < 35	46	7	20	84	116	138	302	153		**868**
>= 35 and < 40	25	4	9	36	55	81	208	101		**520**
>= 40	17	1	3	28	56	93	291	136		**627**
All	**3088**	**5389**	**5496**	**5597**	**5992**	**4736**	**4660**	**2768**	**27831**	**65559**

Frequency Analysis of Wind direction versus Wind speed in km/h (21 Oct 1993 to 30 Apr 2014)

Custom times selected, refer to attached note for details

RICHMOND RAAF

Site Number 067105 • Opened Sep 1993 • Still Open • Latitude: -33.6004° • Longitude: 150.7761° • Elevation 19m

Values are frequency totals.
Other important info about this analysis is available in the accompanying notes.

All Data **58260 Total Observations**

Wind speed in km/h	Wind direction									
	N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**Calm**	**ALL**
>= 0 and < 5	810	829	688	533	650	809	558	495		**18723**
>= 5 and < 10	2053	2675	1930	1375	2466	3193	1269	1042		**16005**
>= 10 and < 15	1292	2253	1668	1167	2078	1742	864	735		**11801**
>= 15 and < 20	466	671	644	648	905	525	508	249		**4617**
>= 20 and < 25	298	356	725	728	702	409	673	245		**4137**
>= 25 and < 30	129	50	157	413	231	159	600	184		**1925**
>= 30 and < 35	24	2	12	81	63	46	232	63		**524**
>= 35 and < 40	8	0	5	34	19	35	211	38		**350**
>= 40	3	0	0	10	13	14	118	20		**178**
All	**5083**	**6838**	**5829**	**4992**	**7129**	**6933**	**5033**	**3072**	**13349**	**58260**

Appendix E – Example DSS Field Sheet

Water Research Laboratory

Date:	**Stretch/Section:**
Time:	
Assessing Personnel:	**GPS Waypoint:** **or E:** **N:** AMG/MGA (circle correct one)
Photo Numbers:	

River Type

Valley Setting:	☐ Confined ☐ Partly confined ☐ Laterally unconfined	☐ Completely armoured ☐ Partially armoured
Longitudinal Continuity of Bank Vegetation Over Whole Stretch:	☐ < 10 % ☐ 10-30 %	☐ 31-60 % ☐ > 60 %

Vegetation (Not required if completely confined or armoured)

	Low Tide Assessment		High Tide Assessment	
Verge Cover (10 m from top of bank):	☐ < 10 % ☐ 10-30 %	☐ 31-60 % ☐ > 60 %		
Upper Bank Cover:	☐ < 10 % ☐ 10-30 %	☐ 31-60 % ☐ > 60 %		
Wave Zone Cover:	☐ < 10 % ☐ 10-30 %	☐ 31-60 % ☐ > 60 %	☐ < 10 % ☐ 10-30 %	☐ 31-60 % ☐ > 60 %
Native Canopy Species Regeneration (< 1 m tall):	☐ None	☐ Scattered ☐ Abundant		
Native Understorey Regeneration:	☐ None	☐ Scattered ☐ Abundant		
Dominant Wave Zone Cover Type:	☐ Bare (vertical slope) ☐ Bare (1:3 – 1:6 slope) ☐ Bare (≤1:7 slope) ☐ Rocks	☐ Grasses ☐ Reeds ☐ Trees/Tree roots ☐ Mangroves	☐ Bare (vertical slope) ☐ Bare (1:3 – 1:6 slope) ☐ Bare (≤1:7 slope) ☐ Rocks	☐ Grasses ☐ Reeds ☐ Trees/Tree roots ☐ Mangroves

Channel Features

Upper Bank Slope:	☐ Near Vertical ☐ ~1:3	☐ ~1:5 ☐ <1:7
Channel Width:	☐ <36 ☐ 36-120	☐ >120
Bank Height	☐ > 3 m ☐ 1-3 m	☐ < 1 m

Erosion

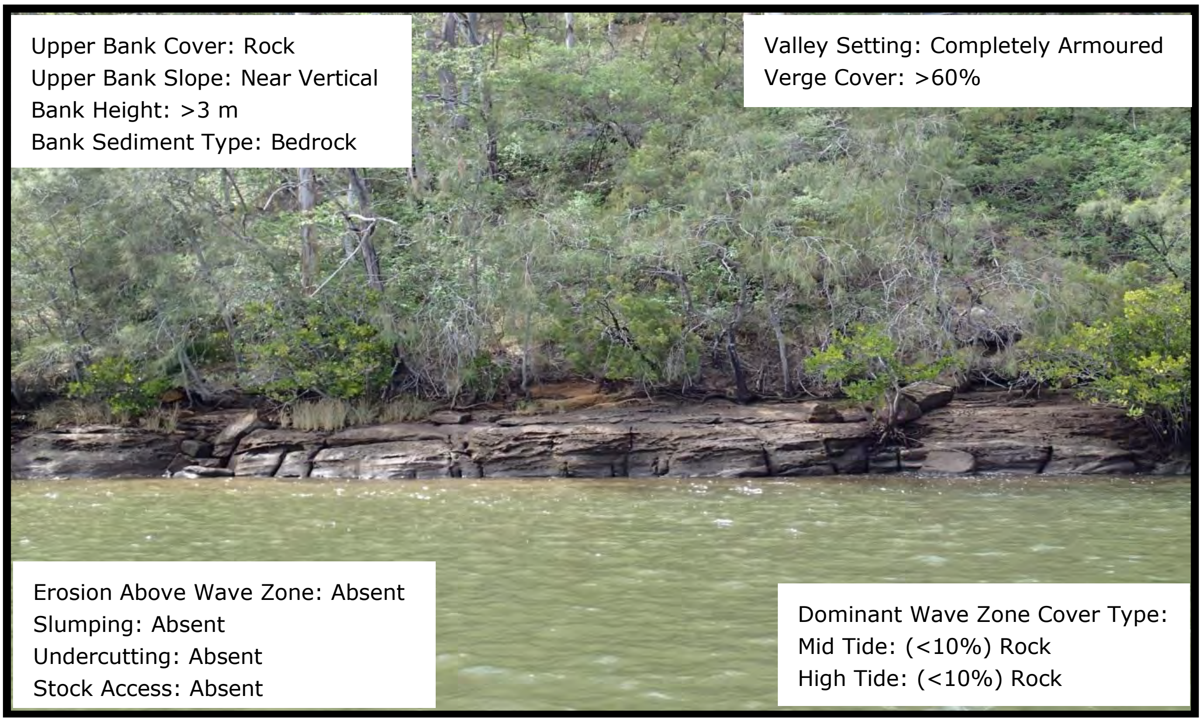
Bank Sediment Type:	☐ Bedrock/Boulders/Cobbles/ Armouring ☐ Cohesive	☐ Complex (sand & clay) ☐ Non-Cohesive
Erosion Above the Wave Zone:	☐ Absent ☐ < 10 % banks	☐ 10-30 % banks ☐ > 30 % banks
Slumping:	☐ Absent ☐ < 10 % banks	☐ 10-30 % banks ☐ > 30 % banks
Undercutting in the Wave Zone:	☐ Absent ☐ < 10 % banks	☐ 10-30 % banks ☐ > 30 % banks

Land use

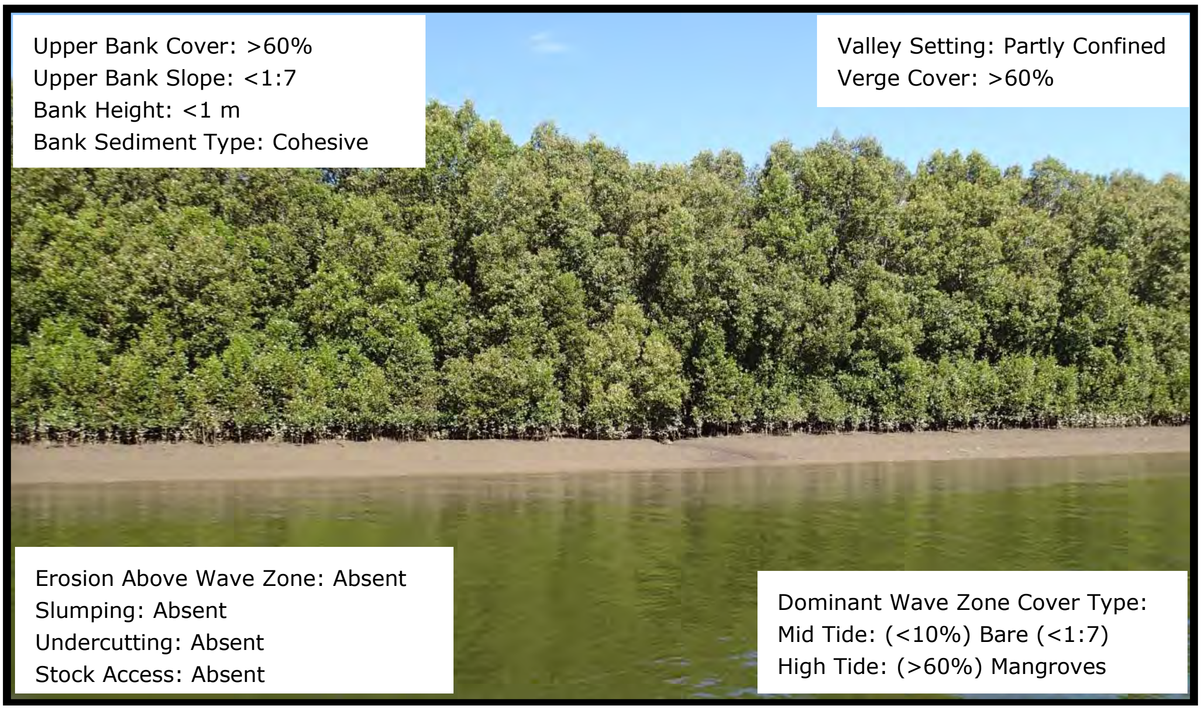
Desnagging:	☐ None	☐ Conducted in last previous year
Excavation:	☐ Present	☐ Absent
Extraction:	☐ None	☐ Water ☐ Sediment
Stock Access:	☐ Absent	☐ Present

Brief Description of Site (include high tide and low tide markers)

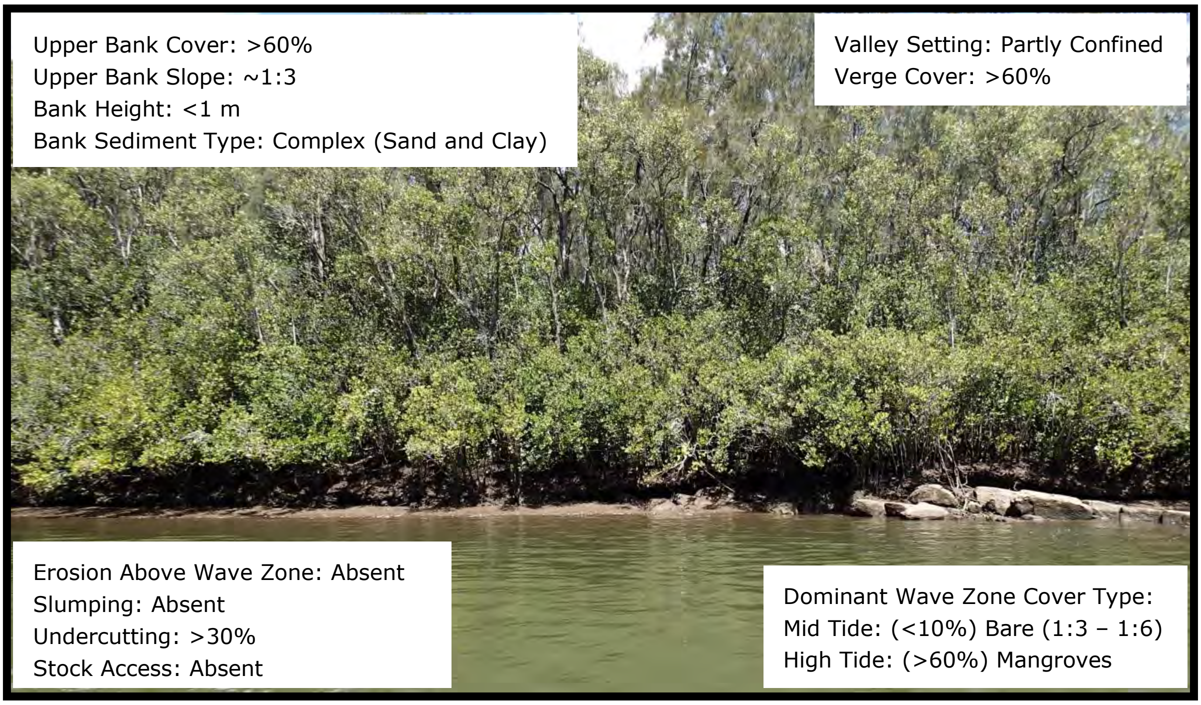
Appendix F – Field Examples of Erosion Potential Categories



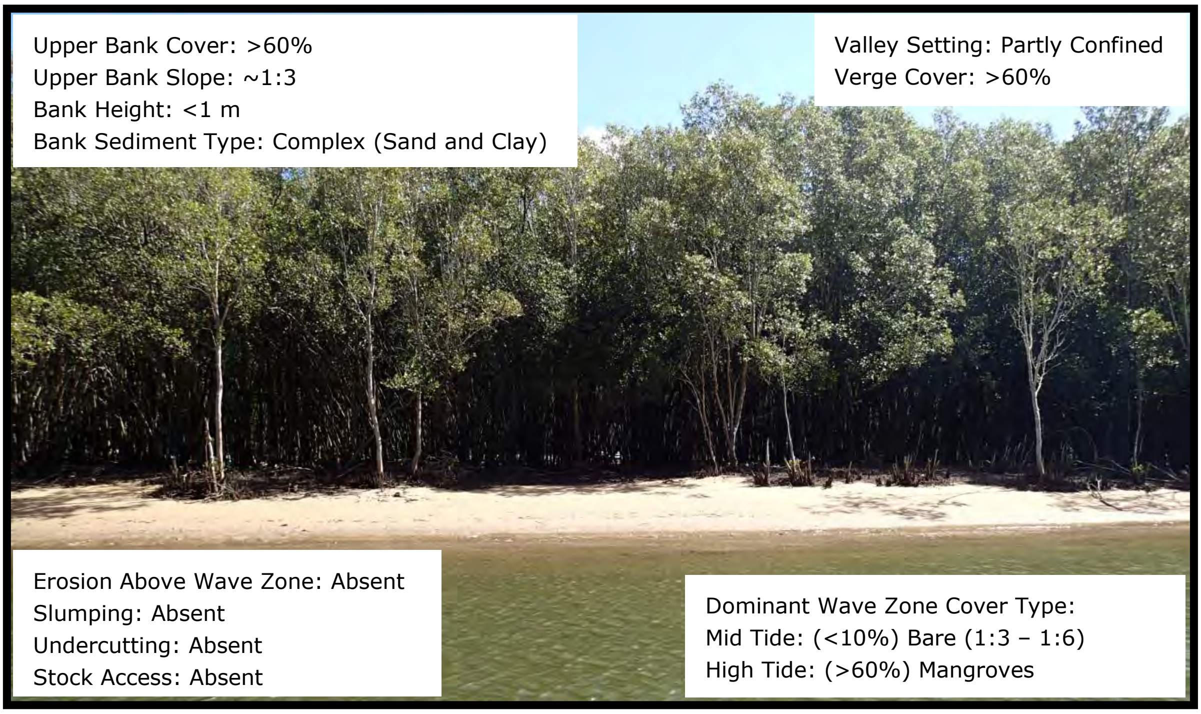
Highly Resistant – L16A



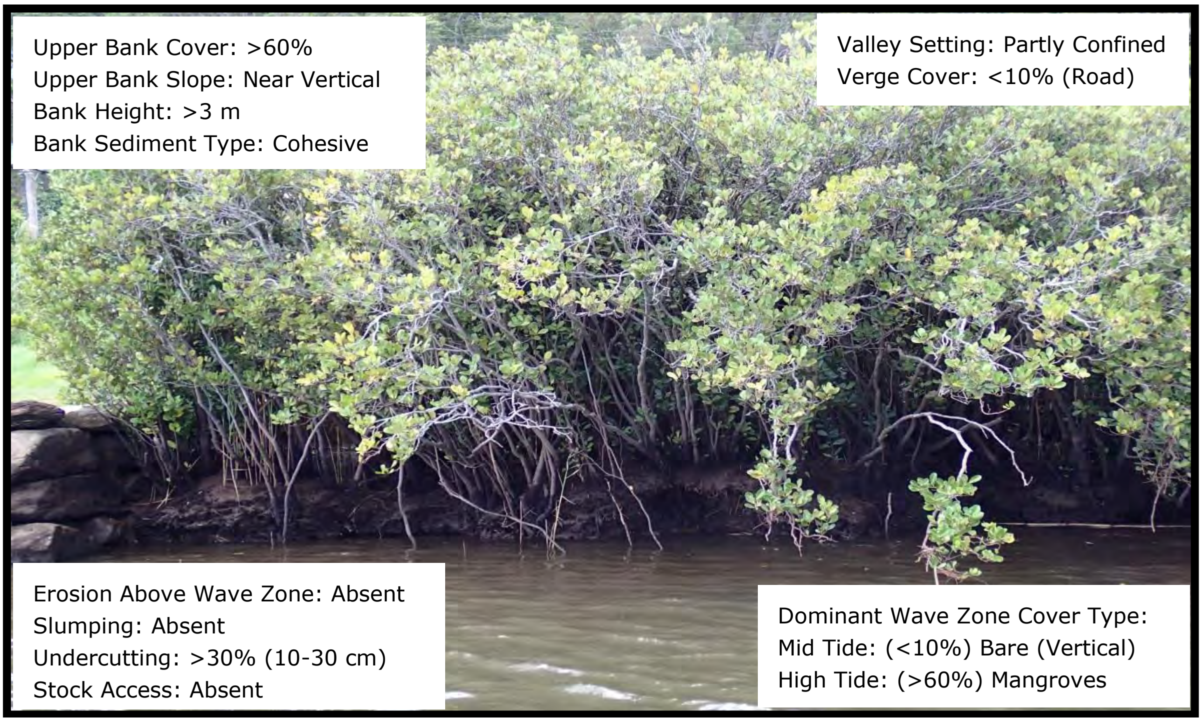
Highly Resistant – R31C



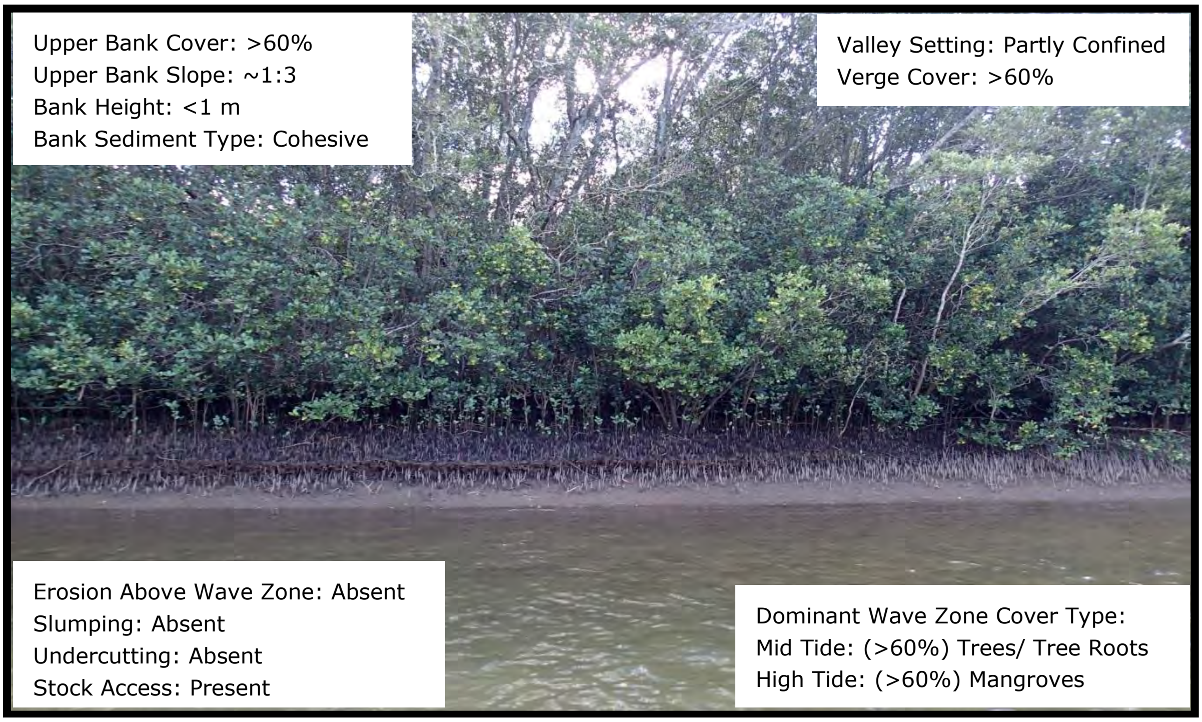
Moderately Resistant – R25A



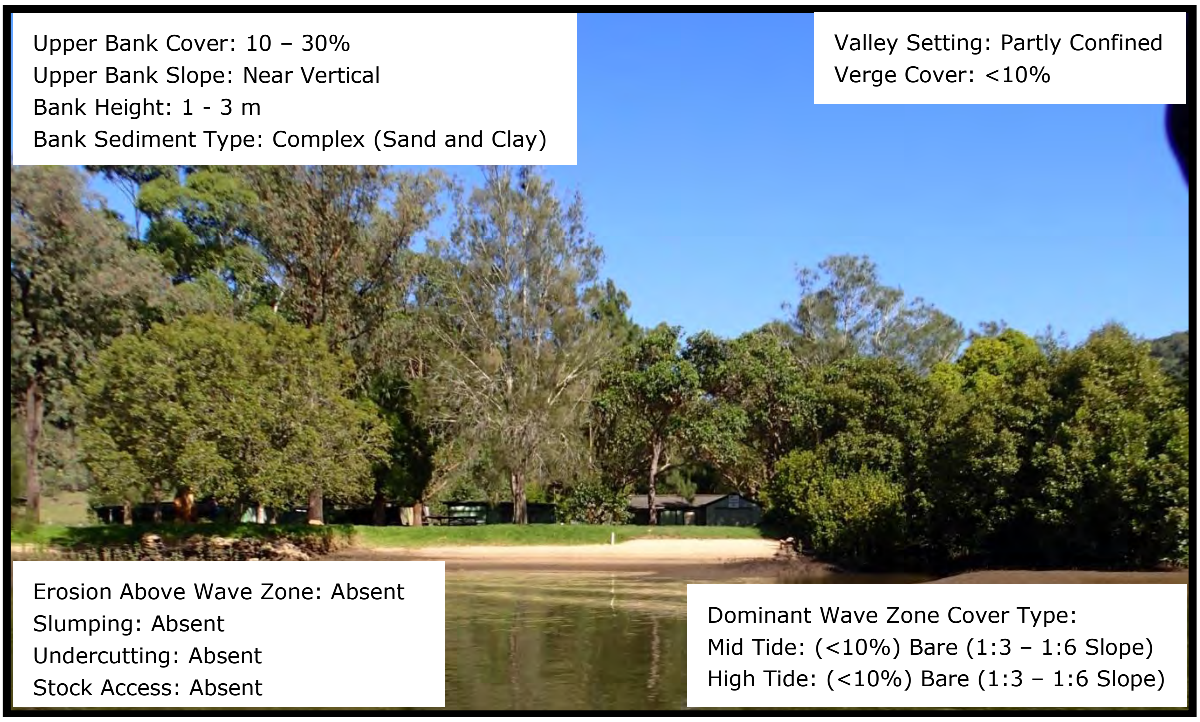
Moderately Resistant – R35C



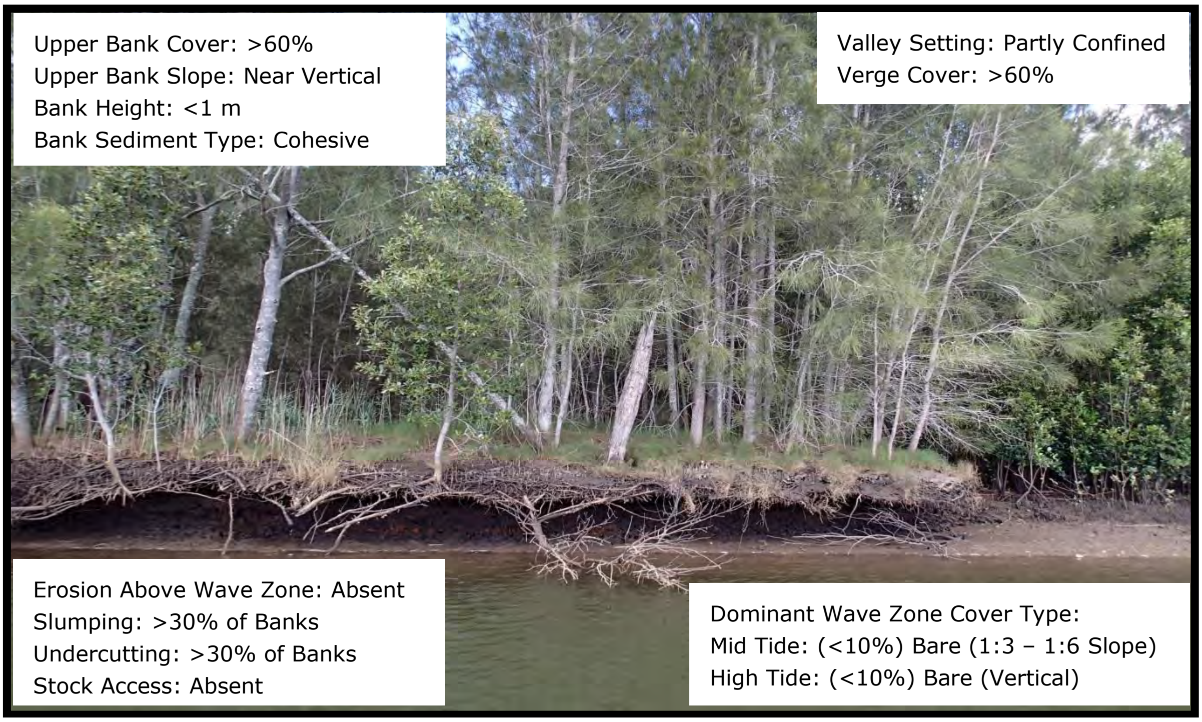
Mildly Resistant – L14C



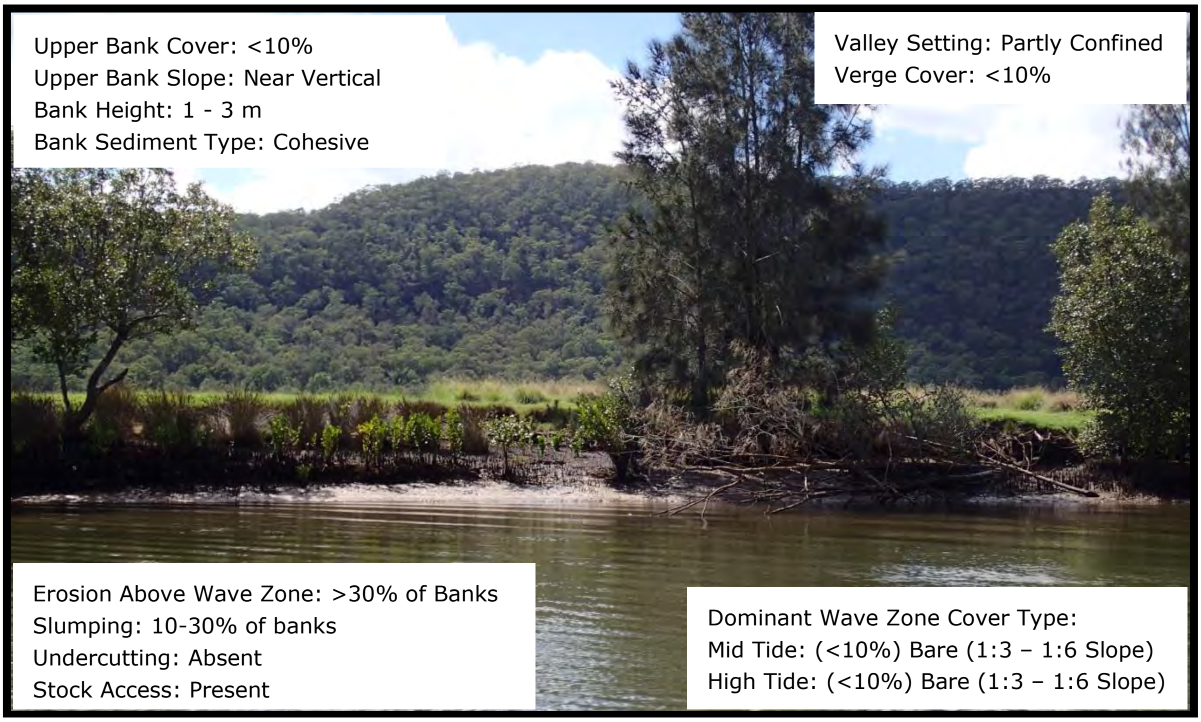
Mildly Resistant – L24C



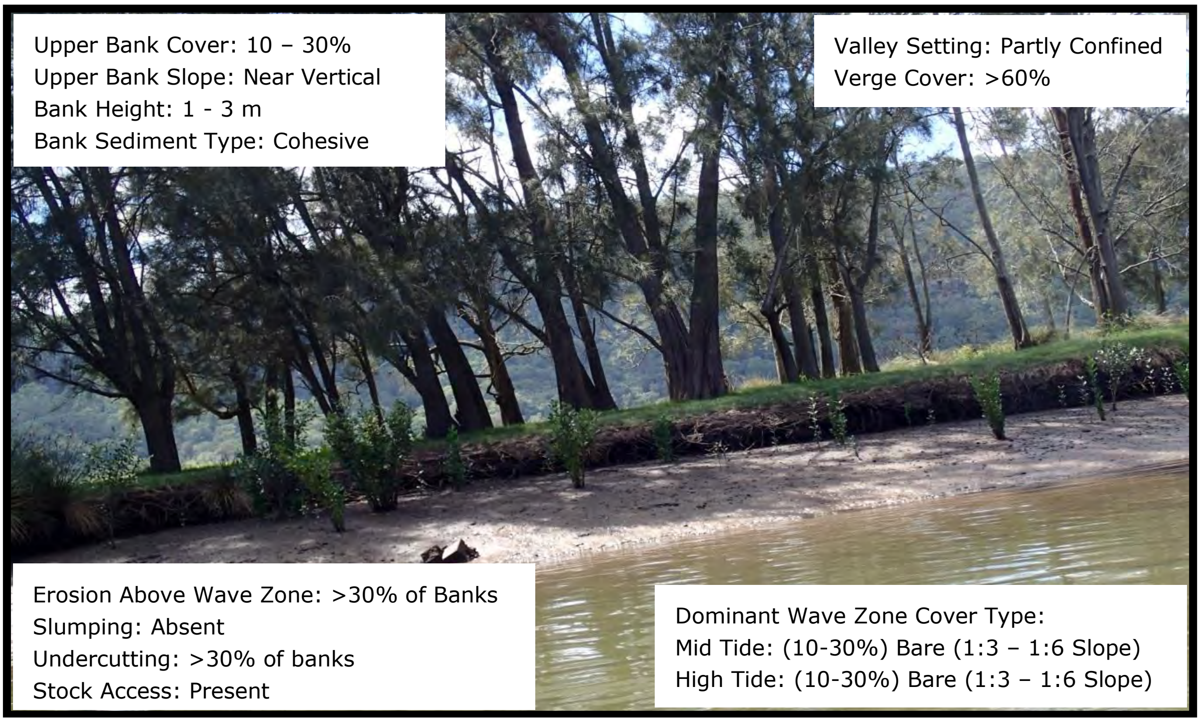
Moderately Erosive – R16B



Moderately Erosive – R31C



Highly Erosive – L18B



Highly Erosive – L18C

Appendix G - Example Wind Wave vs Boat Wave Comparison

G.1 Preamble

The comparison of wind wave and boat wake waves to create an equivalent ARI rating (A-E) is a three step process. Wind information is processed, followed by selection of the boat wave conditions and followed by a comparison of the wind and wake wave energies.

G.2 Processing Wind Information

Processing of the wind information involves five steps:

1. Obtain wind data.
2. Determine fetch lengths, in the centre of each stretch, for each available wind compass direction.
3. Using the local wind rose, complete wave hindcasting for both the single wave and extended duration waves for each wind speed in each direction.
4. Calculate the wind wave energy of the fetch-limited waves and determine the corresponding ARIs of the fetch-limited energy of a single wave.
5. Calculate the total wind wave energy at the site over the extended duration and determine the ARIs of the total wind wave energy for each adjusted wind speed and direction.

Tables G-1 and G-2 provide examples of the ARI, and associated energy of the maximum wave, and the Wind Wave Energy for the extended duration (8 hours), as calculated for two stretches of river (R35 and L35).

Table G-1 – Wave Energies and Associated ARI (R35)

Energy of maximum wave ($kg.m/s^2$)	Total Wind Wave Energy for the Extended Duration ($kg.m/s^2$)	ARI (years)
1.66	53,149	5.70×10^{-3}
1.78	56,328	6.42×10^{-3}
1.78	56,350	8.19×10^{-3}
2.67	79,002	1.76×10^{-2}
4.53	124,949	1.99×10^{-2}
4.85	132,423	2.21×10^{-2}
4.86	132,474	2.51×10^{-2}
6.80	176,413	2.54×10^{-2}
7.26	185,727	6.75×10^{-2}
7.28	186,965	6.96×10^{-2}
7.29	187,037	7.08×10^{-2}
9.77	239,866	7.14×10^{-2}
10.46	254,212	7.28×10^{-2}
10.47	254,311	7.30×10^{-2}
10.89	262,224	1.27×10^{-1}
15.63	356,541	74

Table G-2 – Wave Energies and Associated ARI (L35)

Energy of maximum wave ($kg.m/s^2$)	Total Wind Wave Energy for the Extended Duration ($kg.m/s^2$)	ARI (years)
11.48	308,269	1.56×10^{-2}
12.65	403,048	2.03×10^{-2}
13.15	404,423	2.10×10^{-2}
18.15	1,429,551	3.47×10^{-2}
243.52	3,360,753	1.58×10^{-1}
363.55	4,744,984	3.83×10^{-1}
519.67	6,451,662	74

G.3 Wake Wave Data

Wake wave data from previous studies is included in the DSS. Table G-3 provides an overview of the maximum wave generated at operating conditions, maximum waves produced and the waves generated when travelling at 4 knots.

Table G-3 – Wake Wave Energies (Glamore and Hudson, 2005)

Condition	Boat	Velocity (knots)	Velocity (m/s)	H_{max} (m)	T_{peak} (s)	Boat Length L_w (m)	F_L	Energy H_{max}
Operating	Waterski	30	15.42	0.12	1.5	6.1	2	62
	Wakeboard	19	9.76	0.25	1.57	6.1	1.3	293
Maximum Wave	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
4 Knots	Waterski	4	2.05	0.12	1.29	6.1	0.3	46
	Wakeboard	4	2.05	0.13	1.23	6.1	0.3	49

Additionally, in the 2005 study (Glamore and Hudson, 2005), the energy of the entire wave train (not just the individual wave) was calculated for each boat pass. A relationship was fitted to the data, and was used to estimate the total energy of the wave train with where the characteristics of the maximum wave were known.

Wave attenuation is also included in the DSS, with the distance of the boat from the riverbank playing a role in the values of the wave energy received at the bank.

G.4 Comparison of Wave Energies

The wake wave energy is then compared to the ARI of the wind energy. Table G-4 provides some examples of a wakeboarding vessel under operating conditions, for 8 hours with 50 boat passes at distance of 30 m from the shore in the study stretch 35. The energy of the maximum wave, and the total waves over the extended duration are then compared according to Table C-2 and an Equivalent ARI Rating determined.

Table G-4 – Comparison of Wave Energies

Stretch	Condition	Attenuated Energy Max Wave (J/m)	Equivalent to a Wind Wave with ARI of 1 in ___ years	Energy of Single Attenuated Wave Train (J/m)	Total Energy at the Bank over 8 hours (J/m)	Equivalent to wind waves over 8 hours duration with ARI of 1 in __ years	Equivalent ARI Rating (Table C-2)
R35	Maximum Wave	575	74	1,979	98,928	4.99×10^{-2}	C
	Operating	235	74	950	47,497	4.99×10^{-3}	B
L35	Maximum Wave	575	74	1,979	98,928	3.41×10^{-3}	B
	Operating	235	3.47×10^{-2}	950	47,497	2.59×10^{-3}	A

Appendix H – DSS Sensitivity Test for High Tide Conditions

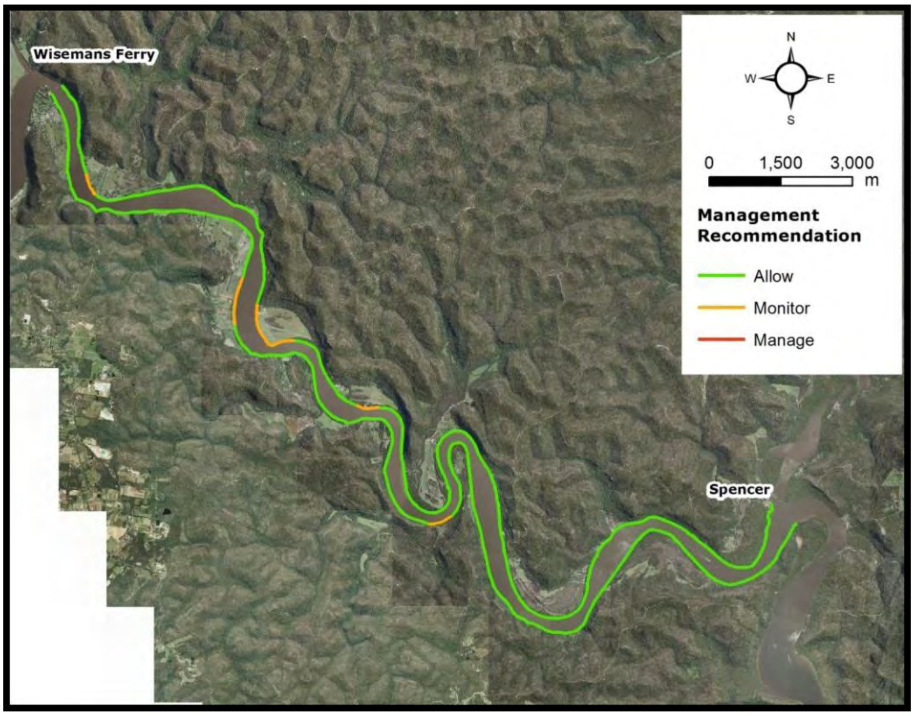


Figure H-1: DSS Management Recommendations – Wakeboard Operating - 10 Boat Passes - 8 Hour Duration (High Tide Conditions)

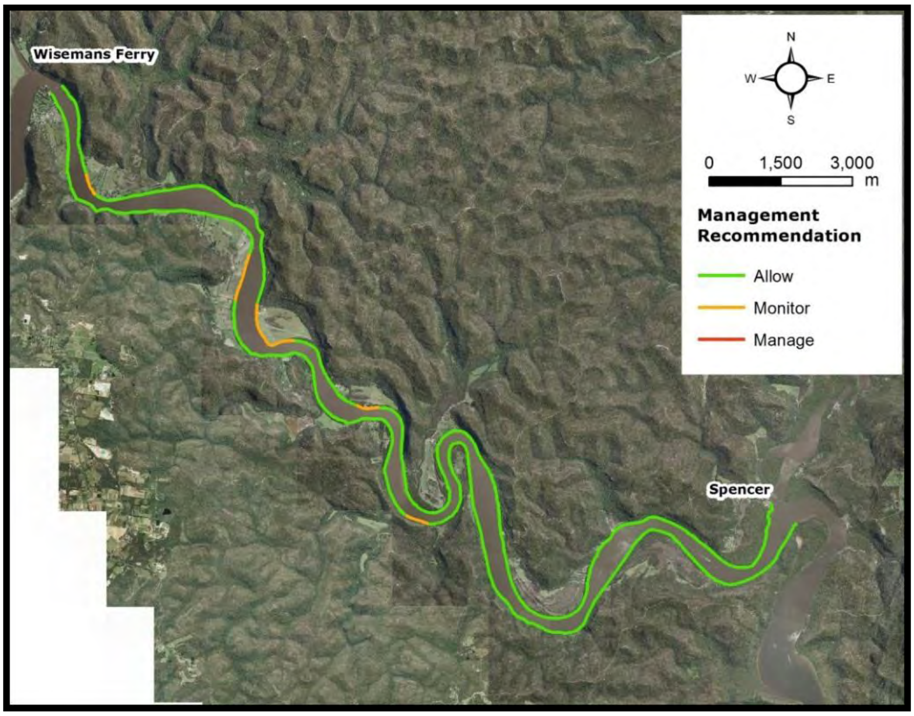


Figure H-2: DSS Management Recommendations – Wakeboard Operating - 50 Boat Passes - 8 Hour Duration (High Tide Conditions)

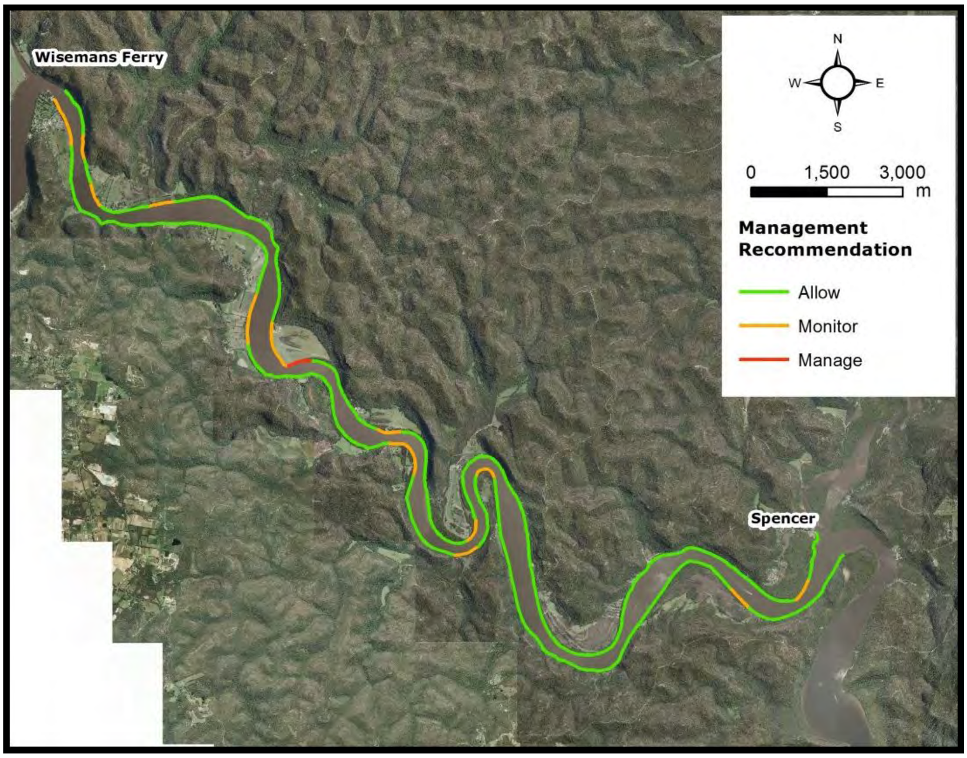


Figure H-3: DSS Management Recommendations – Wakeboard Operating - 150 Boat Passes - 8 Hour Duration (High Tide Conditions)

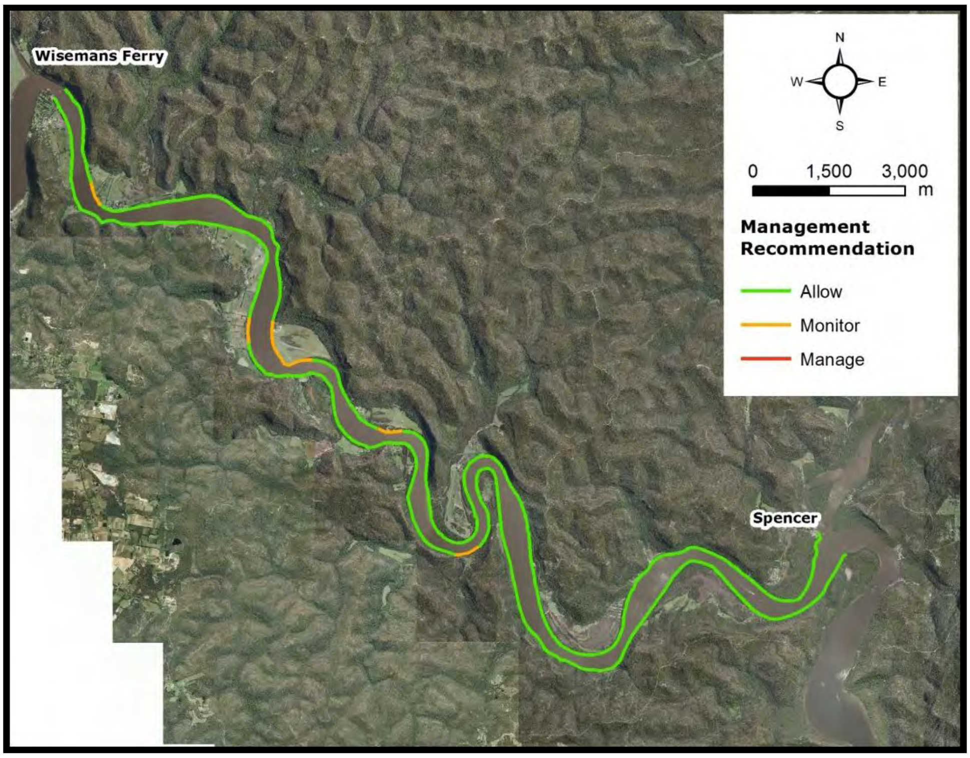


Figure H-4: DSS Management Recommendations – Waterski Operating - 10 Boat Passes - 8 Hour Duration (High Tide Conditions)

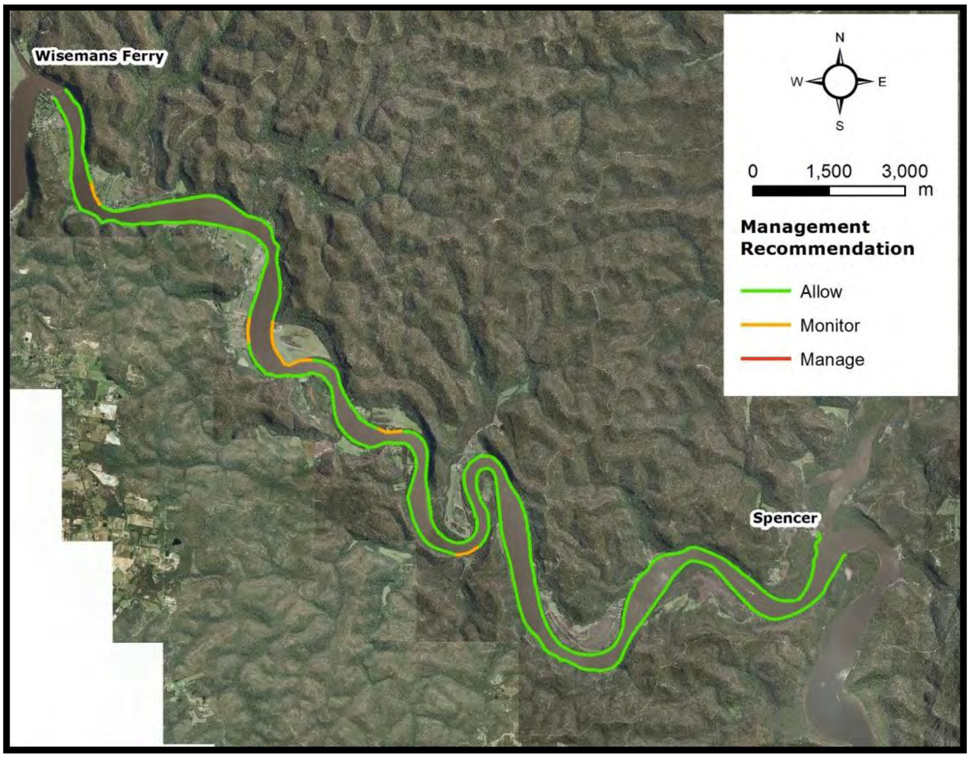


Figure H-5: DSS Management Recommendations – Waterski Operating - 50 Boat Passes - 8 Hour Duration (High Tide Conditions)

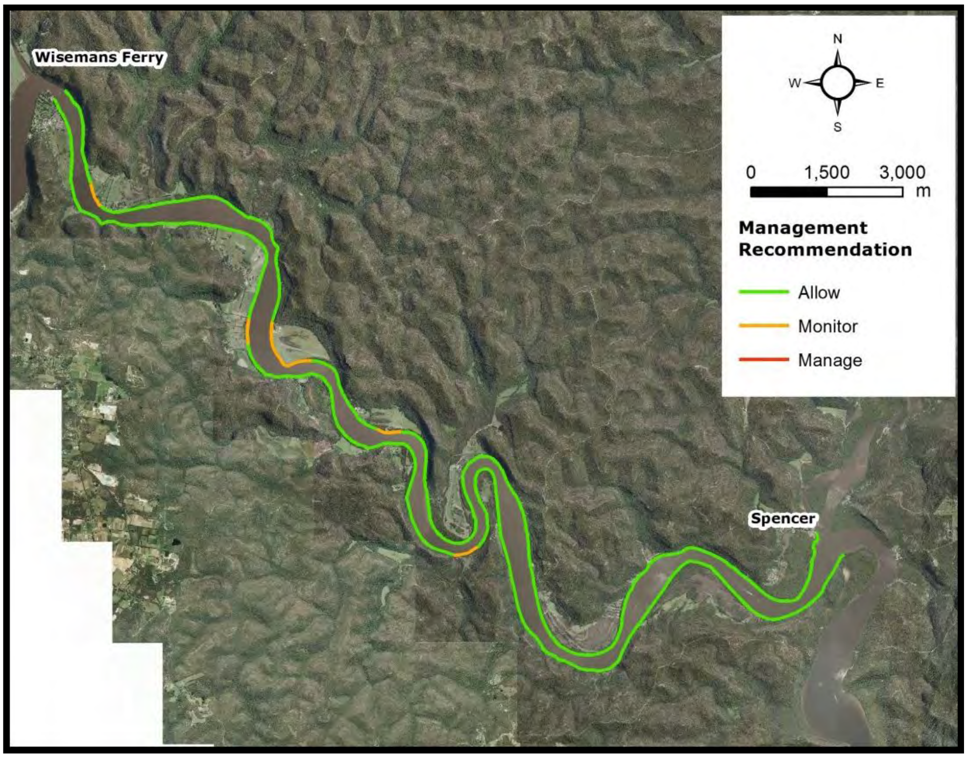


Figure H-6: DSS Management Recommendations – Waterski Operating - 150 Boat Passes - 8 Hour Duration (High Tide Conditions)

Appendix I – DSS Sensitivity Test for Holiday and Competition Conditions

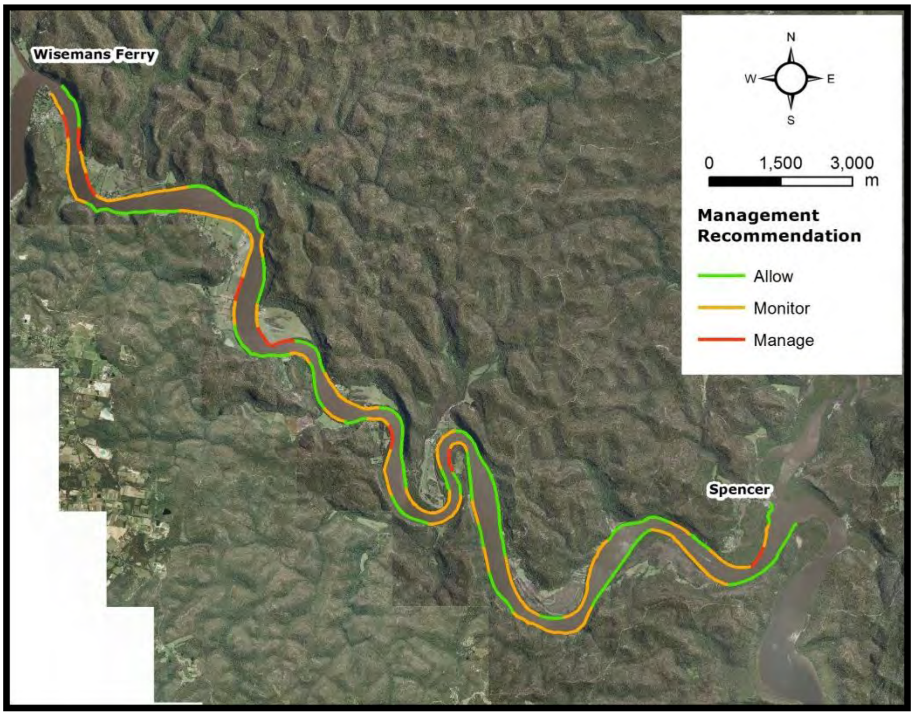


Figure I-1: DSS Management Recommendations – Wakeboard Operating - 500 Boat Passes - 12 Hour Duration (Mid – Low Tide Conditions)

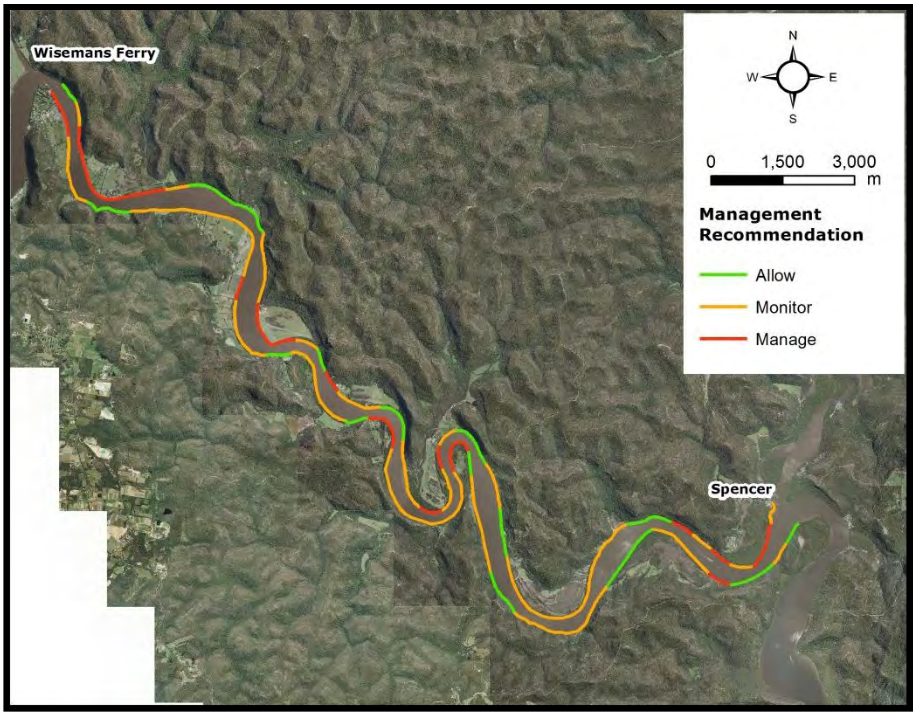


Figure I-2: DSS Management Recommendations – Wakeboard Operating – 1,000 Boat Passes - 12 Hour Duration (Mid – Low Tide Conditions)

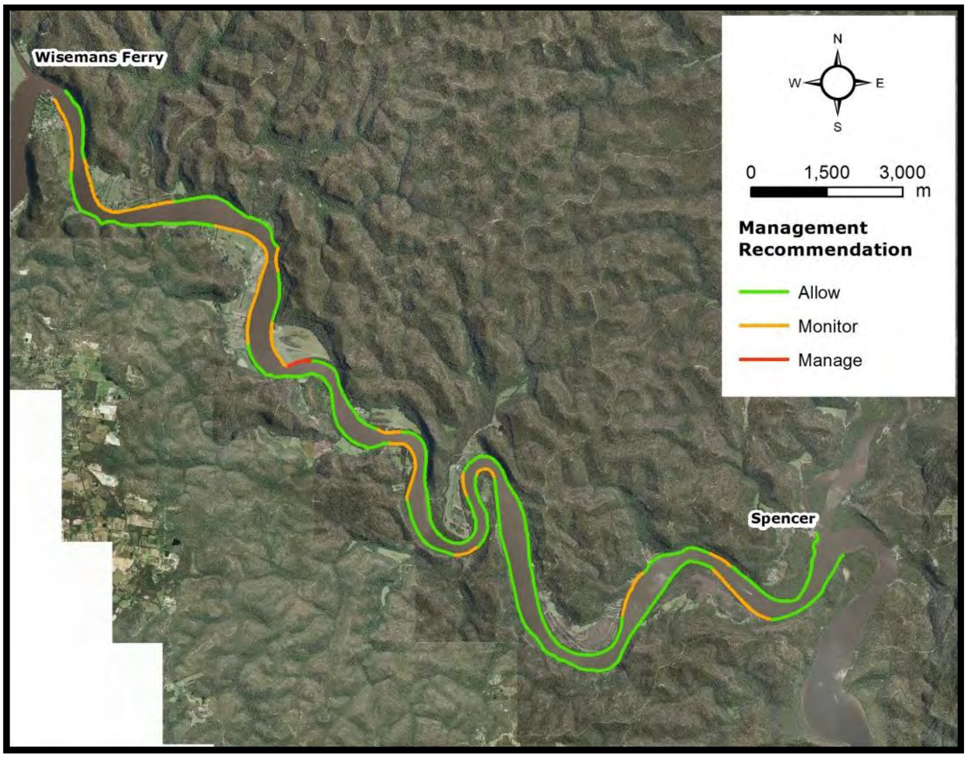


Figure I-3: DSS Management Recommendations – Wakeboard Maximum Wave - 50 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

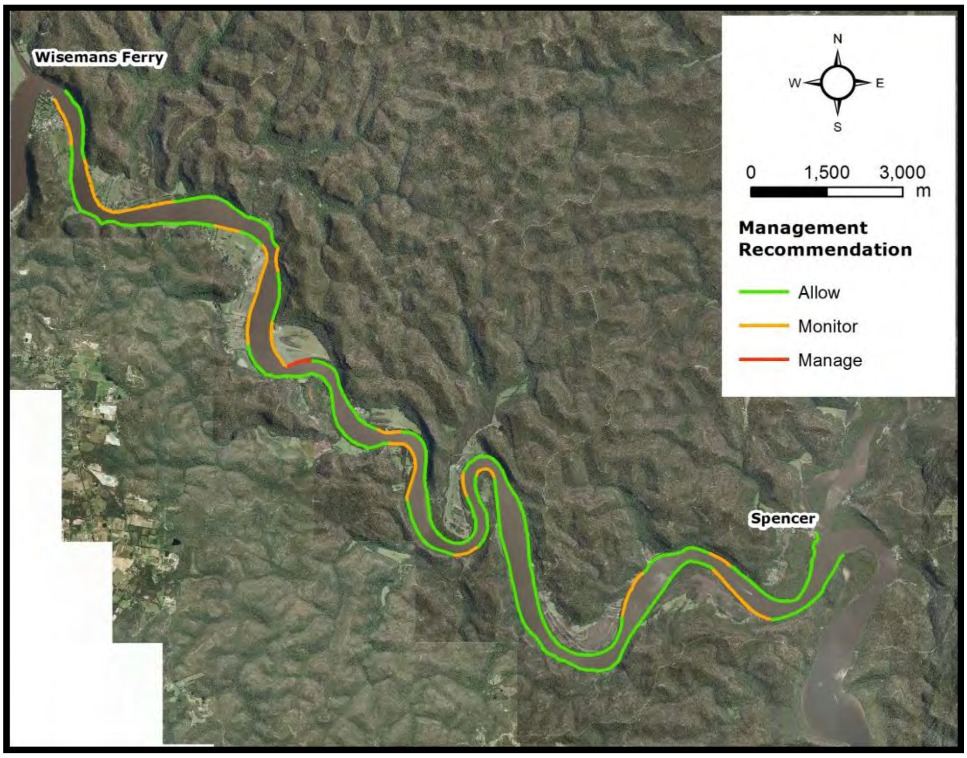


Figure I-4: DSS Management Recommendations – Waterski Operating - 500 Boat Passes - 12 Hour Duration (Mid – Low Tide Conditions)

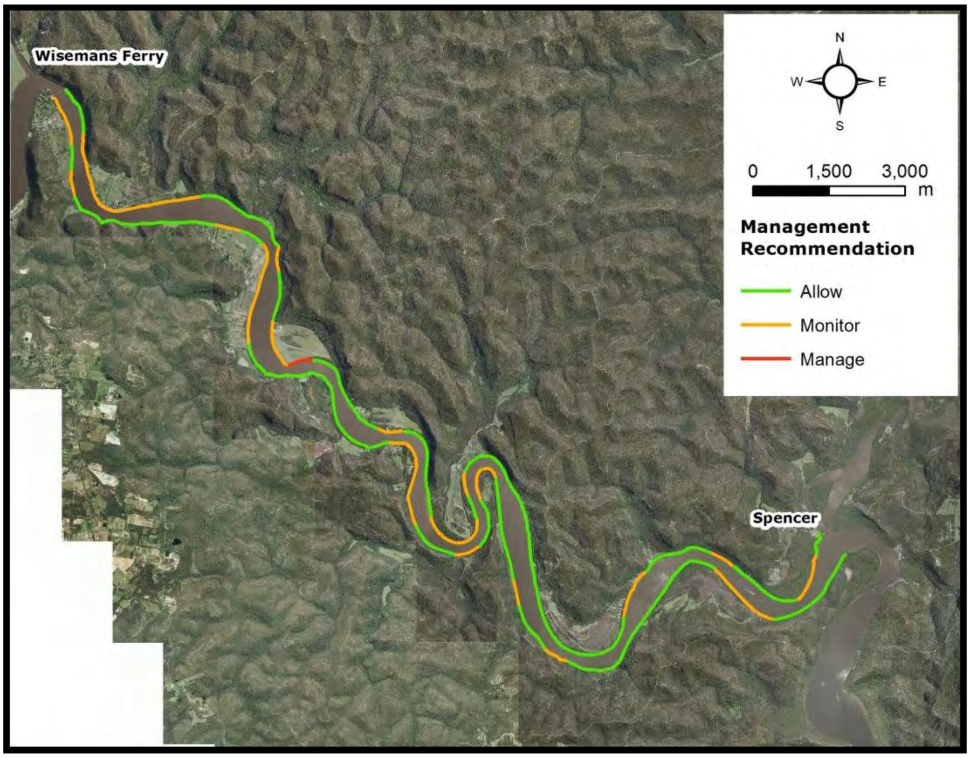


Figure I-5: DSS Management Recommendations – Waterski Operating – 1,000 Boat Passes - 12 Hour Duration (Mid – Low Tide Conditions)

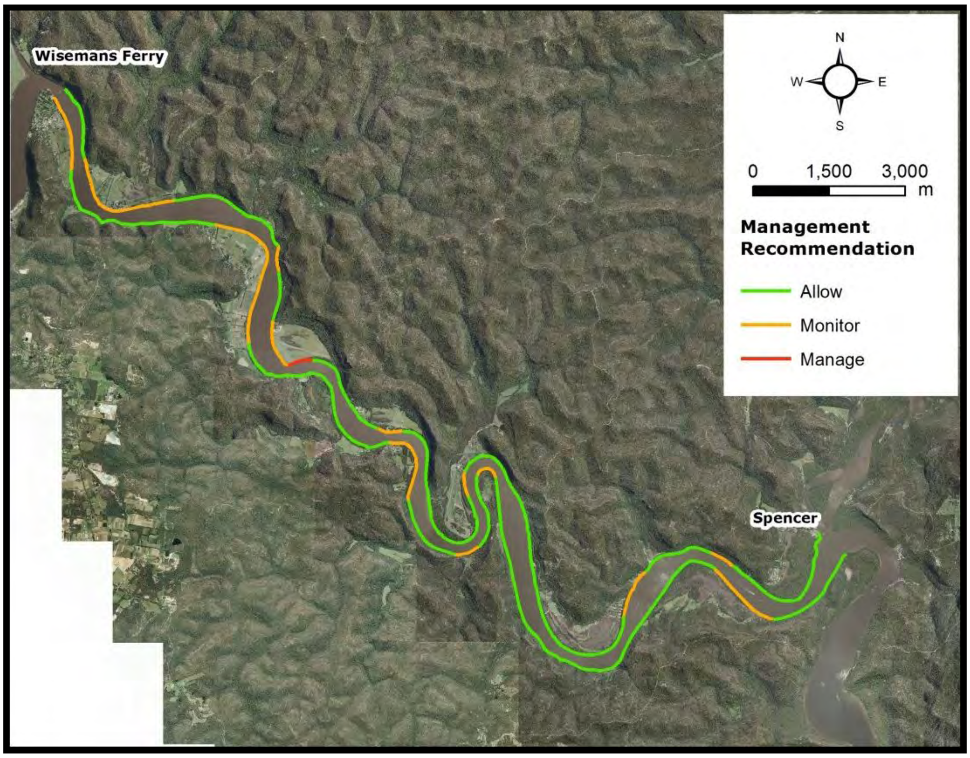


Figure I-6: DSS Management Recommendations – Waterski Maximum Wave - 50 Boat Passes - 8 Hour Duration (Mid – Low Tide Conditions)

Appendix J – DSS Sensitivity Test with Adjusted Local Wind Conditions

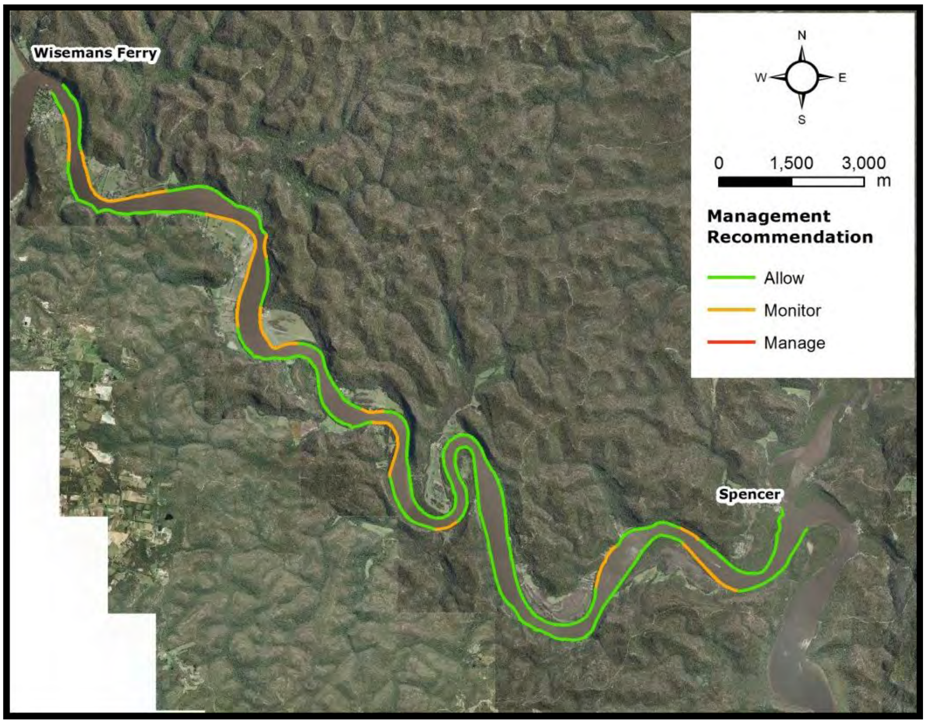


Figure J-1: DSS Management Recommendations – Wakeboard Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 10 Boat Passes)

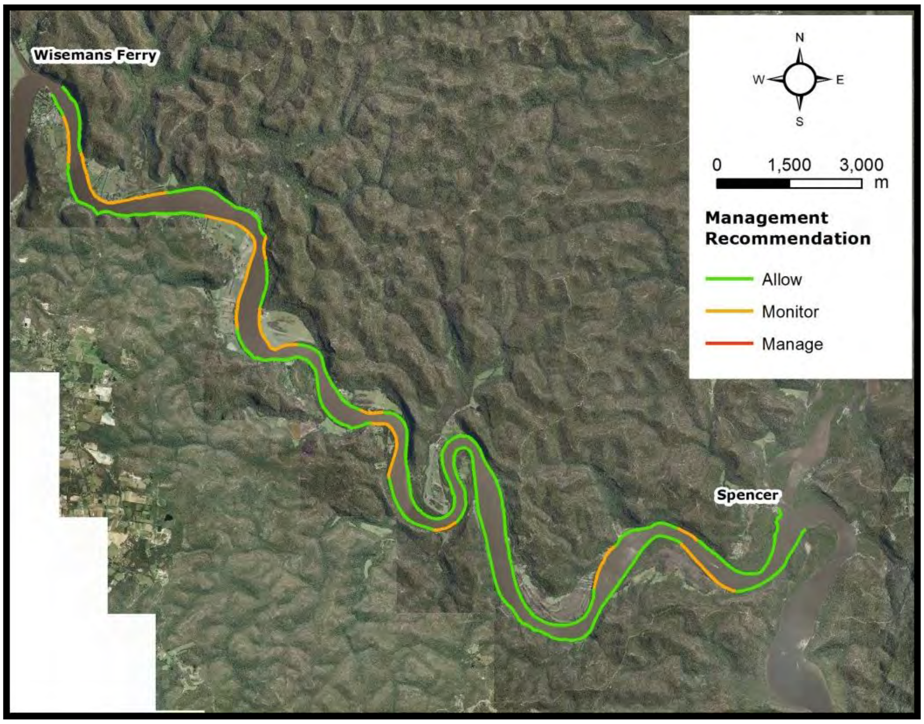


Figure J-2: DSS Management Recommendations – Wakeboard Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 50 Boat Passes)

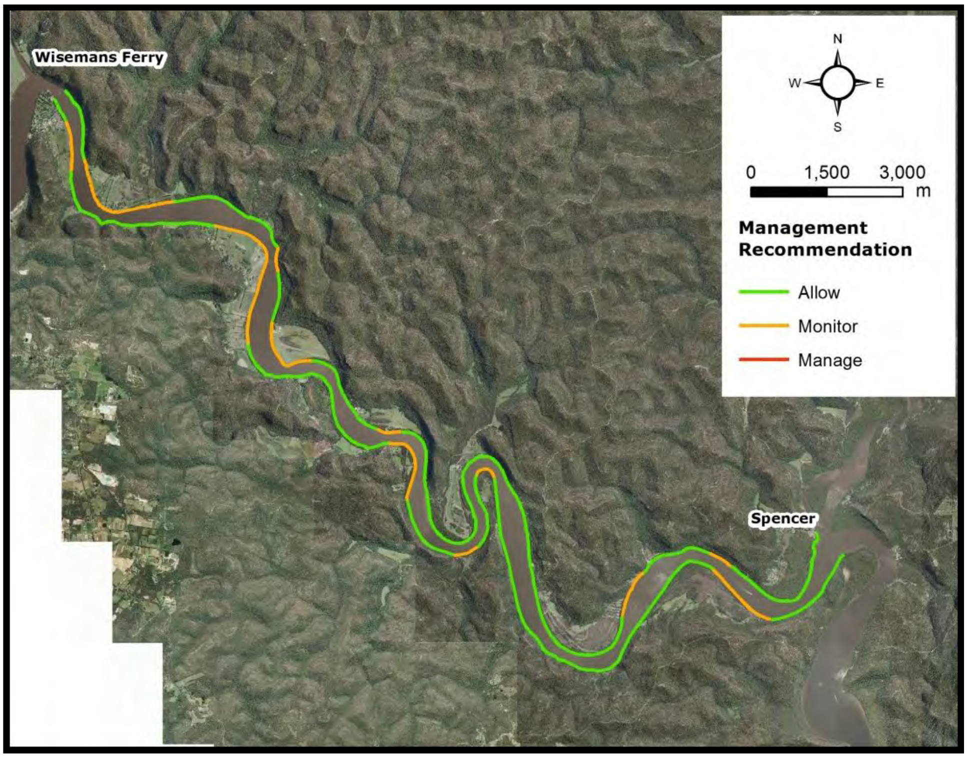


Figure J-3: DSS Management Recommendations – Wakeboard Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 150 Boat Passes)

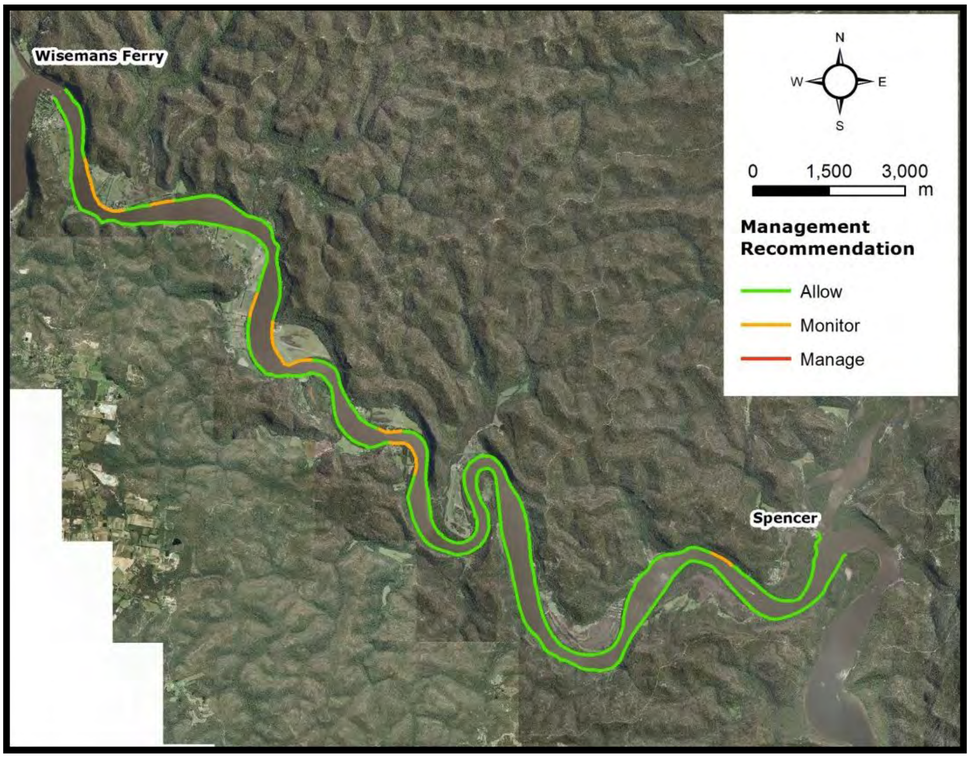


Figure J-4: DSS Management Recommendations – Waterski Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 10 Boat Passes)

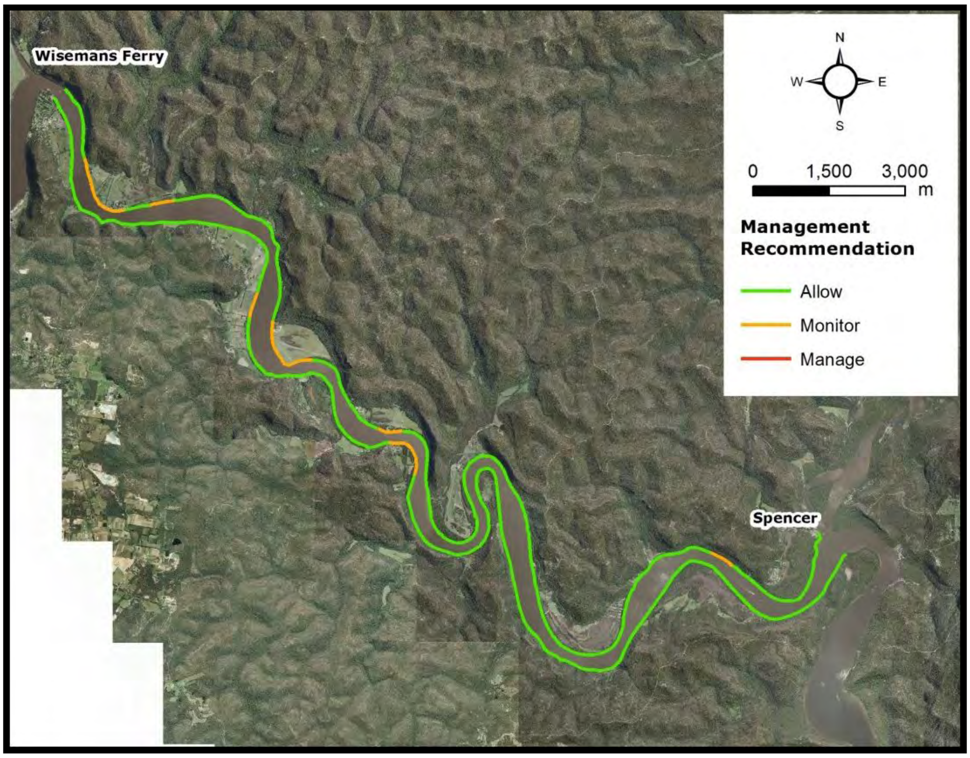


Figure J-5: DSS Management Recommendations – Waterski Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 50 Boat Passes)

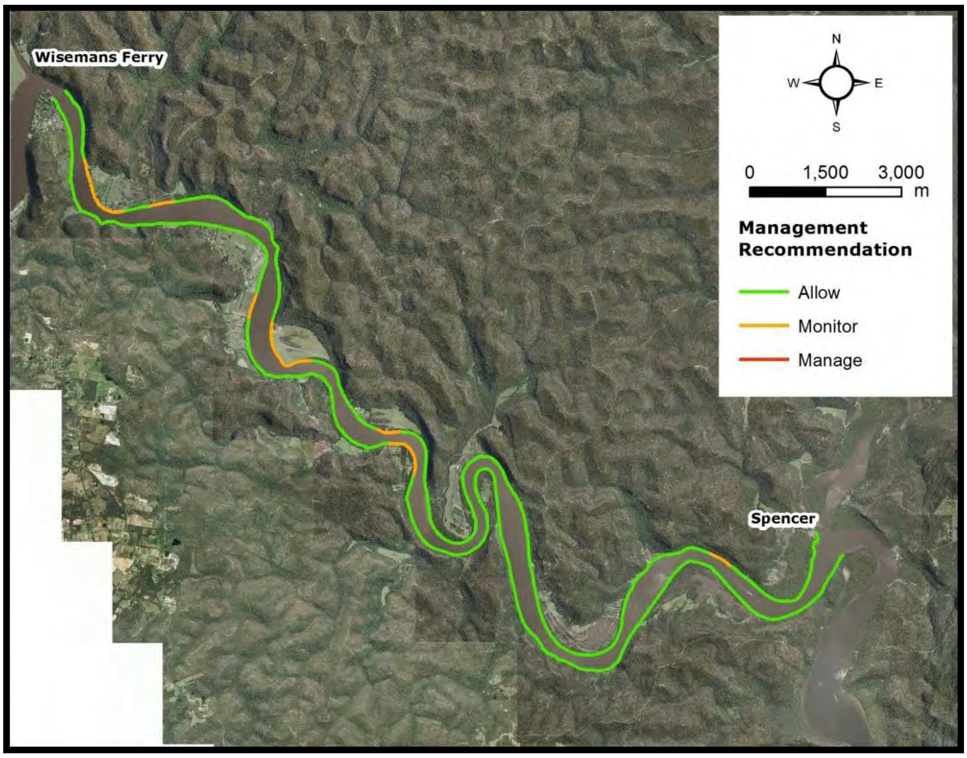


Figure J-6: DSS Management Recommendations – Waterski Operating – Adjusted Local Winds - 8 Hour Duration (Mid – Low Tide Conditions, 150 Boat Passes)