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Boat wakes as a cause of riverbank erosion: a case study from the Waikato River, New Zealand

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Abstract

While the causes of riverbank erosion have been the subject of numerous studies, little work has been done on the influence of waves, even though they are episodic high-energy events. Because of the increasing use of powered craft along much of the Waikato River, vessel wakes have the potential to cause significant shoreline change.

Wake wave characteristics and suspended-sediment concentrations were measured at a number of sites over a range of flow conditions. The sites included both stable reaches and areas where concern had been expressed over bank stability and erosion. The influence of the type of vessel on wave properties, and how these interact with variations in flow and bank characteristics were quantified, together with how these factors affected suspended-sediment concentrations.

The maximum wake waves generated by three different craft (jet boat, outboard-powered boat, and jet ski) ranged in amplitude from 6 to 133 mm. They were 2–80 times larger than background wind-generated waves, and had from 2 to over 100 times the energy of background waves. Boat wakes generated suspended-sediment concentrations of between 1 and 740 mg/l; background concentrations ranged from 1 to 31 mg/l. There was, however, no general relationship between maximum wave amplitude and suspended-sediment concentration. Instead, site-specific conditions such as water depth, the bank profile, the type, size, and supply of sediment, and bank resistance controlled suspended-sediment concentrations. While maximum wave amplitudes were generally lower with increasing distance from shore for non-vegetated sites under low flow conditions, the response was more variable under high flows, and for locations where the bank was vegetated. Vegetation acts as a filter, interrupting and breaking up the wave train. Fast boat speeds (50 km/h) created larger, and therefore higher energy, peak waves and higher suspended-sediment concentrations than slow speeds (10 km/h). During the trials, the jet ski produced smaller, lower energy waves and sediment concentrations than either of the boats when driven in the same manner i.e., in a straight line and sedately, but this is not a common practice for jet ski users. The outboard-powered boat produced much smaller maximum wave amplitudes but similar suspended-sediment concentrations to those measured during the jet boat pass.

The effects of boat wakes on bank erosion along the Waikato River are therefore not easily summarised. There was considerable variation in response both within and between sites for the same boat passing under the same flow conditions, and for different boat types and flow conditions. The effects of the wakes were highly specific to the site and conditions. This has significant manage-

ment implications. While it may be possible to estimate wave characteristics for various types of craft and conditions in deep, open water, such results have little relevance when predicting riverbank erosion at specific sites.

Introduction

Riverbank erosion has been the subject of numerous studies, most focusing on the effects of various flow parameters, such as velocity, turbulence and secondary eddies, on the bank material. Few studies, though, have investigated the influence of waves, either wind-generated or anthropogenic, on bank erosion and on the rate of bank retreat. Such studies are particularly lacking in New Zealand, although there has been a rapid growth in usage of a range of pleasure craft on rivers and lakes throughout the country. This paper examines boat wakes as a factor affecting bank erosion and sediment entrainment. It does not focus on the generation, characteristics, and dynamics of wave trains *per se*, a field in which considerable literature exists.

The passage of pleasure craft along a river, and the resulting waves, can be an important cause of bank erosion and the suspension of riverbed and/or bank sediment through a range of processes, including drawdown, vessel-generated currents and propeller wash (Parchure *et al.*, 2001). When a vessel passes over a water surface, pressure differences are developed at the air-water interface and a series of waves are produced. The magnitude and form of the vessel-generated waves, and currents, are the result of a complex interaction of the relative velocity of flow past the hull, the hull geometry, the clearance between the hull and the channel side and bottom, the hull displacement relative to the channel cross-section, and the speed and direction of travel of the vessel relative to currents in the channel. The period and direction of propagation of the waves depends on the vessel speed and the water depth (Nanson *et al.*, 1994; Sorensen, 1997).

Large vessels tend to generate large drawdown and small wave heights, while small vessels, such as pleasure craft, generate small drawdown and large wave heights (Parchure *et al.*, 2001). The time taken for these wake waves to reach the shore for a given offshore sailing distance, and the angle at which they strike the shore, are controlled by the divergent waves (i.e., oblique to the vessel track) produced by the vessel. These waves are characteristic of the hull shape and the vessel speed. In addition, the waves produced by a given vessel at a given speed have differing heights, periods, and energy levels. It is therefore difficult to predict from theory what the wake wave characteristics will be for a given boat in a particular setting (Kirk *et al.*, 2000). Predicting the dynamics, characteristics, and effects of the waves when they interact with the shore is even more problematic.

Parchure *et al.* (2001) found that the concentration of sediment brought into suspension by wake-induced waves depends on numerous parameters related to the vessel (size and speed, hull shape), the channel (size and shape, bank height), the sediment (type, erodibility), and the waves (height and period, time series of occurrence, time after passage of vessel, distance from vessel). At sites where sediments are finer, concentrations are likely to be higher because these sediments are more easily suspended and stay in suspension for a long time. The potential for downstream or offshore transport of this sediment is consequently increased. Coarser sediments require a higher bed or bank shear stress to be placed in suspension and, even if they are suspended, they settle back to the bed quickly. Small wake-induced waves may therefore not have sufficient energy to entrain these coarse sediments.

In geomorphic terms it is the amount of

wave energy and the rate at which this energy is transported towards the shore (i.e., the ability of the wave to do work) that are most important. Whether the wave energy is sufficient to overcome the resisting forces of the bank, causing erosion, depends on the frequency of wave impact and the energy in the waves relative to the resistance of the bank. Lake shores and riverbanks are sinks, dissipating oncoming wave energy. Where banks slope gently, the incident energy is dissipated so that each unit area of bank receives only a small proportion of the total energy. Where banks are steep the energy is focused over a much narrower surface area. Steep banks can also act like a wall interrupting the wave, so that even though critical break point conditions do not occur, as they would in shallow water, the waves still break at the cliff face. The direct impact of the waves, i.e., their normal force or pressure, or the tangential shearing forces applied by the movement of water, i.e., from waves breaking further from the cliff, may then be sufficient to erode a notch at the base of the cliff if the wave energy exceeds the resistance of the bank material (Pethick, 1984).

The angle at which wake waves strike the shore often differs from that of wind-generated waves, which are determined by wind direction and fetch. Furthermore, in waters where fetch is restricted, the height, period, and energy of wake waves can often exceed those of wind waves at the shore. Therefore wake-induced shoreline change can equal or exceed that caused by natural waves (Pickrill, 1978). Because of the increasing, use of powered craft along much of the Waikato River, and other water bodies in New Zealand, vessel wakes must be considered a potential agent of shoreline erosion and change.

Wake wave characteristics and suspended-sediment concentrations were measured at a number of sites along the Waikato River over a range of flow conditions. These sites included typical stable reaches, as well as all the areas where concern had been expressed over bank stability and erosion. The influence of the type of vessel on wave properties, and how these interact with variations in flow and bank characteristics (i.e., bank vegetation, form, and sediment type) were quantified, together with how these factors affected suspended-sediment concentrations.

Waikato River catchment

At 425 km, the Waikato River is the longest river in New Zealand and it drains the North Island's largest catchment, an area of over 14,000 km^2 (Fig.1). In terms of annual flow, which varies from about 130–190 m^3/s (mean 161 m^3/s) at the Lake Taupo Control Gates to 300–600 m^3/s (mean 421 m^3/s) at Mercer, the Waikato River is also the largest river in the North Island and the sixth largest in New Zealand. Total inflows to the catchment have been increased by about 20% as a result of the Tongariro Power Development and the diversion of water from adjacent catchments (Devgun *et al.*, 1999).

North of Lake Taupo, the Waikato River flows across the central volcanic plateau in a series of deeply incised ignimbrite gorges, transformed by power development into a chain of eight hydro lakes separated by short river reaches. Downstream from Lake Karapiro, the last of the hydro lakes, the Waikato flows across alluvial plains in an entrenched channel to Huntly and through low-lying swampy alluvial areas scattered with small lakes between Huntly and Mercer, reaching the Tasman Sea at the Waikato Heads (Port Waikato), approximately 50 km southwest of Auckland (Hancox *et al.*, 1999).

Power development on the Waikato River has provided a wide range of recreational opportunities and facilities, including boating (both motorised and non-motorised) and other water sports (e.g., water and jet skiing) that may affect the geomorphic processes operating on the riverbanks and lake shores (Roper, 2001; Waikato Valley Authority, 1979).

A survey of bank erosion along the Waikato River showed a strong correlation between wave intensity and energy, and the incidence of erosion (Harding, 2000; McConchie, 2001; Toleman, 2002). A field investigation, including detailed measurements, was therefore carried out to quantify the effect of the interaction of waves with the riverbank and erosion processes.

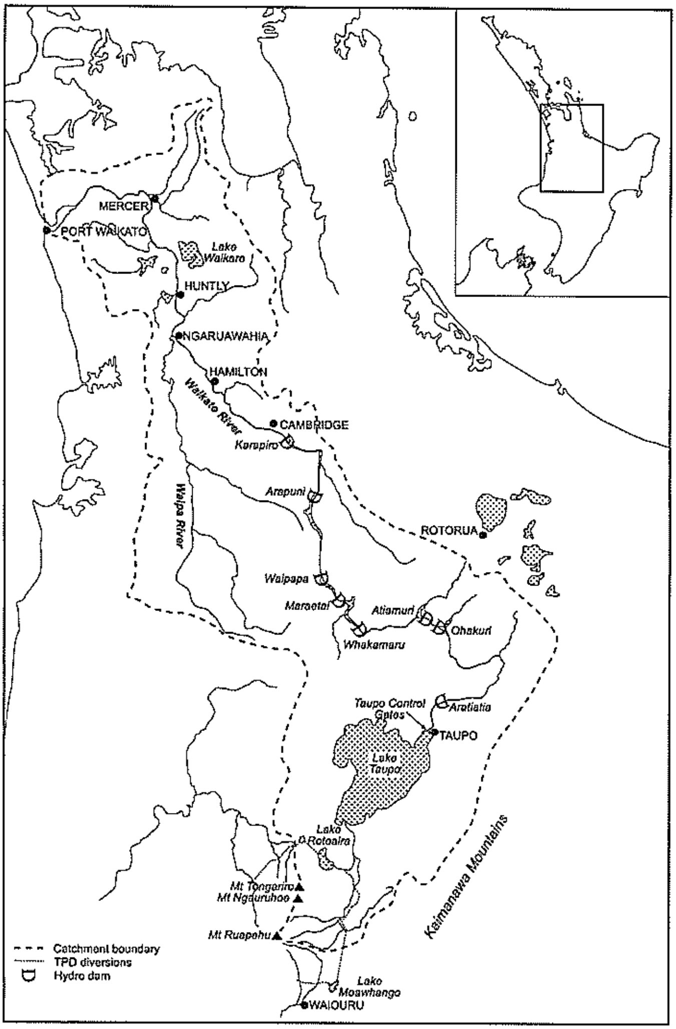

Figure 1 – The Waikato River catchment showing the locations of the eight hydro dams and the major tributaries. Note: the Tongariro Power Development (TPD) diversions from adjacent catchments increase the total volume of flow down the river.

Methods

Site selection and characteristics

Measurements of the wave train and suspended-sediment concentration generated by three different types of powered craft were made at a number of sites on the Waikato River. These sites were chosen to reflect variation in bank form (steep cliff and gently shelving), vegetation (vegetated and non-vegetated), and material (hard cemented bedrock and loose unconsolidated sands). Two sites were located along the upper river, two on Lake Karapiro, and four along the lower river (Fig. 2). Sampling was carried out under conditions typical of the two ends of the flow regime used for hydro-electric power generation.

At *River Road, Broadlands,* a vertical pumice bank of Taupo Alluvium rises directly from the high water level, while a shelving sandy beach exists between low and high operating water levels. At *River Road, Broadlands – downstream,* the slope profile is almost identical, but the bank consists of sands, silts, and clays and is fully vegetated with a mixture of willows, reeds, blackberry,

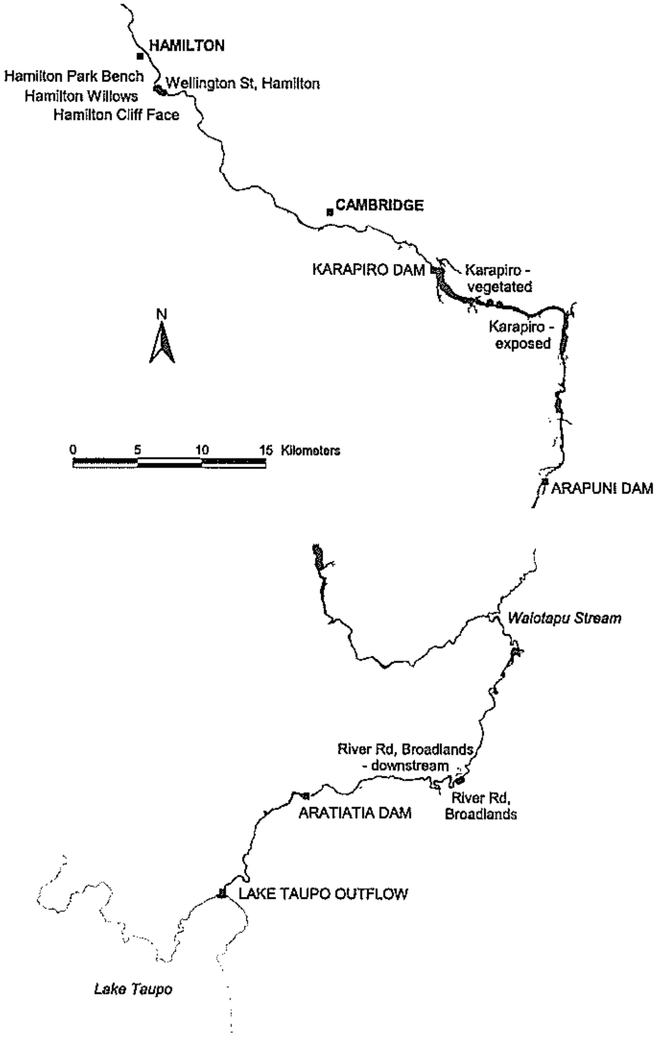

Figure 2 – Measurement sites were located along two sections of the Waikato River: between Lake Taupo and Lake Ohakuri; and between Lake Karapiro and Hamilton City.

and grasses. Measurements were taken at flows of 210 m^3/s (high) and 60 m^3/s (low) at these two sites.

At *Lake Karapiro – exposed*, a gently shelving sandy beach is backed by a small (approximately 0.5 m) bank formed in unconsolidated alluvial sediments. *Lake Karapiro – vegetated*, approximately 200 m north of the exposed site, has a similar profile and material but is fully vegetated with flax and various weed species. Measurements were taken at two water levels: 52.8 m (high) and 51.7 m (low).

At *Hamilton Cliff Face*, *Hamilton Willows*, and *Hamilton Park Bench* the bank is vertical and in consolidated Hinuera Formation. The bank material is primarily sands, silts, and clays. Both *Hamilton Willows* and *Hamilton Park Bench* are well vegetated down to the water level; at *Hamilton Cliff Face*, however, only the upper section of the cliff is vegetated. The offshore profile at *Wellington St, Hamilton* is much flatter than at any of the other sites except those at Karapiro. The site exhibits a sandy shelving beach that extends a considerable distance off shore. At high flows the water extends over a grassed upper slope. At *Hamilton Cliff Face* and *Hamilton Park Bench* measurements were taken at flows of 350 m^3/s (high) and 150 m^3/s (low). At *Hamilton Willows* and *Wellington St, Hamilton*, measurements were taken at flows of 400 m^3/s (high) and 150 m^3/s (low).

Measurements

Wave trains were generated using a 5-metre fibreglass jet boat travelling in the same manner both upstream and downstream at a distance of approximately 15 m from the bank at all sites. The boat travelled past the sites in a straight line at two speeds, a displacement speed of approximately 10 km/h (slow) and planing speed of approximately 50 km/h (fast). The actual speed across the bed, however, will be either increased or decreased by the water velocity, depending on the direction of travel. At *Wellington St, Hamilton,* wave trains were also generated by a 5.5-metre fibreglass boat (powered by a 140 Hp outboard motor) and a jet ski. To ensure the comparability of data all three craft were driven in the same manner, and at the same distance from the bank. From observations made during the field work, jet skis are seldom driven sedately and in a straight line. It is impossible, however, to model and then sample "typical" jet ski use.

Wave amplitudes were measured using Greenspan Model PS225 Pressure Sensors, which have a range of 0–2.5 m and a linearity and repeatability of ± 0.2% of full scale. The transducers were connected to Unidata Yellow Loggers. Values were logged at four hertz. The sensors were attached to poles either driven into the riverbed, or supported from a frame suspended above the water. Measurements were made at three or four locations within 7 m of the water's edge and perpendicular to the river flow. The spacing between measurement positions was determined by the morphology of the riverbank, however, the first position was always located as near to the bank as practicable (Fig. 3). All sensors were at a nominal depth of 300 mm below the water surface. The depths were corrected to a common datum during processing to accommodate variations in water level during sampling, and the shallow depth at the near-bank sampling point. Where the riverbank sloped gradually, the outer-most sensor was placed in water close to one metre in depth. Where the riverbank was steep, the outer-most sensor was placed in water greater than one and a half metres in depth.

Suspended-sediment samples were collected throughout the duration of the wave trains resulting from each boat pass at each sensor position, using submersible, in-line pumps (maximum flow rate of 13 *l*/min). The maximum particle size of the sampled material was potentially restricted by the pump's 6 mm square filter orifice, however, this opening exceeded significantly even the largest particle size in suspension. The samples were depth-integrated, with the exception of the near-bank sample, which required fixed-point sampling because of the limited water depth. To obtain a depth-

Figure 3 – Wave measurements and suspended-sediment samples were collected at each sensor position under a wide range of conditions.

integrated sample the inlet to the pump was moved steadily up and down through the entire water column for the duration of the wave train, and until all sediment had moved through the sampling tube into the collection bucket. Once sampling was complete, the sample was agitated to ensure even mixing, and then a sub-sample was taken to determine the suspended-sediment concentration. It was necessary to collect the near-bank sample by hand at *River Rd, Broadlands* because the excessive amount of suspended material at this site clogged the pump. It is stressed that these sediment concentrations were measured using "pumped samples", rather than sampling sediment actually moving downstream. This is because at many of the sites there was not sufficient downstream flow to carry the sediment into a depth-integrating sampling vessel. As a result, these measurements are likely to overestimate the amount of material actually moving downstream.

The wave signal from each boat pass was modelled using a Fast Fourier Transformation (FFT), optimised to correctly "fit" the measured wave amplitude. Once the wave signal was modelled, the wake and background (of the same duration) wave trains could be separated and their specific characteristics calculated:

- *Number of waves*: calculated as the number of troughs or peaks in the wave train.
- *Duration*: calculated as the difference between the start and end time of the wave train.
- *Energy of wave train*: calculated using Airy wave theory ($E = \frac{1}{8}\rho g \sum H_n^2$, where $\sum H_n$ = summation of all individual amplitudes present in the wave train).
- *Maximum amplitude*: calculated as maximum water level minus mean water level, where the mean water level equals the still water level. The maximum amplitude is therefore half the maximum wave height.
- *Period of maximum amplitude wave*: calculated as the time from the maximum amplitude to the next peak.
- *Energy of the maximum amplitude wave*: calculated using Airy wave theory ($E = \frac{1}{8}\rho g \sum H_{max}^2$, where H_{max} = maximum amplitude).

Discussion of measurements

Wave characteristics that describe the entire wave train may give a better measure of its erosive potential than measures, such as peak amplitude, that describe only part of it. There were, however, difficulties at some sites in determining the exact length of the wake train, particularly the point at which the effect of the boat ceased. It was therefore not possible to calculate consistent, and therefore comparable, energy values for the wake train for all trials. Maximum wave amplitudes were therefore used for analysis. Because wave energy increases with amplitude, maximum energies (and therefore maximum erosion potential) occur at sites with the greatest wave amplitude. It may be argued that maximum wave amplitude is not a good measure of the erosive energy of the wake where the train has a series of peaks close to that of the maximum wave amplitude. However, it is equally possible that the erosive energy of the wave train is concentrated in a small part of the train, with the remaining waves having little effect (Nanson *et al.*, 1994). The maximum wave energies are also more significant, as they are most likely to exceed any resistance threshold of the bank material. Once this threshold is exceeded, and the bank erodes, lower-energy waves or currents may be able to transport the material away from the site. The following analysis therefore refers to the maximum amplitude of both the wake and background waves. Unless otherwise specified, all analysis is based on data collected during runs made using the 5-metre jet boat at two speeds: fast (50 km/h) and slow (10 km/h).

Suspended-sediment concentrations were measured to indicate the effectiveness of the waves at entraining sediment. While not a direct measure of erosion, since the material may not be removed from the site but simply redistributed across the bank profile, such data are indicative of the erosion potential of the waves. Sediment may also be dislodged by the action of the propeller, vessel-induced return currents, drawdown of the water surface, or currents in the area (Parchure *et al.*, 2001), as well as by wave action. However, it is impossible to isolate the contribution of each of these factors. The suspended-sediment concentrations measured are therefore the result of contributions from all sources at each site. The relative difference between the wake and background values, however, must reflect largely the influence of the boat wake.

Results

The nature of the interaction of waves with the bed and banks, and the resulting variation in sediment concentrations along the Waikato River, were highly site-specific. It may have been possible to characterise the wake trains for various types of craft and conditions in deep, open water. However, once the waves neared the shore their nature and effect were controlled by a range of site conditions, e.g., slope profile, material type, and vegetation. A number of general trends, however, could be identified.

The maximum amplitude of wake waves generated by the three craft used in the experiments ranged from 6 to 133 mm by the time they arrived at the bank. Their wave periods ranged from 0.5 to 2.75 s, with an average of 1.6 s. Each wave train consisted of from 9–61 wave crests and lasted from 17.0–71.5 s. Wake waves were 2–80 times larger, and had up to 100 times more energy, than the background wind-generated waves (maximum background waves ranged in amplitude from 1 to 24 mm).

Boat wakes generated suspended-sediment concentrations of between 1 and 740 mg/l, while background concentrations ranged from 1 to 31 mg/l. Concentrations within the boat wake were up to 100 times higher than those under background conditions at sites within 1 m of the shore. They were up to 50 times higher at distances greater than 1 m from the shore. However, although this indicates a trend between wave amplitude and suspended-sediment concentration, no statistical relationship exists. Rather site-specific conditions such as depth; profile; and sediment type, size, supply, and resistance all affect suspended-sediment concentrations, not just the maximum wave amplitude.

Maximum wave amplitudes, and therefore energies, generally decreased with distance from shore for non-vegetated sites under low-flow conditions. The response was more variable under high flows, where the shape of the offshore profile was often less significant because of the greater depth of water relative to wave amplitude (Fig. 4). Bank vegetation acts as a very effective filter, interrupting

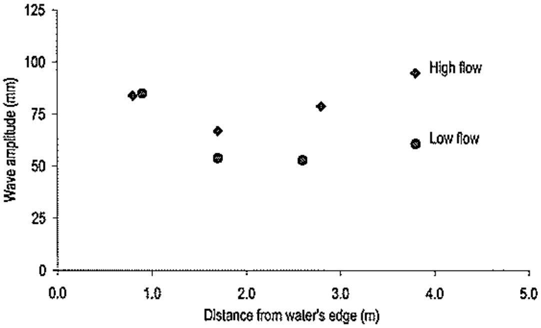

Figure 4 – Vessel-generated near-shore maximum wave amplitudes under high (210 m^3/s) and low (60 m^3/s) flow conditions: *River Road, Broadlands*, with the boat travelling downstream fast.

and breaking up the wave train, so no trend between wave amplitude and distance from shore is apparent at vegetated sites ($r^2 = 0.00$). The exact nature of the change in wave amplitude with distance from the shore therefore again depends on specific site conditions such as profile, water depth, and vegetation.

There was no general relationship between suspended-sediment concentration and distance from the shore ($r^2 = 0.08$), even though sediment concentrations were highest right at the shore. High sediment concentrations at the shore tended to reflect greater sediment availability and turbulence caused by the breaking of the waves.

There was no trend between maximum wave amplitude and flow condition (i.e., high or low discharges). For example, within 1 m of the water's edge at *Hamilton Willows* and *Wellington St*, maximum wave amplitudes were greater under low-flow than high-flow conditions for both boat speeds. At *River Rd, Broadlands* and *Hamilton Park Bench*, maximum wave amplitudes were greater under low-flow conditions for slow boat speeds, but results were more variable for fast boat speeds. At *River Rd, Broadlands – downstream*, maximum wave amplitudes were greater under high-flow conditions for fast boat speeds, but not for slow boat speeds (Table 1).

Likewise, there was no general relationship between suspended-sediment concentrations and flow conditions. For example, at distances less than 1 m from the water's edge, suspended-sediment concentrations were higher under low-flow conditions at *River Rd, Broadlands – downstream*, *Hamilton Willows*, and *Wellington St*. They were higher under high-flow conditions at *River Rd, Broadlands* and *Hamilton Park Bench* (Table 2). The resistance of the bed and banks at the point of wave impact therefore controlled wake-generated sediment concentrations.

Fast boat speeds (50 km/h) created larger, and therefore higher energy, peak waves and higher suspended-sediment concentrations than slow speeds (10 km/h). This was particularly evident within 1 m of the water's edge (Tables 1 and 2). The high boat speeds, even when going slowly, relative to the velocity of the river, probably explains the lack of influence that the direction of travel has on wave amplitude. For example, within 1 m of the water's edge at *Hamilton Cliff Face* under high-flow conditions the boat passing upstream fast created greater maximum wave amplitudes than when it travelled downstream fast. However, downstream slow passes created greater maximum amplitudes than upstream slow passes. In contrast, at *River Rd, Broadlands – downstream*, maximum wave amplitudes were greater during downstream

Table 1 – Maximum vessel-generated wave amplitudes (mm) within 1m of the water's edge.

	Low flow				High flow			
	D/s fast	**D/s slow**	**U/s fast**	**U/s slow**	**D/s fast**	**D/s slow**	**U/s fast**	**U/s slow**
River Rd, Broadlands	85	95	93	26	84	22	118	11
River Rd, Broadlands – downstream	71	Nw	49	Nw	85	Nw	57	12
Hamilton Cliff Face	–	–	–	–	41-78	38-48	58-108	Nw
Hamilton Willows	67	33	79	Nw	46	6	45	Nw
Wellington St, Hamilton	–	42	102	–	61	13	39	37
Hamilton Park Bench	54-70	37-43	55-63	Nw	62-99	16-27	52-73	Nw

Note: Nw indicates that no measurable wave train was detected. A range is shown where measurements were made at multiple points within 1m of the water's edge.

Table 2 – Vessel-generated suspended-sediment concentrations (mg/l) within 1m of the water's edge.

	Low flow				High flow			
	D/s fast	D/s slow	U/s fast	U/s slow	D/s fast	D/s slow	U/s fast	U/s slow
River Rd, Broadlands	175	85	113	1	740	96	324	64
River Rd, Broadlands – downstream	172	17	170	60	130	18	149	29
Hamilton Cliff Face	–	–	–	–	7-20	5	8-71	5-6
Hamilton Willows	84	27	147	8	37	5	29	11
Wellington St, Hamilton	–	164	254	–	18	8	27	10
Hamilton Park Bench	134	3-13	41-164	1-5	282	5-19	19-218	6-14

Note: A range is shown where measurements were made at multiple points within 1m of the water's edge.

fast boat passes than upstream fast passes at both high and low flows (Table 1).

The speed of the boat relative to river velocity may also explain why no general relationship was found between the direction of travel and suspended-sediment concentrations. For example, under high-flow conditions suspended-sediment concentrations within 1 m of the bank were higher during downstream fast passes than upstream fast passes at *River Rd, Broadlands, Hamilton Willows,* and *Hamilton Park Bench.* They were lower during downstream fast passes at *Hamilton Cliff Face* and *Wellington St.* For low flows, downstream fast boat passes generated higher suspended-sediment concentrations than upstream fast passes at *River Rd, Broadlands,* but lower concentrations at *Hamilton Willows* (Table 2).

During the trial, the jet ski produced smaller, lower-energy waves (Fig. 5) and lower sediment concentrations (Fig. 6) than either the 5.5-metre outboard boat, or the jet boat, when driven in the same manner under the same flow conditions. However, the jet ski was driven sedately and in a straight line approximately 15 m from the bank, so that the effect of its wake would be directly comparable to the wakes produced by the other craft in the trials. Jet skis, however, are seldom actually driven in this manner. Modelling the highly variable, and "erratic",

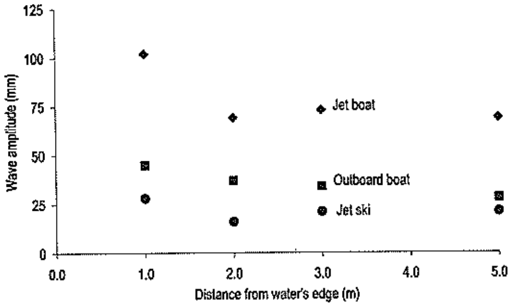

Figure 5 – The effect of different types of powered craft on the maximum wave amplitude: *Wellington St, Hamilton,* under low flow conditions with the craft travelling upstream fast.

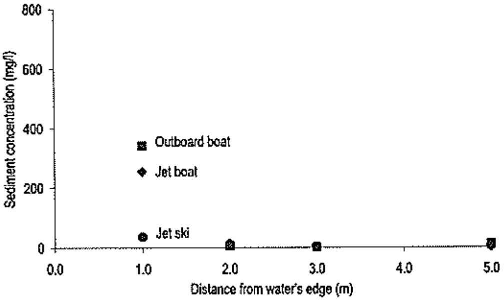

Figure 6 – The effect of different powered craft on suspended-sediment concentrations: *Wellington St, Hamilton,* under low flow conditions with the craft travelling upstream fast.

passage of a jet ski was beyond the scope of this study. The data collected, however, would suggest that site-specific factors are likely to have a major influence on bank erosion and suspended-sediment concentrations. The 5.5-metre outboard-powered boat produced much smaller maximum wave amplitudes, but similar suspended-sediment concentrations, to those measured during the jet boat passes.

Bank vegetation has a significant effect on reducing maximum wake wave amplitudes, peak wave energy and, in combination with other site characteristics, suspended-sediment concentrations. For example, sediment concentrations at *River Rd, Broadlands* were generally higher than those measured at *River Rd, Broadlands – downstream*, which is well vegetated. The vegetation rapidly breaks up the form and energy of the wake wave train (Fig. 7). Suspended-sediment concentrations were higher under high flows at *River Rd, Broadlands* because of the exposure of the pumice bank to the wave energy. Concentrations were highest near the bank at both sites, but peak concentrations did not coincide with maximum wave amplitudes at *River Rd, Broadlands – downstream*. Peak wave amplitudes and suspended-sediment concentrations at *Wellington St* (non-vegetated) and *Hamilton Park Bench* (vegetated), and the vegetated and exposed sites at Karapiro, however, are controlled more by flow conditions and boat direction than vegetation cover alone. During slow passes of the boat, where peak waves were small and low in energy, vegetation reduced variations in water level to the point that the wake waves could not be isolated from background waves.

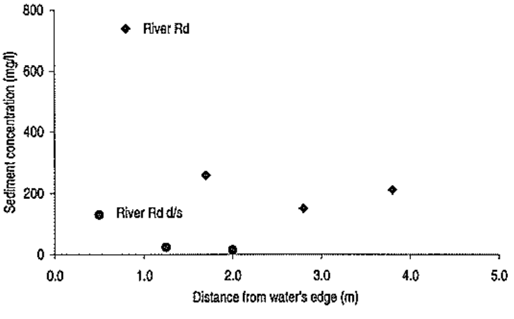

Figure 7 – The effect of vegetation on suspended-sediment concentrations: *River Road, Broadlands – downstream* (vegetated) and *River Road, Broadlands* (exposed pumice bank). The measurements were taken under high flow conditions with the boat travelling downstream fast.

There was no general trend between the characteristics of the bank and near-shore bed profile, and the maximum wake amplitudes at the shore. Wave amplitudes are potentially greater where there are gently sloping profiles because water depths are less. However, the exact nature of the response depends on both site and vessel-related conditions. For example, under high-flow conditions and at a distance of 1.0 m from the water's edge, water depth is approximately 0.3 m at the exposed shelving beach at *Wellington St*, and 0.6 m at the steep bank at *Hamilton Cliff Face*. Maximum wave amplitudes at this distance were higher at *Wellington St* during upstream slow passes but were higher at *Hamilton Cliff Face* during downstream slow and upstream fast passes (Table 1). Comparisons between *Wellington St* and the steep bank at *Hamilton Park Bench* are equally variable. Under low-flow conditions and at a distance of 1.0 m from the water's edge, water depth is approximately 0.2 m at *Wellington St*, and 0.6 m at *Hamilton Park Bench*. Maximum wave amplitudes were higher at *Wellington St* during the upstream fast boat pass. Under high-flow conditions, water depth was 0.5 m at a distance of 0.75 m from the water's edge at *Hamilton Park Bench* and 0.3 m at a distance of 1.0 m at *Wellington St*. Maximum wave amplitudes were higher at *Hamilton Park Bench* for downstream fast and slow, and upstream fast boat passes, but were higher at *Wellington St* for upstream slow passes.

The characteristics of the material forming the bank and near-shore riverbed have a significant influence on the suspended-sediment concentrations. The amount of sediment brought into suspension at sites where the bank and bed material is soft and unconsolidated was much greater than at sites where this material is compact or cemented, and therefore resistant to wave action For example, at high flows, suspended-sediment concentrations at *River Rd, Broadlands* where bed and bank sediment is soft, were 1–2 orders of magnitude greater than at *Hamilton Cliff Face*, where material was hard and compact (Table 2). There was, however, no obvious relationship between suspended-sediment concentrations and the particle size distribution. For example, sediment concentrations were much higher at *Hamilton Park Bench*, particularly during high flows, than at *Hamilton Willows*, even though particle size distributions at the two sites are comparable, i.e., sands, silts, and clays. Similarly, concentrations at *Wellington St* (where bank material is dominated by sands and gravels) were higher than at *Hamilton Park Bench* (where bank material is composed of sands, silts, and clays) under low flows, but much lower under high flows.

The interaction of a range of site-specific factors, including bed profile, material characteristics, and vegetation, therefore affect wave characteristics, their erosion potential, and suspended-sediment concentration. The interaction of these factors with the wake train masks any effects caused by vessel type, speed, and direction of travel. This makes quantifying simple relationships between vessels, wakes, and suspended-sediment concentration extremely difficult.

Discussion

The results presented above indicate that wake-induced waves are more effective at suspending and transporting sediment than wind-generated waves on the Waikato River. This is particularly the case near the shore where the water is shallowest. In general, waves generated at a vessel speed of 50 km/h were higher in energy, and created higher suspended-sediment concentrations, than those generated at a speed of 10 km/h. The exact extent of erosion or sediment suspension was, however, controlled by the presence or absence of vegetation at the bank; the type and resistance of the bed and bank sediment; the bank profile; the level at which waves were interacting with the bank; and the type of vessel. To a lesser degree, the direction of boat travel also affected the impact of waves at the shore.

Of the sites investigated, those most susceptible to wake-induced erosion were characterised by a lack of vegetation, and soft and unconsolidated bed and bank sediments. Sites least affected were characterised by significant bank vegetation and/or hard, cemented bank material. However, the degree of bank exposure, and the position at which wave energy interacted with the bank, i.e., as a function of flow conditions, were also important controls. Depending on the nature of the bed and/or bank profile, higher suspended-sediment concentrations occurred at either low or high flows. In addition, while fine sediment may require higher wave energy for entrainment than larger particles (i.e., fine sands or coarse silts), once suspended the potential for offshore or downstream transport is much greater because of their low depositional threshold.

The suspended-sediment concentrations measured were a combination of newly eroded sediment and material re-suspended from the bed and banks. While this suspended sediment may be transported offshore or downstream, it may also be simply redistributed across the bank profile. The measurements therefore indicate the effectiveness of wake wave action as a potential erosive agent rather than the amount of erosion occurring *per se.*

The response of the near-shore environment to waves is highly site-specific, and influenced by a range of factors. For example, bank material may be cohesive or non-cohesive. Banks can also have highly variable geotechnical properties, even over short distances, both along the bank and vertically up the bank (ASCE, 1998). In addition, it is the combination of several factors, rather than any individual influence, that controls the occurrence and extent of erosion. It must also be remembered that while wake waves have more erosive potential than wind waves, they persist for only a relatively short period. Boating activity, however, is increasing rapidly on the river and hydro lakes and this will lengthen the duration of these high-energy conditions. Because the profile of, and sediment distribution in, the near-shore zone have developed in response to the "natural" energy regime, there is the potential for significant shoreline change as it develops a morphology in equilibrium with the new, higher energy, vessel-induced wave climate. Also, the wake energy may exceed an erosion threshold and destabilise material, resulting in erosion and perhaps bank collapse. Material entrained in this manner may then be able to be moved by lower energy conditions.

Vessel-generated waves

Although the results of the current study are highly site-specific, a number of general comments can be made regarding the potential for wake-induced erosion. As already discussed, the pressure distribution and the resulting height of waves generated by a vessel passing over a water surface depend on the vessel speed, the hull geometry, and the clearance between the hull and the channel side and bottom (Sorensen, 1997). For a given vessel hull form and speed, pressure variations and wave heights increase as the channel width decreases. If channel width remains constant, wave heights will increase with increasing speed, assuming the vessel does not plane (i.e., skim the water surface). Planing alters the magnitude of the pressure gradient and the total pressure change acting along the hull. Wave heights and erosion potential will therefore be greater where channels are confined, such as along the Waikato River.

In addition, wake waves generally fall in height to half their initial value within 4–6 boat lengths from the sailing line. Beyond this distance wave heights decrease much less rapidly and, as a result, wake wave action can propagate over large distances in unconfined waters (Kirk *et al.*, 2000; Pickrill, 1978). Along the Waikato River distances from sailing lines to the shore are usually less than 4–6 boat lengths. The potential for wave decay is therefore reduced, increasing the potential for wake-induced erosion. The geomorphic effect of the wakes is further increased because fetch lengths for wind waves are restricted, particularly along riverine reaches. Wind waves are therefore generally small and low in energy. On the eight hydro lakes, where fetch lengths are longer but still restricted, the distance from sailing lines to the shore may be greater and wake effects are less dramatic. However, waves generated by vessels operating close to the shore, and particularly around boat ramps and jetties, have a significant potential for erosion. This is because of their density, proximity to the shore, significant engine swash in shallow water, and because of the large waves generated as the boat accelerates.

Linear theory of vessel wakes

The wake produced by the passage of a vessel can be classified in terms of a depth Froude number (Maritime and Coastguard Agency, 2001). This is defined as the ratio of vessel speed to the maximum wave speed in a given depth of water:

$$F = \frac{V}{\sqrt{gd}}$$

where:

F = Froude number (dimensionless)
V = vessel speed
g = acceleration due to gravity
d = water depth below the still water level.

When the Froude number (F) is less than 1.0, the operation of the vessel is classified as sub-critical. At a value of 1.0, vessel operation is classified as critical, i.e., the vessel speed equals the maximum wave speed. At values greater than 1.0, the vessel speed is greater than the maximum wave speed and vessel operation is super-critical. As a Froude number increases towards the critical value, either because of increasing speed and/or decreasing water depth, the wave-induced water particle motion begins to interact with the bed, altering the wave characteristics. This occurs initially when F=0.56, but changes become more noticeable at values greater than 0.7 (Sorensen, 1997).

In general, as Froude values increase from 0.7 to 1.0, wave heights, and therefore energy, rise at an increasing rate as a function of speed. At a Froude number of 1.0, a significant proportion of the propulsive power of the vessel is converted to wave energy (Maritime and Coastguard Agency, 2001). All of the wave energy is concentrated in a large leading wave, and waves behind this decrease rapidly in height. Wave heights are greater in confined channels, such as the Waikato, for Froude numbers near 1.0 because the channel dimensions restrict the extension of the waves. For vessel speeds with F>1.0, wave heights are less than the peak height achieved at F=1.0 and heights decrease as the vessel speed increases (Sorensen, 1997). Froude numbers near 1.0 are therefore considered to be critical values.

Based on the above theory, an assessment of vessel operation for the current study was carried out. Water depths along the sailing lines, i.e., approximately 15 m from the shore, were not measured during the trials. However, from measured channel cross-sections at Reid's Farm, Taupo, at Hamilton Traffic Bridge and at Mercer, average mid-channel depths along the Waikato were estimated to be 3–8 m, although they vary slightly in response to water-level fluctuations (Toleman, 2002). These depths are considered to be indicative of the channel at the six riverine sites investigated here. For a vessel speed of 10 km/h, this produces Froude numbers of 0.32–0.52 (sub-critical) and for a speed of 50 km/h, values of 1.57–2.56 (super-critical). Therefore, neither mode of vessel operation tested generated the theoretical maximum wave heights. This suggests that the maximum erosion potential of the vessel-generated waves was also not realised, although it was increased because the channel widths are relatively narrow.

Management implications

At water depths of 3–8 m maximum wake heights (i.e., F=1.0) should be generated at vessel speeds of approximately 20–30 km/h. Typical boat lengths for powered craft operating on the Waikato River range between 3.7 and 6.7 metres, with an average of 5.1 metres. Typical speeds are considered to be 35 knots (approximately 65 km/h) for jet boats and fast outboard-motor-powered craft, and 15 knots (approximately 28 km/h) for slower propeller-driven boats (Kirk *et al.*, 2000). If the average water depth of 3–8 m is again assumed, these vessel speeds correspond to Froude numbers of 2.03–3.32 (super-critical) and 0.87–1.42 (trans-critical) respectively. For a speed of 15 knots, the Froude number reaches unity when water depth is approximately 6 m. It is therefore highly likely that at water depths of 3–8 m, vessel activity on the Waikato River can produce the critical conditions necessary for wave heights and erosion potential to be maximised. However, because the channel cross-sectional profile has not been quantified for the entire river, it is impossible to determine where, or over what reaches, these conditions occur.

Critical conditions at shallower depths occur at much lower vessel speeds. For example, at a depth of 1 m, wave heights are maximised at a speed of only 11 km/h. Therefore, where boats travel closer to the shore at slower speeds, the potential for wake wave erosion is greatest. Along the Waikato River this is most likely to occur at approaches to boat ramps and jetties, where water depths are shallow, boat speeds are slow, and boat traffic is concentrated.

Significance of findings

A number of studies have investigated the effects of wake waves on riverbanks and lake shores. These have involved the use of both small recreational craft and larger cruise vessels. The New Zealand Jet Boat Association (1993), Kirk *et al.* (2000), and Scholer (1974) focused their studies primarily on the effects of smaller jet and propeller-driven vessels. Their results are therefore comparable to those of the current study. The New Zealand Jet Boat Association (1993) study concluded that, while no single factor could be identified, the major causes of erosion along the Upper Kaituna River were water-level fluctuations, stock, and boat wakes. Boat traffic was estimated to contribute 20–50% of the total erosion observed. Two boats, typical of those operating on the stretch of river studied, were used for the trials (both 5.3 metres in length and weighing 1420 kg and 930 kg with full fuel tanks). Both boats generated larger and more powerful waves travelling at 5 knots than at 30 knots. Kirk *et al.* (2000) also found that propeller-driven boats (5.8 metres in length) and commercial jet boats (6.0 metres in length) operating at moderate (10–15 knots) or slow (5 knots) speeds produced larger waves with higher energies than when the boats operated at high service speeds (approximately 35 knots) upstream of *River Rd, Broadlands* and on Lake Aratiatia. Scholer (1974) has also documented larger waves at intermediate speeds than when planing on the Hawkesbury River, New South Wales.

Although these results appear inconsistent with the conclusions reported in the current study, this is a function of differences in wave generation and data collection. The present study focused on the "riverbank", and the data were collected predominantly from within 3 m (but up to 7 m) of the water's edge. Waves were generated approximately 15 m from the shore and at only two boat speeds: a displacement speed of 10 km/h (approximately 5.4 knots) and a planing speed of 50 km/h (approximately 27 knots). When a vessel planes, wave heights are lower than would otherwise be expected for a given vessel speed. However, waves generated at planing speed in this study were still larger than those generated at the displacement speed. This is likely to be a function of both the vessel speed and water depth. At a speed of 10 km/h, water depth was such that the Froude number was less than 0.7 (and probably less than 0.56). This meant that the wave system did not respond to water depth effects, and wave heights remained small.

Kirk *et al.* (2000) collected their data at greater distances from the bank and at greater water depths, where the effects of decreasing water depth and interactions with the channel bed would be less. Waves were also generated much further from the shore, i.e., 25 m from the shore at a depth of 4.0 m upstream of *River Rd, Broadlands* and 60–70 m from the shore at a depth of 4.4 m at Lake Aratiatia. The potential for wave decay is therefore greater than in the current study, where the distance from the sailing line to the shore was less than four boat lengths. For vessel speeds of 5 knots, 10–15 knots, and 35 knots at a water depth of 4–4.4 m (as sampled by Kirk *et al.*, 2000) Froude numbers are 0.40–0.42 (sub-critical), 0.78–1.23 (trans-critical), and 2.74–2.87 (super-critical) respectively. It is therefore expected that the waves generated at vessel speeds of 10–15 knots produce the larger waves because these are the conditions closest to critical. Although Scholer (1974) did not specify channel width or depth, intermediate vessel speeds must have also generated conditions closest to critical along the Hawkesbury River. Similarly, a vessel speed of 5 knots must have generated conditions closer to critical than a speed of 30 knots within the sections of the Upper Kaituna River investigated by the New Zealand Jet Boat Association (1993).

Conclusions

The effectiveness of boat wake as an erosive agent depends on: the resistance of the bed and banks where the waves impact (controlled by sediment, vegetation, water level, and profile characteristics), the conditions under which the waves were generated (water depth; channel width; vessel size, displacement, and speed; the distance from sailing line to shore; and the frequency of vessel traffic), and the characteristics of the resulting waves (wave energy and frequency of wave impacts). Vessel-generated waves, because of their greater amplitude, are more erosive than wind-generated waves in riverine environments, particularly where fetch lengths are restricted. In lake environments, wake waves have a greater erosion potential where boats travel close to the shore i.e., at approaches to boat ramps and jetties.

The effects of boat wakes on bank erosion processes along the Waikato River are not easily summarised. There is considerable variation in response both within and between sites for the same boat making a number of passes under the same flow conditions, and for different types of boat and flow conditions. The effects of boat wakes are highly site-specific. They are controlled by a wide range of characteristics at any site, including vegetation, bed and bank material, availability of sediment, and channel profile. Where the water depth is less than approximately one half the wavelength, water depth and vessel speed will also affect the wave characteristics. While vegetation is often a critical control, it is the combination of all site characteristics that determine ultimately the response of the bank to waves.

Water level and variations in flow alter the height at which vessel-generated waves interact with the shore. The position of the weakest layer in the bank, relative to the water level, is therefore of critical importance. Variations in flow also alter the critical water-depth and vessel-speed conditions for a given position on the channel. Vessel-generated waves have a greater potential effect where the channel is narrow because the distance of the sailing lines from the shore are small, i.e., not much larger than 4–6 boat lengths.

Wake waves also have a greater potential impact where boat use is regular, concentrated, and close to the shore; particularly where fetch lengths are limited. They also have more influence on bank erosion rates within reaches not subjected to high-velocity flood flows, such as the Waikato, with its regulated flow regime.

Because the profile and sediment distribution of the near-shore zone have developed in response to the natural wave climate, there is the potential for significant shoreline change as it adjusts to a higher energy, vessel-induced wave climate. Finally, the wake energy may exceed the resistance of the bank material, leading to erosion and perhaps bank collapse. Material entrained in this manner may then be able to be moved by lower energy wind waves or by the current of the river.

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