# Literature review on the impacts of boat wash on the heritage of Ireland's inland waterways

J. Murphy, G. Morgan and O. Power

An Chomhairle Oidhreachta
The Heritage Council

University College Cork
Hydraulics and Maritime Research Centre
Aquatic Services Unit
And
Moore Marine Services Ltd

# Literature review on the impacts of boat wash on the heritage of Ireland's inland waterways

Final Report

April 2006

J. Murphy, G. Morgan and O. Power

Published November 2006

*Published by*
*the Heritage Council*
*Kilkenny, Ireland.*
*2006*

*Telephone: +353 56 7770777.*
*Fax: +353 56 7770788.*
*E-mail: mail@heritagecouncil.com*
*www.heritagecouncil.ie*

*Photographs:*
*Canadian Wildlife Service*

*The Heritage Council of Ireland Series*

*ISSN 1393 — 68 08*
*ISBN 1 90 1137 90 2*

*Price: €7.50*

TABLE OF CONTENTS


FOREWORD 5

1. EXECUTIVE SUMMARY 6

2. INTRODUCTION 7

3. PROJECT TASKS 6

4. DESCRIPTION AND FEATURES OF BOATWASH 7

4.1. Vessel Speeds 7
4.1.1. Displacement Speed 7
4.1.2. Transition Speed 8
4.1.3. Planing Speed 9
4.2. Vessel characteristics 9
4.3. Boatwash Characteristics 10
4.4. Wake Wash Prediction 12

5. BOATWASH IMPACTS 13

5.1. Introduction 13

5.2. Hydro-morphological Impacts 14
5.2.1. Erosion Mechanism 14
5.2.2. Previous Studies 14
5.2.3. Erosion of Bed Material 16
5.2.4. Structural Design 17

5.3. Ecological Impacts 18
5.3.1. Overview of the Literature Sources 18
5.3.2. Ireland's Inland Waterways – Brief Overview 19
5.3.3. Results of Review 20
5.3.3.1. Aquatic Plants 20
5.3.3.2. Impacts on Fish 22
5.3.3.3. Impacts on Macroinvertebrates 25
5.3.3.4. Noise and Disturbance 26
5.3.3.5. Water Quality 28
5.3.4. Issues of Intensity of Traffic 30

5.4. Cultural Heritage Impacts 33
5.4.1. Literature review 33
5.4.2. Tennessee Valley Authority (TVA) – FEIS 2004 34
5.4.2.1. Scope of study 34
5.4.2.2. Methodology 34
5.4.2.3. Mitigation 34

5.4.2.4. Conclusions 35
5.4.3. Florida Department of State – Archaeological Stabilization Guide 35
5.4.3.1. Scope 35
5.4.3.2. Methodology 36
5.4.3.3. Conclusion 37
5.4.4. Venice Inner Canal Project (UNESCO) 37
5.4.5. Methodology 37
5.4.5.1. Mitigation Measures 39
5.4.5.2. Conclusion: 39
5.4.6. Irish Site Types/Forms under threat 39
5.4.6.1. Riverine and Canal 40
5.4.6.2. Lacustrine 40

6. COMMON MITIGATION MEASURES 42

6.1. USA 42
6.1.1. Seattle 42
6.1.2. New York 43

6.2. Denmark 44

6.3. United Kingdom 44

6.4. New Zealand 45

6.5. Possible Irish Mitigation Measures 45

7. RESEARCH PROGRAMME REQUIREMENTS 47

8. REFERENCES 50

APPENDIX 1 58

APPENDIX 2 64

APPENDIX 3 69

# Foreword

Since 2002, the Heritage Council, in partnership with Waterways Ireland and local authorities, has carried out a series of waterway corridor studies along Ireland's navigable waterways. The impact of boat wash on heritage has been identified as an issue in each of these, in particular in relation to natural heritage.

In the summer of 2005, the Heritage Council commissioned the Hydralics and Marine Research Centre (UCC) to undertake a literature review which considered the findings, methodologies and mitigation strategies used elsewhere, across the UK, Europe, and N. America, in relation to boat wash. The review is intended to inform the debate in Ireland on boat wash and to help guide the direction and scope of future field work on Ireland's waterways.

The literature review focused on the following potential impacts:

- Ecological impact – terrestrial and aquatic flora and fauna, and terrestrial and aquatic habitats;
- Cultural heritage impact – underwater archaeology, upstanding archaeological structures such as crannogs, landing places, harbours, piers and bridges from the medieval to the mid 20th century; and
- Hydro-morphological impact – river and canal channels, river and canal banks, different soil types to assess their susceptibility to erosion, sediment mobilisation and depositional patterns, navigational and engineering structures.

Issues relating to health and safety were not included in the study.

While the focus of the review concentrated on inland waters, experience gained from coastal contexts have also been included where it was felt appropriate.

The review was completed in spring 2006.

The main findings that have emerged from this literature review include, *inter alia,*

- Although research on the potential negative impacts of boat wash has been carried out for the past 50 years, much of this is ad-hoc and there are very few examples of integrated research programmes covering all aspects of the topic.
- The main sources of research are in N.America, mainly on commercial waterways and the UK where work has concentrated on the canal system and the Norfolk Broads.
- It is difficult to separate the impact of boat wash from other impacts associated with boats e.g. propellers mechanical action of the hull, pollution from hydrocarbons and noise.
- User education programmes are vital for the reduction in boat wash.
- There are a number of mitigation measures that have been proven effective and these could be applicable to Ireland. These are listed in section 6.5.

The Heritage Council has published this document with the intention of informing the debate on the potential impacts of boat wash on heritage. Further study can only be achieved with the co-operation of navigational authorities, such as Waterways Ireland, local authorities and users. We hope this document will help to initiate greater awareness and research in this area, on an integrated basis. The Heritage Council is prepared to assist as far as possible in further work in this area.

# 1. Executive Summary

The impact of boatwash (boat-generated waves) on natural and cultural heritage of Ireland's waterways has been identified as an important issue in the four waterway corridor studies carried out to date. To address this, in 2005 the Heritage Council commissioned a literature review on the research and current practice carried out in relation to boatwash. The purpose of the review is to provide an overview of the findings, methodologies and mitigation strategies used elsewhere and to direct a second stage of research involving field study. In particular the impacts in relation ecology, cultural heritage and hydro-morphology were of interest.

The study team consisted of the Hydraulics and Maritime Research Centre (HMRC) and the Aquatic Services Unit (ASU) both of University College Cork and Moore Marine Services Ltd. The approach taken was to search on-line databases of scientific peer-reviewed literature (journals and conference proceedings) for papers or reviews on the subject and to obtain as many of the relevant papers as possible in the UCC journal collection (hard copy or on-line). In addition, several papers, which were not present in the UCC collection, were obtained by inter-library loan. These data were supplemented by reference to the abstracts (only) of a range of broadly related papers. Primarily only those publications which were deemed relevant to the Irish context i.e. recreational boating in freshwater rivers, lakes and canals were chosen for review. It is worth noting that the review doesn't purport to be exhaustive. Nevertheless, it is believed to address most of the key issues and processes which are generally accepted at this juncture to be pertinent to the impact of pleasure craft in inland waterways in the Irish context.

The study of literature in addition to allowing the current state of knowledge to be outlined also enabled the project team to formulate, guidelines as to possible mitigation measures that could be employed in Ireland and recommendations on elements of an Irish research programme.

The general conclusion is that boatwash is a significant issue in many countries and does cause damage to sensitive coastlines. In Ireland, there is currently not enough information to quantify the impact of boatwash on inland waterways. Practically no field studies have been undertaken but anecdotal evidence suggests that in some cases the damage caused is quite severe. However, definitive studies are required to verify visual observations and to give policymakers the information to make correct management decisions.

## 2. Introduction

Boat-generated waves or boatwash can have significant impacts on natural and artificial features along inland waterways or coastal systems. At many locations their impacts are only regarded as important if wave heights are greater than wind generated waves. Therefore in coastal areas, where normal wind wave conditions are moderate to severe, boatwash is mainly of concern only in relation to safety. However, at sheltered locations such as small lakes, rivers and channels they can from the most significant form of wave loading. The characteristics of these waves, once they move away from the vessel, are much the same as wind generated waves and so also can have the same potentially negative effects. The more obvious impacts are as follows;

- Mobilisation/Suspension of bed sediment and subsequent erosion by currents
- Erosion of soft shoreline with loss of vegetation and habitat
- Excessive disturbance inside marina structures
- Damage to structures and moored vessels
- Safety to passing vessels and in particular to smaller craft
- Safety to people on floating marina structures

Boatwash is a major issue in many countries particularly since the advent of high speed ferries. Regulations have been put in place regarding the operation of these craft and criteria have been established with regard to the minimisation of boatwash. Recent research through field monitoring, physical modelling and numerical modelling have significantly improved the understanding of boatwash and its impacts. There is thus a large amount of reference literature now available, much of which has been used in the preparation of this report.

It is also important to point out that the issue of boatwash and its potential environmental impacts must be seen in a wider context also. Considerations of Strategic Environmental Assessment (SEA) surrounding the use of pleasure craft in inland waterways are also extremely important and should be considered in consort with those impacts immediately associated with vessels themselves. SEA issues include the numbers of and siting of marinas in a given water body, the size, design and construction methods for marinas, dredging and maintaining of navigation channels and access to marinas, provision of on-shore facilities (toilets, showers, bilge pump-out and re-fuelling facilities), residential accommodation and associated amenities, sometimes in areas which are otherwise relatively remote and environmentally sensitive. All of these matters will have implications for the environment, some may lead to environmental degradation, which could be reversible short-term or long-term, or indeed irreversible. One might expect that many of these issues to be scale and density dependent in terms of their significance. However, in some sensitive areas developments of any scale or density may be potentially negative in their impacts.

There are also socio-cultural issues, which need to be taken account of, such as those related to potential conflicts of interest between different groups of water users e.g. between commercial salmon nets men (e.g., in the Suir/Nore/Barrow) system and other boat users or between anglers and other boats users. The issue of excessive speed, noise and low regard for other water users has also been raised.

Ireland is lagging behind in terms research in this field, as there has been no direct funding available. Since some of our inland aquatic environments are unique from an ecological and heritage viewpoint, it is important that they are preserved. The process of understanding these environments and then deciding on the correct mitigating measures that should be taken to prevent boatwash damage should commence as soon as possible.

# 3. Project Tasks

The following section outlines the project tasks and the methodology used.

**Task1**: Collection of all relevant literature regarding the ecological, cultural heritage and hydro-morphological impacts of boatwash. The literature search incorporated the following,

- Library Search
- Web search
- Query via international 'coastal list' emailing group
- Direct contact (telephone and email) with known experts in the field
- Consultation with Archaeological Services Unit in UCC
- Software sourcing – examine capabilities of existing software

**Task2**: Evaluation of collected information. All items collected in the literature search were read and categorised into one of the following headings;

- Boatwash Generation
- Ecological Impacts
- Cultural Heritage Impacts
- Hydro-morphological Impacts
- Structural Impacts
- Research Techniques
- Common Mitigation Measures
- Computer Software
- Other

**Task 3**: The following organisations and people were contacted in order to get an overview of perceptions on the impact of recreational boating in Ireland.

- Heritage Council (Beatrice Kelly)
- Waterways Ireland (Paula Treacy & Liz Gabbett)
- Inland Waterways Association of Ireland (Colin Becker)
- National Parks and Wildlife Service (John Matthews)
- Central Fisheries Board (Joe Caffrey)
- Birdwatch Ireland (Olivia Crowe)

In addition, Mr Henrik Kofoed Hansen, of the Danish Hydraulic Institute (DHI), who has published many papers on ship-generated waves kindly agreed to act as an outside adviser to the project partners.

**Task 4**: Recommendations on a feasible research programme based on the work of Tasks 2 and 3 and also the experience of the HMRC and ASU.
**Task 5**: A report will be prepared outlining all aspects of the work. Report headings to be similar to those outlined in Task 2.

# 4. Description and Features of Boatwash

Boatwash results from water being displaced by the hull of a moving vessel. The displaced water first moves up whereupon gravity acts upon it, resulting in the familiar form of the oscillating wave. As waves move away from the source and toward the shoreline (i.e. into shallow water) they can be affected by the bathymetry, in a similar manner to wind waves, and such processes as refraction, shoaling and breaking can occur. The magnitude and direction of propagation of boat-generated waves is dependent on a number of factors but most significantly on the vessel characteristics and environmental properties. Vessel characteristics that are relevant to wake generation include hull form, trim, displacement, heading and speed of travel. Important environmental factors include wind speed and direction, current speeds and directions, water depths, tidal range and shore geometry. Boat-generated waves are greatest in height close to the vessel and decrease in height as the distance from the source increases. Generally their effects are most noticeable in narrow channels if the vessels travel at relatively high speed. Very often such channels need to be protected in order to prevent erosion and damage to the banks. Previous HMRC studies have shown that boatwash to be the most significant form of wave loading at some marina sites in Ireland e.g., Poolbeg marina, Dublin.

This section considers the influence of vessel speed and hull shape on boatwash generation. In addition the characteristics of boatwash in terms of the wave parameters are also described.

## 4.1. Vessel Speeds

In terms of the magnitude of boatwash being related to the speed of the vessel the following three modes have been identified.

### 4.1.1. Displacement Speed

Generally when vessels are travelling at relatively low speeds they are in displacement mode. The boat operates with its bow down in the water and usually the wake generated is small. The speed up to which a vessel can stay in displacement mode is largely dependent on the hull length. Tobiasson *et al.* (1991) states that a general rule of thumb is to multiply the square root of the hull length at the waterline (in feet) by 1.3 and this will give the limit speed. Therefore a 40ft vessel has a limit displacement speed of 8.2kts. Plate 4.1 shows a motor boat in displacement mode.

Plate 4.1 Vessel in Displacement mode (Picture from Canadian Wildlife Service)

Plate 4.2 Vessel in transition mode (Picture from Canadian Wildlife Service)

Plate 4.3 Vessel in planing mode (Picture from Canadian Wildlife Service)

### 4.1.2. Transition Speed

Many larger vessels cannot travel faster than their displacement speed but smaller vessels can go into planing mode and exceed the limit speed. The transition speed occurs as the vessel is going from displacement mode to planing mode or vice versa. In this case the bow rises causing the stern to plough through the water and often leads to the creation of very large boatwash. Whilst boats must go through this phase to reach planing or displacement speeds (depending on whether it is speeding up or slowing down) the general recommendation is that the deceleration or acceleration is fast in order to minimise the generation of large boatwash. Plate 4.2 shows a motor boat in transition mode.

### 4.1.3. Planing Speed

This is the desired speed of travel of most small vessels and at this speed boatwash is much reduced as compared to the transition speed. The bow has dropped back down and only a little of the hull is in contact with the water. Plate 4.3 shows a motor boat in planing mode.

## 4.2. Vessel characteristics

Boatwash size is very much dependent on the characteristics of the vessel hull. In order to provide a general overview of this effect a brief description of the wake generating capacity of various vessels is now provided. It should be noted that many of the vessels described would not operate in Ireland's inland waterways but their inclusion is important to indicate the range of conditions that can be generated.

- Large container vessels and bulk carriers move slowly and generate very little wash unless they travel in narrow channels where they can displace a large amount of water.
- Tugs usually move about close to maximum speed and so generate large high energy short period wash.
- Monohull ferries generally do not create large wake as they travel at relatively low speeds. However some larger monohull ferries operate at 20kt which can lead to a wave of up to 0.6m at 300m distances.
- High Speed ferries can generate very large wash (in excess of 1m high) and are subject to strict operating regulations
- For typical leisure craft vessels operating in Ireland's waterways they can generate waves of up to 0.5m depending on hull form, speed etc.

An important point regarding wave heights is that visual observations usually overestimate their magnitudes and it is common to hear of waves from small craft to be in excess of what that vessel could generate. Accurate estimates of wave heights are best obtained by use of a suitable wave gauge.

The following table was taken from the Coastal Engineering Manual and gives an indication of the influence of vessel characteristics and speed of travel on the maximum wake height ($H_m$). Two values of wave height are provided, the first measured 30m from the vessel and the second 150m away.

| Vessel | (m/s) | At 30m | At 150m |
|---|---|---|---|
| **Cabin Cruiser** | | | |
| length-7.0m | 3.1 | 0.2 | 0.1 |
| beam-2.5m | 5.1 | 0.4 | 0.2 |
| draft-0.5m | | | |
| **Coast Guard Cutter** | | | |
| length-12.2m | 3.1 | 0.2 | 0.3 |
| beam-4.0m | 5.1 | 0.5 | 0.3 |
| Draft-1.1m | 7.2[1] | 0.7 | |
| **Tugboat** | | | |
| length-13.7m | 3.1 | 0.2 | 0.1 |
| beam-4.0m | 5.1 | 0.5 | 0.3 |
| draft-1.8m | | | |
| **Air-Sea Rescue Vessel** | | | |
| length-19.5m | 3.1 | 0.2 | 0.1 |
| beam-3.9m | 5.1 | 0.4 | 0.3 |
| draft-0.9m | 7.2[1] | | |
| **Fireboat** | | | |
| length-30.5m | 3.1 | 0.1 | 0.1 |
| Beam-8.5m | 5.1 | 0.5 | 0.3 |
| draft-3.4m | 7.2 | 0.9 | 0.8 |
| **Tanker** | | | |
| Length-153.6m | 7.2 | | 0.5 |
| beam-8.5m | 9.3 | | 1.6 |
| Draft-8.5m | | | |

Note: The above data are from tests conducted at water depths ranging from 11.9 to 12.8m.
[1] Denotes that the vessel was starting to plane

## 4.3. Boatwash Characteristics

The general characteristics of waves generated by moving vessels are now described. A more theoretical and thorough description is provided in Appendix 1.

The two main wave types that are generated by displacement vessels moving through channels are known as primary and secondary waves. Primary waves result from changes to the water level caused by a moving vessel. They are composed of a frontwave at the bow, a water level depression along the length of the ship and a transversal stern wave. The wavelength of this wave corresponds to the length of the vessel and also dictates the limit speed of the ship. A primary wave has many of the characteristics of a negative solitary wave. Secondary waves on the other hand take the form of a wave train being made up of a number of periodic oscillations. They are generally generated at discontinuities in the hull with those created at the bow usually being the more

dominant. These waves radiate from the source in the form of transverse and diverging waves which combine to form interference peaks. They propagate in a direction of 35 degrees from the vessel courseline and for vessels travelling at relatively high speeds can result in significant disturbance.

The HMRC monitored waves at the site of a proposed marina development project and recorded the wave signal as shown in Figure 4.1. It shows many of the characteristics of boatwash. This wave packet was generated by a vessel moving past the wave recorder and is quite significant in terms of the magnitudes of wave heights and periods. (Note the wave height is the vertical distance between a wave crest and trough whilst the period is the time difference between two corresponding points of the wave.

One of the first obvious features of the waves as shown in Figure 4.1, that differs from wind generated waves, is that they are regular in period and generally of short duration, building to a peak when the vessel is closest to the measurement point and then tailing off as the vessel moves away.

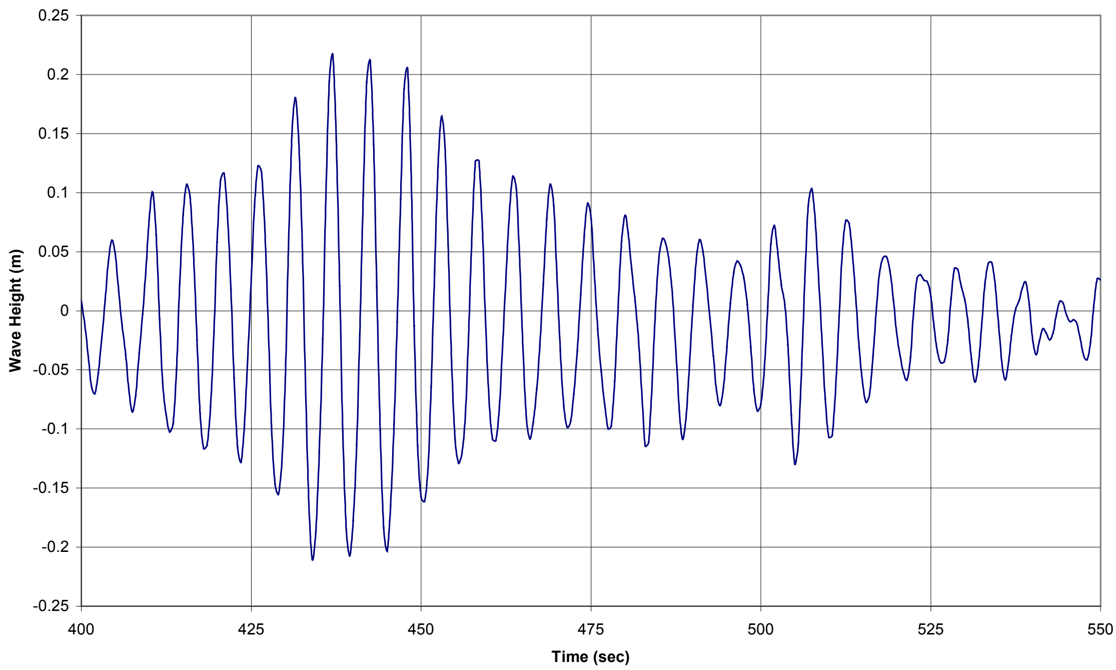



Figure 4.1 Boatwash wave packet

The normal analysis that allows the determination of the design wave condition (significant wave height ($H_s$)) is not directly applicable to ship generated waves. The $H_s$ value is defined as the mean of the highest one third waves over the measurement period, which in most cases is about 18 minutes. A wave burst from a passing vessel may last less than one minute so using $H_s$ in the normal sense will underestimate the wave heights generated by the passing vessel. Therefore the best way to consider these waves is by analysis of the time series data. From Figure 4.1 it can be seen that the maximum wave height has a value of 0.43m and a corresponding period of about 5.5 seconds. An interesting feature about this wave record is that waves reflected off quay

walls can be identified by the subsequent lesser peak. Figure 4.2 is a spectral plot (plots energy against wave frequency) and shows that all energy is concentrated into one main frequency (0.182Hz or 5.5sec).

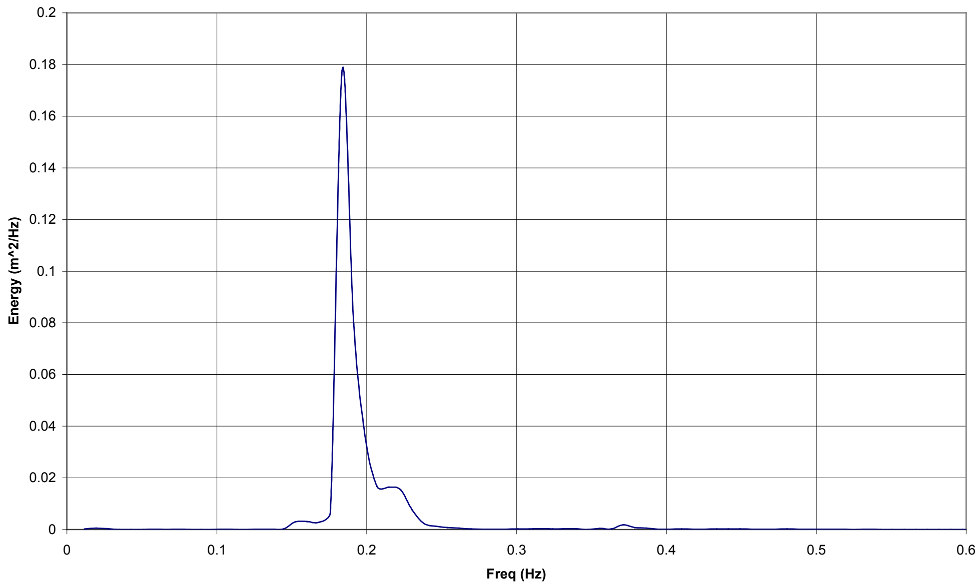



Figure 4.2 Wave Spectra for recording

## 4.4. Wake Wash Prediction

The determination of the magnitude of boatwash is important for design purposes. There are various semi-empirical methods/formulae in use but in general they fail to give a complete picture on the generation and propagation of waves from a moving vessel. Therefore modelling (both physical and numerical) and more recently field monitoring are used to provide estimates of boatwash size. Physical modelling involves fabricating a scaled replica of the vessel, towing it along a large tank and measuring the boatwash generated. This method is useful but can be time consuming and may not incorporate all of the variables that may be important in a field situation. Numerical modelling is thus seen as the tool that can best examine the magnitudes and impacts of boatwash. A number of software packages have been developed for this purpose and a description of the most relevant is provided in Appendix 2.

# 5. Boatwash Impacts

## 5.1. Introduction

This section examines the various identified impacts of boatwash on water systems. Particular attention is given to the following items, as identified by the Heritage Council.

- Hydro-morphological impact – river and canal channels, river and canal banks, different soil types to assess their susceptibility to erosion, sediment mobilisation and deposition patterns, navigational and engineering structures.
- Ecological Impact – terrestrial and aquatic flora and fauna, and terrestrial and aquatic habitats.
- Cultural Heritage Impact – underwater archaeology, upstanding archaeological structures such as crannogs, landing places, harbours, piers and bridges.

Although boatwash has been an identified phenomenon for centuries it has only been in the last 30 years or so that consideration has been given to possible negative impacts. Initial issues related to safety of smaller vessels and erosion of channel banks. In more recent times environmental issues have increased in importance and they, along with safety, act as the main drivers for the introduction of boating regulations to control boatwash.

Research into the impacts of boatwash has been very much ad-hoc and there are very few examples of integrated, co-ordinated research programmes that encompass all aspects of the subject. In general research papers deal with one particular impact (i.e. ecology or erosion) and as such it is difficult to get from available literature a complete overview of the effects boating activity has on a waterway. In the following discussion in this section each impact is dealt with separately. Although in some cases there is natural overlap this is not generally reflected in the type of research undertaken. It is obvious that various boatwash impacts are related (i.e. bank erosion results in loss of habitat or heritage) and it is recommended that any research programme that is initiated in Ireland will be properly integrated.

## 5.2. Hydro-morphological Impacts

### 5.2.1. Erosion Mechanism

Boat-generated waves generally propagate out from the source (moving vessel) until they reach a shoreline were they are either dissipated through wave breaking or partially or totally reflected. The magnitude of the waves when they reach the shoreline along with the nature of the bank material dictates the amount of erosion that will occur. In general the worst scenario is for a large vessel to travel at high speed in a narrow unprotected channel. In addition to wave heights causing bank erosion propeller turbulence can also result in mobilisation of bed sediment.

If the propagation of boatwash towards the shoreline is considered, wave processes that are of direct relevance are shoaling and breaking. Shoaling occurs as a wave moves into shallow water and results in an increase in height as the total energy of the wave is squeezed into a smaller depth. Therefore, long period waves that have quite a small height in deep water can shoal to a large height. Eventually, because of decreasing water depths, the wave will shoal to a height at which it is unstable and it will break, usually in the form of a plunging breaker. It is this shoaling and breaking of the incoming waves that can cause shoreline erosion

The impact of a wave on a shoreline or structure is dependent on the parameters, wave height, wave period, wave direction and water depth. However, the common form of analysis as used for wind waves is not directly applicable as there is so much variability in the parameters over the course of a single event. Stumbo *et al.* (1999) used an energy based analysis, whereby the total energy in the wave packet was determined and used as a design value. Using this technique he was able to assess the impact of different wave events on shorelines and structures. Parnell *et al.* (2001) assessed the capability of boatwash to generate both longshore and cross shore sediment transport. For longshore transport to occur waves need to approach the shoreline at an angle whereby the swash motions sets up longshore currents. However, because boatwash is a short duration process the currents required to initiate longshore transport are not able to develop. With regard to cross shore transport boatwash results in a net movement of sediment onshore and results in a steepening of the beach profile. Parnell *et al.* (2001) also outline that in confined waters with small fetch lengths vessels can generate waves more typical of open ocean beaches rather than limited fetch beaches. In such cases the hydrodynamic regime may be dominated by the ship waves and could result in an increase in the width of the beach and the upper limit of the swash zone. Larger beach sediment (pebbles, cobbles etc.), which, would not normally be moved, may now be transported along the beach profile as the shoreline adjusts to a new wave regime.

### 5.2.2. Previous Studies

Finding a direct correlation between boatwash and shoreline erosion is a difficult task and requires detailed monitoring of both bank position and vessel movements over an extended period of time. A few studies are outlined by Asplund (2000). Nanson *et al.* (1994) found a positive correlation between vessel speed and shoreline erosion after undertaking a monitoring program of bank position and vessel speeds. It was found that erosion was generally observed when wave heights exceeded 0.35m and such waves were regularly generated by passing vessels. In addition the study showed that reducing vessel speeds and frequency decreased the amount of recession that took place. Johnson (1994) measured shoreline erosion on several stretches of the Mississippi over a 3.5 year period and observed that in areas of intensive boating activity the shoreline receded at an approximate rate of 1m per year. Erosion rates in areas with little to no boating activity were less than a third of this value. Johnson *et al.* (2000) investigated shoreline erosion due to recreational boating activity at fourteen sites on the La Croix National Scenic Riverway between 1995 and 1998. They found that erosion occurred at nine sites, deposition at two sites whilst there was no net change at the other three sites. The sites with little change corresponded to locations of low

boating activity and it was also observed that foot traffic trampling was a contributory factors at erosive sites. Further studies indicated that there was a correlation between sediment mobilised and boatwash wave height. For the site examined sediment was not mobilised for wave heights less than 0.1m.

Dauphin (2000) outlines a study undertaken by the Canadian Wildlife Service that revealed that ship generated waves was a contributory factor to shoreline erosion in the ecologically sensitive archipelagos between Montreal and Sorel. The position of the shoreline was monitored over a period of time both before and after the shipping industry adopted a voluntary speed reduction in order to reduce wake size (in 2000). Whilst not all shipping complied with the speed reduction it was found that in the three subsequent years the shoreline erosion had reduced in many areas by as much as 45%. This evidence was used to convince the shipping industry to maintain the speed reduction measure.

Asplund (2000) indicates the following unknowns with regard to boatwash and shoreline erosion

- Most studies so far have been undertaken in river environments so it is not certain whether the same rules apply to the still water lake environments.
- ·The cumulative effects of boatwash and wind generated waves on shorelines.
- ·Guidelines on how much boat traffic a specific shoreline will tolerate.
- ·Most studies consider the waves generated from individual boats but waves created by several vessels operating in close proximity can combine to give a very high resultant wave.

The Kenai River Boat Wake Erosion Study (Alaska EPA Watershed Initiative: 2005) proposes to evaluate boat wake impacts on riverbanks. While primarily concerned with the impact of boat wake on fish habitat, it is planned to use wave gauges and time-lapse video photography in order to monitor boat passages past the study location. Characteristics typical of wave-induced erosion will be identified and catalogued in order to better understand the overall impact of boat wake. Studies conducted in 2000 by the Kenai Boat Wake Erosion Survey were designed to quantify variables in the production of boat wakes such as differing hull shapes, boat lengths, passenger loadings and distance from the shoreline (DNR , 2003).

A methodology, as shown in Figure 5.1, was proposed by Osbourne and McDonald (2005) for assessing shoreline impacts as a result of boatwash. The method involves stepping through a series of questions whereby the feasibility of a vessel route is assessed. Ultimately if the issues in relation to boatwash are not properly addressed the proposed route could be abandoned. This flow chart although developed with large ferries in mind could be adapted and re-applied to *Ireland's* Inland Waterways.

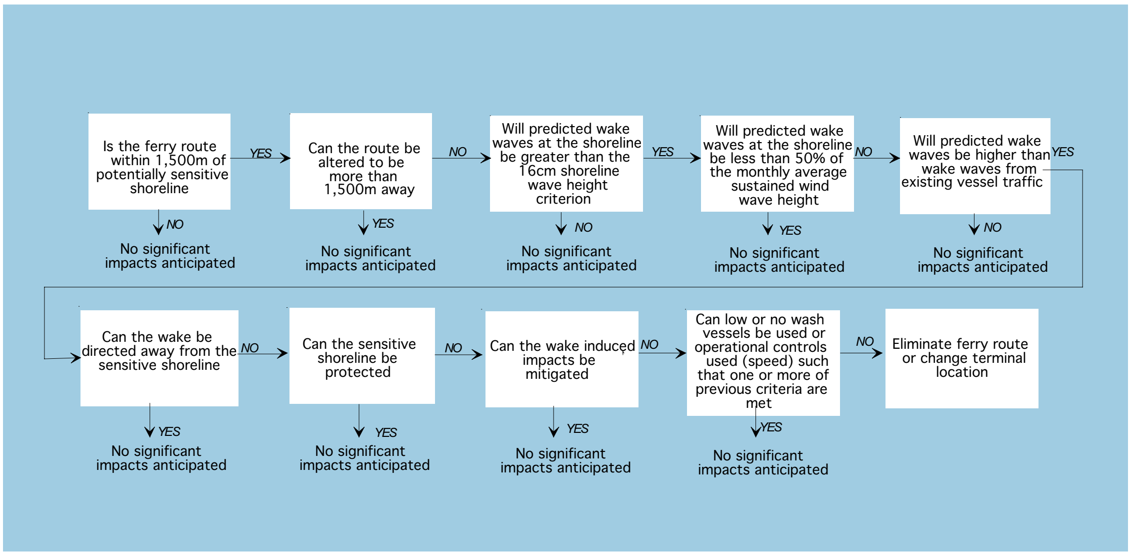



Figure 5.1 Example of methodology for assessing shoreline impacts (Osborne and McDonald (2005)

### 5.2.3. Erosion of Bed Material

There is very little quantitative information available on the erosion/mobilisation of bed material as a result of boat wash. It is generally assumed not to occur in deeper water and in shallow water is dependent on the wave parameters and bed conditions (in a similar manner to wind waves). What seems to be more relevant to the scouring of bed material are the effects of propellers and bowthusters. For design purposes propeller wash is assumed to be equivalent to a circular jet and the equations used to describe the hydraulics of the jet are used in the analysis. Although it is likely that this assumption is not correct it is the approach used. For the calculation of bottom erosion the velocity of the propeller jet ($u$) is equated to the critical velocity for sediment mobilisation ($u_c$). Schiereck (2001) provides the following equation to determine the depth of erosion at a distance x behind the propeller.

$$h_s = x\sqrt{\frac{-\ln\left(\frac{u_c x}{5.6 u_o d}\right)}{15.7}} - z_b$$

where

$h_s$ is the erosion depth
x is the horizontal distance from the propeller
$u_c$ is the critical velocity for sediment mobilisation
$u_o$ is the jet/propeller outflow velocity
d is the sediment mean grain diameter
$z_b$ is the vertical distance from the centreline of the propeller to the bed

### 5.2.4. Structural Design

With regard to the design of structures to protect against boatwash only limited experimental data is available for use in design formula. It has been suggested that a form of the well known Van der Meer formula, used for determining rock armour size to withstand wind wave attack, should be used. This formula takes the form,

$$\frac{H_s}{\Delta D_{n50}} = 6.2P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2}\xi_m^{-0.5} \quad \textit{for plunging waves}$$

$$\frac{H_s}{\Delta D_{n50}} = 1.0P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2}\sqrt{\cot\alpha}\,\xi_m^{P} \quad \textit{for surging waves}$$

*where P is a notional permeability factor (values range from 0.1 when there is an impermeable core to 0.6 when there is no filter or core), S is the damage number =* $A_e / D_{n50}^2$ *(=2 for 'no damage') and* $A_e$ *is the erosion area, N is the number of waves (normally take storm to have a 3 hour duration and then divide this value by* $T_m$*),* $\xi_m = \frac{\tan\alpha}{\sqrt{2\pi H_s / g T_m^2}}$ *is the Iribarren number and* $T_m$ *is the mean wave period(=0.82*$T_p$*).*

*The transition between plunging and surging waves can be calculated from*

$$\xi_{mcr} = \left(6.2P^{0.31}(\tan\alpha)^{0.5}\right)^{1/(P+0.5)}$$

if $\xi_m > \xi_{mcr}$ plunging waves
if $\xi_m < \xi_{mcr}$ surging waves

For wind waves Van der Meers formula uses Hs which is the mean of the highest one third waves whilst a ship generated wave train only contains a small number of waves with a maximum height H. Schiereck (2001) states that for the design of protection measures the plunging wave part of the Van der Meer equation should be used with P = 1 (revetment), S = 2 (little damage) and N = 7000 (ship loads are usually very frequent hence the large number of waves) and instead of Hs a figure equal to 1.4Hs should be used (this approximately equates to the maximum wave size). This results in the stability equation reducing to,

$$\frac{H_s\sqrt{\cos 55^o}}{\Delta D_{n50}} = 2.7\xi_m^{-0.5} \qquad \frac{H_s}{\Delta D_{n50}} = 3.6\xi_m^{-0.5}$$

where 55° is the angle of approach of the waves to the bank. The protection against diverging and transverse waves should extend vertical distances of between (2-3)H above and below the design water level.

## 5.3. Ecological Impacts

The impact of boat wash on aquatic habitats and ecology is rather a specific theme of enquiry and there appears to be little in the way of recently published work ascribed to this exact theme. Understandably, when assessing the impact of boat waves, it is difficult to separate out the impact, which may be specifically associated with waves from that associated with the craft as a whole e.g. propellers, mechanical action of the hull or for that matter noise, either in air or in water. Furthermore, there are issues of water quality e.g. arising from hydrocarbon contamination of water and sediments from outboard or inboard motors or associated with the use of anti-fouling paints on the hulls of these craft. For these reasons, the present review has taken a broader view of boating and looked at impacts under the following main headings:

- Aquatic Plants
- Fish
- Macroinvertebrates
- Other Species
- Water Quality

In the current review the author has concentrated on issues related to boating and individual boats rather than the wider strategic impact issues.

### 5.3.1. Overview of the Literature Sources

There are many publications related to the impacts of recreational boating and many of these seem to be pre 1980. The stimulus for much of these publications in Britain (and perhaps also in the US and Europe) seems to have been the explosion in recreational water use, which commenced in the first decades following the Second World War. Much of the British work seems to relate either to the canal system or to the Norfolk Broads, whereas in the US much of the literature relates to the impacts of large commercial towboats on the navigable channels of the Mississippi and its larger tributaries. There is also a significant body of US literature on impacts on specific habitats such as seagrass beds or tidal flats. Pearce and Eaton (1983) list 453 references in their bibliography, 'Effects of Recreational Boating on Freshwater Ecosystems'. This list was whittled down from around 1300 publications which their very wide search retrieved. These were distributed 56% (USA) 31% UK and 13% (other countries). Table 5.1 lists the numbers of papers in each main subject area and associated sub-areas of Pearce& Eaton 1983. These figures give some indication of the numbers of papers dealing with specific issues. It is notable that a large proportion of the papers emanating from the United States are in the form of technical reports by federal or state agencies and universities.

| Main Subject Areas | Sub-Areas | Nos. |
|---|---|---|
| Major Reviews (6) | | 6 |
| Physical Effects (129) | | |
| | Mechanical Stresses Casued By Hulls and Prepellors | 12 |
| | Noise, Vibration and Visual Disturbance | 27 |
| | Sedinment Disturbance and Water Turbidity | 27 |
| | Bank Erosion and Bank Protection Works | 48 |
| | Transport of Plants and Animals | 15 |
| Pollution (121) | | |
| | Multiple Pollutant Studies | 26 |
| | Fuel Leakages and Engine Emissions – Hydrocarbons and Combustion Gases | 52 |
| | Fuel Lakages and Engine Emmissions - Lead | 7 |
| | Boat Paints | 5 |
| | Domestic Wastes | 31 |
| Management (150) | | |
| | Boats in Multi-user Systems | 27 |
| | Boats and Fisheries | 16 |
| | Boats and Nature Conservation | 35 |
| | Environmental Impact Case Studies | 18 |
| | Recreational Boating Domand | 8 |
| | Boat Carrying Capacity | 14 |
| | Traffic Estimates | 8 |
| | Marinas | 24 |
| Navigation Engineering (12) | | |
| | Dredging | 4 |
| | Locks and Water level Control | 8 |
| Hydrodynamics of Boat Movements | | 34 |

**Table 5.1** A breakdown of the subject area of recreational impact papers in the bibliography of Pearce and Eaton (1983)

### 5.3.2. Ireland's Inland Waterways – Brief Overview

The principal navigable waterways in Ireland include the Shannon Navigation, with its associated, rivers, lakes and canals, the Royal and Grand Canals, the River Barrow Navigation and the Shannon-Erne Waterway (which straddles the border). Then in Northern Ireland there's the Lower Bann Navigation, Lough Neagh and the Erne System. In addition, there are very many medium-sized and smaller lakes used by angling boats, powerboats, jets-skis and other pleasure craft throughout Ireland. For example Lough Currane in Kerry, Loughs Corrib, Mask and Conn in Galway and Mayo, Loughs Ennel, Owel and Derravarragh in Westmeath. Many of these water bodies have significant areas, which are relatively shallow (<5m depth) with marginal emergent and submerged beds of aquatic vegetation (macrophytes), whose species composition and diversity is characteristic of the [1]conservative water chemistry, water quality (nutrient levels), turbidity/transparency/depth, and current speed at each site. These macrophyte beds are home to a wide variety aquatic insects and other macroinvertebrates and zooplankton as well as harbouring different life stages of fish especially coarse fish e.g. roach, perch, bream, rudd and pike, providing cover from predators, food sources and spawning sites. River and lake shores are also home to a range of mammals and bird species, some of which may be susceptible to noise and other disturbance from recreational boating activities. The following review will demonstrate that shallow

[1]Conservative water chemistry refers to parameters such as conductivity, total hardness, calcium and magnesium, which are determined by the geology and soil types within the catchment of a waterbody.

and confined waters generally are likely to be the most susceptible to environmental damage from recreational boating.

### 5.3.3. Results of Review

#### *5.3.3.1. Aquatic Plants*

An recent study in the brackish waters of the Baltic in the Stockholm archipelago (Eriksson *et al.* 2004) correlated the structure and species composition of aquatic macrophyte communities at 44 shallow embayment sites split more or less equally between marinas, areas adjacent to medium-sized ferry (<350 passengers) routes and reference sites with similar morphological characteristics but without ferryboat or marina activities.

The inlets varied in size from 1-11 ha, with an average depth of 0.6m-2.9 (max depth 5m) and a salinity range of 4-7 ppt. All inlets with marinas and 6 adjacent to ferry routes had been dredged within the previous 10 years of the study; none of the reference sites had been dredged.

There was a statistical difference between the turbidity levels in the inlets with the marina inlets having a higher turbidity than the reference sites.

When the data was analysed at 0.5m depth intervals to a depth of 2.5m, it was shown that the reference sites (i.e. with no marinas and little if any traffic) had greater plant abundance (on average +20% cover) at all sites except close to the surface (0.0-0.5m), as well as a higher species diversity (on average 1-2 species) at all depths.

The study showed that *Chara*- and *Ruppia*- species (several in each genus) and *Potamogeton pectinatus,* were less abundant in inlets with marinas, while *Chara tomentosa* and *Ruppia maritima* were less abundant at sites adjacent to ferry routes. In contrast, *Myriophyllum spicatum* and *Ceratophyllum demersum* were more abundant in inlets with marinas, as was *Potamogeton perfoliatus*, adjacent to ferry routes. These differences have in part been explained by the differences in depth between the reference sites, which were significantly shallower than both the inlets with marinas, and those adjacent to ferry routes as the latter two types are dredged.

*Chara* and *Ruppia* have a preference for high water clarity and would be expected to be adversely affected by light attenuation associated with increased turbidity. The authors suggest that taking depth and turbidity effects into account that ‘it is likely that the depth dependent effects on vegetation characteristics and species composition in marinas and ferry routes are related to lower light conditions due to increased sediment re-suspension’ These effects will tend to push species such as *Myriophyllum* and *Ceratophyllum* which would normally dominate in deeper water into shallower depths while at the same time eliminating those clear water species which would normally dominate at shallower depth. (e.g. *Chara spp*. and *Ruppia spp*.)

They further suggest that differences in response to mechanical damage may have contributed to some of the observed inter-species trends. For example they cite Cohen *et al.* (1986) who demonstrated in clipping experiments, *Myriophyllum spicatum* regenerated from below the damage point, while *Potamogeton pectinatus* regenerated from the roots, and quote further studies (Kanrud, 1990) which suggest that this would favour *M. spicatum* over *P. pectinatus* in a situation where competition for light is coupled with grazing. Therefore in a situation where boating increases turbidity levels and competition for light is combined with frequent disturbance from cutting by propellers, *M. spicatum* would be favoured over *P. pectinatus*. A species such as *Ceratophyllum,* which mainly regenerates by fragmentation, may well be favoured by the action of boat propellers.

Cragg *et al.* (1980) reported that *P. pectinatus* disappears when recreational boating results in highly increased turbidity levels and Asplund & Cook (1997) noted in a study of a Wisconsin lake that *P. pectinatus* was more susceptible to propeller damage than *Chara*, which is a low-growing turf-forming species because it it taller growing and more spindly in habit. However, in a study on the impact of recreational traffic on canals in England (Murphy and Eaton, 1983), *P. pectinatus* was shown to be fairly tolerant, occurring frequently at the most heavily trafficked sites.

Cragg *et al.* (1980) studied the distribution of vegetation over several years in the 1970's in a Welsh lake. They noted the decline in submerged macrophytes, especially *P. pectinatus* but also *Eleodea canadensis, Potamogeton crispus,* and *Ranunculus circinatus* and several more species, which were present in much smaller densities. They attribute this in the main to increased turbidity generated this shallow lake by increased recreatuional boating. Most of the lake in question is less than 2m deep where macrophytes occur. They also noted a retreat in *Phragmites* reedbeds marginally, which they attributed to increased wave action and sediment re-suspension associated with recreational activity. Other emergent species including *Schoenoplectus lacustris, S. tabernaemontanii* and *Equisetum palustris,* were reduced.
Ali *et al.* (1999), showed that wave induced stress from tourist ships were an important factor influencing plant community composition in the River Nile in Upper Egypt. One of the effects of the wave action was to winnow out finer more organic rich sediment from bottom substrates, a tendency also noted in the Baltic close to ferry routes (Eriksson *et al.* 2004). A similar affect was noted in shallow ponds (<0.75m) caused by the frequent passage of boats with outboard motors. (Lagler *et al.* 1950 in Liddle & Scorgie, 1980). These latter effects have the result of uprooting certain soft-bottom dwelling species and may promote species, which prefer more exposed, coarser and silt-free substrates. Asplund and Cook (1997) used enclosures in a lake in Wisconsin to study the affect of recreational boating on plants. Their 2-month study showed that plants within enclosures increased significantly in biomass compared to non-enclosed control areas, which remained susceptible to recreational boating pressure. They also note that there was increased plant %-cover and growing height in the enclosures. They suggest that continuing scouring of the sediments by passing boats in shallow areas may reduce survival of plants and prevent re-colonization, particularly in the early summer when plants are developing. The enclosures and control sites were in 1.0-1.2m depth which was typical of the areas where submerged macrophytes grew in the lake.

Haslam 1978 (quoted in Liddle and Scorgie 1980) lists four groups of macrophytes, all of which are common in Ireland, based on their degree of resistance to erosion. (Table 5.2) These were determined experimentally by directing a horizontal jet of water from upstream onto the soil at the base of the plants and noting the time taken for the plants to be eroded. The fourth group, which are described as the most resistant are according to Liddle and Scorgie (1980) often present in the more heavily used waterways, which still have marginal vegetation.

| | |
|---|---|
| **(1) Very easily eroded** | |
| *Agrostis stolonifera* (submerged) | *Epilobium hirsutum* (rooting fragments) |
| *Ceratophyllum demersum* | *Rorippa amphibia* |
| *Eleodea candensis* | *Rorippa nasturtium-aquaticum* |
| **(2) Easily Eroded** | |
| *Callitriche spp.* | *Myriophyllum spicatum* |
| *Epilobium hirsutum* | *Sparganium erectum* |
| *Myosotis scorpoides* | *Zannichellia palustris* |
| **(3) Rather difficult to erode** | |
| *Apium nodiflorum* | *Potamogeton perfoliatus* |
| *Berula erecta* | *Schoenoplectus lacustris* |
| *Potamogeton crispus* | *Sparganium emersum* |
| **(4) Difficult to erode** | |
| *Glyceria maxima* | *Potamogeton pectinatus* |
| *Nuphar lutea* | *Ranunculus calcareous* |
| *Oenanthe fluviatilis* | *R. fluitans.* |
| *Phalaris arundinacea* | *R. penicillatus* |
| *Phragmites communis* | *R. trichophyllus* |
| | |

**Table 5.2** List of aquatic plants given in Haslam (1978) showing their degree of susceptibility to erosion.

## Conclusion

It is apparent that plants may be impacted by a range of factors associated with recreational boating including, increased erosion due to wave wash, up-rooting due to sediment removal, increased turbidity causing reduced photosynthesis, mechanical damage due to propellers, and direct physical damage due to collisions with boats. These impacts are likely to be more pronounced in shallow and more confined watercourses especially those areas which are less than 2-3m deep and where there are higher densities of boats. Submerged, emergent and floating macrophytes are all susceptible to damage depending on the level and nature of the pressures involved.

### *5.3.3.2. Impacts on Fish*

## Overview

The impacts of boating on fish are both direct and indirect. The direct impact derives from mechanical damage by propellers and pressure waves, as well as physical displacement by wash. Indirect impacts, which may be the more significant, relate to

alteration of aquatic habitats especially macrophytes. All of these impacts are difficult to quantify and some are difficult to detect in the field or even in the laboratory, none operates simply.

## Fish – Indirect Impacts (via changes in Aquatic Vegetation)

In a parallel study to that on the impact of boating activity on aquatic vegetation in Stockholm Archipelago (Eriksonn *et al.*, *loc. cit.*), Sadström *et al.* (2005), undertook an assessment of the impact of boating and navigation activities on fish recruitment as the same sites. Using the same general approach, they assessed the diversity of fish species and the abundance of young-of-the-year (Y-O-Y) fish in inlets adjacent to small boat marinas (12), in the vicinity of ferry routes (15) and reference areas (9) where there was relatively little boating activity. Surface salinity in the study area varied from 4.5 ‰ to 5.4 ‰. Analysis of the data showed that bream (2 species), perch, roach, rudd and tench (all bar one of the bream species occur in freshwater in Ireland), commonly occurred together in inlets, while pike, bleak, ruffe and gobies (*Potamoschistus spp.*) were not distinctly associated with other species. (Note that bleak and ruffe do not occur in Ireland). The study also showed that the species composition tended to be different between marinas and non-marinas, whereas, in the case of the sites adjacent to ferry routes there was a large variation in species composition, which commonly overlapped with reference inlets and marina sites. The study pointed to the fact that dredging appeared to be an important variable influencing the fish community composition. However, it wasn't possible to separate this effect from that of direct disturbance related to boating and navigation.

Species richness was not affected in inlets disturbed by boating or navigation or dredging. However, composition was altered by favouring some species and suppressing others. The authors speculate that successful fish recruitment of some species depended on the presence of vegetation. Thus, species that are highly dependent on vegetation as spawning substrate and refuge/feeding habitat during their early life stages clearly tend to be more abundant in reference inlets than in inlets disturbed by boating and navigation. The species listed by the authors to be strongly dependent on vegetation include: roach (*Rutilus rutilus*), pike (*Esox lucius*) bream (*Abramis brama*), Rudd *(Scardinius erythropthalmus)*, tench (*Tinca tinca)* and pipefishes *(Syngnatha/Nerophis)*. Thus, the abundance of species highly dependent on vegetation was significantly correlated to the cover of *Chara tomentosa* and *Potamogeton pectinatus*, two plant species, which were shown by Eriksson *et al.* (2004) to be negatively affected by boating activity in the Stockholm Archipelago.

These general observations are supported the work of Wolter *et al.* 2000 whose analysis of historical fish data for waterways in Berlin showed that there was a sharp decline in phytophilus (plant-loving) species after macrophytes were completely lost due to eutrophication. For example the catches of pike, common carp (*Cyprinus carpio*) and tench all became negligible. Interestingly, roach, common bream, silver bream *(Blicca bjoerkna)* and perch *(Perca fluviatilis)* now make up 85% of fish taken in what are described as polytrophic or hypertrophic waters. Clearly, these fish, all of which are common in Ireland (except Silver Bream which doesn't occur here), are fairly tolerant of a range of environmental pressures and are referred to by the authors as eurytopic (i.e. of widespread occurrence, in terms of habitat type).

Another study showed that in the Oder-Havel-Kanal, a navigable waterway in the German lowlands which is subject to dense ship traffic, is dominated by tolerant species, principally rudd and roach which have a relatively low recruitment potential in this waterway. The authors (Arlinghaus *et al.* 2002) attribute this to a combination of poor marginal habitats (all the embankments are constructed) and the high water velocities generated by the dense shipping traffic.

These studies demonstrate the strong link between waterway habitat diversity, especially, though not exclusively, aquatic plants, as being very important for maintaining fish species diversity and recruitment rates. However, the relationship between fish and vegetation is a very complex one. For example a study on habitat use in the Saône in France by four species of juvenile cyprinids (Grenouillet and Pont, 2001) indicated that macrophyte species and associated structural diversity of the beds combined with the size and abundance of associated zooplankton populations, which acted as a food resource for the juvenile fish, were very important variables explaining juvenile fish distribution. Furthermore, other important factors included the size of the juveniles (within the same species) and, to a lesser extent, physical variables such as depth and light-intensity. These distribution patterns relate to availability of suitable food, predator avoidance, foraging success etc.

These preferences are likely to be further complicated by the degree of turbidity in the water as has been shown by Snickars *et al.* (2004) who demonstrated that while vegetated habitats were preferred by juvenile perch in the presence of predator pressure (ike), the degree of use was reduced with increasing turbidity. Thus, it has been postulated in other studies, that increasing turbidity can offer a degree of protection against predators and may be influential in determining the distribution and composition of fish communities at certain sites.

In their review of the impacts of navigation on fisheries on British canals, Murphy and Eaton (1981) quote several studies, which would suggest that increasing navigation intensity is associated with a decline in fish biomass although serious declines may not be apparent until boat movements reach more than 5000 movements per annum. In some much more heavily used canals, however, the presence of refugia for fish in the form of unused side-channels, backwaters or joining river tributaries can help to maintain quite a heavy population of fish (coarse species) in the main navigation. In general, however, the authors suggest that the optimum degree of boat use is canals is between 2000-4000 movements per hectare per year (mhy), which at the lower end would maintain open water (i.e. prevent overgrowth by aquatic plants) and at the higher end prevent too much damage to submerged macrophytes; although, according to the authors, this range could be extended to 1000-5000 mhy, without a great loss of usefulness to any one water user. (i.e. anglers or boaters).

## Fish - Direct Impacts

The direct impacts of boat propellers on the mortality of adult fish have been demonstrated in the field for the specific case of barge towboats on the Mississippi

River (Gutreuter *et al.* 2003) and in lab studies Killgore *et al.* (2001) assessed the impacts of the same boat props on the juvenile stages of fish native to that part of the river. The mortality rate of the adults was calculated (among other things) as a function of the intensity of towboat traffic, which in one section of the river was estimated in one year as approximately [2]312,000 km. Given that the props have a diameter of over 2.5m, which can constitute anything from 20%-100% of the depth of a confined navigational canal, the opportunity for fish kill is considerable. In the case of juveniles, smaller larvae were more vulnerable with mortality rates of >75% when entrained by propellers while the eggs of some species were virtually unaffected. Overall it is extremely difficult to detect such mortalities in the field. Nevertheless the authors believe that for some species, even these low mortality rates may have population implications.

However, these props are much larger than recreational boat prop sizes and the level of water they entrain is consequently very large. Furthermore the traffic densities are very high and some of the waterways relatively confined. Referring to typical recreational boating, Liddle and Scorgie (1980) quote Lagler *et al.* (1950) as concluding after an intensive study, that neither fish production nor fishing success, were affected by prolonged use of outboard motors in experimental ponds. Under some circumstances, however, particularly where activity is concentrated in a small area, there may be local problems. Murphy and Eaton (1981) also quote other authors to the effect that the direct affect of powered pleasure boats on fish populations are relatively slight. This aspect of the review probably needs further investigation, however.

#### *5.3.3.3. Impacts on Macroinvertebrates*

Detailed studies on two small streams in Switzerland examined the impacts of aquatic macrophyte removal by hand-cutting and dredging. The impacts on the macrophytes (Kaenal *et al.* 1998a) and macroinvertebrates (Kaenal *et al.*1998b) were assessed and it was concluded that both communities recovered within one year of the removal operation. In the case of the plants, recovery took place during the same growing season if the plants were cut in spring before flowering had taken place. However, it was delayed until the following spring if cutting took place in the post-flowering summer period. Macroinvertebrates recovered within 4 to 6 months but the recovery seemed to be seasonally dependent with faster recovery occurring when macrophytes were removed in spring. The authors also recommend keeping some macrophyte beds as refugia in order to shorten the recovery period.

In an earlier study undertaken in Ireland, (Monahan and Caffrey, 1996) the authors also highlight the importance of refugia for macroinvertebrate recovery, pointing to the preservation of weeded marginal fringes as being desirable during weed removal operations in order to minimise the impact on macroinvertebrates. Their study, on the impact of managed weed removal from the Royal and Grand Canals, concluded that macroinvertebrate recovery was rapid after the cutting occurred and that no adverse effect on dependent fish life resulted.

These studies indicate that provided some vegetation remains and presumably has the time to grow back that associated macroinvertebrate populations will also recover rapidly. They also point to the importance of the timing of plant removal operations,

[2] This figure refers to the total distance travelled by vessels within the study reach assuming that only one vessel had done all the travel.

which will depend on the priorities being set (i.e. to increase the rate of macrophyte recovery or macroinvertebrate recovery). One must be cautious, however, when trying to extrapolate from experimental studies, even those based in the field, to other situations. A very important factor will be the scale of any operation or impact. Clearly, if all the in-stream vegetative cover over a very extensive length of a waterway is removed, significant ecological impacts are bound to ensue and so the value of that waterway for sensitive receptors, be they rare macrophytes, protected macroinvertebrates (e.g. White-clawed crayfish), fish or lampreys, each situation must be assessed on its own merits.

Murphy & Eaton (1981) in their review of the impact of boating on navigable canals noted a positive and significant relationship between summer abundance of submerged waterplants and invertebrate diversity, measured as number of taxa recorded, at canal sites (surveyed in 1977-78). They concluded that plant-associated invertebrate diversity declined with decreasing vegetation, and hence generally with increasing boat traffic and they quote other studies in support of this hypothesis and further suggest that it would appear likely that high densities of boat traffic degrade the invertebrate food base available to fish, especially that part of it which is plant-associated (as opposed to that portion dwelling in bottom sediments).

These issues are important for pleasure boating as they impinge on waterway maintenance programmes (i.e. weed-cutting operations), the impact of boat wash on macrophyte beds and even the structural design of navigation canals, where it has been shown in many studies that the provision of a diversity of marginal habitats e.g. embayments and backwaters or shallow water areas greatly enhance biodiversity for all groups when compared to straight sided engineered banks. While the latter is clearly a much greater issue in heavily-trafficked, commercially operated ship canals in Europe and North America the underlying principles remain the same for all waterways.

#### *5.3.3.4. Noise and Disturbance*

## Introduction

The area of bird disturbance by human activities has been the subject of a large body of investigation, especially in relation to coastal and estuarine sites. While some work has also been undertaken in inland waterways, the literature here is less extensive. In any case, this area of investigation is very specialised and only a very brief overview is given here.

## Inland Wetland Bird Habitats in Ireland

Ireland's principal wintering waterfowl sites occur at estuarine and coastal sites all around the coast. While the same numbers of birds do not occur inland, there are nevertheless many important sites along sections of our navigable rivers and in many lakes. The most important single site is Lough Corrib, with Lough Derg, Lough Ree, the Shannon Callows (Athlone-Portumna), the Little Brosna Callows also very important. Other sites worth mentioning include Lough Ennell, Lough Deravarragh nad Lough Iron in Co. Westmeath. These sites are visited by a large variety of waders and other waterfowl and species which are common include Whooper swan, White-

fronted Geese, Pochard, Teal and Tufted Duck, Great Crested Grebe and waders such as Lapwing, Curlew, Snipe and Black-tailed Godwit. Details of all the many Irish sites are to be found in "Ireland's Wetlands and their Birds"[3]. These sites are used most intensively between September and March each year, with the peak numbers generally occurring in the November-January period. Certain sites for example Lough Cullen and Lough Conn in Co. Mayo are both important for summer nesting species (mainly seabirds) and other sites contain small tern colonies.

It is clear from these data that there is a significant potential for disturbance of over-wintering birds that are foraging as well as certain summer-nesting species also.

## Evidence and Significance of Disturbance to Birds

It is not difficult to demonstrate disturbance, its likelihood, intensity and frequency in a wide range of bird species and many disturbance types. In fact, according to Birdwatch Ireland (*pers. comm*. Olivia Crowe) their surveyors on [4]IWeBS counts in the September-March period, not uncommonly encounter disturbance of birds by motorised leisure craft (boats and jet-skis) in inland waters (e.g. Lough Corrib). This often means that the counts have to be postponed or abandoned as the local populations are displaced to other sites. However, gauging the significance of these disturbances e.g. in terms of reproductive success and consequent impacts at a population or sub-population level is very difficult. Excessively intensive or frequent disturbance is generally believed to be a detrimental impact and some species, which are either rare or particularly sensitive, need to be considered carefully in this context.

A Scandinavian study on the impacts of disturbance on migrating Pink-footed Geese, concluded that in areas where the flocks were not subject to disturbance by famers in their spring fattening sites these flocks subsequently reproduced better than those geese whose fattening sites were subject to disturbance (Madsen, 1994).

## [5]Flush Distances & Buffer Zones

Rodgers and Schwikert (2002) undertook a study into the flush distances of foraging and loafing waterbirds in Florida caused by personal watercraft PWC's – (believed to refer to jet-skis) and outboard motor powered boats. As one might expect, they found a range of sensitivities both between and within species. One of their findings was that 11 species (i.e. 68.8% of those looked at) showed no significant difference in the length of their flush distance response to the approach of either a PWC or an outboard, while one species was significantly more sensitive to PWC's and four species were significantly more sensitive to outboards. They conclude that a single buffer zone width could be developed for both PWC's and outboards and suggest that a 180m for wading birds, 140m for terns and gulls, 100m for plovers and sandpipers and 150m for ospreys would minimise the disturbance to these groups at the foraging and loafing sites they were working at in Florida.
An analysis of Wetland Bird Survey (WeBS) data in the UK for the years 1995/96 and 1989/99 (Robinson and Pollitt, 2002), showed that over 68% of counters recorded no disturbance at the sites they were counting and that only in <2% of cases was heavy disturbance recorded. The data refer both to inland and coastal sites and in the inland

[3] Crowe, O. (2005) *Ireland's Wetlands and their Birds.* Birdwatch Ireland, Wicklow
[4] IWeBS = Irish Wetland Bird Survey
[5] Flush distance = is farthest distance from a bird at which a boat or other agent causes the bird to fly or swim away.

sites the main sources of disturbance was from motor-driven machines and un-powered boats. These findings may seem to contrast with the IWeBS data for Ireland but one couldn't determine that without analysing the Irish data set in a similar manner.

Birds can habituate to human disturbance, something that has been demonstrated in many studies, which suggests that areas, which normally receive less human disturbance, may need a more conservative approach to protection. In a comparison of bird disturbance along developed and undeveloped lake shorelines, Traut and Hostetler (2003) conclude that buffer zones may be warranted along undeveloped shores to protect waterbirds that show heightened alert/flee behaviour when compared to waterbirds along developed lake shorelines.

These studies seem to indicate that in some instances the use of buffer zones might be appropriate in order to protect specific shoreline nesting, loafing/roosting or foraging areas of waterbirds. The need for such measures will depend on a wide variety of factors but presumably the sensitivity or conservation status of the bird species concerned will be high on the list. It is important to point out that not all interactions between water birds and humans need necessarily be negative, many may be neutral and some positive (Bright *et al.* 2004). Therefore a species by species and site-specific approach is recommended and the National Parks and Wildlife Service and BirdWatch Ireland and the [6]RSPB (in Northern Ireland) are probably best placed to highlight areas of potential conflict between wetland birds and recreational boating.

***5.3.3.5. Water Quality***

## Turbidity

The link between boating and turbidity is well established (Yousef, 1974; Hilton and Phillips, 1982). Furthermore, Anthony and Downing (2003) have shown that heavy boat traffic can act in isolation or in combination with wind-induced turbulence to re-suspend bottom sediments in shallow lakes and delay the settlement of wind-induced turbidity. They postulate that these processes contribute to the cycle of eutrophication and slow the process of recovery (their example was Clear Lake in Iowa at 2.9m average depth). In their studies in the Norfolk Broads (Hilton and Phillips *loc. cit.*) have shown that while boating induced turbidity can be significant at some sites it was much less so than that generated by phytoplankton derived from nutrient enrichment effects.

The magnitude of the turbidity generated in lakes and rivers by boating will be a combination of many different factors including the depth and general morphology of the water body, the size, and speed of the boat (though not necessarily its top speed – Beachler and Hill 2003), the size of the propeller and the engine power, the type of bottom substrates etc. Thus passage through deep open water or over coarse substrates (bedrock, gravel or coarse sand) may generate little or no turbidity. Whereas, passage through narrow, shallow, muddy bottomed channels is likely to generate much more turbidity

As several studies have shown, turbidity is a very important factor determining the composition and depth of growth of macrophyte communities as well as being and important influence on fish predator-prey dynamics. In general, waterway management should aim to keep turbidity levels at background (non-boating) levels, wherever

[6] RSPB = Royal Society for the Protection of Birds

feasible, as any significant rise above these levels may have adverse impacts on the ecology of a site. .
As several studies have shown, turbidity is a very important factor determining the composition and depth of growth of macrophyte communities as well as being and important influence on fish predator-prey dynamics. In general, waterway management should aim to keep turbidity levels at background (non-boating) levels, wherever feasible, as any significant rise above these levels may have adverse impacts on the ecology of a site.

## TBT & Antifoulants

Apart from being aware of occasional slight oil sheens on the waters of some marinas most people are probably not aware of significant boat-related water quality or emissions problems in inland waterways in Ireland. Some research overseas has pointed to water quality problems. The classic case of this was the use of TBT (tributyl tin) in anti-fouling paints in marine pleasure craft. However, since this has been banned on vessels under 25m (i.e. the vast majority of pleasure craft) since about the mid 1980's, the problem has diminished in most places, even though TBT remains for many years in sediments and is likely to be still exerting some adverse impact in coastal marinas. Hall *et al.* (2002) who undertook a probabilistic risk assessment of TBT in the Chesapeake Bay area of the U.S. indicated that in general freshwater systems were less sensitive to TBT impacts than marine systems. While there have been several studies undertaken into the impacts of TBT in Irish coastal sites there are none published for inland waterways (pers. comm. Dr. Dan Minchin). It is likely that some residual TBT remains in the sediments of some of the larger marinas where water exchange is poor because TBT was used on pleasure craft in Ireland in the early 1980's.

Other products have replaced TBT in antifouling coatings, one of which Irgarol 1051 is known to be toxic to aquatic plants (much more so than to aquatic animals) and which is getting some attention in the literature, especially in the US. Two recent studies from there indicate that Irganol 1051 and its principal breakdown product GS262575 (which is much less toxic) have been detected at many US sites, with the highest concentrations detectable in marinas, especially ones which are poorly flushed. The levels measured were generally well below the provisional benchmark set for plant protection (251 ng/l for Irgarol 1051 and 12,500 ng/l for GS262575) (Hall and Gardinali, 2004; Hall *et al.* 2005). The level of use of this anti-foulant in Irish waters is unknown. However, based on the US data it is unlikely to present a significant threat at this stage. Other anti-foulant preparations contain for example copper compounds and these are frequently used on Irish pleasure craft. However, there is no data on whether they present a significant ecological risk at this stage. Monitoring in poorly flushed marinas e.g. Portumna (Connaught Harbour) or the Inner Basin at the Derg Marina in Ballina. The EU inland fisheries directive (78/659/EC) sets a receiving water level for copper of <0.005 mg/l, in soft water and < 0.04 in water of hardness of 100 CaCO3. Data published by the EPA for the period 1999-2000 (EPA, 2001) indicated that these levels were exceeded only in exceptional situations in Irish freshwaters and none of these are likely to have anything to do boating activities. It is not possible to say if the extensive sampling programme of the EPA targeted marinas, but it seems unlikely. In which case, some level of contamination cannot be ruled out at this stage.

What we can say is that is certainly isn't widespread and may not be significant.

## Hydrocarbons and Fuels

This matter hasn't been reviewed in detail although there appears to be a lot of information in the literature about hydrocarbons entering the environment as a result of recreational boating and marinas. These arise at marinas from leakages from storage areas, spillages during fuel transfer and in open water through leakage of poorly combusted fuel and fuel exhaust especially from inefficient, larger or poorly maintained two-stroke engines. Mineral oils tend to be of relatively low toxicity, volatile and readily biodegradable so that in trace amounts they are unlikely to have significant ecological impacts.

In contrast, polycyclic aromatic hydrocarbons (PAH's), which form a minor compositional component of fuel oils and of fuel combustion products, are toxic and more persistent in the environment and in some cases are believed to be carcinogenic to humans. PAH's comprise at least 16 separate compounds known as congeners, some of which are more harmful than others. Their occurrence in the environment as a result of boating activities has been documented (Cranwell and Koul, 1989) and the potential risk to human water supplies has been looked at in cases where water abstraction reservoirs are also heavily used for recreational boating (Mastran *et al*. 1994). The latter study showed evidence of PAH increases in the water column associated with seasonal boating and also demonstrated higher PAH levels in sediment at marina sites as compared to non-marina sites. The long-term ecological impacts of PAH's or fuel oils from boating on the environment is not known but probably only worth checking in areas of heavy boat traffic around poorly flushed marinas. Again, the public health issues related to water supplies would only be relevant in areas where recreational boat use is high on reservoirs or navigable rivers from which water is abstracted for potable supply.

### 5.3.4. Issues of Intensity of Traffic

Navigable waterways in Ireland experience moderate boating densities compared to waterways in parts of Britain e.g. the Broads or the Thames (pers. comm. Colin Becker) and consequently would not be expected to experience the same level of boating-associated environmental stress. Certain waterways such as the Royal Canal experience quite low traffic to the extent that excessive weed growth may present problems for navigation. However, some sections of our waterways probably experience boating traffic high enough to cause ecological impacts. Figure 5.2 shows the level of traffic as assessed by passes through locks between 1995 and 2004 on the Shannon-Erne System; note that these are not lock openings but actual boat counts.

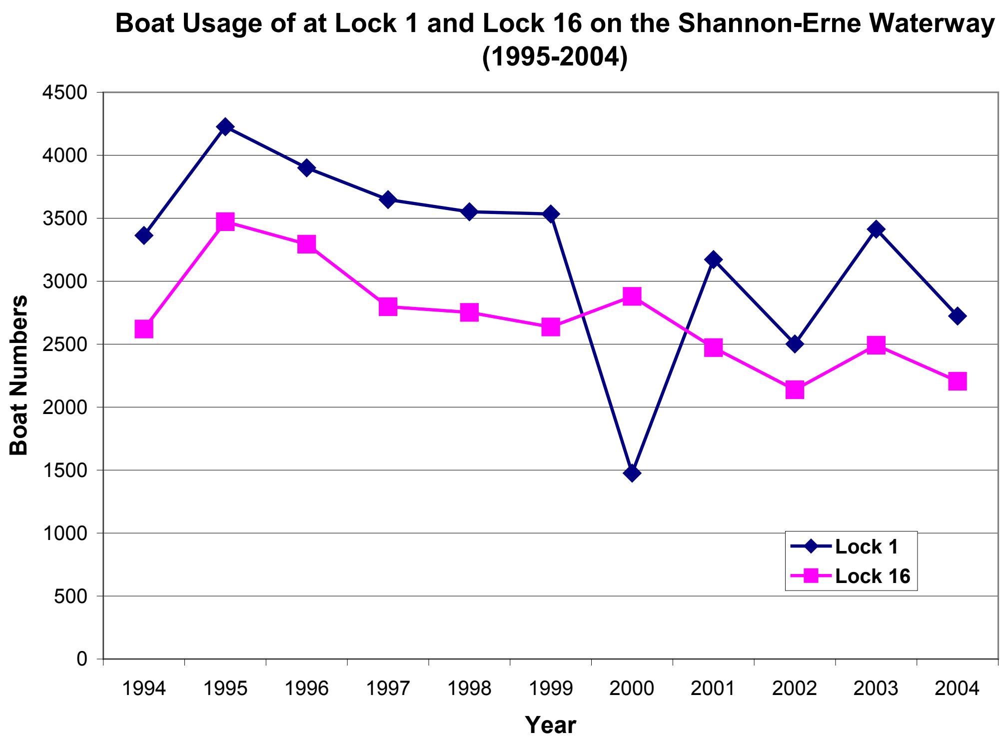



**Figure 5.2** Boat movements on the Shannon Erne Waterway.
(data courtesy of Waterways Ireland)

Intuitively, one would expect that higher boat numbers would result in greater levels of impact on waterways. However, few studies appear to have systematically compared between a sufficiently broad range of sites to say for sure what would be acceptable and what potentially damaging levels of traffic. This isn't surprising when one considers the very broad range of variables involved other than boat numbers. These include the size of boat, boat speed, nature of the bankside habitats / structures, water depth, channel width, nature of the bottom substrate etc. However, a study on English canals (Murphy & Eaton, 1983) linked the intensity of boat traffic to a reduction in abundance (biomass) of aquatic macrophytes, particularly, submerged macrophytes. They demonstrated that at traffic movements of less than 2000 per year, submerged macrophyte abundance was generally high (up to 916.5g/m$^2$) but that at densities greater than 4000 per year, macrophyte crops were very small (<20g/m$^2$). In between these densities the abundances were variable but tending to decline with increasing density. The authors point to turbidity and mechanical damage as the most likely mechanisms of impact on macrophytes.

Their numbers, however, are standardised to a theoretical canal of 10m wide, 1km long and 1m deep giving numbers of boats per hectare, per metre depth, per year. So the figures are not simply transferable to Irish canals without taking account of the dimensions of the Irish canals. However, the authors suggest that the depth dimension can be dropped from the standardisation without much loss in accuracy, such that knowledge of canal width is all that's needed for a reasonable comparison.

These figures wouldn't automatically be applicable to other channels such as lakes and navigable rivers because of differing dimensions (some times markedly so). Nevertheless, they suggest that other things being equal (which they rarely are!), increasing numbers of craft are more likely to result in adverse impacts than if numbers remain at an as yet undefined lower level. For English canals, Murphy and Eaton (1983) are suggesting that boat movements of 2000-4000 mhy (i.e. movements per hectare per year) would be compatible with both nature conservation and recreational activities.

On just over 5000km of navigable waterways in Britain there are about 100,000 registered vessels. In Ireland we have just over 1000km of navigable waterways but proportionally fewer registered vessels. Even if it is assumed that there are significant numbers of unregistered vessels in Ireland, we probably still have, on average, a significantly lower level of usage on Irish inland waterways. Nevertheless, there are some locks on the Upper Shannon, for example, where up to 11,000 boats movements are recorded annually and there is some indication in the past decade that the numbers of larger boats being purchased is increasing, even though the number of boat movements through locks doesn't appear to have risen significantly in that time. In any case, it cannot be assumed that because our boat numbers may be low, in general, that they will remain so into the future. Also, it cannot be said for definite that the present levels of traffic are not already causing localised impacts where the numbers are sufficiently high and the nature of habitats make then vulnerable (i.e. shallow depths and/or narrow channels) or plant and animal communities are particularly sensitive. One might perhaps begin to look for such impacts for example, in communication with Waterways Ireland engineering staff, in some of the narrower Shannon routes between Athlone lock and Clarendon lock, a stretch of the Shannon where there are relatively high boat movements.

## 5.4. Cultural Heritage Impacts

While boat wash has been identified as a contributing factor in the destabilization of cultural resources in freshwater zones, little research has been conducted in this area. In fact, data relating to the impact of general waves on the shorelines of freshwater environments is also virtually non-existent (Allan and Kirk, 2000). As a result, the majority of sources accessed for this report depend primarily on observational data relating to the erosion effects of boat wash. Despite the absence of quantitative data, many insist that any competent observer could identify the association between boat wash and erosion problems. (Gill and Blake, 32: 2002)

O'Halloran (2000) discusses the impact of recreational boating on aboriginal cultural sites in Lake Hume, New South Wales. Heightened levels of erosion and greater artefact dispersal can be attributed to the direct impact of wave action, subsequent inundation and exposure. The detrimental effects of boat wakes, have also been noted at the site of the USS Utah in Pearl Harbour (NPS, 2001 ) and on the Panama Canal at the Pedro Miguel Saddle Dam (c.1900) (Bragar, 2001). From an Irish perspective, the impact of boat wash on submerged cultural heritage at Rindoon Harbour, Co. Roscommon has been noted with concern (Breen, 1998).

### 5.4.1. Literature review

As previously noted data relating to the impact of waves on the shorelines of freshwater environments is virtually non-existent. This paucity of information is further heightened when one considers the effect of boat wash on the archaeological resources. The reason for this lack of information appears to relate more to the current trend in the archaeological discipline of focusing on material culture or historic landscape evolution rather than current landscape evolution.

The collection of all relevant literature regarding the cultural heritage impacts of boat wash incorporated the following:

- Library Search
- Web Search
- Query via international archaeological and aquatic archaeological emailing groups.
- Direct consultation with known experts in the field in Ireland, Continental Europe, USA and Australia

The following studies have been taken as a representative sample of the scope of research conducted in this field.

- Tennessee Valley Authority, Final Environmental Impact Statement (FEIS) 2004
- Florida: Archaeological Stability Guide 2000
- Venice Inner Canal Project – Final Report 2002

### 5.4.2. Tennessee Valley Authority (TVA) – FEIS 2004

The TVA was established in 1933 and manages a series of power plants, hydroelectric dams and reservoirs along the Tennessee River. Overall, the authority has responsibility for a 41,000 square mile watershed within the states of Virginia, South Carolina, Tennessee, Alabama, Georgia and Mississippi (T.V.A., 2005).

An important commercial waterway, barge traffic plays a large part in the generation of boat wake energy. In 2000, commercial traffic exceeded 49 million tonnes, ranking the Tennessee River fourth among U.S. waterways (T.V.A., 4.21-1). The river system is also a recreational hub. Activities on the river amount to an annual '4 million user days', and are mainly attributed to water sports (T.V.A.,4.24-4)

As part of a Reservoir Operations Study, the TVA produced a final environmental impact statement (FEIS) to document the environmental, social, and economic impacts associated with projected changes in reservoir management strategies.

#### *5.4.2.1. Scope of study*

An important component of the study was the assessment of factors affecting the integrity of the cultural resources located within the remit of the TVA. Bound by

the requirements of the National Historic Preservation Act (NHPA) 1966 and the Archaeological Resource Protection Act (ARPA) of 1979, the TVA has a responsibility to identify, evaluate and protect cultural resources. The survey defines cultural resources as properties that are either archaeological sites or historic structures and maintains two separate databases for each (TVA, 2004: 4.18.1)

Although not all of the valley's shorelines have been surveyed, the TVA has recorded 7, 726 archaeological sites (pre-1600 A.D), and 5,322 historic structures (Ibid : 4.18.4).

Shoreline erosion was identified as one of the four major factors threatening the integrity of cultural resources (Ibid: 4.18.1). In 1997, erosion of the banks of the Tennessee River destroyed a large section of the Shiloh Indian Mounds, a National Historic Landmark (A.I.A.,1997).
While shoreline erosion is primarily attributed to natural factors and seasonal fluctuations in water level, human activities, particularly recreational and commercial boating, are also responsible. A 16% increase in recreational boating is projected for the coming 25 years. Accordingly, it is predicted that the associated boat waves are likely to further accelerate the erosion of shorelines (T.V.A, 4.16-3: 2004)

#### *5.4.2.2. Methodology*
Although several rating systems have been developed to characterize the extent of shoreline erosion, none systematically assesses the impact of boat wash (4.16-3). However, cultural sites are identified, documented and monitored for changes.

#### *5.4.2.3. Mitigation*
TVA identifies mitigation as actions which are taken to avoid, offset, reduce, or compensate for adverse effects to the resource (Ibid: 7.1) With regards to cultural resource management, sites in need of treatment or protection are identified as a result of archaeological surveys of shorelines. Sites at risk are then included in the Shoreline Treatment Program which endeavours to rectify the situation. Treatment is carried out in conjunction with the appropriate State Historic Preservation Office and other relevant bodies, such as native American tribes. (Ibid).

TVA found that a range of erosion processes, including boat wake energy, would continue the present trend of shoreline erosion.(Ibid: 6.8) Such shoreline erosion is expected to have adverse impacts on the integrity of cultural resources on shoreline, and near-shore reservoir bottom areas, regardless of policy change and mitigation measures (Ibid: 6.9). For example, maintaining high water levels in certain reservoirs tends to protect areas susceptible to erosion (5.16.1). However, maintaining such levels over a long period of time increases recreational boat activity, which accelerates the rate of erosion (5.16.3)

A proposed change in navigation policy includes the deepening on the river's central channel in order to allow barges to be loaded more fully. The deeper draft of the vessels is predicted to send more wave energy in the form of boat wash to the shorelines (T.V.A.:5.16.8). No substantial change in erosion is anticipated as 'fewer trips are projected under this alternative' (Ibid). However, in a subsequent chapter, the authority

concludes that were federal investment in the river's infrastructure be made available, the Tennessee River could experience an increase in barge movement of commodities. (4.21.6)

#### *5.4.2.4. Conclusions*

The T.V.A. identifies boat wash energy as having a negative effect on its shoreline and riparian cultural heritage. Overall, the resulting shoreline erosion is systematically monitored. However, the mitigation strategies proposed focus primarily on measures to repair shoreline erosion, as opposed to restricting boat traffic in certain areas, or the promotion of boater education. The reason for this repair focus is that the project identified erosion as one of the primary threats to the stabilisation of the archaeological resource and boat wash was only a contributing factor of this overall erosion threat.

### 5.4.3. Florida Department of State – Archaeological Stabilization Guide

The Archaeological Stabilization Guide was prepared with a view to protecting sites and providing stabilization solutions for private landowners. Presented as a 'how-to' guide, it briefly presents case studies along with their management problems and subsequent outcomes (FDS, 2000: 2)

#### *5.4.3.1. Scope*

A wide range of sites were selected, including several freshwater sites which are directly threatened by currents and boat wash. However, due to the nature of the guide, most case studies include boat wash mitigation measures which are reactive as opposed to proactive. For example, solutions include the use of physical barriers such as riprap and seawall replacements, as opposed to boater programs and education strategies.

#### *5.4.3.2. Methodology*

***Case Study 1: Crystal River State Archaeological Site (Ibid: 6)***

Located on the north side of Crystal River in Citrus County, Florida, the site is a prehistoric ceremonial complex and burial site. A seawall collapse, attributed to boat wakes and natural erosion, resulted in the loss of archaeological deposits.

The suggested solution is to recover the eroded cultural deposits, some of which were located on the submerged seawall, others on the river bottom. A seawall replacement is then installed in order to protect the remainder. (Fig 5.3)

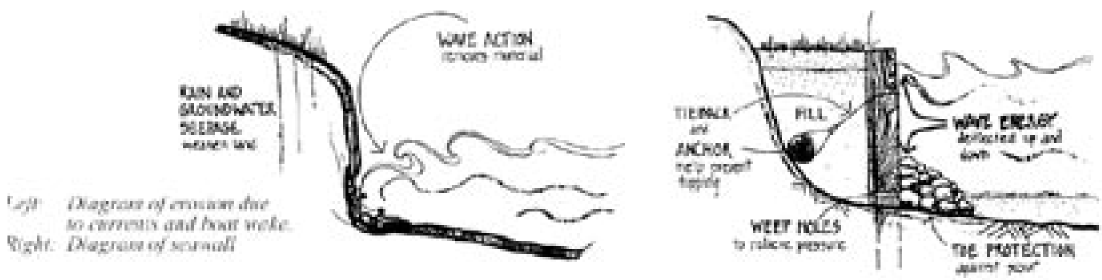



Fig 5.3 – (FDS : 2001: 6)

***Case Study 2: Fort San Marcos de Apalache. (FDS: 2000 : 8)***

Located at the confluence of the Wakulla and St. Marks Rivers in Wakulla Country, Florida, the fort was initially constructed by Spanish settlers in the early 1600s. Oil barge and boat traffic have accelerated the erosion of the river banks, causing archaeological material to be deposited in the water. Archaeological features present along the riverbank include wooden structural features, artefacts associated with a mid-19th century wharf.

While planning protective measures, a temporary protective bulkhead was constructed. Although this is a relatively effective measure, the archaeological deposits are still at risk.

***Case Study 3: Shell bluff landing site***

Shell bluff landing site is located along the eastern shoreline of the Tolomato River, St. John's County, Florida. Listed on the National Register since 1991, the site contains materials dating from circa 200BC to the present. (FDS,2000: 16) The main factor affecting the site was erosion due to tidal fluctuations and waves due to boat wash and natural action.

An erosion-monitoring project was conducted in 1987 by the US Army Corp of Engineers. It was concluded that although the damage directly resulting from boat wake could not be accurately established, a no-wake zone could only have a positive effect on site preservation. At this point, it was proposed that a) the site be monitored at six month intervals for a minimum of two years; b) a topographic map of the site be completed; c) an interdisciplinary literature search be conducted to inform the mitigation of erosion at the site; and d) a long-term plan for site management be prepared to include strategies for reducing the effects of erosion.

***5.4.3.3. Conclusion***

The handbook briefly describes the management problems and solutions of 16 case studies and is designed to alert members of the public to the importance of site stabilization measures. In several cases, boat wake is identified as a contributing factor to site destabilization. The mitigation strategies proposed in Case Study 1 and 2 (above) involve physical barriers to protect the resources from boat wash energy. Case Study 3 alludes to comprehensive site preservation measures which included long-term management strategies. Unfortunately, the original text of the 1987 erosion monitoring project could not be located for this report.

### 5.4.4. Venice Inner Canal Project (UNESCO)

In 1990, UNESCO launched a study in order to measure the wakes produced by canal traffic and to create a methodology for the collection of traffic, cargo and wake data. Another aspect of the study was to assess the impact of boat wash on the canal walls and facades of waterfront buildings, several of which had collapsed in the centre of the city. As a result, and in conjunction with the Worcester Polytechnic Institute (WPI), New England a complete catalogue of structural and impact damage on the walls of the inner canals was completed (UNESCO, 2002). In 1998, it was possible to prove that "the root cause of wall damage is lack of dredging, which is only later compounded by boat traffic and wakes."(UNESCO, 2002b: 1)

### 5.4.5. Methodology

A comprehensive fieldwork programme, conducted at low tide, catalogued all of the damage along the canal walls while the respective sewer outlets were assessed. All damage was measured, photographed and processed as either Structural or Impact related (UNESCO, 2002b: 4). The data collected was then mapped onto a G.I.S. layer. (Figure 5.4)

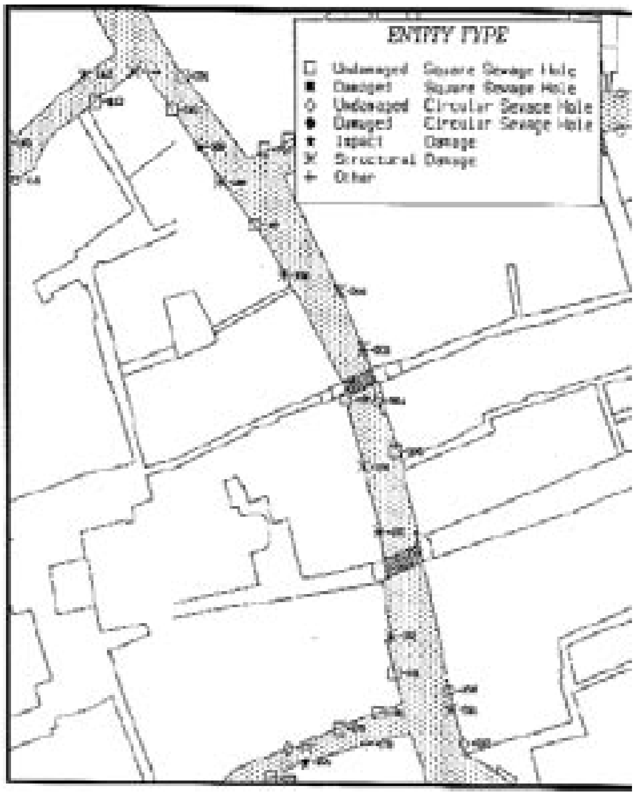



Figure 5.4: 1992 GIS Map

Structural damage is attributed to the accumulation of sediment around sewage outlet, which leads to a build up of pressure, causing the sewer pipe to rupture. Seeping sewage gradually corrodes the mortar of the canal wall leaving it susceptible to the 'hammering and suction' effect of wake action and tides. In the past few decades, canal walls have degraded more markedly due to a) the lack of dredging of the canals/lack of maintenance of canal walls and b) the increased number and power of motorised boats in the city.

By studying traffic volumes in different locations, the team were able to correlate the data with the data relating to varying degrees of canal wall damage. (Fig.5.5)

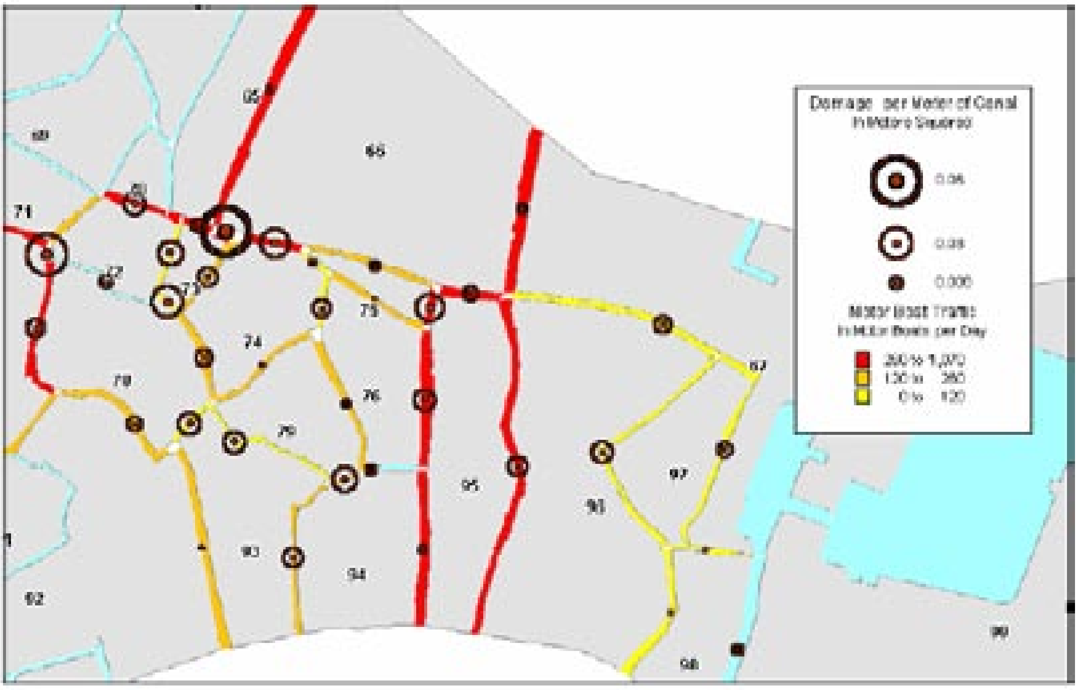



Fig 5.5. Size and location of damage Vs Boat Traffic (UNESCO: 2002b: 11)

While some areas of high traffic volumes coincided with heavily damaged zones, others did not. However, when levels of sedimentation were correlated with the data relating to structural damage, the following result was achieved. (Fig 5.6)


Fig 5.6: Sedimentation levels vs structural damage (UNESCO: 2002b: 12)

#### *5.4.5.1. Mitigation Measures*

The results of the above study have highlighted the necessity of dredging and traffic restrictions within the inner canal system. This study led to the creation of the 'Moto Ondoso Index', or the 'Boat wake Index' which makes it possible to convert levels of boat traffic to levels of "wake-loading" (i.e. how much wake energy is discharged in

the canal. This helps to assess the links which exist between boat traffic and canal wall damage. (UNESCO, 2002)

Using this information, lobby groups and associations such as 'Pax in Aqua – per la lotta al moto ondoso' 'Architetti Veneziani' and the 'Comitato Santa Guiustina contro el moto ondoso' (Mencini:200:48) were involved in the reduction of canal speed limits from 20 km/hr to 8km/hr and the restriction traffic in certain areas (Ibid: 49).

#### *5.4.5.2. Conclusion:*

This comprehensive study focuses on the impact of boat wash energy in combination with increased sedimentation along the Inner Canals in Venice. Although primarily concerned with structural engineering and its associated concerns, it asserts the potentially negative impact of the 'hammering and suction' effects of boat wash on built heritage. The increase in public awareness as a result of the study was another positive outcome.

### 5.4.6. Irish Site Types/Forms under threat

The study team has identified the following Irish site types to be under threat both from the effects of boatwash and natural degradation. The degree to which boatwash is contributing to the loss of some of Ireland's heritage/cultural sites is not known and should form part of a future study.

#### *5.4.6.1. Riverine and Canal*

Many of our canals were constructed in the 18$^{th}$ and 19th centuries and are an important component of our industrial heritage resource. Riverbank and canal erosion gradually undercuts the shoreline leaving it susceptible to collapse. During this process of attrition shoreline material is deposited beneath the waterline and/or swept away (FDS, 2000: 8). With this in mind, many site types may be under threat including, *inter alia:*

**Built and Industrial heritage**

- Cut stone bridges, and bridge piers and footings
- Marinas, Jetties, Piers
- Military and defensive structures (Castles, batteries, look outs)
- Residential structures (Castles, Lock keepers cottages, mill houses)
- Quay walls
- Slips, Hards and Docks
- Revetments
- Mills and Millraces
- Warehouses
- Fish traps
- Navigational structures: lock chambers, canal walls and embankments, fixed navigational markers.
- Railway pillars
- Training Walls*
- Lightbuoys

**Archaeological heritage**

- Crannógs and shoreline settlement sites (Along with material remains associated with the sites)
- Monastic Sites
- Boat Houses
- Ford and Bridge Crossings
- Disused harbours, landing places and associated features
- Dugout canoes (submerged or embedded in shoreline)
- Wooden fishtraps
- Intertidal Resource exploitation sites
- Submerged landscapes

*Training walls are another name for riverine groynes, there are examples of these in the River Boyne (designed by Alexander Nimmo in the early 19$^{th}$ century (1810 - 1825) in the River Moy and in the River Bann. These structures constitute industrial archaeological evidence for widespread attempts to (re)claim riverine mudflats and train river courses.

***5.4.6.2. Lacustrine***

Many Irish lakes have undergone changes in water levels, e.g., Lough Gara has experienced change since the Mesolithic. Fluctuating water levels and wave impact in lacustrine sites (due to human activity or natural causes) accelerate processes of erosion of cultural deposits (O'Halloran, 2000; DIPNR, Australia, 2004 : 2). With this in mind, many site types may be under threat including, *inter alia:*

**Built and Industrial Heritage**

- Shoreline structures (marinas, jetties, piers)
- Residential structures (Castles, game keepers lodges)
- Quay walls
- Slips, Hards and Docks, and landing places
- Revetments
- Ferry crossing sites and associated material
- Flying Boat sites*
- Poitín stills
- Warehouses
- Revetment walls and embankments
- Railway pillars

**Archaeological Heritage**

- Crannógs and shoreline settlement sites (Along with material remains associated with the sites)
- Monastic Sites
- Boat Houses
- Ford and Bridge Crossings
- Disused Harbours, slips and hards, jetties and other landing places
- Dugout canoes (submerged or embedded in shoreline)
- Submerged landscapes

The key concerns and impacts from the effects of boat wash on our cultural heritage take two forms: Short term and Long term.

**Short term concerns and impacts include**

- Exposition of previously buried archaeological material features or horizons
- Undermining of structures
- Compromising of foundations
- Increased weight stress caused by erosion

**Long term impacts and concerns**

- Loss of archaeological integrity of sites
- Removal of archaeological horizons
- Collapse of structures
- Destruction of cultural heritage

*There are at least two flying boat sites in Ireland. The first and most obvious of these is in Lower Lough Erne where from February 1941 to 8th May 1945, Castle Archdale served as the most westerly Flying Boat base in the UK. During this time several Flying Boats were lost in the lake where they remain to this day. The second site would be in the River Shannon at Foynes. This was the location of a civilian flying boat base from 1939 to 1945. In addition to these there are records of other flying boat losses in Irish waterbodies (Cummeenapeasta Lake).

# 6. Common Mitigation Measures

From the previous section it is clear that the negative impacts of boatwash have been recognised in many countries. In some cases the waterway regulatory bodies have taken steps to limit boatwash mainly by applying speed restrictions. Such speed restrictions in some cases are unnecessarily restrictive but represent a first step in terms of protecting the environment.

The biggest offender in terms of wake production are high speed ferries and it is the advent of these vessels that has prompted regulatory bodies to act. In general the wake produced by conventional ferries is acceptable given that they operate at speeds of 10-15knots as compared to 40+ knots of high speed craft. A sample of regulations in place in the USA, Denmark, UK and New Zealand, mainly designed for high speed craft, are outlined below.

Finally in this section, a draft set of mitigation measures is proposed for Ireland. These measures are adapted from similar measures in place in other countries

## 6.1. USA

Regulations and mitigation measures in relation to boatwash vary from state to state and in general relate to reducing vessel speeds near sensitive areas. Examples for Seattle and New York are given below

### 6.1.1. Seattle

In Seattle the criterion is that the wake wash height is less than 0.28m and wake wash energy is less than 2450 joules/m energy density at a distance of 300m from the centreline of vessel travel. In an area called Rich Passage landowners filed a lawsuit charging that boatwash from ferries was damaging structures, eroding beaches and harming marine life. As a result ferry operators were compelled to reduce speeds to 12 knots. This decision was later appealed until a study was undertaken. The Rich Passage wave action study recommended that the slow down should be enforced only at certain sections of the ferry route.

The significant criteria includes a 0.16m wave height at potentially sensitive shorelines and a 1.5km distance from shorelines to ferry routes. Potentially sensitive shorelines include mudflats, saltmarshes, narrow channels and sandy beaches (rocky or armoured shorelines are not included). Assessment need to be made of wind wave magnitudes and shoreline effects of boatwash would only be considered significant if they are greater than the 50% of the average sustained wind wave height on a monthly basis.

If possible ferry routes are adjusted away from sensitive areas – this requires detailed refraction and diffraction modelling to decide the best route. In addition it is recommended that advances in hull designs are used to reduce the boatwash energy and the height of the largest waves

### 6.1.2. New York

A detailed study on ferry wake wash in New York/New Jersey harbour is documented by Bruno *et al.* (2002). The study consisted of field measurements and physical model studies and makes the following recommendations regarding the mitigation of boat wash effects. The view taken is that a co-operative and combined approach from the various stakeholders (boat operators, marina operators, regulators and the general public) is required in order to achieve a workable solution. The following is a summary of their recommendations for each stakeholder type

**Ferry Operators**

- Minimise time in transition speed while adjacent to or pointing at a wake sensitive area
- Avoid turning with a wake sensitive area inside the turn
- In general a ferry should proceed from the dock to the centre of the navigation channel well below transition (displacement speed), then make its turn to go along the channel, rapidly accelerate to optimum speed until adjacent next stop, decelerate to a speed well within displacement mode, then turn into dock for landing.
- Vessel route assignment should be made with wake characteristics in mind; inefficient hull forms (produce high wakes) should be used in most insensitive areas and the most efficient hull forms in the most sensitive areas.
- Whilst arbitrary speed limits are applied in many countries worldwide Bruno *et al.* (2002) state that is many cases such restrictions are unnecessary and only affect profitability and journey times and do not significantly reduce wake

impact. Therefore speed restrictions are not recommended unless they are accompanied by field and laboratory measurements that show a reduction in wake wash energy.

**Marina operators**

- Design of marinas to cater for boatwash should include the following features.
- Provide protection for waves of in excess of 0.5m in heights with periods greater than 4.5sec.
- Protection types could include floating breakwaters, continuous wave screens or wave absorbing barriers with a width of not less than half the design wavelength.
- The protecting structure should stop waves from all relevant directions of approach
- Reflective structures should be avoided and at worst one entire side of a marina should be dissipative.
- Marina openings should be as small as possible.
- Minimum water depth in the marina should be greater than 1m such that to minimise wave shoaling.

**Regulators**

- Should not apply vessel speed reductions without proper research
- Encourage and promote the development of dissipative type shoreline structures where possible
- Provide proper education to the general public on issues and risks in relation to boatwash.

## 6.2. Denmark

The Danish Maritime Authority established wake wash regulations in 1997 in response to the proposed use of high-speed craft (HSC) by a number of Danish ferry operators. The regulations were considered necessary to ensure that the marine environment was protected and that safe navigation conditions prevailed for all users in Danish waterways. They set out criteria which must be satisfied before a shipping company can operate such a ferry out of a Danish port.

With regard to marine environment there are no set criteria for quantifying impact and applications are considered on an individual basis. However, for safe navigation the operator has to prove that that the vessel does not exceed the following wave height criterion at any point along the proposed route.

$$H_h \leq 0.5\sqrt{\frac{4.5}{T_h}}$$

where $H_h$ is the maximum wave height (in metres) and $T_h$ is the mean wave period of the long period waves (seconds). This formula is applicable at a still water level of 3m. Typical limiting values of $H_h$ for high speed craft are of the order of 0.35m ($T_h$ = 9sec).

## 6.3. United Kingdom

In the UK operators need to provide an assessment plan outlining an analysis of the hazard severity and its likelihood of occurrence. This qualitative approach has its limitations and is due to be replaced by a more quantitative approach based on the output from the Ships Wash Impact Management (SWIM) Research Project. This project had the following research objectives:

- To develop empirically-based techniques which can predict the wash generated by a variety of ship configurations, at critical and super-critical speeds, and which have been validated by model and full-size data
- To explore methods for predicting wash propagation, taking account of wave non-linearity, and for predicting interaction with bottom sediments
- To develop techniques for quantifying the effect of different wash types on shorelines and banks, taking account of littoral morphology and ecology
- To interpret the above in order to propose methods for characterising wash types and shoreline/bank types in terms of their damage potential and wash sensitivity respectively.

The project was due for completion in late 2003 but it has not been possible to source any output.

## 6.4. New Zealand

In New Zealand a ferry wash monitoring program and risk assessment was carried out on vessels operating in the Marlborough Sounds. As a result in 2000, a bylaw was passed imposing an 18knot speed restriction on all HSC. However exemptions are allowed if the operator can demonstrate that the boatwash will not exceed prescribed levels.

## 6.5. Possible Irish Mitigation Measures

Although little research has been conducted into the impact of boat wash on cultural heritage, it is evident that erosion is a threat to shoreline deposits (ICOMOS, 2001). While erosion is frequently attributed to a combination of factors, in certain cases, boat wash is the primary cause. Boat waves retreating from riverbanks can often be 'thick with mud' and 'full of sediment' (Gill and Blake, 2002: 27). Increased turbidity can have a detrimental impact on aquatic plant life, preventing penetration of sunlight and checking photosynthesis.(Asplund, 2000:7) Unvegetated banks are more susceptible to shoreline erosion (WDNR, 1993) due to the fact that aquatic plants play an important role in the dissipation of wave energy and the consolidation loose material (Ellis *et al.*2002: 256).

Turbidity and increased sedimentation due to shoreline erosion also contribute to the obstruction of navigational channels. This in turn may result in dredging, a process which has an unquantifiable impact on archaeological material (Oxley, 2001: 5)

The following measures have proven effective internationally and may also be applicable to Ireland.

**(A) Establish and enforce no wake zones to decrease turbidity, shore erosion and damage to shoreline structures.**

Adopted by numerous national parks and private interest groups, this measure has reduced the impact of wave action on sensitive sites. In 2000, as part of the St. Lawrence River Vision Action Plan, 80% of commercial ships agreed to reduce their boat wake. After three years of monitoring, the shoreline recession rate had decreased by 45% along the archipelagos between Montreal and Sorel. (Fisheries and Oceans Canada, 2004). In Wisconsin boats must operate with no wake within 30m of fixed structures.

**(B) Restrict boating activity in shallow-water areas. Encourage navigation in deeper channels**.

Boat wash and propeller action in shallow-water areas frequently results in damage to aquatic vegetation. The riverbed sediment is exposed to currents making it difficult for new vegetation to establish itself. (EPA, 2000). Furthermore, studies in the US involving experimental enclosures and the use of no wake zones and no motor zones have shown increased growth and re-colonisation rates and increased structural complexity in shallow lake plant communities as a result of these measures (Asplund and Cook 1997, 1999). The impact of boat propellers in shallow waters may also have a negative impact on submerged cultural deposits (Breen, 1998).

**(C) Boater education regarding the boat wake created at the displacement, transition and planing speeds ( e.g.WDNR :1993)**

Programs for educating the public as to the negative impacts of boatwash are undertaken in many countries. Many boat operators can simply be unaware of the damage they are causing and on techniques and procedures that they can apply to reduce impacts yet still operate efficiently. It is found, particularly in the U.S and Canada, that education through various media forms can be very effective specially when combined with information on consequences of not complying with regulations. In many American states there are fines for exceeding speed limits and the boat owner is made legally responsible for any damage that his/her boat's wake causes. Examples of some of the literature issued to increase public awareness is included in Appendix 3.

**(D) Encourage boater awareness as to the nature of the protected zones.**

Destruction of marine zones is frequently due to lack of knowledge as opposed to negligence (EPA, 2000). In certain areas, maps highlighting sensitive areas are circulated to boaters. (e.g. Parks and Wildlife Service, Tasmania).

**(E) Encourage the use of low impact equipment**

The Kenai River project in Alaska proposes schemes to encourage the use of "low or no wake" boat hulls (EPA Watershed Initiative: 2005, 1). Programmes to promote the purchase of flat bottom or non-motorized boats are hoped to lower the impact of human activity, particularly boat wake, along the river system.

**(F) Install physical barriers and/or structures to stabilise the shoreline**.

Shoreline stabilization is an expensive mitigation measure (WDNR, 1993) but can prove to be an effective last resort (Bragar, 2001). Organic barriers, such as brush bundles, have also proved to be effective against boat wake induced levée erosion (Ellis *et al.*l: 2002: 263).

**(G) Establish exclusion zones around sensitive foraging and nesting sites for vulnerable or protected bird species.**

Where river side or lake side nesting or foraging sites are being repeatedly disturbed by passing boats, then exclusions zones might be established in proximity to these sites as a protection measure. This is in keeping with studies, which have established that some bird species are susceptible to disturbance when watercraft approach within a certain distances. Such areas would be identified between the relevant state conservation bodies and NGOs.

It should be stated that no measure, that would be very constrictive to the fishing, tourism or transportation industries, should be put in place without prior research.

# 7. Research Programme Requirements

A strategic research programme to fully determine the impacts of boatwash on Ireland's inland waterways is considered necessary, based on the analysis undertaken in this study. It is clear that boat-generated waves can have negative impacts and at the moment Ireland has no scientific information quantifying their severity or their long term impacts. It is important to initiate a research programme that will address some of the critical issues and a few ideas as to the content of such a programme are outlined below.

**(a) Basic Inventories**

A number of inventories are required to collect some basic information essential to both research and decision making processes. These include the following,

- Shoreline categorisation; Development of a GIS (Geographic Information System) of *Ireland's* navigable inland waterway shoreline containing maps, aerial photographs (similar to coastal survey) and an assessment of shoreline composition and its susceptibility to degradation and erosion
- Relevant/Important features on waterways; The GIS should also contain information on all features as listed in section 5.4.5. Information should be provided on the current state of these features
- Waterway usage figures; Information on all major vessels using the inland waterways. Details should be supplied on all characteristics of the vessel that

are pertinent to the generation of boatwash. In addition information on the normal operating route of each vessel should be collected.

**(b) Ecological Impacts Assessment**
As a first step, it would seem sensible to examine all the traffic data on the Irish system and focus in on those waterways, which have the highest recorded densities i.e. greater than 2000-4000 movements per annum, especially if these areas coincide with shallow waters, narrow channels and fine substrates. One might further prioritise areas of known sensitivity (for fishing, waterfowl, riparian habitats, submerged macrophyte beds etc.) At the very outset of such a process, consultation with Waterways Ireland engineers, local NPWS rangers, CFB staff, angling representatives and Inland Waterways representatives/local water users would be essential. These agencies or personnel could point to areas where impacts were known or suspected. Having identified areas of potential or suspected impact, these would need to be combined with areas, which were similar in other respects but lacking boat traffic or having very low traffic. These might then be compared for signs of impact based on indicators such as submerged macrophyte abundance and diversity, evidence of bank erosion, excessive turbidity etc. Additionally, studies such as on fish or other wildlife would only follow if initial studies indicated that impact on the other indicators was significant or if other data or reports pointed to a significant problem in these areas.

**(c) Water and Sediment Quality**
This exercise should be easier to plan and execute but more expensive to undertake, given the costs of certain organic constituents. In this aspect of investigations one would target marinas, especially intensively used larger ones in poorly flushed situations and examine the water and bottom sediment quality for mineral oil, PAHs, heavy metals (e.g. copper), TBT and coliform bacteria (water only). Sampling should coincide with the busiest boating season.

A quantitative examination of soft-sediment benthic macroinvertebrates communities at marinas and at control sites would also be worthwhile as a means of detecting impact. These latter surveys should be accompanied by sediment analysis for particle size, organic carbon content, kjeldahl nitrogen and phosphorus.

**(d) Shoreline Erosion**
A monitoring program should be initiated at a location identified as suffering from erosion as a result of boatwash. Such a program would extend over at least a three year period and could consist of the following elements,

- Topographic surveying at regular intervals
- Boatwash measurement – set up measurement trials with vessels that pass this location and measure wave conditions, vessel speed and direction (set up GPS on board vessel), water turbidity before and after vessel pass.

**(e) Numerical Modelling**
Assess the capability of numerical models to reproducing the wake conditions as measured in the field experiments.

**(f) Archaeological Assessment**
Of primary importance is the identification, evaluation and protection of shoreline cultural deposits. Accordingly, a site-specific assessment of the impact of boat wake on Ireland's cultural heritage within the inland waterways system is necessary. Once this has been launched, subsequent measures to minimise that impact may be established. A detailed assessment of riverbanks and lakeshores which are exposed to particularly high levels of boat wash energy is also required. Similarly, management plans for cultural sites threatened by boat wash should be formulated in accordance with the findings of the initial assessments.

Many archaeological deposits are often only detected once they have begun to erode from the shoreline (ICOMOS, 2001). In-situ preservation is often feasible. However, as exposure to oxygen and other factors of erosion threaten a previously waterlogged resource, any changes should be monitored over time (Gumbley *et al.* 2005:6) Deterioration should be matched with appropriate, site-specific mitigation measures in order to reduce the impact of wave action. The last resort should be the recording and/or salvaging of archaeological features, stratigraphy and artefacts before they are washed away (ICOMOS, 2001).

Generally, data collection due the impact of boat wake forms a part of in-depth, interdisciplinary reports detailing the overall 'health' of a water system and are conducted by national parks, government agencies and private interest groups (e.g. T.V.A,2003, Florida Keys National Marine Sanctuary, 2004)

(g) Management Implication
It is likely that a research programme as envisaged above will raise many issues in relation to the management of *Ireland's* inland waterways. Detailed knowledge not only of the impacts of boatwash but also of the ecology, heritage and hydro-morphology may require various management strategies to be formulated. For coastlines, Integrated Coastal Zone Management (ICZM) is very topical and similar techniques and structures may need to be developed for inland waterways. This may be very important if usage of the waterways continue to increase.

# 8. REFERENCES

AIA (Archaeological Institute of America). (1997) "Shiloh Threatened" in Archaeology, Volume 50 Number 3, May/June 1997. Internet resource, accessed 1st October 2005

Ali M.M., Murphy K.J. and J. Langendorff (1999) Interrelations of river ship traffic with aquatic plants in the River Nile, Upper Egypt. Hydrobiologia 415, 93-100

Allan, J. and Kirk, M. 2000 Wind wave characteristics at Lake Dunstan, South Island, NewZealand Journal of Marine and Freshwater Research, 2000, Vol. 34: 573-591, Internet resource, accessed 1st October 2005, www.rsnz.org/publish/nzjmfr/2000/48.pdf

Anthony, J.L. and Downing J.A. (2003) Physical impacts of wind and boat traffic on Clear Lake, Iowa, USA. Lake and Reservoir Management 19 (1), 1-14.

Arlinghaus R, Englhardt C, Sukhodolov A and C Wolter (2002) Fish recruitment in a canal with intensive navigation: implications for ecosystem manmagement. Journal of Fish Biology. 61 (6), 1386-1402

Asplund T. and Cook C (1997) Effects of motor boats on submerged aquatic macrophytes. Lake and Reservoir Management. 13 (1) 1-12.

Asplund T. and Cook C (1999) Can no-wake zones effectively protect littoral zone habitat from boating disturbance? Lakeline. 19 (1) 16-18.

Asplund, T. 2000 The effects of motorized watercraft on Aquatic Ecosystems, Wisconsin Dept., of Natural Resources. Bureau of Integrated Science Services, Internet resource, accessed 1st October 2005, http:// www.wblcd.org/Science fornowakezoneinmarsh.pdf

Austin, I. 1999. High-speed vessels and their impacts on wetlands and habitat: A case study from San Francisco. Paper presented at High-Speed Conference, Victoria, BC, Canada, 17-19 May.

Beachler MM, and Hill DF (2003) Stirring up trouble? Resuspension of bottom sediments by recreational watercraft. Lake and Reservoir Management 19 (1), 15-25.

Bertram, V., and Hughes, M.J. 1999. Practical predictions of wash using full non-linear wave resistance codes. In Proceedings of the International Conference on High-Performance Marine Vehicles (HIPER'99), Zevenwacht, South Africa, 12-18.

Bragar, M.2001 Protection from Propwash: Erosion Control on the Panama Canal's Pedro Miguel Saddle Dam in Erosion Control, May/June 2001, Internet Resource, accessed 1st October 2005, http://forester.net/ec_0105_project_protection.html

Breen, C.1998 'The Medieval Harbour at Rindoon', Heritage Council Archaeological

Reports, No. 1. Internet Resource: Accessed 1st October 2005 http://www.heritagecouncil.ie/publications/rindoon/plan23.htm

Bright A., Waas JR and J. Innes (2004) Correlations between human-made structures, boat-pass frequency and the number of New Zealand dabchicks (Poliocephalus rufopectus) on the Rotorua Lakes, New Zealand. New Zealand Journal of Ecology 28 (1), 137-142
British Columbia Ferry Corporation. 2000. Fast ferry program-Wake and wash report. Unpublished report.

Bruno M. S. *et al.* (2002) Ferry Wake Wash in NY/NJ Harbour, Technical Report SIT-DL-02-9-2812, Prepared for New Jersey Department of Transportation

Cohen Y., Moen R. and M. Schecterly (1986) Interspecific interactions between Potamogeton pectinatus and Myriophyllum exalbescens in the face of grazing in a simulated ecosystem. Freshwater wetlands and wildlife: perspectives on natural, managed and degraded ecosystems. Ninth Symposium, 24-27 March 1986, University of Georgia, Savanah River Ecological Laboratory 169.

Cragg, B.A. Fry J.C., Bacchus Z. and S.S. Thurley (1980) The aquatic vegetation of Llangorse Lake, Wales. Aquatic Botany 8, 187-196.

Cranwell P.A. and Koul V.K. (1989) Sedimentary record of polycyclic aromatic and aliphatic hydrocarbons in the Windermere catchment. Water Research 23 (3), 275-283

DIPNR (Department of Infrastructure, Planning and Natural Resources, Australia.) 2004, Outline Rehabilitation and Cultural Heritage Protection Plan (Chapter 30), Internet resource, accessed 1st October 2005, www.ap.urscorp.com/menindee_lakes/_EIS/_pdf/_chapters/CH.30.PDF

DNR (Department of Natural Resources) (2003) Kenai River Boat Wake Erosion Study – Funding Proposal. Internet Resource, accessed 1st October 2005 http://www.gov.state.ak.us/omb/03OMB/budget/DNR/proj35934.pdf

Ellis, Sherman, Bauer, Hart (2002) Assessing the Impact of an Organic Restoration Structures on Boat Wake Energy in Journal of Coastal Research, Special Issue 36, 2002. 256-265. Internet resource accessed 1st October 2005, http://www.science.ulst.ac.uk/ics2002/ellis_jt%20et%20al.pdf

Environmental Protection Agency (2000) Management Measures for Boat Operation, Internet resource accessed 1st October 2005, www.epa.gov/owow/nps/mmsp/section4-14.pdf

Environmental Protection Agency (2005) Watershed Initiative Kenai River Boat Wake Erosion Survey (Proposal), Internet resource, accessed 1st October 2005, http://www.epa.gov/owow/watershed/initiative/2004/2004proposals/04kenai.pdf

EPA (2001) A Survey of Dangerous Substances in Surface Freshwaters 1999-2000. Environmental Protection Agency, Johnstown Castle, Co. Wexford.

Eriksson, B.K., Sandström A, Isæus M, Schreiber H and P Karås (2004) Effects of boating activity on aquatic vegetation in the Stockholm archipelago, Baltic Sea. Estuarine Coastal and Shelf Science. 61, 339-349

FDS (Florida Department of State) (2000) Archaeological Stabilization Guide, Internet resource: accessed 1st October 2005, http://dhr.dos.state.fl.us/archaeology/education/culturalmgmt/stab_guide.pdf

Fisheries and Oceans Canada 2004 Shoreline Erosion caused by boat wake, Internet resource, Accessed 1st October 2005, http://www.marinfo.gc.ca/Doc/Erosion/Erosion_des_berges_En.pdf

Florida Keys National Marine Sancturay 2004 Managing the National Marine Sanctuary, Internet Resource, accessed 1st October 2005, http://mpa.gov/what_is_an_mpa/florida_keys.html

Fox Associates (2002) M/V Condor Express Wake Wash Measurement Trials

Fox, K. 2000. Wake wash and motion control discussed at conference. Fast Ferry International 39(9):24-26.

Gadd, G. E. 1994a. Boat wash at channel banks. Journal of the Institution of Water and Environmental Management 9:49-54.

Gadd, G. E. 1994b. The wash of boats on recreational waterways. Transactions of the Royal Institution of Naval Architects W2:261-280.

Gill and Blake (2002) A preliminary estimation of riverbank erosion within the Tamar Estuary. Tamar region natural resource management strategy, Launceton. Australian National Heritage Trust, Internet Resource, accessed 1st October 2005, http://tamar-nrm.org.au/pages/frames/reports/report_pdfs/RIVERBAN.PDF

Grange K, G. Foster, and M. McLean. 1995. Shoreline and marine biological surveys coincident with the passage of conventional and fast ferries, Queen Charlotte Sound, January 1995. Unpublished report to Marlborough District Council, Marlborough, New Zealand.

Grenouillet G and Post D (2001) Juvenile fishes in macrophyte beds: influence of food resources, habitat structure and body size. Journal of Fish Biology. 59, 939-959.

Gumbley, W.; Johns, D.; Law, G. 2005: Management of wetland archaeological sites in New Zealand.in Science for Conservation 246. 76 p. Internet Resource, accessed 1st October 2005, www.doc.govt.nz/Publications/004~Science-and-Research/ Science-for-Conservation/PDF/sfc246a.pdf

Gutreuter S., Dettmers J.M. and D.H. Wahl (2003) Estimating mortality rates of adult fish from entrainment trough the propellers of river towboats. Transactions of the American Fisheries Society 132, 646-661.

Hall L.W, Scott M.C, Killen W.D and M.A Unger (2000) A probabilistic ecological risk assessment of tributyltin in surface waters of the Chesapeake Bay watershed. Human and Ecological Risk Assessment 6 (1), 141-179.

Hall L.W. and Gardinali P. (2004) Ecological risk assessment for Irgarol 1051 and its major metabolite in United States surface waters. Human and Ecological Risk Assessment 10 (3), 525-542.

Hall L.W., Killen W.D., Anderson, RD., Gardinali P.R. and R. Balcomb (2005) Monitoring Irgarol 1051 concentrations with concurrent phytoplankton evaluations in East Coast areas of the United States. Marine Pollution Bulletin 50 (6) 668-681.

Haslam, S. M. (1978) *River plants: the macrophyte vegetation of watercourses.* Cambridge, Cambridge University Press.

Hilton J. and Phillips G.L. (1982) The effect of boat activity on turbidity in a shallow broadland river. Journal of Animal Ecology 19, 143-150.
http://www.archaeology.org/9705/newsbriefs/shiloh.html

ICOMOS (Canada) 2001 Effects of shoreline erosion on Archaeological Sites in Canada Internet Resource: Accessed 1st October 2005 http://www.international.icomos.org/risk/2001/cana2001.htm

Johnson, S 1994, Recreational Boating impact investigations – Upper Mississippi river System, Pool 4 Red Wing Minnesota. Repport by the Minnesota Department of Natural Resources, Lake City, Minnesota for the National Biological Study, Environmental Management Technical Centre, Onalasta, WI. EMTC 94-s004. 48 pp + appendices

Johnson, S. *et al.* (in preparation). St Croix shoreline studies, 1995 – 1998; Executive Summary, Minnesota Department of Naturam Resources

Kaenel B.R. and Uehlinger U (1998a) Edffects of plant cutting and dredging on habitat conditions in streams. Archiv fur Hydrobiologie 143 (3) 257-273.

Kaenel B.R., Matthaei C.D, and U. Uehlinger (1998b) Disturbance by aquatic plant management in streams: effects on benthic invertebrates. Regulated Rivers-Research & Management 14 (4) 341-356.

Kantrud H.A. (1990) Sago pondweed (Potamogeton pectinatus L.): a literature review. U.S. Fish and Wildlife Service, Fish and Wildlife Resources Publications 176. Jamestown, ND. Northern Prairies Wildlife Center HomePage.http://www.npwre.usgs.gov/resources/literature/pondweed/pondweed.htm (Version 16JUL97).

Killgore K.J, and Maynord S.T (2001) Evaluation of propeller-induced mortality on early life stages of selected fish species. North American Journal of Fisheries Management. 21, 947-955

Kirk, R.M., Single. 2000. Coastal impacts of new forms of transport: The case of the interisland fast ferries. Environmental Planning and Management in New Zealand, Eds. P.A Memon and H. Perkins, 228-233, Palmerston North, New Zealand: Dunmore Press.

Kirkegaard, J., H Kofoed-Hansen, and B. Elfrink. 1998. Wake wash of high speed craft in coastal areas. In Proceedings of the 26th International Coastal Engineering Conference, Denmark, 325-337. American Society of Civil Engineers.

Kirkegaard, J., N. Hojtved, and H.O.H Kristensen. 1998. Fast ferry operation in Danish waters. In Proceedings of the 29th International Navigation Congress. The Hague, 5-12. International Navigation Association.

Kofed-Hansen, H., T. Jensen. J. Kirkegaard, and J. Fuchs. 1999. Prediction of wake wash from high-speed craft in coastal areas. In Proceedings of the International Conference of Hydrodynamics of High Speed Craft, 24-25 November 1999, London, UK.

Kofoed_Hansen, H., T. Jensen., O.R. Sorensen, and J. Fuchs. 2000. Wake wash risk assessment of high-speed ferry routes—A case study and suggestions for model improvements. Paper presented at International Conference of Hydrodynamics of High Speed Craft, 7-8 November, London, UK.

Kos, J. S., and S. Bielby. 1995. Fast ferries decision: Seeing sense in its wake. New Zealand Law Journal1995: 363-368.

Macfarlane, G.J., and M.R. Renilson. 2000. When is low wash low wash? An investigation using a wave wake database. In Proceedings of the International Conference on Hydrodynamics of High Speed Craft, 7-8 November. London: RINA .

Lagler , K.F., Hazzard, A.S., Hazen W.E. and W.A. Tomkins (1950) Outboard motors in relation to fish behaviour, fish production and angling success. *Tans. N. Am. Wildl. Conf.*, 15, 280-303

Liddle, M.J. and H.R.A. Scorgie (1980) The effects of recreation on freshwater plants and animals: a review. Biological Conservation. 17, 183-206.

Madsen J (1994) Impacts of disturbance on migratory waterfowl. Ibis, 137, S67-S74

Maritime and Coastguard Agency. 1998. Research project420: Investigation of high speed craft (HSC) on routes near to land or enclosed estuaries. Maritime and Coastguard Agency. Southampton, England.

Mastran T.A., Dietrich, M. Gallagher, D.L. and T.J. Grizzard. (1994) Distribution of Polyaromatic hydrocarbons in the water column and sediments of a drinking water reservoir with respect to boating activity. Water Research 28 (11), 2353-2366.

Mencini, G. (2000) Sull' onda viva del mare. Moto ondoso –storia de una problema Editoriale Verde Ambiente. Roma Internet resource, accessed 1st October 2005: http://politicheambientali.provincia.venezia.it/pubblicazioni/onda.pdf

Monahan C, and Caffrey J.M. (1996) The effects of weed control practices on macroinvertebrate communities in Irish canals. Hydrobiologia 340 (1-3), 205-211

Murphy and Eaton (1981) Waterplants, boat traffic and angling in canals. Proceedings of the 2nd British Freshwater Fish Conference.

Murphy, KJ and Eaton JE (1983) Effects of pleasure-boat traffic on macrophyte growth in canals. Journal of Applied Ecology. 20, 713-729

Pearce H.G.and J.W. Eaton (1983) *Effects of recreational boating on freshwater ecosystems – an annotated bibliography. Waterway Ecology and the Design of Recreational Craft,* Appendix B. Inland Waterways Amenity Advisory Council, London.

Nanson *et al.* (1994) Experimental measurements of river bank erosion caused by boat-generated waves on the Gordon River, Tasmania. Regulated Rivers: Res and Manage. 9(1) 89-99

National Park Service(2001) USS Arizona, Submerged Cultural Resources Study Internet Resource, Accessed 1st October 2005 http://www.nps.gov/usar/scrs/scrs3k.htm

O'Halloran, C. 2000. 'Submerged Heritage': A study of threats to archaeological sites on the bottomlands of Lake Hume (2000) Masters Thesis (Abstract) Internet resource : Accessed 1st October 2005 http://athene.riv.csu.edu.au/~dspennem/Hons_OHalloran.html

Osborne and McDonald 2005 Rich Passage Passenger only fast Ferry Study – Phase 1

Oxley, I. O'Regan, D. 2001. The Marine Archaeological Resource, Institute of Field Archaeologists, Paper No. 4. Internet Resource: Accessed 1st October 2005 www.archaeologists.net/modules/icontent/inPages/docs/pubs/maritime_resource.pdf

Parks and Wildlife Service, Tasmania (2003) Motorised Craft on the Gordon River Internet resource, accessed 1st October 2005 www.parks.tas.gov.au/factsheets/boating/Gordon.pdf

Parnell, K. E. 2000. Vessel wakes and slope instability in Tory Channel and Queen Charlotte Sound: Wave measurements. Unpublished report to Marlborough District Council, Marlborough, New Zealand.

Parnell, K.E. 1996. Monitoring effects of ferry wash in Tory Channel and Queen Charlotte Sound. Unpublished report to Marlborough District Council and the Director General Conservation, Marlborough, New Zealand.

Pickrill, R. A. 1985. Beach changes on low energy lake shorelines, Lakes Manapouri and Te Anau, New Zealand. Journal of Coastal Research (14):353-363.

Rich Passage Wave Acton study Team 2001, Rich Passage Wave Action Study final Report, WAC 197-11-970 Prepared for Washington State Ferries
Robinson., J.A. and Pollitt M.S (2002) Sources and extent of human disturbance to waterbirds in the UK: an analysis of Wetland Bird Survey data, 1995/96 to 1998/99. Bird Study 49, 205-211

Rodgers J.A., and Schwikert S.T. (2002) Buffer-zone distances to protect foraging and loafing waterbirds from disturbance by personal watercraft and outboard-powered boats. Conservation Biology 16 (1), 216-224.

Sandström A, Eriksson B.K, Karås P, Isæus M and H Schreiber (2005) Boating and navigation activities influence the recruitment of fish in a Baltic Sea archipelago area. Ambio 34, (2) 125-130

Schiereck (2001) Introduction to Bed Bank and Shore Protection, ISBN 90-407-1683-8, Published by Delft University Pres

Snickars M, Sandström A and J. Mattila (2004) Antipredator behaviour of 0+ Perca fluviatilis: effect of vegetation density and turbidity. Journal of Fish Biology 65 (6) 1604-1613.

Stumbo, S., K. Fox F. Dvorak, and L. Elliot. 1999. The prediction, measurements, and analysis of wake wash from Marine vessels. Marine Technology and SNAME News 36(4): 248-260.

Stumbo, S., K. Fox, and L. Elliot. 2000b. Hull form considerations in the design if low wake wash catamarans. Unpublished paper presented at the SNAME International FAST'99 Conference, Seattle, August.

Stumbo. S.,K. Fox, and L Elliot 2000a. An assessment of wake wash reduction of fast ferries at supercritical Froude numbers and optimised trim. In Proceedings of the International Conference on Hydrodynamics of High Speed Craft, 7-8 November. London: RINA.

Sukopp, H. (1971) Effects of Man, especially recreational activities, on littoral macrophytes. Hydrobiologia Bucuresti 12, 331-340.

T.V.A (2005) TVA Homepage Internet resource accessed 1st October 2005 www.tva.gov

T.V.A 2004 Final Environmental Impact Statement. Internet resource, accessed 1st October 2005 http://www.tva.gov/environment/reports/ros_eis/

Tobiasson, B.O. and Kollmeyer, R.C. 1991 Marinas and Small Craft Harbours, Library of Congress Catalogue Card number 91-14287, ISBN 0-442-00233-5, Published by Van Nostrand Reinhold.

Traut A.H. and Hostetler M.E. (2003) Urban lakes and waterbirds: effects of development on avian behaviour. Waterbirds 26, 290-302
U.S. Army Engineer Research and Development Centre, 2002, Proceedings Navigation vessel effects Workshop, Gulfport, MS

UNESCO (2002) Venice Inner Canals Project. Research Results. Internet resource accessed -1st October 2005. http://www.unesco.ve.it/

UNESCO (2002b) Synthesis Report on Physical conditions. Internet resource –accessed 1st October 2005. http://www.unesco.ve.it/results/5_Physical%20Conditions/Results/Summary%20of%20UNESCO%20Research%20on%20Physical%20Conditions.pdf

Whittaker, T.J.T., R. Doyle, and B. Elsasser. 2000. A study of the leading long period waves in fast ferry wash. In Proceedings of the International Conference on Hydrodynamics of High Speed Craft, 7-8 November, London: RINA

Wisconsin Dept. of Natural Resources 1993 Mississippi: River Bank Erosion and Boating. Facts and Solutions Internet Resource: Accessed 1st October 2005, http://files.dnr.state.mn.us/education_safety/safety/boatwater/riverbankerosion.pdf

Wolter C., Minow J., Vilcinskas A and U.A. Grosch (2000) Long-term effects of human influence on fish community structure and fishries in Berlin waters: an urban water system. Fisheries Management and Ecology. 7 (1-2), 97-104.

Yousef, A. Y. (1974) Assessing the effects on water quality by boating activity. US: Nat. Env. Res. Centre Report EPA-670/2-74-072.

Yousef, A.Y, McLellon, W.M. and H.H. Zebuth (1980) Changes in phosphorus concentrations due to mixing by motorboats in shallow lakes. Water Research 14, 841-852.

# Appendix 1

## Theoretical Description of Boatwash

**Introduction**

Lord Kelvin determined the pattern of diverging and transverse gravity waves created by a moving disturbance. This is shown in Figure A1.1 and A1.2(a). In science and engineering non dimensional terms are often used and for ship generated waves it was found that the Froude Number (used when gravity forces are dominant) is most relevant for defining when the wake pattern changes from one form to another. The depth Froude number (Fd) is defined as

$$F^{d} = \frac{V}{\sqrt{gD}}$$

where v is the vessel speed, g is acceleration due to gravity and D is the water depth. For $F^d$ <1 the vessel is in sub critical mode and for values up to about 0.6 the wave pattern as shown in Figure A1.2(a) persists. As $F^d$ increases due to an increase in speed or a reduction in water depth the higher period waves of the wash become affected by the seabed and the wave pattern begins to change. At the critical $F^d$ of 1 (figure 3.2(b)), transverse waves are no longer being created and the divergent waves form a wave of translation. At supercritical speed $F^d$ > 1 the long waves speed is limited by the water depth and they propagate at an angle of  from the direction of travel of the vessel (Figure A1.2(c)). In this case the vessel is moving faster than a wave of the same wavelength can travel in a given water depth and so cannot be described by the Kelvin wake pattern.

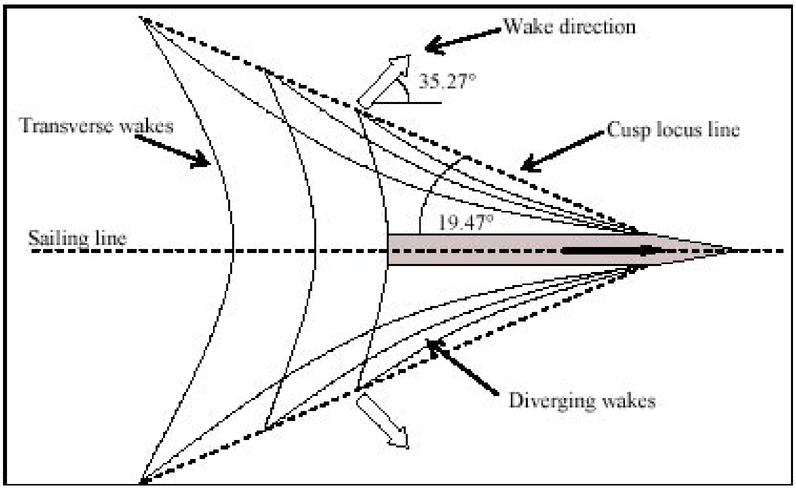
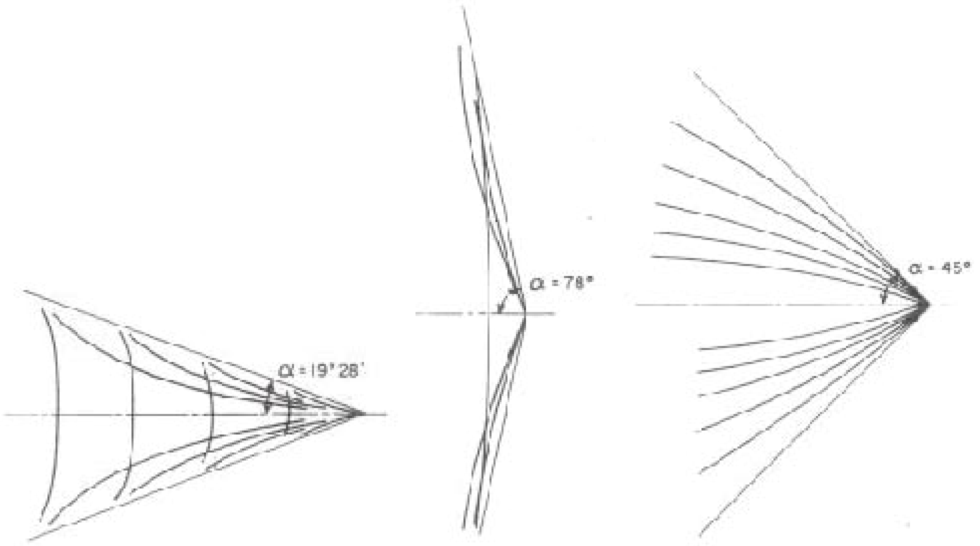


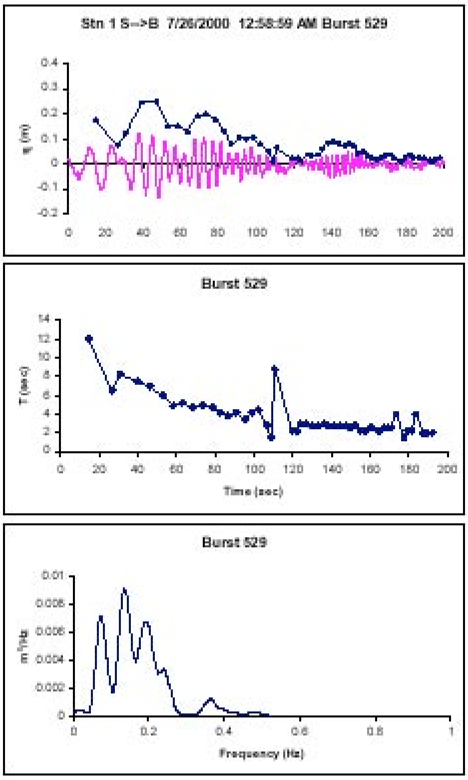

Figure A1.1 Kelvin Wave Pattern (Bruno *et al.* 2002)




(a) $\frac{V}{\sqrt{gD}} = 0.4$  (b) $\frac{V}{\sqrt{gD}} = 0.9$  (c) $\frac{V}{\sqrt{gD}} = 1.4$

Figure A1.2 Sub critical, Critical and Super critical conditions

The difference between supercritical and sub critical vessel wakes is illustrated in Figures A1.3 to A1.5. Each figure contains 3 separate plots; surface elevations and wake height, wake period and wake spectra (this is a summation of the energy at different frequencies) obtained from monitoring a passing high speed ferry. For the supercritical condition (Figure A1.3) it can be seen that the higher longer waves first reach the measurement point with a decay in both height and period as time progresses. When waves are not propagating in shallow water, higher periods travel faster and this is what is seen in Figure A1.3 with a separation of the various generated wave period due to different celerities. The wave spectrum shows the degree to which the energy is spread out over different frequencies (frequency is the inverse of the wave period) and for this case the maximum period is about 10 seconds. Another point from the spectra is that the energy is concentrated in certain frequency multiples (known as harmonics). The frequency of these harmonics is related to the depth Froude Number. The subcritical mode condition as shown in Figure A1.4 is much more uniform. Wave heights again decay with time but the wave period remains constant. The wave spectra shows that the energy is concentrated in one frequency band, about 4.5 seconds.



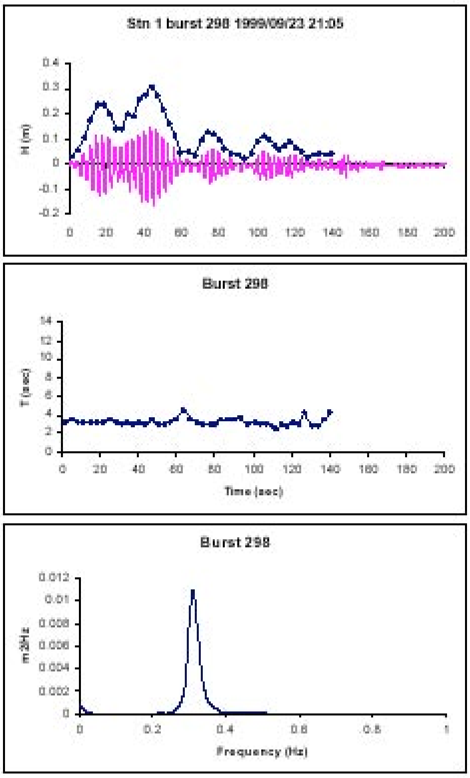




Figure A1.3 Supercritical Condition     Figure A13.4 Sub Critical Condition

The wake characteristics of a purely displacement vessel (car ferry), as shown in Figure A1.5, has many of the same characteristics of the sub-critical wake. The energy is substantially grouped into a single frequency. In this case however the energy is spread out more, particularly in the low period part of the spectrum. Osborne and McDonald (2005) attribute this to the greater drawdown caused by the acceleration of the flow around the vessels large hull.

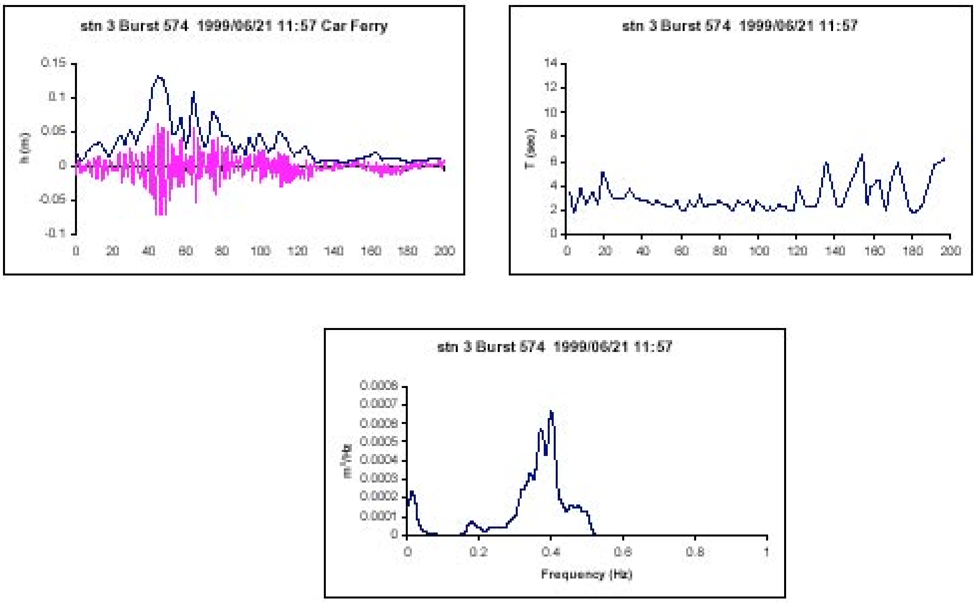



Figure A1.5 Displacement Vessel

The amount of energy contained in a wake train can be related to another dimensionless parameter known as the length Froude Number $F^L$

$$F^L = \frac{V}{\sqrt{gL_s}}$$

where Ls is the length of the vessel. This quantity is useful in defining the point (known as the hump) when the vessels power requirements and wake making capability are maximised at a certain speed. The 'hump' occurs when the vessel is travelling at such a speed that the length of the wave is twice the length of the vessel. The detailed mathematics of this phenomenon is outlined in Osborne and McDonald (2005) but the final equations are as follows

Deep water condition

$$V = \sqrt{\frac{gL_s}{\pi}} \quad \text{for} \quad F_L = \sqrt{\frac{1}{\pi}}$$

Shallow water condition

$$V = \sqrt{gD} \quad \text{for} \quad F_L = \sqrt{\frac{d}{L_s}}$$

Therefore the hump speed for a 20m long vessel would be 15kts (water depth 30m). Kofoed Hansen *et al.* (1999) state that there is a clear tendency for the highest waves to be generated at length Froude numbers between 0.4-0.5.

The decay of ship waves with distance from the vessel is outlined by Kofoed Hansen (1999). In deep water the theoretical rate of decay (due to diffraction) as given by linear wave theory is $r^{-0.5}$ (r is the distance from the vessel track) which means that the transverse waves decay at a rate inversely proportional to the square root of the distance from the disturbance. At the wake boundary the decay rate is given by $r^{-0.33}$ which show that diverging waves decay less quickly. In Figure A1.6 it can be seen that the best fit has a decay rate of $r^{-0.55}$ for diverging waves. At small distances from the vessel the rate of –0.33 provides better agreement.

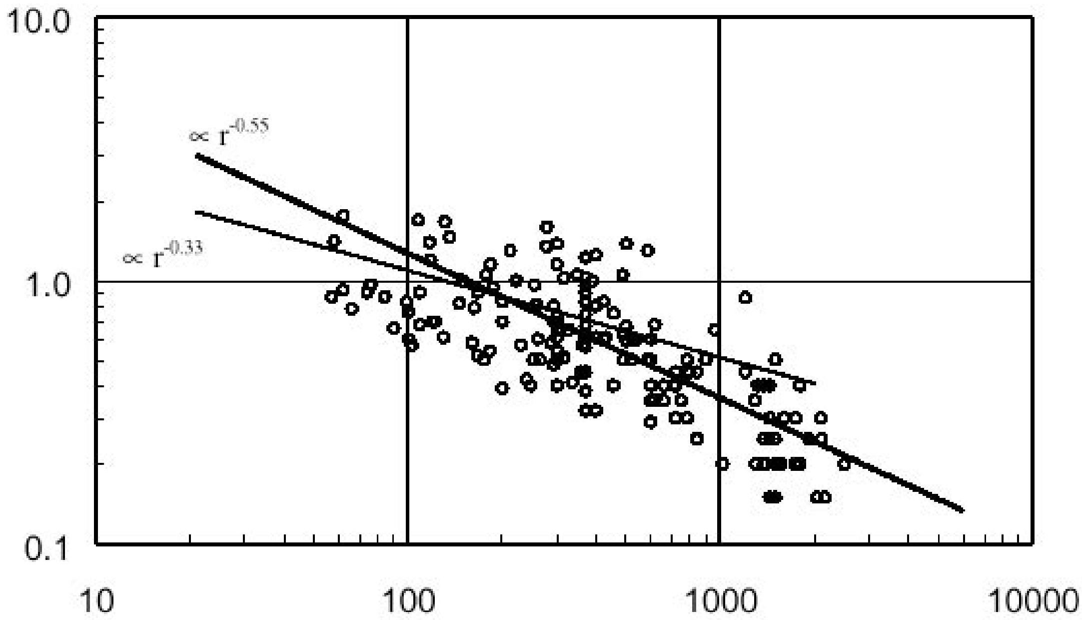



Figure A1.6 Wake height decay with distance from vessel track

The direction of propagation of the diverging waves can be calculated using the relationships shown below. The wake direction ( ) is measured relative to the advancing ship direction (see figure A1.1).

$$\alpha = 35.267\left(1 - \exp\left(12\left(F^d - 1\right)\right)\right) \quad \text{for} \quad F^d \leq 1$$

$$\alpha = \arccos\left(\frac{1}{F^d}\right) \quad \text{for} \quad F^d > 1$$

Figure A1.7 shows the propagation directions of diverging waves for various depth Froude numbers.

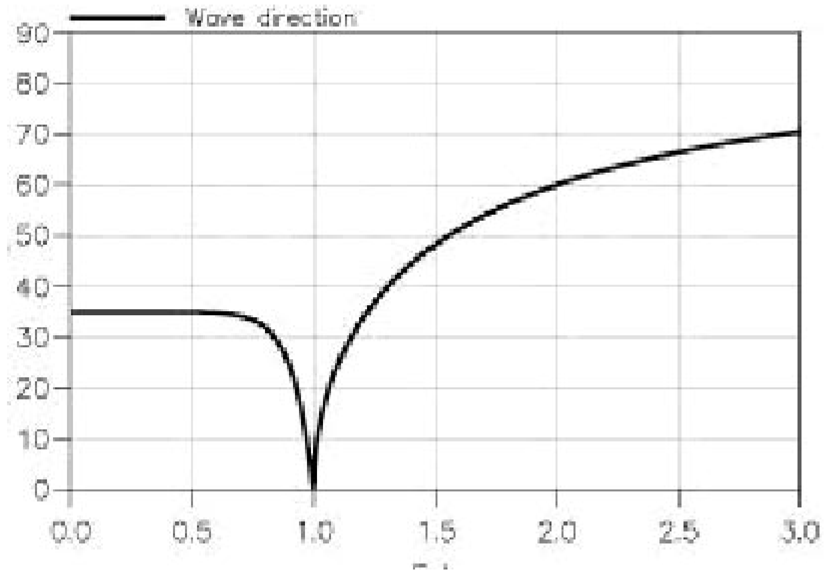



Figure A1.7 Wave propagation direction for diverging waves Vs depth Froude Number (Kofoed Hansen *et al.* (1999)

# Appendix 2

## Computer Software - Wake Wash Prediction

**Introduction**

Kofoed-Hansen *et al.* (1999) states that the ultimate tool required for the calculation of ship generated waves, wave propagation and wave transformation in non-homogeneous media would be a numerical non linear time domain model. Such models could be used to,

- Predict the instationary flow field and the associated wave pattern around the ship
- Calculate the dynamics of the transient waves in the surf zone including the wave height before wave breaking
- Determine run-up and sediment movement on the shoreline

Such a model does not fully exist and if it did it would be computationally very demanding. The following section outlines the capabilities of a number of wake prediction models.

***SGH (Ship Generated Hydrodynamics) Model***: This model developed by PI Engineering in the U.S. for determining the wake and the drawdown currents of large vessels. The model is provides reliable predictions but is limited to large displacement vessels operating at sub-critical speeds.

***CFD (Computational Fluid Mechanics) Techniques***: These models focus on the wake after it has propagated a distance from the vessel. They generate the wake directly from the solution of the governing equations and the standard kinematic boundary condition applied on the ships hull. They give good predictions of wake sizes provided the hull shape has been accurately defined. Other limitations of these models as outlined by Osborne and McDonald (2005) include,

- They are limited to steady state conditions
- They are only applicable to areas of constant depth
- They require extremely fine spatial distribution which results in prohibitive computational requirements. Kofoed Hansen *et al.* state that even with the use of very high powered computers these techniques are limited to within 3 to 5 wavelengths of the vessel.

***Wake2d***: This model was developed by the Canadian Hydraulics Centre and it is a fully non linear Boussinesq ship wake model. The Boussinesq model allows for the non hydrostatic pressure distribution and can deal with short period dispersive waves. Wake2d has very high computational requirements and it has been found that 3 minutes of ship passage, in which the wake only propagated one half of the distance from the sailing line to the shore, required over 24 hours to simulate.

***DHI (Danish Hydraulic Institute) Models***: DHI is a leading international supplier of hydraulic software and whilst they have developed a Boussinesq based ship wave model they have found it to be computational too demanding for practical use. Therefore they have modified their MIKE21 NSW (Nearshore Spectral Wave) software to allow for the practical modelling of ship waves over very large areas. The model is formulated based on the phase averaged energy conservation approach and calculates the propagation and transformation of the wave field. Ship generated waves are input as trains of long crested waves at the model boundary. Kofoed Hansen *et al.* (2002) tested this model against field measurements and in general found very good agreement. However it does have the following limitations,

- It does not reproduce dispersion, which causes wave height decay as the wake travels away from the vessel
- The model is run in steady state form with the wake input along a straight boundary line. The model is therefore not very flexible for irregular ferry routes

As a consequence DHI are currently developing a combined CFD and Boussinesq modelling approach. It is envisaged that the resultant model will combine the advantages of both these techniques without being as computationally demanding. DHI predict that the resulting model will accurately determine wave heights in the surf zone and run up on beaches. In addition it has the potential to also model the forces responsible for beach erosion and morphological change.

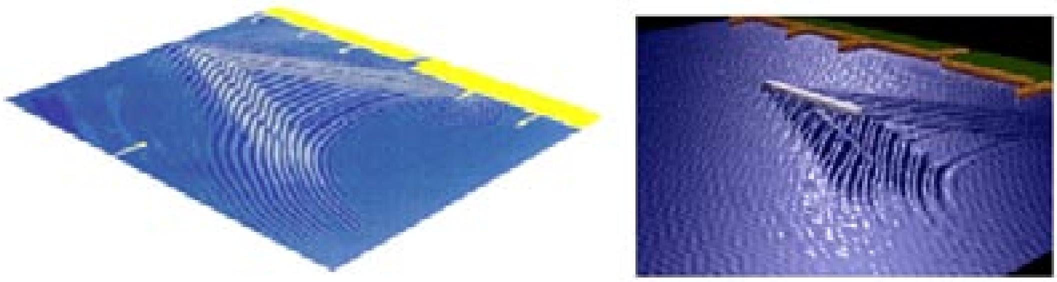


Figure A2.1 Images of instantaneous surface elevation (diverging waves) in the Elbe river simulated using the combined CFD and Boussinesq model (Kofoed Hansen *et al.* (2000))

***LSV (Lagrangian Super critical Vessel) Model***: This is a kinematic and dynamic wake conservation model that uses a Lagrangian formulation. It has the following capabilities;

- Generation of sub and super critical wakes
- Variable vessel routing and speed
- Wave Transformation including the effects of current refraction, depth refraction, shoaling, breaking and dispersion
- Efficient solution for large areas and numerous simulations

Waves are input as individual packs of wave energy transferred from the moving vessel to the flow. These wave packets are then tracked as they propagate across the model domain. This is a newly developed model with good potential and it is outlined in detail in Osborne and McDonald (2005).

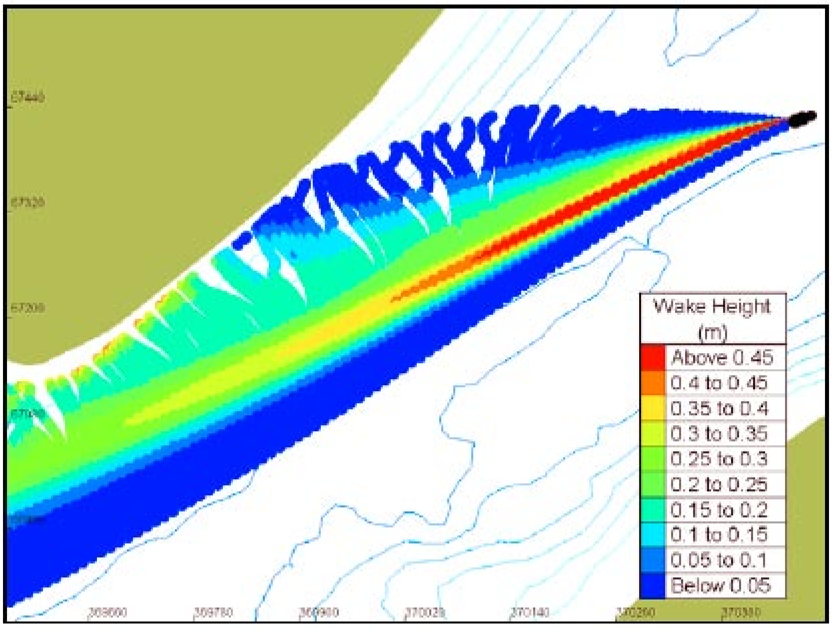



Figure A2.2 Map of Port side wave height Pattern for High Speed Ferry using the LSV Model

The U.S Army Engineer Research and Development Centre convened a navigation vessel effects workshop on October 2002 and they summarised the following solution techniques/models for ship generated waves

- Shallow water equations utilize a hydrostatic pressure field and generate non-dispersive waves. These equations are better suited for estimating longer period drawdown and return periods. They are not valid in regions with slope discontinuities.
- Boussinesq equations utilize non-hydrostatic pressure fields and are able to deal with shorter-period dispersive waves. They also are able to handle nonlinear wave effects, wave breaking, wave-induced currents, runup, and overtopping. However, they provide a poor description of flow fields around ships when compared to boundary-integral methods.
- Boundary-integral methods provide an accurate description of the flow field around ships. However, they are exceedingly computationally intense for large areas where it is necessary to discretize the in addition to the ship body and free water surface.
- Navier-Stokes equations are able to deal with viscous effects and provide an accurate description of flow around the ships with boundary-fitted grids. Again, these equations are computationally intense for large areas and are limited to only a couple of ship lengths.
- HIVEL2D is an unstructured, static grid model of hydrodynamics. Vessels are simulated by moving pressure fields. The conservative form of the equations captures shocks and bores. Two vessels can be computationally described at

the same time.

- ADH is an unstructured, adaptive grid, parallel model of hydrodynamics and sedimentation. The ADH computational engine can handle unsaturated groundwater equations, shallow water equations, and Navier-Stockes equations. A moving pressure field should be added to the code, as well as a method for estimating sediment entrainment under the vessel.
- NAVEFF is used to determine the physical effects produced by shallow draft navigation (barge tows). Propeller jet near-bed velocity and bed shear lateral and longitudinal distribution are determined by empirical methods. NAVEFF is a screening tool for covering large systems.
- NAVSED is used to determine sediment resuspension resulting from the physical effects determined in NAVEFF. NAVSED output is a cell-by-cell history of sediment concentration.

In addition the workshop issued the following recommendation regarding future research into numerical modelling of ship wave phenomena,

- Adaptation and/or interfaces to connect the near-field to the far-field should be enhanced.
- There is a need between shallow water and deep water to describe the wave field that will dissipate wave energy or modify a strong hydraulic jump to describe an undular jump which is more representative of bore dissipation and wave breaking.
- Analytical tools and numerical simulation models should be better validated with more precise laboratory physical model data and prototype field investigations. These data should be acquired through collaborative agency data collection protocols for precision, reduction, storage, and sharing to eliminate duplication of effort and reduce exceedingly high costs for obtaining synoptic field data.
- There should be acceptable end points to the computational discreteness, depending upon the specific phenomena of interest.
- Cross-shore and along-shore transport of non-cohesive materials for wind waves is moderately-well understood; however, there exists essentially no research pertaining to the interaction and superposition of wind waves and ship waves which simultaneously impact shorelines of restricted waterways and beaches.
- Bank erosion models should be integrated with the hydrodynamics of coasts and rivers to better understand both cohesive and non-cohesive sediment transport. There exists great uncertainties in the modelling of mixed sediment transport which constitutes a large percentage of bay and estuary material movement.
- Vessel effects pertaining to forces resulting from ship-ship wave generation should be more comprehensively investigated. Coupling of interacting ship waves with wind-generated surface gravity waves is not well understood, and the mechanisms of both bottom sediment initiation and stresses on moored vessels is significantly impacts by these interactions.
- There should be a standardized development for better technology transfer through web-based knowledge management and e-learning.
- There is an immediate need for obtaining better mooring criteria for lock approach walls, and for getting those criteria transferred expediently to field operating offices.

# Appendix 3

## Educational Material

Canada

# Watch Your Wake

## Rideau Canal

NATIONAL HISTORIC SITE OF CANADA

The Rideau Canal is one of the world's premiere waterways and an angler's paradise. It invites and attracts a wide variety of recreational users, from power boaters to sailors, canoeists, kayakers, swimmers and varied shoreline users.

We all wish to enjoy the Rideau in our own way and we all have a responsibility to ensure that others enjoy the waterway to its fullest. To accomplish this, we need your support.

Every person in charge of a vessel should operate the vessel and control its wake in a manner that does not endanger the safety of themselves or other boaters. Special consideration should be given to small vessels such as canoes and kayaks.

Our waterway is fragile, with wildlife and shoreline habitat exposed to the elements and man-made hazards. It is at risk without proper use and management by everyone, including property owners and boaters.

This brochure provides some information and tips to help us all gain the maximum enjoyment possible from the Rideau Canal.

Parks Canada · Parcs Canada · Canada

How your boat reacts with the water depends on its hull shape. All hulls, from deep vee planing hulls to displacement hulls can cause damage, depending on speed and other circumstances.

**Myth** - Planing hulls on plane create less wash and less damage.
**Fact** - On the surface, wash may have less height when the boat is on plane but the wave created is longer, faster, deeper and contains more energy. It is potentially more damaging, especially as it enters shallower water and rises above the surface.

**Myth** - Displacement hulls do not create wash that is damaging.
**Fact** - A displacement hull moving at a minimum speed causes less wash and usually of a lower height than that produced by a planing hull. However, a displacement hull may push a wave in front of it which, in narrow, shallow channels, can produce a return flow between the boat and the shore. This flow, combined with propeller-induced flow can scour the bottom and reverberate off the shoreline, causing significant damage.

## HAS THIS HAPPENED TO YOU?

*"...waves from a cruiser caused damage as items fell and crashed in the boat..."*
*"...fridge and cupboard contents strewn..."*

## DEFINITIONS

**Wake** - A disturbed column of water around and behind a pleasure craft as it makes its way through the water.

**Wash** - A specific component of the wake consisting of loose and broken water. It includes water thrown aft by the propeller and the waves that roll off the side of the boat.

**Careless Operation** - An offense under the Small Vessel Regulations that reads:

*"No person shall operate a small vessel in a careless manner without due care and without reasonable consideration for other persons."*

You are responsible for the cost of repair or restitution for damage and discomfort your boat causes to people, objects, wildlife and shoreline. Under the Contraventions Act, enforcement authorities can ticket offenders on the spot, instead of requiring them to appear in court. The fine for operating a vessel in a manner that endangers the safety of persons or property and for failure to control wake resulting in danger to the safety of persons or property is $200.

## SPEED LIMITS

The Ontario Provincial Police patrol from Kingston to Burritts Rapids and the Ottawa Police

*"... I had concern for my safety in the canoe, where I had little ability to escape their path - most boat captains were unaware of the affect of their wake on small craft..."*
*"...while repairing our dock, the wash from a fast boat was so violent it threw my husband off his feet onto the dock and he cracked three ribs..."*
*"...commonly a wash is so violent that it throws water six or more feet high and soaks an area four feet from the shoreline – my fear is that one day a child will be thrown into the water as a result of the dangerous wash..."*
*"... in mid-summer, we were asked to tow a customer's pontoon boat which, while stopped in the water, had been turtled by a quick series of intense washes..."*

## WHAT CAN I DO?

- Watch your wash. **As you travel, watch behind you.** If your wash is sending other boats rolling, forcing them sideways or causing occupants to scramble for a hand-hold or if it is crashing against the shoreline, you are creating too much wash.
- Watch out for and be considerate of small vessels such as canoes and kayaks.
- Slow down well before meeting and overtaking other boats and well before posted speed zones and narrow channels. Leave as much room as possible between you and boats you meet or overtake.
- Give special consideration while passing harvesting machines which manage vegetation growth in the navigation channel, scows maintaining aids to navigation and other vessels working in or along the canal.
- Maintain a proper look-out at all times to avoid emergency manoeuvres.

Service patrols from Burritts Rapids through Ottawa. Speed zones have been established along the navigation channels. All zones are posted with signs and regulated under the Boating Restrictions Regulations, part of the Canada Shipping Act.


There are two types of signs - the boundary markers (arrow signs) which identify the beginning and end of a speed zone, and speed limit signs (circles), which remind boaters to obey the speed limit while they are in the zone. Both types of signs are either posted on the shoreline, on structures, or are attached to floating white buoys adjacent to the navigation channel. Where posted, the speed limit is 10 km/hr (6mph).


## WATCH YOUR WAKE

Boat wake and wash is a major problem along the Rideau Canal. While cruising close to shore, in narrow channels, near other boats, swimmers and docks, **operate as close to dead slow as possible** while maintaining steerage and control of your craft.

### *Did You Know?*

What is immediately on the surface after your boat passes is easy to see, although its true force and depth may not be easy to judge. There is also danger underneath your boat.

Drawdown caused by all boats, especially in narrow channels, can be more damaging than surface wash. Combined with propeller disturbances, your boat can easily damage the bottom of the river bed, disturbing habitat as well as washing away shoreline without your knowledge.

- Remember that your hull shape determines the damage you cause on the surface and below the surface. **All hulls can cause damage.** It is your responsibility to be aware of your boat's characteristics so we can all enjoy the Rideau.

Note: This list is not all inclusive. You should also be familiar with publications such as *Boating Safely* and *Historic Canal Regulations.*

## IMPORTANT CONTACTS

**OPP:** Toll Free - 1 888-310-1122
Cell Phone *677

**Ottawa Police Emergency:** 911
Non-emergency 1 613-236-1222

**Coast Guard:** Radio - VHF Channel 16
Cell Phone - *16; Weather - VHF Channel 21B & 83B

**Search and Rescue:** 1 800-267-7270

**Charts, Publications and Information:**

Available at many marinas and from:

Friends of the Rideau
1 Jasper Ave.
Smiths Falls, ON K7A 4B5
1 613-283-5810
www.rideaufriends.com

Parks Canada, Rideau Canal Office
34a Beckwith St. South
Smiths Falls, ON K7A 2A8
1 800-230-0016
www.parkscanada.gc.ca/rideau
rideaucanal.info@pc.gc.ca



*Aussi disponible en français*


# Watching Your Wake: A Boater's Guide

by Oregon State Marine Board

**P.O. Box 14145 Salem, OR 97309-5065**

**(503) 378-8587**

with information supplied by - *Seaworthy*, the BOAT/U.S. Marine Insurance and Damage Avoidance Report and the Minnesota Department of Natural Resources

Oregon's waterways offer something for everyone. People head to our lakes and rivers to boat, ski, swim, fish, watch wildlife or to make their homes. As Oregon's population continues to grow, more people will want to take part in these activities. That's great- everyone can be proud of the opportunities that this state has to offer. However, it also means that we all need to be more aware of our surroundings while we're out enjoying the water. This is especially important when it comes to boat wake.

## *WAKE AND ITS EFFECTS*

*Wake, the path of moving waves a boat leaves behind it, is a natural product of boating. All boats create some wake. Unfortunately, along with wake come some undesirable side effects. The good news is that by understanding what these are and what can be done about them, boaters can take a big step towards making the water more relaxing and enjoyable for everyone*

*Many boaters have first-hand experience with the effects of wake. A large wake might damage your boat or injure your passengers. Wake may affect the environment too. It can be a factor in shoreline erosion. Sediment may be washed into the water, along with trees and other plants whose roots have lost their support. Wake can affect recreation and safety, property and wildlife in the following ways:*

### RECREATION AND SAFETY

- Wake may endanger inexperienced swimmers or wading anglers.
- It can rock, swamp or capsize other boats. Passengers might be thrown off balance or overboard, leading to serious injury.
- Sediment from shoreline erosion may cloud the water, making it uninviting for swimming, boating or fishing.

### PROPERTY

- Wake may damage docked boats by thrusting them against their moorings.
- Trees that have fallen into the water could be washed up against docks or other structures.
- Shoreline property owners may lose a small part of their land to erosion.

### WILDLIFE

- Sediment can be churned up by boat wake and settle to the bottom, silting in fish spawning habitat and smothering aquatic vegetation, an important food source for many fish and animal species.
- Large wake may disturb birds nesting along the shore.

Does the size of a wake matter? Hydrologists estimate that a wake 5 inches high produces limited damage to the shoreline. A 10-inch wake is 5 times more destructive, and a 25-inch wake is 30 times more destructive than a 5-inch wake. On plane, runabouts and larger fishing boats may create a 10-inch wake, while craft with displacement hulls (like houseboats or cruisers) can create wakes of 25 inches or higher.

### LEGAL RESPONSIBILITY

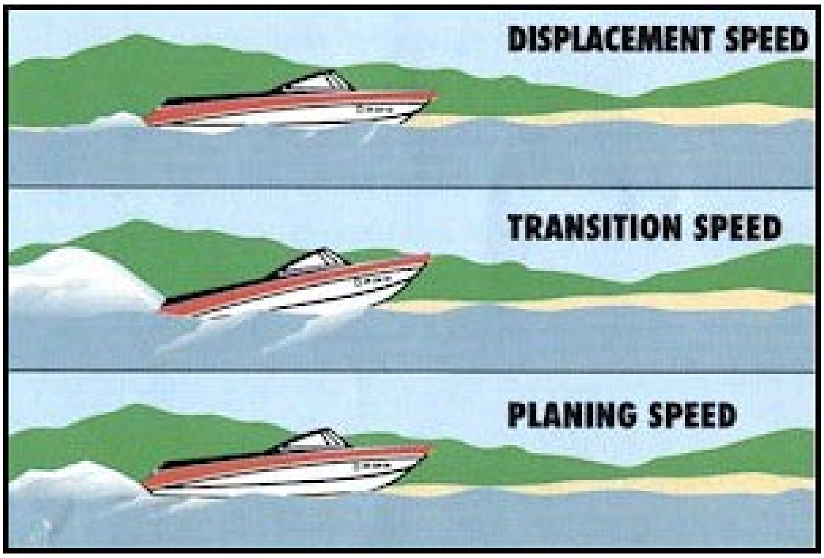
Remember, you are legally responsible for your wake and the damage or personal injury it causes no matter how large or small the wake. So protect yourself and others by limiting your wake. The cost of repairing someone's boat or dock or paying their medical bill may far outweigh the inconvenience of slowing down, and a day free of conflicts will be much more enjoyable for everyone.

## WHAT BOATERS CAN DO

### WATCHING YOUR SPEED

As a boat operator, it can be easy to control your wake.  Understanding the speeds under which your boat operates is the first step.

Displacement Speed- This is the slowest speed for most motor boats. It also creates the least wake. The boat operates with the bow down in the water.
Transition Speed- As you increase the power while attempting to get on plane, the bow rises, causing the stern to plow through the water. This speed creates the largest wake.
Planing Speed- At planing speed, the bow drops back down and only a little of the hull contacts the water. This speed creates less wake than transition speed, but more than displacement. Many large craft are not designed to reach this speed.




Often a boat operator can cause a large wake unintentionally. He or she may drop to transition speed instead of down to displacement speed, and actually increase wake size. It's easy to avoid this pitfall, though. Just make a habit of checking your wake (or have a passenger check it), especially as it hits the shore. Slow down far enough in advance of sensitive areas to give yourself time to drop all the way to displacement speed. This will minimize your wake's impact.

### THE SLOW-NO WAKE RULE

Oregon has a slow no wake rule designed to protect our waterways and the people who use them.  The basic rule (OAR 250-10-025) reads:

Operators of boats must observe Slow-No Wake, Maximum 5 MPH Speed Limit within 200 feet of a boat ramp, marina, or moorage with a capacity for six or more vessels; a floating home moorage with six or more structures; or people working at water level. Operator may be liable for damage caused by wake. This rule does not

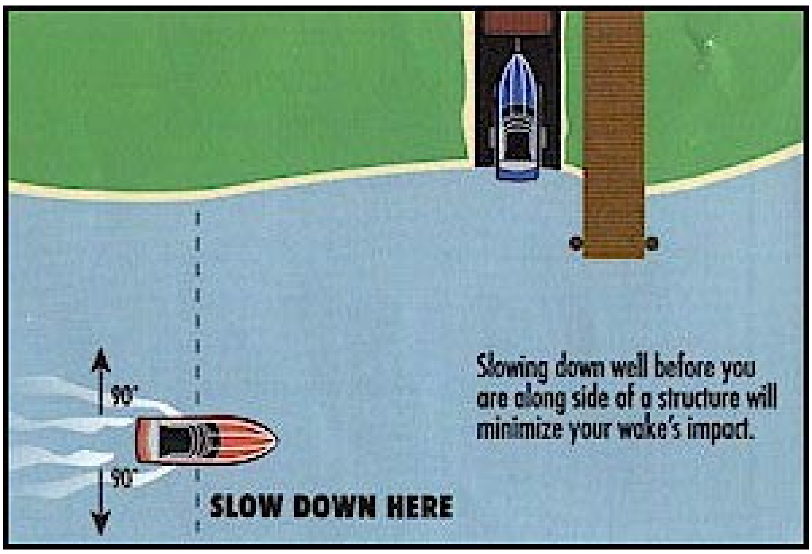
apply to commercial vessels or river navigation when more speed is needed to assure safe passage.

Remember, 5 MPH is a maximum, so if you have to go slower than this to eliminate your wake, you must do so. Violation of the slow no wake rule is a class B infraction, and can result in a fine of up to $350.  Please refer to the Oregon boating regulation, available from the Marine Board, for local restrictions on wake.

## LIMITING YOUR WAKE

Along with the rule, here are some other simple ways you can help to limit your wake:

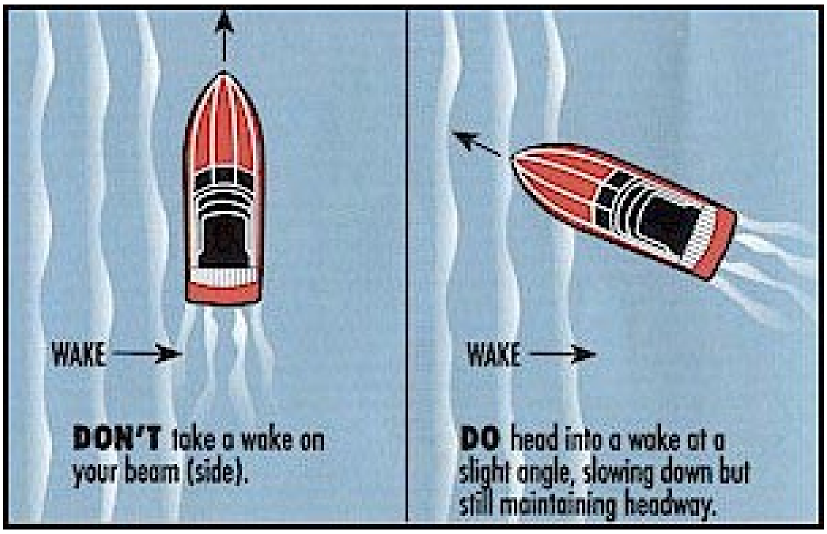
- Always be aware of your wake, especially when changing speeds or navigating in shallow waters. (Which can make wake larger).
- A little extra speed can create a lot of extra wake, so slow down enough to eliminate your wake when required.
- Trim tabs will help keep you boat level and will limit you time in transition speed.
- Boat in deeper waters, and avoid getting too close to other boats or the shore.
- Position passengers throughout the boat. A heavy stern will increase wake size.
- Your wake moves out at right angles from your boat, so slow down well before you are abeam of another boat or other structure to avoid a following wake.



### PROTECTING AGAINST ANOTHER BOATS WAKE

Chances are, you will have to face a large wake created by someone else during your time on the water. Here are several things you can do to safely navigate through a wake.

- Warn your passengers! Passengers below deck are especially at risk of hitting their heads or falling, so be sure they can hear you.
- Slow down before the wake arrives to lessen impact, but don't stop completely. You need headway to be able to manoeuvre through the wake.
- Have passengers who may susceptible to injury stay aft.
- Instead of crossing a wake at perpendicular, cross at a slight angle (quarter the wake) so your bow can grip the wave longer. This will keep the bow from being thrown high in the air.
- While overtaking another boat, cross it's wake quickly instead of riding it. Signal the skipper, keep both hands on the wheel, and stay away from the other boats stern.
- Try not to take a wake on your beam. Instead, turn into the wake and come back on course when it is passed.




## WATCH YOUR WAKE… AND HAVE FUN

Being aware of your actions and the actions of others out on the water can go a long way in preventing potential conflicts related to wake. Paying attention to what's along the shoreline can protect the facilities you rely on and the healthy environment that makes boating such a great experience. With your help, boating in Oregon can be safer, friendlier and more enjoyable for everyone.