Modelling the *Norovirus* contamination of an Oyster Farm in Cork Harbour

Final Report

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Executive Summary

The oyster farm in the North Channel of Cork Harbour, behind Cobh Island, has been closed for approximately five years due to outbreaks of gastroenteritis following consumption of its oysters. The outbreaks have been attributed to viral contamination. Regular assays for the presence of the *Norovirus* in oyster flesh have been consistently positive.

In 2006 Cork County Council asked the lead author of this report to carry out an objective study of the sources of contamination and to determine the contribution, if any, by the Midleton municipal discharge to the contamination. In order to achieve this objective several computer models of the discharge, transport and decay of the *Norovirus* in Cork Harbour have been made.

We are not aware of any dynamic, spatio-temporal, epidemiological model of Winter Vomiting Bug outbreaks that would allow us to estimate the episodic loads from all discharges around the harbour. We have therefore conceptualised each discharge in exactly the same way in the interests of equity: every person within the catchments of the Harbour is assumed to excrete the same number of *Norovirus* particles per day each day for twenty days and then ceases. The relative contribution of each discharge to the contamination of the model oyster farm can then be calculated. Several assumptions have been made regarding the *Norovirus* in the model harbour: the viruses 1.) are neutrally buoyant 2.) are non-cohesive 3.) have the same rate of decay, or inactivation, in each successive unit of time at every point in the Harbour during the thirty seven days of the simulation under common reference conditions of tide, wind and river flow.

We have studied eleven significant discharges of *Norovirus.* They are listed by acronym in the first column of Table 1-1. The twenty day pulses discharged at each location are independent of each other. In order to compare them they are shifted to a common time axis, where they are added together to determine the relative contribution of each irrespective of when they occur in winter or summer in each of the following three periods.

Period 1 – before Midleton waste water treatment plant (WWTP) was constructed (up to 1st July, 2000)

Period 2 – after Midleton WWTP was constructed (with 85% to 95% removal), before Carrigrennan WWTP was constructed (between 1st July 2000 and 24th July 2003)

Period 3 – after Carrigrennan WWTP (with 85% to 95% removal), was constructed (after 24th July 2003)

Summer conditions (no storm overflows at Midleton and relatively rapid decay of viruses with a T90 of seven days) and winter conditions (storm overflows at Midleton and relatively slow decay of viruses with a T90 of thirty days) have been considered.

A summary table of the relative contributions of the averaged concentrations for each period is presented below. A pie chart for each of the cases is then presented.

	PERIOD 1		PERIOD 2		PERIOD 3	
	Summer CASE 1	Winter CASE 2	Summer CASE 3	Winter CASE 4	Summer CASE 5	Winter CASE 6
CC_S&C	49.8	77.7	66.5	75.7	-	-
CG	-	-	-	-	14.5	14.4
ALL_CLOY	5.6	2.3	7.5	2.3	19.1	8.0
CH	0.1	0.1	0.1	0.1	0.2	0.3
RC_S&C	26.4	10.5	-	-	-	-
RC_T	-	-	1.8	0.5	4.5	1.8
PGM	1.9	1.9	2.6	1.9	6.6	6.6
COBH_R	5.6	3.7	7.4	3.6	18.9	12.8
HOUSES	10.6	3.7	14.2	3.6	36.1	12.7
SW_BAILICK 1	-	-	-	11.7	-	41.3
SW_BAILICK 2	-	-	-	0.6	-	2.2
Summation	100%	100%	100%	100%	100%	100%

Table 1-1 Summary Table

CC_S&C = Untreated Waste from Cork City

CG = Carrigrennan (Treated waste from Cork City)

ALL_CLOY = Untreated waste from all the outfalls near Cloyne

CH = Carrigtohill

RC_S&C = Untreated waste from Rathcoursey (Midleton)

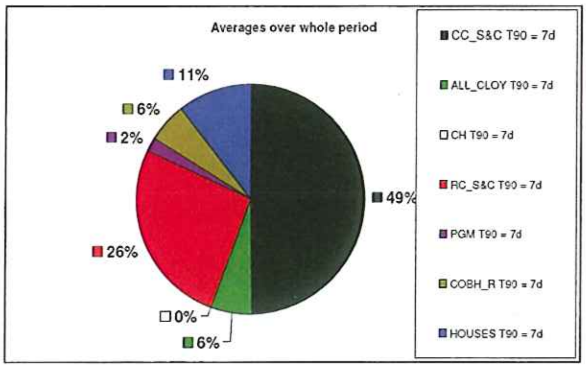
RC_T= Treated waste from Rathcoursey (Midleton)

PGM = Untreated waste Passage West & Glenbrook & Monkstown

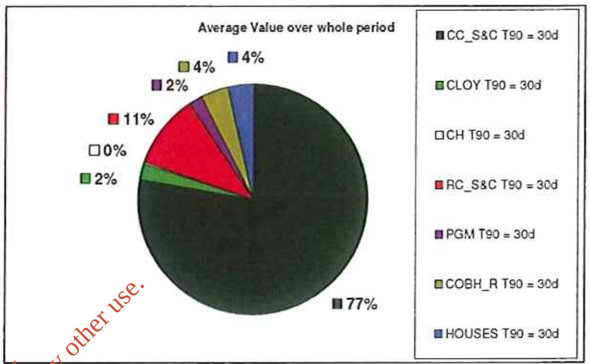
COBH_R = Untreated Waste from Cobh & Ringaskiddy

HOUSES = Untreated Waste from the houses

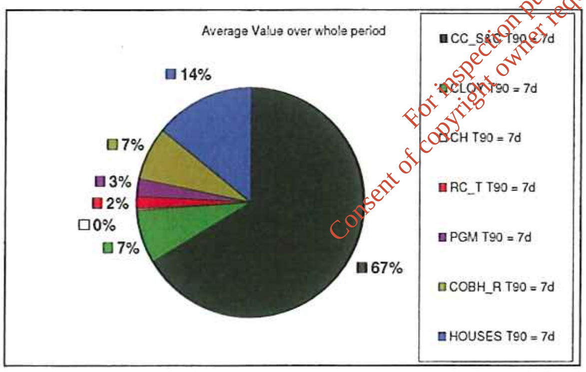
SW_BAILICK_1/ SW_BAILICK_2 = Contribution from Stormwater Overflows at Bailick 1



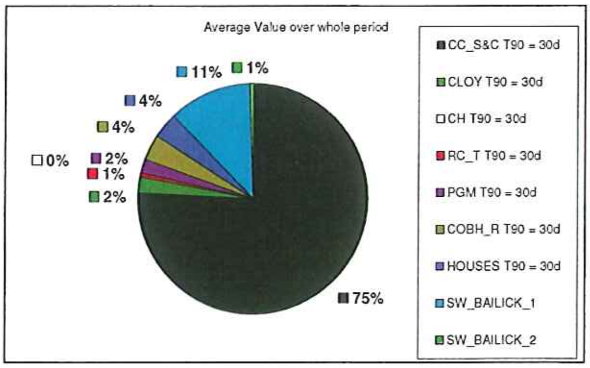
CASE 1 - summer



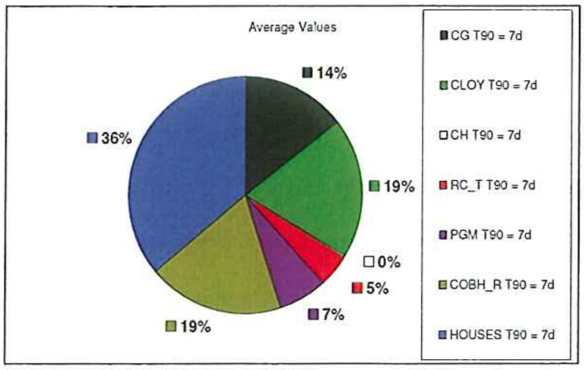
CASE 2 - winter



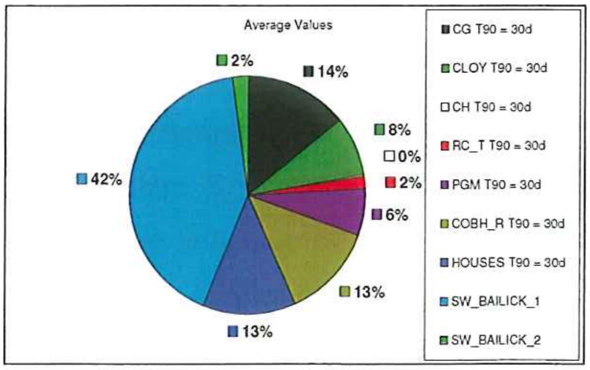
CASE 3 - summer



CASE 4 - winter



CASE 5 - summer



CASE 6 - winter

The conclusions to be drawn from the study are the following.

1. Because Cork Harbour is a macro-tidal lens of shallow water, one thousand times as wide as it is deep, the twice daily variation of 2m (Neaps) to 4m (Springs) in water level implies a corresponding oscillatory horizontal motion of 5km (Neaps) to 10km (Springs) approximately. Consequently, long-lived, non-cohesive, neutrally buoyant, particles, such as our model *Norovirus,* are dispersed very widely by water movement throughout the harbour. Our model says all discharges within the Harbour, from Cork City to the mouth at Roches Point, can contaminate the oyster farm with model viruses to a greater or lesser extent.

2. We have used our well-calibrated model to examine in detail the relative contributions of all significant sources in their historical context. We have divided the historical examination into three periods defined by the dates of commissioning of the two wastewater treatment plants that serve Cork City and Midleton. In each period we distinguish between model winter conditions (T90 of 30 days and storm overflows) and model summer conditions (T90 of 7 days and NO storm overflows). The six cases tell the story of the changing contamination of the model oyster farm.

3. Because the potential burden of *Norovirus* from Cork City is the largest, it is of singular importance, even though it is the furthest away of all the sources. The model viruses from Cork have two routes to contaminate the model oyster farm, through Belvelly Channel, especially under conditions of westerly wind, and more circuitously around Cobh Island, with the assistance of southerly winds through East Passage into the North Channel.

4. The potential sources of *Norovirus* closest to the oyster farm are (a) the isolated houses close to the shore of the North Channel, and (b) the treated and untreated discharges of sewage from Midleton. The relative importance of these sources changes in each of the three periods and under winter and summer conditions.

5. The construction of the secondary waste water treatment plants at Carrigrennan, serving Cork City, and at Midleton, have reduced both average and peak concentrations of *Norovirus* at the model oyster farm in the North Channel behind Cobh Island. This follows from our assumption that secondary treatment removes 95% of organic matter and consequently the same percentage of model viruses. Secondary treatment is planned for the sources around the Outer Harbour with a further reduction in contamination.
6. As more and more treatment is applied, intermittent discharges of untreated sewage during storms become significant. This is already the case in Midleton where the discharges of screened and diluted sewage from the Bailick 1 and 2 pumping stations are currently the most important source of contamination of the model oyster farm under winter conditions (assuming that the removal efficiency of Carrigrennan WWTP is 95%).
7. The discharges of screened and diluted sewage from Bailick 1 and 2 in periods 2 and 3 (winter conditions) i.e. after the construction of the Midleton secondary waste treatment plant, contaminate the model oyster farm to roughly the same extent as the previous discharge of all Midleton's untreated sewage at Rathcoursey Point during period 1 (winter conditions).
8. The reference storm overflows from Bailick 1 and Bailick 2 used in the simulation occurred in December 2002/January 2003. The data from the current year, winter 2006/2007, show that there has been a further disimprovement in the Midleton sewerage system: more frequent, longer lasting, and intense overflows to the river. Consequently, our model results for storm overflows at Bailick 1 and Bailick 2 underestimate for the current year.
9. The discharges of untreated domestic sewage from the houses around the North Channel are the largest contributor to the contamination of the model oyster farm for the current summer conditions (period 3). During current winter conditions the discharges from Bailick 1 and 2 are dominant.

10. A sensitivity analysis of the model, varying the assumptions and parameters on which it depends, showed that the above conclusions remain unchanged, except

    a. During the model winter conditions i.e. slow decay of viruses and storm overflows of screened and diluted sewage from Midleton, the treated discharge from Carrigrennan can be comparable to the discharge from Bailick 1 and 2 in contaminating the model oyster farm [numerical result from model];

    b. During the model winter conditions, when a salinity feedback on momentum is included, the contributions from Cork City (both treated and untreated) to the contamination of the model oyster farm may increase, while the contribution of the untreated discharge at Rathcoursey (period 1) may remain the same [numerical result from model];

    c. When *Norovirus* is adsorbed on suspended sediment, discharges further away from the oyster farm may become less important because of possible sequestration of viruses in stationary bottom sediment; these processes are controlled by rates of sedimentation, resuspension, adsorption and desorption; insufficient data are available to make a secure model [qualitative statement].

11. The study underlines the importance of the civil works planned (1) to cater for a greater population in Midleton by increasing the capacity of the waste water treatment plant, and (2) reconstructing the sewers to ensure no infiltration of groundwater and very rare discharges of storm runoff.

12. Detailed recommendations are made in section 8.3.

Acknowledgements

The authors would like to thank a number of people who contributed a considerable amount of time and effort to this objective study.

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Jimmy Murphy, Hydraulics and Maritime Research Centre, UCC.

Colin Bell, Proudman Oceanographic Laboratory.

The SOS team at DHI.

While we have listened carefully to many opinions on the problem of *Norovirus* in Cork Harbour all the judgements in the report are the responsibility of the authors.

This report contains all that has occurred to us at the present time.

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Chapter 1 Introduction

1.1 The background – EU Directives

The EU COUNCIL DIRECTIVE of 15 July 1991 (91/492/EEC), the so-called Shellfish Hygiene Directive, lays down the health conditions for the production and the placing on the market of live bivalve molluscs [such as oysters, mussels and scallops] (OJ L 268, 24.9.1991).

An EU Expert "REPORT OF A MISSION CARRIED OUT IN IRELAND FOR THE EVALUATION OF THE SYSTEM OF CONTROL FOR THE PRODUCTION OF SHELLFISH DESTINED FOR HUMAN CONSUMPTION [under] DIRECTIVE 91/492/EEC [from] 16 - 20 NOVEMBER 1998" states the following[1]:

1. "The Irish authorities [have] put a great effort into the implementation of the Shellfish Hygiene Directive 91/492/EEC.
2. Ireland produces [as of 1998] annually some 30 000 tonnes of shellfish, mussels (18 000 tonnes) being the main production.
3. Ireland has 75 dispatch centres, 22 of these are both dispatch/purification centre. There are no establishments working only on purification.
4. The competent authority is the Department of the Marine and Natural Resources (DOM&NR) - Seafisheries Control Division (SCD)-. The DOM&NR is responsible for the policy, legislation and enforcement of Directive 91/492/EEC. Part of the responsibilities is shared with the Department of Health (DH) which has in particular the power for closing the production areas. The Regional Health Boards are responsible for the closure of the production areas. From January 1999 the newly-established Food Safety Authority will take over the responsibility for food safety and public health.

[1] The following paragraphs are copied from the report and re-ordered. Interpolated comments are indicated with square brackets.

5. The classification of the production areas is the responsibility of the head of the SCD. A formal system, whereby the classification will be signed by the Minister[2] is to be adopted. The classification of the production areas is based on the parameters prescribed by the Shellfish Hygiene Directive 91/492/EEC. Results of shore surveys have been considered. 74 production areas have been opened, with the following classification: 25 A-, 46 B- and 3 C-areas[3]. Ireland has no relaying areas [as of 1998].

6. An environmental monitoring programme has been organised. The programme is based on yearly sampling of 25 sampling points distributed all along the Irish coast and representing 21 production sites. The 14 microbiological and 3 biotoxines laboratories involved in shellfish control have been approved by the authorities and do participate in intercalibration tests. Furthermore, the Irish authorities have organised a collaboration programme with an UK virological laboratory for the use of bacteriophages as indicators of viral pollution."

A second EU Directive is also relevant, the so-called Shellfish Waters Directive: COUNCIL DIRECTIVE of 30 October 1979 on the quality required of shellfish waters (79/923/EEC) (OJ L 281, 10.11.1979, p. 47) . Article 5 states that "Member States shall establish programmes in order to reduce pollution and to ensure that designated waters conform, within six years following designation in accordance with Article 4, to both the values set by the Member States in accordance with Article 3 and the comments contained in columns G and I of the Annex."

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[2] Presumably the Minister of the Marine and Natural Resources, since the EU Mission Report recommends "The Department of the Marine and Natural Resources, as the national competent authority should be given the legal powers to close down the production areas".

[3] Presumably in accordance with the ANNEX CHAPTER I CONDITIONS FOR PRODUCTION AREAS of the Shellfish Hygiene Directive 91/492/EEC. The EU Mission Report is not explicit.

On 11 September 2003 in Case C-67/02 the European Court declared "by not adopting programmes for all its designated shellfish waters in accordance with Article 5 of Council Directive 79/923/EEC of 30 October 1979" Ireland had failed to fulfil its obligations under the Directive.

On 22 May 2006 the Minister for Communications, Marine and Natural Resources signed into Irish Law STATUTORY INSTRUMENT No. 268 EUROPEAN COMMUNITIES (QUALITY OF SHELLFISH WATERS) REGULATIONS 2006. The Regulations giving effect to Council Directive 79/923/EEC of 30 October 1979 on the quality required of shellfish waters and replace earlier Statutory Instruments Nos. 200 of 1994 and 459 of 2001. The regulations in the instrument prescribe quality standards for shellfish waters and designate the waters to which they apply, together with sampling and analysis procedures to be used to determine compliance with the standards. The Regulations also require the preparation and implementation of action programmes in respect of all such waters.

STATUTORY INSTRUMENT No. 268 designates 14 areas around the Irish coast for compliance with the Shellfish Water Directive. No part of Cork Harbour is designated.

1.2 Recent Judgement by the EU

On the 14th of June 2007 the European Court of Justice ruled that Ireland was in breach of EU regulations protecting water quality and failed to implement pollution-reduction measures in designated shellfish sites around the country. The court found that Ireland failed to fulfil its obligations under the 1979 European Shellfish Directive, under which EU states are required to introduce laws protecting areas where shellfish grow.

The 1979 directive required member-states to designate each shellfish production area in its jurisdiction and to implement water quality standards that would allow molluscs to be eaten safely in a raw state.

The judgement from the court is given in the following box[4].

Parties

Applicant: Commission of the European Communities (represented by: B. Doherty and D. Recchia, Agents)

Defendant: Ireland (represented by: D. O'Hagan, acting as Agent, and N.J. Travers BL)

Re:

Failure of a Member State to fulfil obligations — Incomplete transposition of Articles 3, 4 and 5 of Council Directive 79/923/EEC of 30 October 1979 on the quality required of shellfish waters (OJ 1979 L 281, p. 47) — Failure to designate certain shellfish waters, to establish pollution-reduction programmes and to set control parameters

Operative part of the judgment

The Court:

1. *Declares that, by failing:*

— *in accordance with Article 4 of Council Directive 79/923/EEC of 30 October 1979 on the quality required of shellfish waters, to designate all shellfish waters requiring designation;*

— *in accordance with Article 3 of Directive 79/923, to set all the required values in respect of shellfish waters designated or requiring designation pursuant to Article 4; and*

— *in accordance with Article 5 of Directive 79/923, to take all necessary measures to establish pollution reduction programmes for waters requiring designation pursuant to Article 4, Ireland has failed to fulfil its obligations under that directive.*

2. *Orders Ireland to pay the costs.*

[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2007:183:0003:02:EN:HTML

Following this judgment the Government announced its intention to spend €500 million over the next 10 years to improve water quality around Ireland. Additional areas around the coast are to be designated as shellfish production waters. In addition to this "pollution reduction programmes" are to be introduced for all shellfish producing waters.

1.3 Oyster Fishery in Cork Harbour

The oyster farm in the North Channel in Cork Harbour behind Cobh Island, has been closed for approximately five years due to outbreaks of gastroenteritis following consumption of its oysters (Fig. 1.1 & Fig. 1.2). The outbreaks have been attributed to viral contamination. Regular assays for the presence of the *Norovirus* in oyster flesh have been found to be positive. [5]

[5] The Shellfish Hygiene Directive, COUNCIL DIRECTIVE 91/492/EEC of 15 July 1991, lays down the health conditions for the production and the placing on the market of live bivalve mollusks. The preamble to the directive states *inter alia* "it is primarily the responsibility of the producers to ensure that the bivalve molluscs are produced and placed on the market in compliance with the health requirements prescribed" and "the competent authorities must, by carrying out checks and inspections, ensure that producers comply with those requirements". Article 5 paragraphs 2 and 3 of "CHAPTER II Provisions for Community production" state

"2. (a) The competent authority shall establish a list of production and relaying areas, with an indication of their location and boundaries, from which live bivalve molluscs may be taken in accordance with the requirements of this Directive and, in particular, with Chapter I of the Annex. This list must be communicated to those affected by this Directive, such as gatherers and operators of purification centres and dispatch centres.

(b) The monitoring of the production and relaying areas shall be carried out under the responsibility of the competent authority in accordance with the requirements of this Directive. If such monitoring reveals that the requirements of this Directive are no longer being met, the competent authority shall close the production or relaying area concerned until the situation has been restored to normal.

3. The competent authority may prohibit any production and harvesting of bivalve molluscs in areas considered unsuitable for these activities for health reasons." The competent authority is "the central authority of a Member State competent to carry out veterinary checks or any authority to which it has delegated that competence."

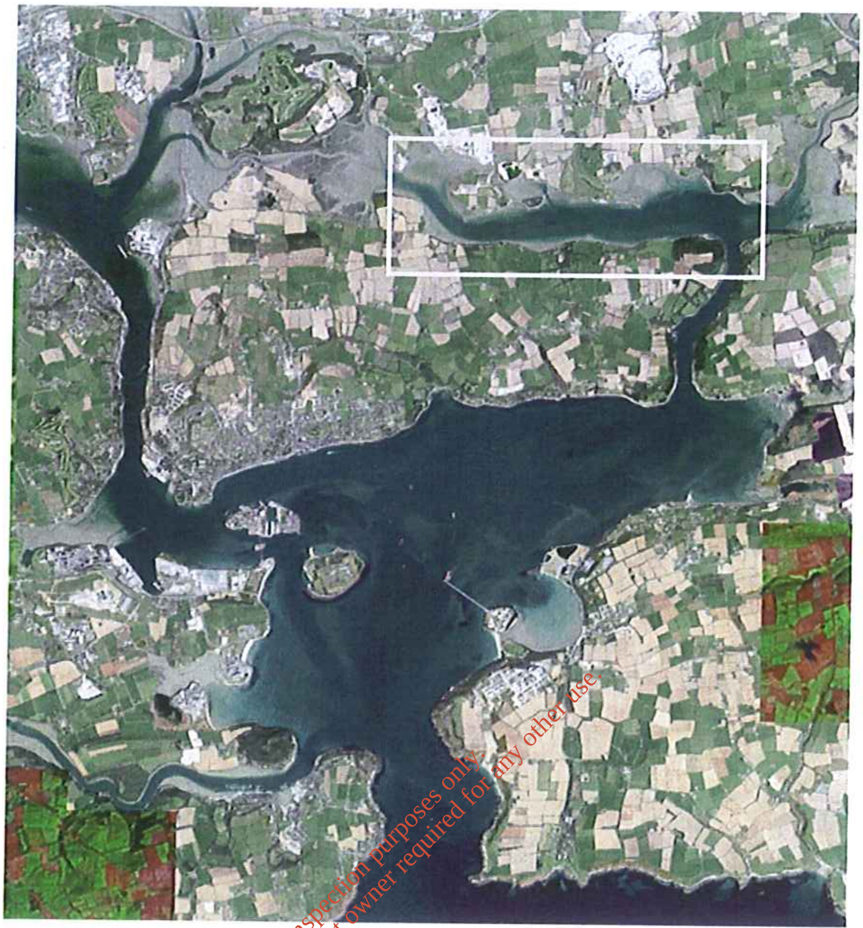

Fig. 1.1 Cork Harbour (Quickbird Image). The main shellfish producing area is indicated by the white box. A close up view of this area is plotted on the following page

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Chapter V of the Annex sets out "REQUIREMENTS CONCERNING LIVE BIVALVE MOLLUSCS" that are "intended for immediate human consumption". The requirements cover visual characteristics, toxic or objectionable compounds occurring naturally or added to the environment, Paralytic and Diarrhetic Shellfish Poison, radionuclides, and "in the absence of routine virus testing procedures and the establishment of virological standards, health checks must be based on faecal bacteria counts" covered in sections "2. They must contain less than 300 faecal coliforms or less than 230 E. Coli per 100 g of mollusk flesh and intravalvular liquid ..." and "3. They must not contain salmonella in 25 g of mollusc flesh." "The effectiveness of the faecal indicator bacteria and their numerical limits as well as the other parameters laid down in this Chapter [of the Annex to the Directive] must be kept under constant review and, where scientific evidence proves the need to do so, be revised following the procedure laid down in Article 12 of this Directive".

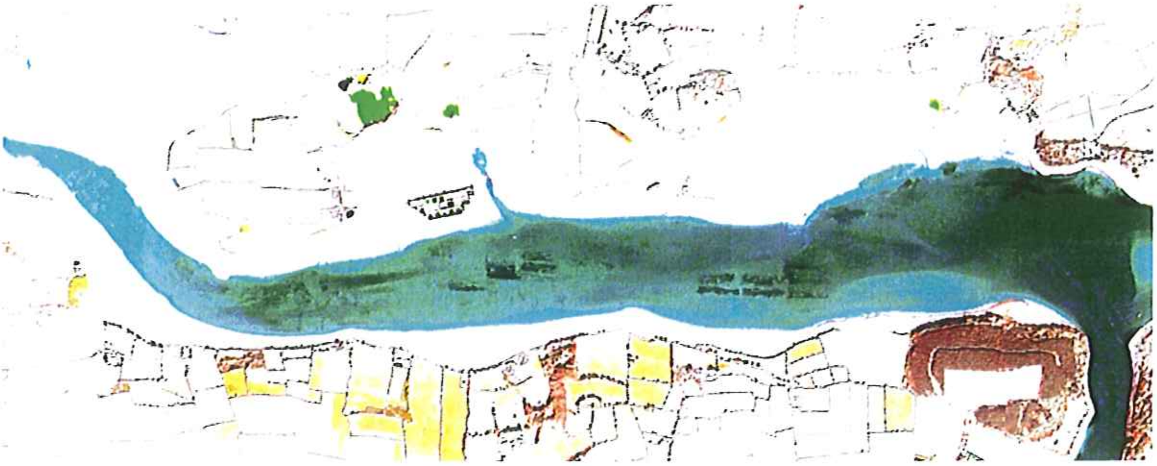

Fig. 1.2 Quickbird image of the Oyster Fishery in the North Channel. The colours in the original image have been altered to highlight the trestles in the North Channel

In 2006 Cork County Council asked the lead author of this report to carry out an objective study of the sources of contamination and to determine the contribution, if any, by the Midleton municipal discharge to the contamination.

We have interpreted this as a request to estimate the relative contribution of all significant sources of municipal and domestic effluent, including Midleton, to the contamination of the oyster farm[6]. Each source is conceptualised in exactly the same way in the interests of equity[7].

1.4 Response to the brief

We have considered all important discharges of treated and untreated sewage, both continuous and intermittent, as the source of the *Norovirus* contamination. We have made several computer models of the discharge, transport and decay of the *Norovirus* in Cork Harbour.

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[6] Storm water overflows from Cork City, as part of the Carrigrennan WWTP, have not been considered. This would have required modelling the sewer system in Cork thereby greatly expanding the scope and duration of this study.

[7] We have not considered ships, pleasure craft, fishermen, or bathers as sources of viral contamination. Our results can be used to support this judgement. Neither have we considered phytotoxin shellfish poisoning associated with algal blooms.

The models have two parts. The first part is the hydrodynamic part. It is based on the concepts and scientific principles of geometry and classical physics[8], and on relevant data[9]. The models predict the numerical variation in water level and the speed and direction of currents throughout Cork Harbour. We have achieved satisfactory agreement with measurements of these quantities. Pilots and sailors have also identified and confirmed the location of transient tidal eddies predicted by the model. We can predict with confidence, many, but not all, aspects of the motion of the waters of Cork Harbour under different conditions of tide, wind and river inflow.

The second part of the models describe the dispersal and decay of *Norovirus* discharged at any location in the Harbour. The accurate and precise identification and the high-frequency measurement of *Norovirus* in sewage effluent and natural waters has not yet been achieved anywhere in the world. Because of the lack of such data it is not possible to calibrate and verify a model of the dispersal and decay of *Norovirus* in the Harbour in the same manner as the hydrodynamics. Consequently, we must resort to reasonable assumptions, starting with the simplest. The most important are the following.

We are not aware of any dynamic, spatio-temporal, epidemiological model of Winter Vomiting Bug outbreaks that would allow us to estimate the episodic loads from all discharges around the harbour. Therefore in order to make equitable statements on the ***relative contribution*** of all significant discharges to the contamination of the oyster farm, each discharge must be conceptualised in

[8] These are represented as partial differential equations, expressing conservation of mass and linear momentum, with attendant boundary and initial conditions, and environmental forcing functions. These equations are listed in Appendix A.

[9] Bathymetry of the Harbour from the Waterworks Weir to the Old Head of Kinsale; wind speed and direction; river flow and the tide at the mouth, and very limited data on salinity.

exactly the same way[10]. Consequently, we have assumed that each and every person living within the catchments of the harbour

(a) experiences an identical attack of noroviral gastroenteritis, and

(b) discharges the same large number of identical *Norovirus* particles to the nearest sewer at a constant rate for the duration of the outbreak.

Each discharge from a sewer is therefore characterised by several numbers

(1) a constant *flow per person* of 480 litres per day[11] carrying the viruses; it is the same for every person, irrespective of age, social class, likelihood of infection or geographical location;

(2) multiplying the carrier flow per person by the *number of people* contributing to the discharge from an outfall gives the *carrier flow rate* for the outfall[12];

(3) A constant *source concentration* of viruses, 50 million *Norovirus*, in each and every cubic metre of sewage; it is the same for every person.[13]

[10] Such equitable statements are judgements based on scientific principle, field data and scientific findings elsewhere. They are not to be interpreted as statements of historical fact in Cork Harbour.

[11] The value of 480 is somewhat larger than the conventional value used in Ireland for the so-called dry-weather flow.

[12] The storm water overflow at Midleton has a varying *carrier flow rate*. The constant carrier flow per person may be augmented by rain and by infiltration of groundwater into Midleton's combined sewer system. The capacities of the pumps at the Bailick Pump Houses divide the sewer discharge between the secondary treatment plant and the river. The details are described in a later section.

[13] The secondary waste treatment plants at Carrigrennan and Midleton are assumed to remove the same constant fraction of the concentration of viruses (numbers per cubic metre) from the influent to each plant. The results are in proportion to the fraction removed. In the absence of high frequency measurements anywhere in the world we have examined two cases: 95% and

The product of the ***carrier flow rate per person*** and the ***source concentration*** is the source discharge rate of the numbers of *Norovirus* per unit time and is assumed to be the same for every person around the Harbour *i.e. 0.480 x 50 =* ***24 million Norovirus per person per day***.

Further assumptions are required when the viruses enter the waters of the Harbour. We assume that each *Norovirus* particle

(1) Is neutrally buoyant,

(2) Is non-cohesive, and

(3) Has the same fractional rate of decay, or inactivation, in each successive unit of time at every point in the Harbour.

The first assumption says the viral particles do not (1) settle to the bottom under the action of gravity[14], or (2) may collect close to the surface due to the fact that the density of treated sewage may often less than that of the receiving waters. The second says they do not stick to other larger particles in the water, forming aggregates that may be removed from the water.[15] The third assumption recognises that viruses do not survive indefinitely. A fast rate of decay corresponds to a short survival time and *vice versa*. The decay rate is a constant fraction per unit time.

Under these assumptions the transport of *Norovirus* is identical to the transport of the water which carries them. In the models they are added to the water at

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85% removal of *Norovirus*. The removal efficiency of the WWTP's is discussed further in Appendix D.

[14] The *Norovirus* is extremely small in size, much smaller than a bacterium, and may be classified as colloidal material.

[15] Larger particles may be removed by filter feeding organisms, such as oysters or mussels, or they may settle to join the sediments on the bottom to be consumed by benthic feeders, or they may subsequently be re-suspended during storms in a continuing cycle between sediment and water. Since the *Norovirus* has not yet been cultivated *in vitro* no experimental data exists in the scientific literature on the interaction of sediment and *Norovirus*. Other viruses have been studied in relation to adsorption on sediment; see below. The sensitivity of our conclusions to this assumption is addressed in a later section.

each point of discharge at the appropriate rate, and removed from the water at a constant fractional rate everywhere. The models predict the changing concentrations of *Norovirus* averaged over the vertical depth of water on a horizontal grid of points that cover the whole Harbour under varying conditions of wind, tide and river flow. Such models are called two-dimensional models. The third dimension is not ignored; it is simplified by using averages over the vertical depth of water.

In shallow macro-tidal[16] estuaries the energy supplied by the tides, and also by wind, is usually sufficient to mix the vertical column of water so that deviations from vertical averages are small. The limited data on salinity show that this is the case in Cork Harbour, except for short periods of time in areas close to the inflow of rivers, such as the Lee, which can discharge substantial quantities of freshwater during floods. Freshwater tends to flow over the more dense, but diluted sea water underneath, until vertical mixing has erased the vertical differences in salinity. We have chosen not to model transient and localised stratification due to floods.

Models are a simplification of reality; there is always something missing. It is a matter of judgement what to include and what to exclude[17].

[16] Macro-tidal estuaries have a daily variation in water level, of the order of 4m during spring tides, and 2m during neap tides. The twice-daily M2 tidal component provides such variation throughout Cork Harbour. Conservation of water mass implies that this vertical motion in the level of a shallow body of water is accompanied by a large horizontal oscillatory motion of the order of 5 to 10km. This is a very important characteristic of Cork Harbour in understanding the dispersal of contaminants. In 6 hours contaminants can be spread over 10km of water flowing past the point of discharge.

[17] Because available computing resources are usually fixed, a trade-off must be made between horizontal and vertical resolution in a model. More detail in the horizontal plane implies less detail in the vertical direction and *vice versa*. Since coastal waters are extensive (tens of kilometres wide) and relatively shallow (tens of metres deep), vertical averaging over a few metres is the price paid for greater horizontal resolution of harbours, bars, islands, bays, creeks, channels, currents and transient eddies. When there are strong salinity gradients in the vertical direction the opposite may be required to resolve the stratification.

It can be proved mathematically that the assumption of a constant fractional decay rate makes all our computer models of the *Norovirus* obey the principles of superposition and scaling in both time and space.

The **superposition principle** says that the combined effect of many discharges acting together is identical to the sum of their individual effects when they are regarded separately.

The **scaling property** is a special case of superposition. It says the effect of multiplying, or scaling, any individual discharge by a constant positive number, x, is x times the concentration of viruses in the Harbour due to that discharge before scaling *i.e.* when x is one.[18]

The property of superposition allows us to define the **relative contamination** of the model oyster farm as the contribution of each discharge to the contamination divided by the sum of all the contributions.

1.5 Epidemiology of Winter Vomiting Bug outbreaks

The reader is asked to bear in mind the principal objective of this study is to estimate the relative contribution of all sources of *Norovirus* to the contamination of the oyster farm in the North Channel behind Cobh (or Great) Island. In the interests of equity all sources of contamination are conceptualised in exactly the same way. We assume that the *Norovirus* load measured in numbers per second discharged from each sewer, and before any treatment, is

- constant in time,

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[18] The necessary conditions for the theorem are (1) the boundary conditions must be zero, and (2) all carrier flows must be present in each individual case in both the hydrodynamic and *Norovirus* parts of the model. Consequently, superposition and scaling applies *sensu strictu* to the source concentrations only. The proof of the theorem follows immediately from the linearity of the partial differential equation that describes the dynamic number-balance of the *Norovirus*. A proof of the one-dimensional case may be found in O'Kane, JPJ "Estuarine Water Quality Management with moving element models and optimisation techniques" Pitman, London. 1980. Chapter 5. Superposition is discussed further in Appendix B

- proportional to the population served by each sewer,
- lasts for 20 days in each case,
- decays at a constant rate per unit time, and is subjected to advection and dispersion due to identical conditions of tide, wind and river inflow in a two-dimensional, depth integrated model of Cork Harbour.

These are the simplest assumptions that can be made. Clearly they do not correspond to any particular historical event, or set of events. How can they be justified?

We are not aware of any dynamic, spatio-temporal, epidemiological model of Winter Vomiting Bug outbreaks that would allow us to estimate the episodic loads from all discharges around the harbour. Even if such a model were available, the problem of calibration would remain.

No measurements of the discharge rates of *Norovirus* with a frequency that resolves the hourly, daily and seasonal variability in numbers *in water* have been made anywhere in the world. The only measurements of *Norovirus* with which we have been supplied are the results of the monthly assays for the presence or absence of the virus *in oysters* taken from the oyster farm in the North Channel. The numbers present in oyster tissue have not been determined. Since the minimum infective dose is one to ten viral particles, it is not necessary to determine the numbers present when food safety is the primary concern. In the scientific literature we know of only one comparison with data when numbers in oyster tissue are available[19].

Oysters bio-accumulate viruses from their aquatic environment by a factor of 10 to 1,000. The associated ambient concentration may lie below the detection limit of the PCR method of measurement, the technique of choice at present among environmental virologists. We know of no model comparison in the international literature against concentrations of *Norovirus* in ambient water.

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19 Pommepuy, M. et al. "Fecal contamination in coastal waters: An engineering approach" Book chapter (p331-359) in Oceans and Health: Pathogens in the Marine Environment. Springer 2006. http://www.springerlink.com, http://www.ifremer.fr/docelec

In the absence of (a) epidemiological data, and (b) numbers bio-accumulated, a comparison of predicted concentrations of *Norovirus* with measured concentrations in either water or oyster tissue in Cork Harbour is not possible at this time.

Consequently, our approach may be described as a method of thinking about the problem of relative contamination, starting from the simplest assumptions. We have varied some, but not all of these assumptions, in a series of sensitivity analyses that inform our conclusions and recommendations.

Each twenty-day discharge of *Norovirus* at all eleven locations in the harbour has been simulated *separately* with our model, and therefore *independently of each other.* The timing of their occurrence is arbitrary within each of the winter and summer periods considered. In each case the absolute numbers of *Norovirus* per cubic meter in the model output are available at all points in the harbour throughout the simulation period of 37 days[20].

In order to compare all fifteen *independent* 37-day outputs with each other, we mentally shift their arbitrary times of occurrence, so that they lie on top of each other on a common time axis, which happens to be labelled as February 1992 and March 1992 on the axes of all the plots. This does not mean they all occur simultaneously during this precise period; the shifting in time is simply a device for determining the relative contribution of each discharge to the contamination of the oyster farm *without regard to when the contamination occurs, within a summer period, or winter period.* After shifting, each individual output is divided by the sum of all the outputs at each point on the common time axis to determine the relative degree of contamination from each discharge[21] without regard to when the contamination occurs.

[20] If the reader wishes to know the effect of any two simultaneous discharges of *Norovirus* it is not necessary to run the model again; the result is simply the sum of their individual outputs since the model is linear.

[21] The sum of all the outputs may also be interpreted as an extreme case in itself. It corresponds to a massive and simultaneous outbreak of the Winter Vomiting Disease everywhere around the

To eliminate the effect of different environmental conditions when the eleven discharges are compared with each other, we must use identical conditions of wind, tide and river flow. These conditions should be typical. We have chosen the period referred to already from the 14th of February 1992 to the 22nd of March 1992.

1.6 Sensitivity analysis

The conclusions of our objective study on "the sources of contamination and the contribution of the Midleton municipal discharge to the contamination" are informed by the models that we have developed and depend on both the data and the assumptions made. Because of the many uncertainties in our assumptions, we have carried out a sensitivity analysis of the results. A sensitivity analysis addresses the question:

What is the effect of a change in the model on the conclusions?

The change in the conclusions may be quantitative or qualitative, and may be significant or insignificant. For example, we have examined the quantitative change in the predicted concentrations of *Norovirus* when

1. The constant source concentration of *Norovirus*, 50 million, in each and every cubic metre of sewage is reduced to 20 million.
2. The removal rate of *Norovirus* from the secondary WWTP is reduced from 95% to 85% (the removal efficiency of the WWTP's is discussed in Appendix D)
3. The numerical scheme in the *Norovirus* model is changed from the Quickest scheme to the ULTIMATE scheme.
4. The dispersion coefficient, a key parameter in the *Norovirus* model, is defined as being proportional to the current as opposed to independent of the current. A very high

harbour. Lacking any epidemiological data, we cannot estimate the probability of such an event and we do not consider the matter further in this report.

"independent of the current" value of the dispersion coefficient was also examined.

5. The wind forcing is omitted from the hydrodynamic model.
6. The pulsed release from Rathcoursey is varied and a direct comparison is made between releasing *Norovirus* at Rathcoursey and at Bailick road in Midleton.
7. A period of exceptionally low river flows occurs during summer.
8. The location of the open boundary of the model is moved out to sea away from the discharge closest to the harbour mouth.
9. The feedback between horizontal salinity gradients and the hydrodynamics is included in the momentum balance.
10. The setting of the switches controlling the wetting and drying of the mudflats is changed.
11. Superposition of individual results is used instead of a new run with all inputs present simultaneously.

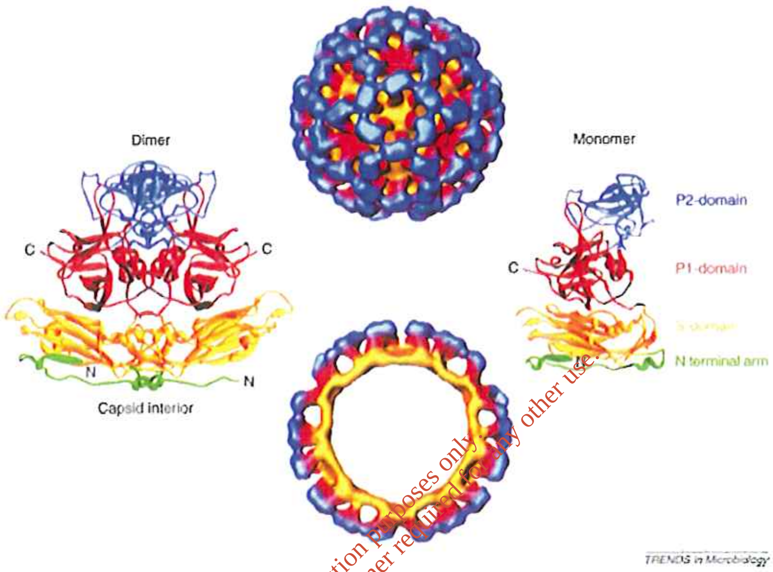
In the case of adsorption on sediment, the sensitivity analysis is qualitative.

The superposition and scaling properties of our *Norovirus* models ensure that certain sensitivity analyses can be done very easily, namely, the effect of scaling up, or down, the individual discharge rates of *Norovirus*.

1.7 Scientific background

The following paragraphs present some scientific background to the study. They are not intended to be comprehensive, or definitive. They are sufficient for our purpose, which is to indicate why oysters in the North Channel may be contaminated by discharges of sewage effluent.

The discharge of sewage effluent to coastal waters used for the cultivation of oysters poses a risk to human health.[22] The primary pathogen in outbreaks of gastroenteritis following consumption of raw oysters is the *Norovirus* or "winter vomiting bug" (WVB), formerly known as Norwalk-like viruses, and shown[23] schematically on the following page.



[22] Pommepuy, M. et al. "Fecal contamination in coastal waters: An engineering approach" Book chapter (p331-359) in Oceans and Health: Pathogens in the Marine Environment. Springer 2006. http://www.springerlink.com, http://www.ifremer.fr/docelec

[23] Hutson, Anne M., et al. (2004) "Norovirus disease: changing epidemiology and host susceptibility factors". Review TRENDS in Microbiology Vol.12 No.6 June 2004. The figure caption reads "The Norwalk virus-like particle (NV VLP) structure has been solved by cryo-electron microscopic reconstruction to 22 (top, surface representation; bottom, cross-section) and by x-ray crystallography to 3.4 . The NV VLPs have 90 dimers of capsid protein (left, ribbon diagram) assembled in T ¼ 3 icosahedral symmetry. Each monomeric capsid protein (right, ribbon diagram) is divided into an N-terminal arm region (green) facing the interior of the VLP, a shell domain (S-domain, yellow) that forms the continuous surface of the VLP, and a protruding domain (P-domain) that emanates from the S-domain surface. The P-domain is further divided into subdomains, P1 and P2 (red and blue, respectively) with the P2-subdomain at the most distal surface of the VLPs. Adapted, ... , from Prasad, B.V. et al. (1999) X-ray crystallographic structure of the Norwalk virus capsid. Science 286, 287–290; and Bertolotti-Ciarlet, A. et al. (2002) Structural requirements for the assembly of Norwalk virus-like particles. J. Virol. 76, 4044–4055".

The first recorded epidemic attributed to Norwalk virus occurred in an elementary school in Norwalk, Ohio, in 1968. Bacteria-free faecal filtrates derived from adult patients were fed to volunteers. These volunteers consequently became ill and provided evidence that gastroenteritis could be induced with a non-bacterial agent[24] In contrast to the recent and more dangerous SARS virus[25], one of the six Koch-Rivers postulates[26] for confirmation of the aetiology of the WVB disease is still outstanding: Norovirus has not yet been cultivated in host cells.

Human intestinal cells are the only hosts for *Norovirus* growth. There is no animal model in which to study the disease. There is "a correlation between a person's genetically determined carbohydrate expression and their susceptibility to Norwalk virus infection".[27]

The *Norovirus* virus is endemic in many countries. Outbreaks of "winter vomiting" may occur all year round and are often made public in Ireland by the closure of hospitals to visitors. Waters et al. (2006) [28] reported that "Since 2002, the burden of Norovirus (NoV) infection in Ireland has increased. Outbreaks in institutional settings are the most common causing widespread disruption to

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[24] Hutson, Anne M., et al. (2004) "Norovirus disease: changing epidemiology and host susceptibility factors" Review *TRENDS in Microbiology* Vol.12 No.6 June 2004. Elsevier Science Direct. http://www.sciencedirect.com/

[25] Fouchier, R.A.M. "Aetiology: Koch's postulates fulfilled for SARS virus" *Nature* **423**, 240. 15 May 2003

[26] In the 19th century Robert Koch laid down three postulates for establishing the causal agent of a disease: isolation of the agent from a diseased host, production of the disease in the same host species, and re-isolation of the agent. Three further postulates were added by Rivers in the 1930s when particles much smaller than bacteria were suspected of causing disease. The additional Rivers postulates are: cultivation of the agent in host cells of the same or related species, proof of filterability establishing its very small size and detection of an immune response.

[27] Hutson, Anne M., et al. (2004) Op. cit. ante.

[28] Waters, A., et al. (2006) "Molecular epidemiology of Norovirus strains circulating in Ireland from 2003 to 2004" *Epidemiol. Infect.*, Page 1 of 9. Cambridge University Press. http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=420336#

health service delivery." Kelly et al. (2006)[29] reported 226 outbreaks in Ireland during 2004 and concluded: "Results so far indicate that the majority of reported outbreaks in the island of Ireland are associated with hospitals and residential institutions." There is no comment on the probable number of non-reported outbreaks.

The virus is life-threatening to those with post-operative stress in hospitals and to the very young and very old. In healthy adults it is not very dangerous. The *Norovirus* is a colloidal particle 27-38nm in diameter. It is highly infectious especially in the case of projectile vomiting. The minimum infective dose is very low, between one and ten ingested particles. Incubation takes 24 to 48 hours.

The oyster selectively concentrates the *Norovirus* in its digestive ducts.[30] *Norovirus* cannot be removed by conventional depuration of the oyster.

The detection limit of the most sensitive and easy-to-use measurement method, reverse-transcription PCR[31] is roughly 2 particles/100g of shellfish[32]. Surrogate

[29] Kelly S., Foley B., Coughlan S., Dunford L., O'Neill H., Smyth B., McKeown P., Lynch M. "Epidemiology and molecular analysis of norovirus outbreaks in Ireland" Abstract p1030: "This study set out to describe the epidemiology of norovirus outbreaks in the island of Ireland, over a one-year period. The study commenced on 01/10/04. Epidemiological data from outbreaks was collected in an electronic database, which was established for this project. A link for the sharing of epidemiological and virological data was established leading to an enhanced data set. Samples from outbreaks in the Republic of Ireland were sent to the National Virus Reference Laboratory in University College Dublin for confirmation of the diagnosis by RT-PCR (Reverse Transcription Polymerase Chain Reaction). Due to enhance surveillance during the study period there was a high rate of submission of samples. In the North of Ireland, samples were sent to the Regional Virus Reference Laboratory at the Royal Victoria Hospital in Belfast where a nested PCR was used for diagnosis of norovirus. Sequencing was carried out on the PCR products to determine the circulating strains of norovirus in Ireland. Over a one-year period, 153 norovirus outbreaks were reported in the Republic of Ireland. In the North of Ireland, over the same period, 73 outbreaks of norovirus infection were reported to the Regional Virus Reference Laboratory. Results so far indicate that the majority of reported outbreaks in the island of Ireland are associated with hospitals and residential institutions. In the Republic of Ireland the noroviruses associated with the majority of outbreaks were a new variant of Genogroup II.4, known as the JAM strain. A small number of noroviruses associated with outbreaks in the Republic of Ireland belonged to Genogroup II.2. The database will be used as a source of data for the Food borne Viruses in Europe Network. Safefood-the Food Safety Promotion Board funded this research."

European Society of Clinical Microbiology and Infectious Diseases 16th European Congress of Clinical Microbiology and Infectious Diseases. Nice, France, April 1-4, 2006.

[30] Le Guyader, F.S. et al., "Norwalk Virus-specific Binding to Oyster Digestive Tissues" in Emerging Infectious Diseases. www.cdc.gov/eid , Vol.12, No. 6, June 2006.

[31] RT-PCR (Reverse Transcription Polymerase Chain Reaction).

viruses have been used to establish that viral particles may persist in shellfish tissue for several weeks.[33]

The average infected person may excrete[34] roughly 0.15 billion *Norovirus* particles per day to the sewer system. Roughly 3 to 6% of the population of a town or city may be infected during an outbreak. Asymptomatic excretion from infected persons may persist for a period of up to 2 to 3 months.[35]

Secondary treatment of sewage may still allow a discharge to waterways of 5-15% of this very large number. It may rise to 50% from combined sewer systems when the treatment capacity is overloaded during intense rainstorms or by infiltration of groundwater into poorly constructed or maintained sewers.

Whereas "it is presumed that Norovirus genes are damaged and the toxicity of the viruses is lost after conventional ultraviolet disinfection treatment" gene testing methods [such as RT-PCR] have shown that *Norovirus* genes survive chlorination, and UV-irradiation.[36]. Photocatalytic (*TiO_2*) UV disinfection destroys the individual genes (Kato et al; 2005. Op. cit. ante).

The virus has a long survival time in coastal waters from 7 days (summer T90) to 30 days (winter T90)[37]. Even longer survival times have been suggested for surrogate viruses[38]. These times are at least ten times those for the indicator

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[32] Pommepuy, M. et al. "Sewage impact on shellfish microbial contamination". Water Science and Technology. Vol. 50, No. 1 pp 117-124. IWA publishing, 2004. See page 122

[33] Loisy, F. et al. "Use of Rotavirus Virus-Like Particles as Surrogates To Evaluate Virus Persistence in Shellfish" Applied and Environmental Microbiology, Oct 2005, Vol. 71, No.10, p.6049-6053.

[34] Pommepuy, M. et al., 2004. Op. cit. ante.

[35] Pommepuy, M. et al., 2004, 2006 and references therein. Op. cit. ante.

[36] Kato, Toshiaki et al. "Degradation of Norovirus in Sewage Treatment Water by Photocatalytic Ultraviolet Disinfection" NIPPON STEEL TECHNICAL REPORT No. 92 July 2005. http://www0.nsc.co.jp/shinnihon_english/kenkyusho/contenthtml/n92/n9208.pdf

[37] Pommepuy, M. et al. 2006. Op. cit. ante. The T90 time is the time required for 90% decay.

[38] As there are currently no *in vitro* cultivation techniques for Norwalk viruses much of the information on virus survival in coastal waters and bivalve shellfish is based on surrogate viruses.

bacteria, such as faecal coliforms, used in regulatory instruments for the protection of consumers of oysters and the quality of coastal waters where oysters are produced. Consequently, when the infective agent is viral, absence of indicator bacteria does not imply the absence of contamination and health risk. Protection against *Norovirus* may also protect against most other viral pathogens as well.

The processes of adsorption and desorption of viruses to and from natural sedimentary material have been studied intensively in relation to the problem of protecting groundwater intended for public consumption[39]. These processes are complex and depend on

1. the type of virus and sedimentary material,
2. the distribution of electric charge on their surfaces,
3. colloidal size,
4. pH,
5. dissolved surfactants,
6. organic carbon content,
7. ionic strength,
8. temperature, and
9. surface tension at air-water interfaces when they are in contact with a virus.

Because of their extremely small size it has been suggested that viruses must first be adsorbed on the surface of phytoplankton before they can be ingested

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Arnal *et al* estimated the T90 of the HAV capsid antigen as being 178 days at 25 deg C and 212 days at 19 deg C. (Arnal C., Crance J.M., Gantzer C., Schwartzbrod L., Deloince R., Billaudel S. Persistence of infectious hepatitis A virus and its genome in artificial seawater. Zentralbl. Hyg. Umweltmed. 1998 Sep;201(3):279-84).

[39] Schijven, J.F. and Hassanizadeh, S.M. "Removal of Viruses by Soil Passage: Overview of Modelling, Processes, and Parameters" Critical Reviews in Environmental Science and Technology, 30(1): 49-127 (2000). CRC Press.

and accumulated by filter feeding oysters; but "many suspension feeders manage to trap particles whose diameter is considerably smaller than the "mesh size" of the organs used for feeding".[40]

In a review of adsorption of viruses in saturated groundwater flow, Schijven and Hassanizadeh[41] (2000) concluded

1. "The enhancing and attenuating effects of organic matter are very difficult to quantify and may be responsible for considerable uncertainty when predicting virus removal" [Abstract];
2. "predictions[42] of virus removal [by adsorption] at larger distances are severely overestimated if they are based on removal data from column experiments or from short-distance field studies" [Abstract];
3. "humic substances are, similar to viruses, negatively charged, and hence they compete with viruses for the same binding site. ... Thus, detachment of viruses may be strongly increased by dissolved or suspended organic matter" [Section F p84].

1.7.1 Conclusions

In the light of these judgements and because the estuarine environment is rich in organic and inorganic material (dissolved and particulate, suspended and

[40] Denny, Mark W. "Air and Water – The Biology and Physics of Life's Media" Princeton University Press, 1993. Page 140, section 7.9, referencing the paper by Rubinstein, D.L. and Koehl, M.A.R. "The mechanism of filter feeding: some theoretical considerations" *Amer. Nat.* 111: 981-994.

[41] Schijven and Hassanizadeh; Op. cit. ante.

[42] In spite of its difficulty, modelling the transport and fate of viruses in groundwater used for public water supply is of considerable interest. It is the only method available for managing water-borne disease based on a maximum acceptable level of risk of infection e.g. not more than one case per 10,000 persons per year, when action levels are below the detection limit of analytical instruments. See Schijven and Hassanizadeh for references; Op. cit. ante.

surficial) and exhibits rapid variations in ionic strength at fixed locations, we have not included in our model the interaction of *Norovirus* and sediment.

Instead we have taken the simplified case[43] of no adsorption on sediment in our examination of the relative contamination of the oyster farm by all significant sources of human effluent around Cork Harbour. All sources have been conceptualised in exactly the same way in the interests of equity. However Kelly et al. (2006; Op. cit. ante) have stated that epidemiological "results so far indicate that the majority of reported outbreaks in the island of Ireland are associated with hospitals and residential institutions". They made no comment on non-reported incidences and the possibility of "observer bias".

Hence, sewer catchments containing hospitals and residential institutions may discharge *Norovirus* in larger numbers per inhabitant compared to other catchments that do not contain them. In the absence of specific data on outbreaks around Cork Harbour we have assumed that this not the case, but the possibility should be borne in mind when interpreting our conclusions.

If necessary, our results can be rescaled to account for any departure from a constant number of *Norovirus* per inhabitant of the Harbour Region.

1.8 The Models

Two separate models have been developed as part of this study. The first, the Roches Point (RP) model, has been used to determine the relative contributions of *Norovirus* contamination of the model oyster farm in the North Channel for all the outfalls in the harbour (Fig. 1.3) with the exception of Carrigaline and

[43] A more complex model would treat the transport of water, salt, heat, suspended and surficial sediment, organic and inorganic sediment, and the concentrations of *Norovirus* in water and adsorbed on all types of sediment. The latter model is non-linear and the principles of superposition and scaling would not apply. Consequently, an examination of the relative contributions of the different sources of contamination would require a specified sequence of changes to all effluent discharges in historical order, a much more demanding task than that undertaken in the study reported here.

Crosshaven. The combined outfall for these towns has been omitted from the RP model as it lies too close to the open boundary of the model at Roches Point.

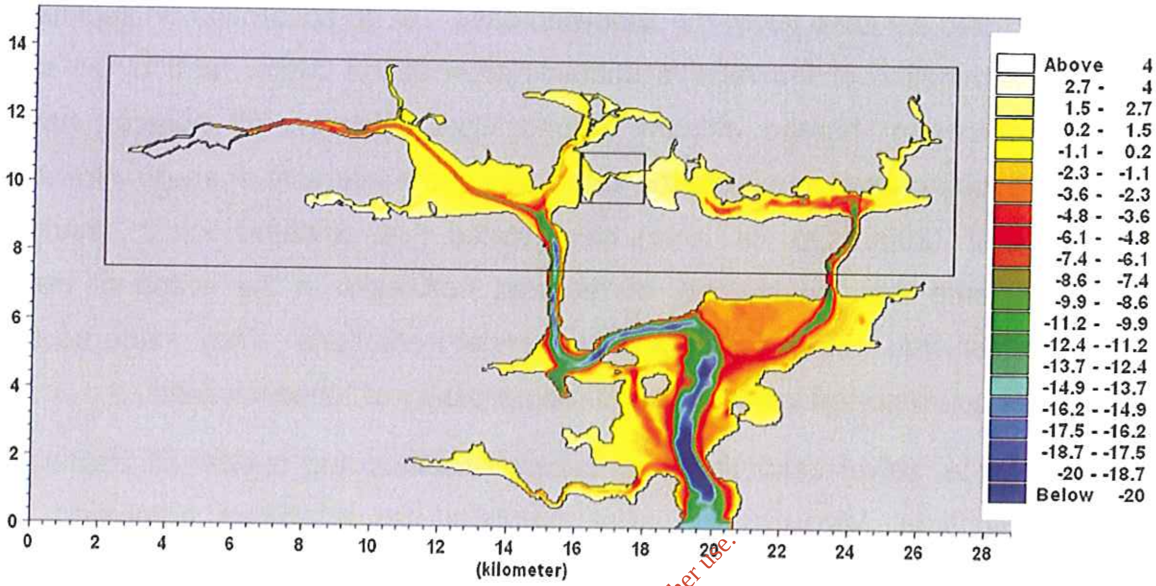

Fig. 1.3 RP bathymetry plot – 54m, 18m & 6m nested grids. The colour palette on the right-hand-side indicates the depth of the harbour bed in metres.

The model has three finite-difference grids each with a different resolution (54m, 18m and 6m). The data used to construct the model is described in Chapter 2. The model set-up and its calibration and validation are described in Chapter 3. Slight adjustments were made to the layout of the grids for modelling (a) the storm water overflows at Midleton[44], and (b) the houses surrounding the North Channel. Recorded timeseries of tidal elevation from a gauge deployed at Fort Camden in 1992 acts as the boundary condition of the model. The model is well calibrated against measurements of water level and currents for a number of sites within the harbour.

The second model, the Old Head (OH) model, has been used to determine the relative contribution of the Carrigaline/Crosshaven outfall to contamination of the Oyster Farm (Fig. 1.4). The boundary conditions for this model are provided by

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[44] Storm water overflows from Cork City, as part of the Carrigrennan WWTP, have not been considered. This would have required modelling the sewer system in Cork thereby greatly expanding the scope and duration of this study.

output from a numerical model of the North Atlantic Shelf[45]. The agreement between the modelled and measured data for this model is not as good as that of the RP model. Consequently the OH model has only been used when the RP model is inappropriate.

A list of all the outfalls considered in the study is given in Table 1-1. The population[46] serving each outfall is also listed as well as the carrier flow for the viruses. The carrier flow is based on the assumption of a constant flow per person of approximately 480 litres per day carrying the virus. The X,Y Irish national grid coordinates of each outfall was supplied by Cork County Council. The houses around the harbour were identified using the Quickbird imagery (as described in Section 1.9)

Three separate periods[47] have been considered as part of the study:

- **Period One** – before the secondary waste water treatment plant (WWTP) serving Midleton was constructed i.e. up to the 1st July 2000;
- **Period Two** – after the construction of the WWTP at Midleton, but before the WWTP at Carrigrennan, serving Cork City was built i.e. between 1st July 2000 and 24th July 2003;
- **Period Three** –after the construction of Carrigrennan i.e. after 24th of July 2003

Summer and winter conditions were considered for each of the three periods.

[45] The Proudman Oceanographic Laboratory in the UK provides hindcasts of water level and currents for locations on the North-Atlantic-Shelf through the use of its CS3 hydrodynamic model.

[46] The population numbers were obtained from the 2002 census. The allocation of the population to sewer catchments was changed a number of times during the study, but never by more than 7%. There is uncertainty concerning the location of a person with Winter Vomiting Disease at any moment in time: at home, at work, or in hospital, or temporarily in an institution with a mass outbreak. The concept of "population equivalent" is not appropriate, since we are not considering organic waste.

[47] The populations serving each outfall were assumed to be equal for each of the 3 periods

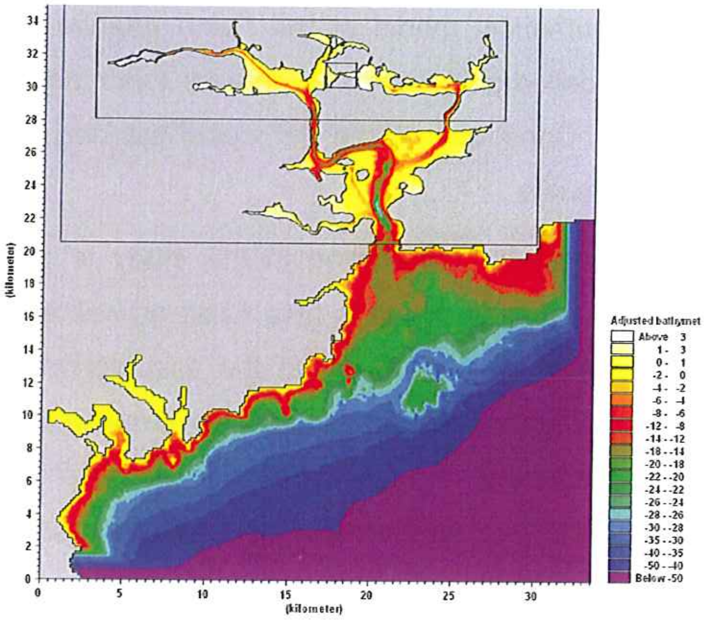

Fig. 1.4 Old Head (OH) model

	Outfalls	Treatment	Population	Flow Rate (m^3/s)
1	Cork City - Untreated	None	186,000	1.000
2	Cork City - Carrigrennan	Secondary	186,000	1.000
3	Carrigaline/Crosshaven	None	12,600	0.068
4	Cobh	None	10,000	0.054
5	Midleton - Untreated	None	7,700	0.041*
6	Midleton Treated	Secondary	7,700	0.041*
7	Passage West	None	3,300	0.018
8	Glenbrook	None	300	0.002
9	Monkstown	None	1,000	0.005
10	Carrigtohill	Secondary	1,400	0.008
11	Whitegate/Upper Aghada	None	790	0.004
12	Cloyne	Secondary	1,000	0.005
13	Ringaskiddy	None	500	0.003
14	Saleen	None	300	0.002
15	Lower Aghada	None	200	0.001
16	Rostellan/Farsid	None	200	0.001
17	SW Overflows at Bailick 1 & 2	None	7,700	Timeseries
18	Houses around North Channel	None	576**	Various

* = this constant flow rate has been adjusted in the model to account for the pulsed release at Rathcoursey. Thirty minutes after high tide the effluent is released by a tidal clock for 3 hours. For the rest of the tidal cycle there is no discharge from Rathcoursey

** = 144 houses identified around North Channel. It is assumed that there are 4 people in every house.

Table 1-1 List of Outfalls considered in the study. A map showing the location of all the outfalls is provided on the following page.

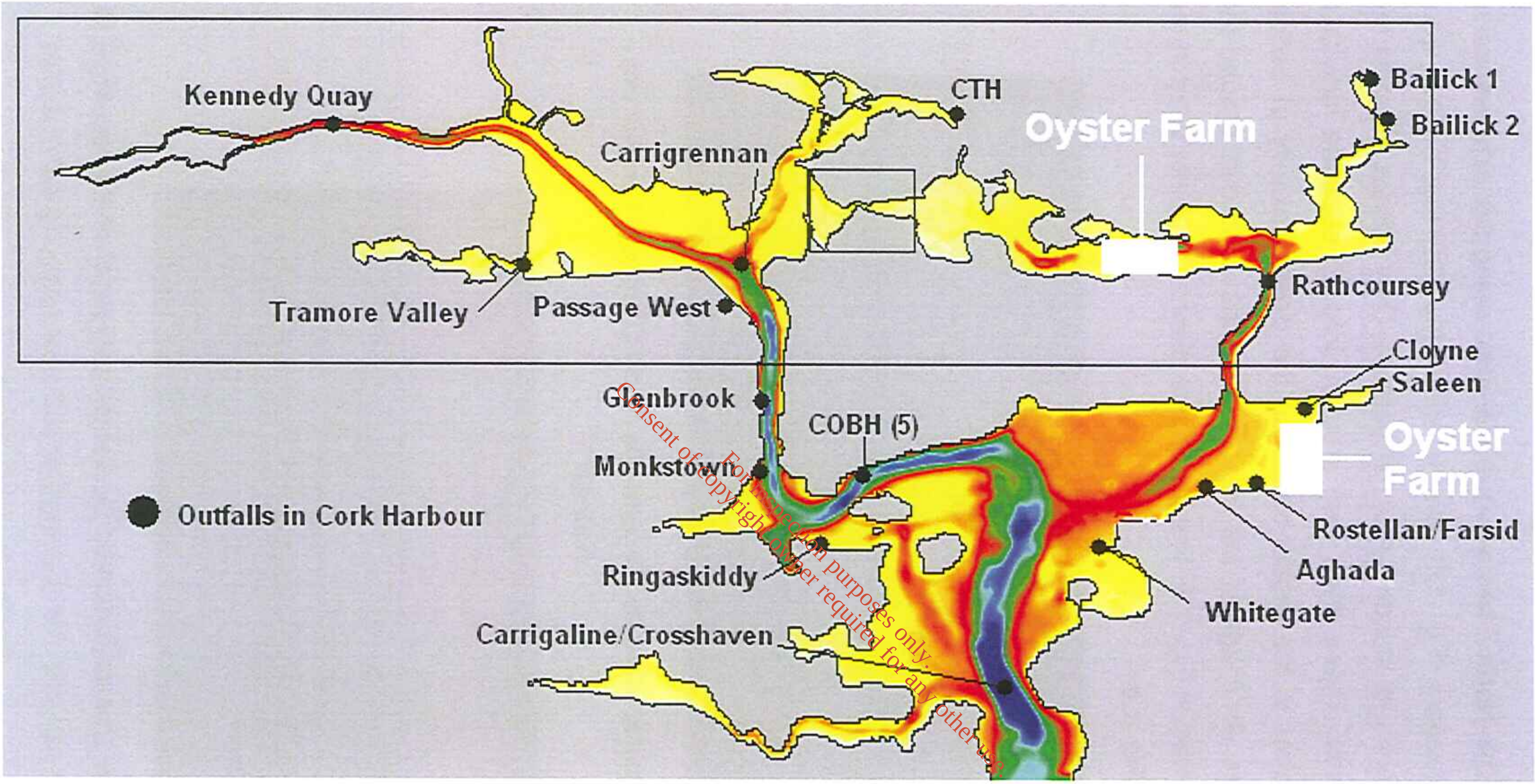

Fig. 1.5 Location of outfalls in Cork Harbour

1.9 Identification of Houses around the harbour

The houses around the North Channel were identified using the high-resolution IKONOS Quickbird imagery (Fig. 1.6). One hundred and forty four houses were identified based on a visual inspection of the dataset. Only houses close to the shore were considered. These were then grouped into 40 separate individual source discharge points in the model based on the close proximity of certain houses to each other. An image of the individual groups of houses around the oyster farm is presented in Fig. 1.7. The 40 source discharge points used in the model are shown in Fig. 1.8.

Fig. 1.6 The 144 houses identified around the North Channel (1 yellow dot = 1 house)

Fig. 1.7 Six separate groups (indicated by the red polygons) of houses close to Oyster Farm. We can see that the number of houses serving each source discharge point varies.

Fig. 1.8 Source discharge points

We have assumed that each of the 144 houses identified discharge untreated sewage into the North Channel and that there are 4 people in each house[48].

Over the course of the study the authors undertook a site visit to the North Channel and Midleton. A number of pipes discharging waste close to some of the houses were observed (Fig. 1.9). All 144 houses however were not inspected.

Fig. 1.9 Two pipes on the foreshore discharging close to two houses on the North Channel

[48] The average house occupancy for the towns studied as part of the proposed Outer Harbour Main Drainage Scheme (Cork Harbour Main Drainage Scheme Preliminary Report, Volumes 1-5, E.G, Pettit & Company) ranged from 3.33 to 3.45 people per house. Our assumed value of 4 people per house is therefore slightly conservative.

1.10 Structure of the report

Chapter one provides an introduction to the study and lists the assumptions in our models. The scientific background to the *Norovirus* is also described. Chapters two and three are concerned with the development of the RP and OH models. The methodology used in calculating the release of *Norovirus* from the stormwater discharges from Bailick 1 and Bailick 2 in Midleton is described in Chapter 4. The results of our findings are contained in Chapter 5. A considerable number of charts and diagrams are presented for the six periods considered as part of the study. A comparison between the three periods is provided. The influence of Carrigaline and Crosshaven is discussed in Chapter 6. The sensitivity analysis is presented in Chapter 7. The conclusions to our objective study are contained in the final chapter.

Appendix A presents the mathematical equations used in MIKE 21. Appendix B discusses the superposition principle. Appendix C presents results from the Outer Harbour while the Appendix D discusses the removal efficiency of the Waste Water Treatment Plants.

A DVD is included at the back of this report which contains a number of animations highlighting the release, transport and decay of *Norovirus* from the relevant outfalls as presented in Chapters 5 and 6.

Chapter 2 The Datasets

2.1 Introduction

Data was collected from various sources over the course of the study to facilitate the development of the numerical models. A list of the data is provided below. A description of each dataset and its application to the study is given in section 2.2.

Data type	Format	Source
Bathymetric data of Cork Harbour (type 1)	X,Y,Z soundings	Irish Hydrodata
Bathymetric data of the Belvelly Channel (type 2)	X,Y,Z stereoscopic data	DLR (German Aerospace Agency)
Water level recordings from the harbour	Timeseries	Irish Hydrodata / Port of Cork
Current speed & direction recordings from the harbour	Timeseries	Irish Hydrodata
Hydrodynamic output from CS3 model	Timeseries	Proudman Laboratory (UK)
Quickbird - remotely sensed satellite imagery	High-resolution imagery	DigitalGlobe/ERA Maptec
River flows	Timeseries	ESB/EPA
Wind speed & directions from Cork Airport	Timeseries	Met Eireann
Bridge survey	AutoCad drawings	Cork CoCo
'As built' outfall drawings/Sewer networks	Paper copies/AutoCad	Cork CoCo
Urban populations	Numbers from table	2002 Census

Table 2-1 Datasets

2.2 Datasets

2.2.1 Bathymetric data

Irish Hydrodata Ltd. undertook a bathymetric survey of Cork Harbour in 1992 as part of a study of locations for an outfall from the Cork Main Drainage Scheme. A number of other surveys have since been carried out by Irish Hydrodata Ltd. for smaller localised areas. These surveys were commissioned by different parties to update the bathymetry in site-specific areas as part of various modelling studies. The main bathymetric datafile used in this study is an amalgamation of all these surveys and represents the most up-to-date dataset of the harbour bed profile that exists at present. A comprehensive quality-assurance of the dataset was carried out.

2.2.2 Modification to the Bathymetry at Belvelly Channel: Merging of the Bathymetry with a Digital Elevation Model

The Belvelly Channel is the western entrance to the North Channel behind Cobh Island. Westerly winds can drive contaminants from Lough Mahon through the channel towards the oyster farm. Consequently the accurate representation of the geometry of this narrow body of water is important.

In the region near Belvelly, the bathymetric data consisted of depth data derived from the 1992 survey and historical Admiralty Charts which have a horizontal resolution greater than 25 metres. The Department of Civil and Environmental Engineering at UCC also possesses a Digital Elevation Model (DEM) of the topography for Cork City and the Upper Harbour. The DEM is derived from the stereo-matching of aerial images from the HRSC-A (High Resolution Stereo Camera-Airborne) digital stereo-camera developed by the German Aerospace Agency (Deutsches Zentrum für Luft und Raumfahrt) for the Mission to Mars. The HRSC-A camera consists of a nine-line push-broom camera arrangement with five panchromatic stereo channels. It was flown over Cork in 2001. The resulting DEM has a planimetric resolution of 1 metre and represents elevation values in multiples of 10 cm (1.4 metres, 1.5 metres, etc.). The HRSC-A survey was conducted at low tide. Consequently, there is DEM coverage for most of the tidal mudflats in the Belvelly Channel.

The DEM of the exposed mudflats near Belvelly showed differences between the DEM topography and the Admiralty bathymetry. As the DEM was of a higher spatial resolution and, as it was a more recent survey, it was considered beneficial to replace the low-resolution bathymetry with DEM data for areas of the DEM above the water line and, below the water line, to retain the remaining channel bathymetry.

The target resolution of the bathymetric data in the vicinity of Belvelly was six metres. There were two challenges to achieving a seamless integration of the bathymetry with the DEM of the mudflats.

1. The depth transition where the bathymetry and the added DEM data meet should be minimal. That is, there should be no apparent offset between the two data sets.

2. The added DEM data should represent the surface in a manner consistent with the representation in the bathymetry. This requires the DEM data to be filtered appropriately to remove artefacts and spikes.

The second point arises because the DEM represents the visible surface from stereo images. Sometimes, the calculation of vertical elevation by matching stereo images may be erroneous, particularly in the presence of water which can give scattered reflections of light. To deal with this, a number of filters were applied to the DEM to suppress spikiness in the data. The filters included Gaussian Low Pass Filters and area median filters. The data was then sub-sampled from 1-metre data to a 6-metre resolution. When the DEM data was finally integrated with the remaining bathymetry a further smoothing step was applied to make the stitching of the two data sets seamless.

2.2.3 Pools in the Bathymetry at Lough Mahon: Dealing with an Unexpected Consequence of the Triangulation of Irregular Data

The bathymetry used in all the models in this study has been interpolated onto uniform grids covering the Inner and Outer Harbours and the coast as far as the Old Head of Kinsale.

In those areas of concern to shipping, depth (z) surveys of the harbour floor have been carried out regularly by Irish Hydrodata using single beam echo-sounding from a boat whose (x, y) position is measured with a differential GPS system on board. We have used the latest (x, y, z) data sets from these surveys. These data points are separated by approximately 6 metres along the boat's survey track. Adjacent survey tracks are separated by a distance of approximately 25 metres. See Fig. 2.1

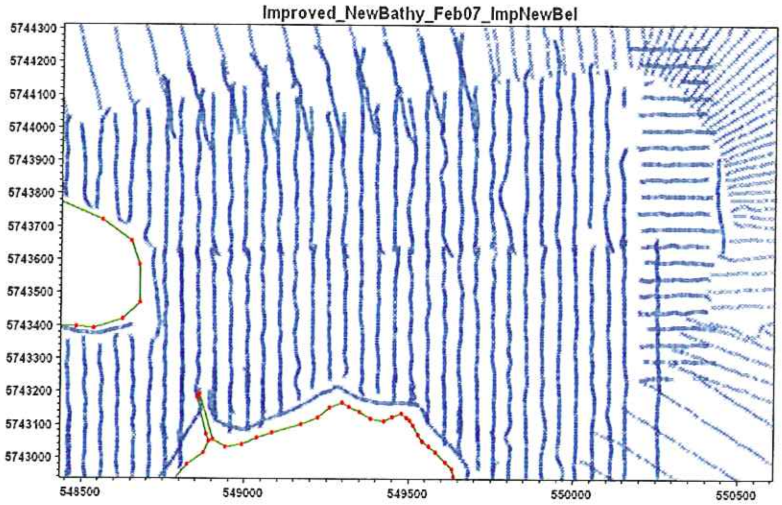

Fig. 2.1 Raw bathymetric data (outer harbour). Survey tracks shown in blue with each point on a track indicating a depth measurement.

When a Triangulated Irregular Network (TIN) was generated from the (x,y,z) data in Lough Mahon, peaks and pits appeared in the bathymetry. In particular, the peaks and pits coincided with the path of narrow drainage channels in the mudflats. When such artefacts arise in the bathymetry for use in a computational model such as Mike 21, the usual remedy is to convolve the bathymetry with a smoothing filter. This is an adequate response when the modeller is happy to sacrifice effective bathymetric resolution for stability in the computational model.

An alternative solution to the problem of erroneous peak/pit generation in the presence of narrow channels in the bathymetry has been found in this case. The approach taken was:

1. Manually identify channel paths with reference to a geo-rectified aerial ortho-image of the target area.
2. In the vicinity of a defined channel path, constrain the triangulation method to interpolate only between samples that are similarly distant from the centre of the channel, thereby preventing the formation of erroneous pits/peaks in the course of the channel.
3. Triangulate/interpolate as normal in all other areas.

The resulting bathymetry is of a higher effective resolution than that resulting from the Low Pass filtering approach offered by Mike 21 while also delivering a more faithful representation of the actual surveyed bathymetry.

The DLR data around the Belvelly channel replaced the data derived from Admiralty Charts and old surveys.

2.2.4 Other modifications to the bathymetry

Detailed examination of instabilities, first in the nested hydrodynamic (HD) model, and subsequently in the corresponding advection-dispersion (AD) model sitting on top of the HD model, showed that oscillations in the bathymetry at the grid scale were responsible for numerical explosions.

Instabilities occurred along the sides of the narrow West and East Passages even though these channels were deliberately aligned with the axis of the grid. They also occurred on the northern shore at the entrance to Lough Mahon close to the mouth of the Glanmire River, and in the narrow channel immediately downstream of Midleton.

In all cases we believe the bathymetry to be inaccurate. These locations are either in the inter-tidal zone, or very close to it, and consequently of little concern to shipping. In most cases the instabilities were removed by smoothing the bathymetry using the low-pass filters (two-dimensional convolution operators) available for this purpose in the Mike Zero toolbox.

Grid cells that can dry out at the open boundary, or at the changes in grid spacing, can also cause instabilities. Small increases in bathymetry were made at the boundary to ensure cells never dried. Near Midleton the bathymetry was modified to ensure that the Owenacurra never dried out at low water.

The bathymetry in the North Channel behind Cobh Island contained two anomalies: an apparent causeway across the channel (Fig. 2.2) and a pit (Fig. 2.3). The quality assurance of the bathymetric data highlighted a series of duplicate points at the location of the causeway and so was removed from the dataset. The high-resolution aerial imagery of the North Channel did not indicate any pits in the exposed mudflats of the North Channel and so it too was removed from the dataset.

The special tool in the Mike21 toolbox was applied to the bathymetry, Manning M and eddy viscosity fields to ensure compatibility across lines where the grid spacing changes, always by a factor of three. These fields were also modified at the open boundaries of the model to ensure that instabilities are not fed into the model domain from the boundary condition.

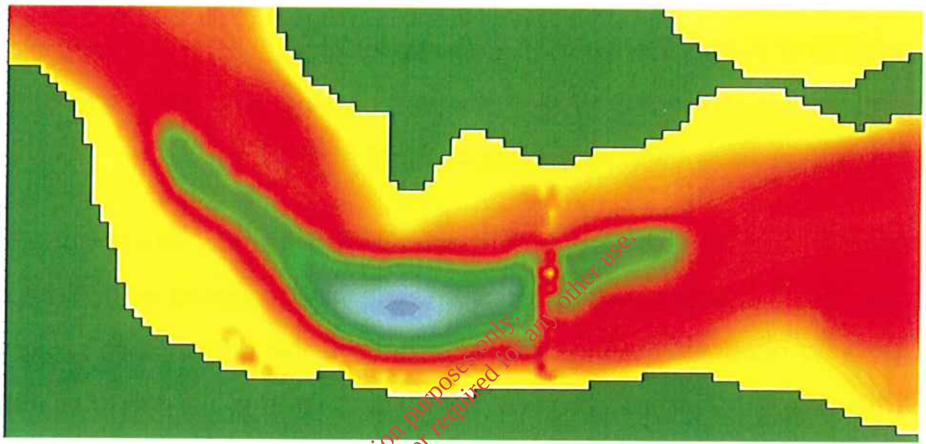

Fig. 2.2 Causeway in North Channel

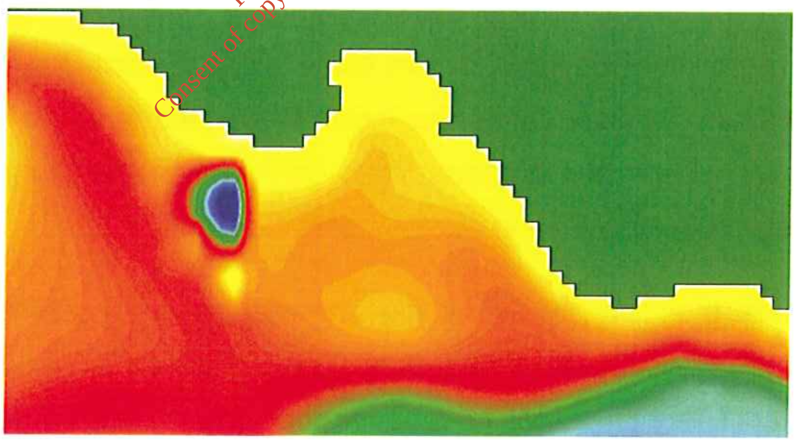

Fig. 2.3 Pit in the North Channel

2.2.5 Water Level & Current Speed Direction Recordings – 1992

As well as the bathymetric survey undertaken for the 1992 outfall study, Irish Hydrodata Ltd placed a number of gauges in the harbour to record water levels, current speeds and current directions. Six automatic level recorders were deployed for a period of three months from the 6th of December 1991 until the 14th of March 1992. Readings were taken every minute. The current speed and direction meters recorded data from mid-December to mid-February, a period of approximately 65 days at 10 minute intervals. A number of the water level gauges shifted on their mountings during the first month of deployment and so this data was discarded. Fig. 2.2 shows the location of the gauges. Table 2-2 lists the grid coordinates and dates of deployment. The water level recordings from the Maltings and Albert Quay in the North and South Channel of the River Lee were not used in this study.

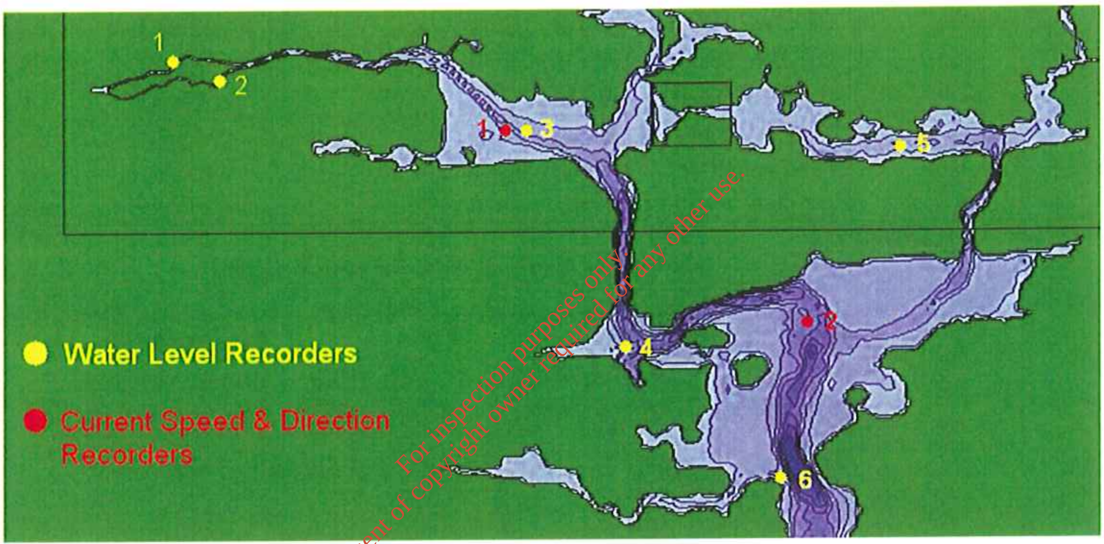

Fig. 2.4 Location of Gauges in Harbour

The Fort Camden data was used to drive the hydrodynamics of the model by acting as the boundary condition. The recordings from the Pfizer Jetty, Lough Mahon and Belvelly gauges were used to calibrate and validate the hydrodynamic model as described in the following chapter.

Site	From	To	Comments	I.N.G. Coordinates	
Lee Maltings	06 Dec 1991	06 Jan 1992	Not used	166760	71885
	06 Jan 1992	07 Feb 1992	Not used	166760	71885
	19 Feb 1992	16 Mar 1992	Not used	166760	71885
Albert Quay	06 Dec 1991	06 Jan 1992	Not used	167990	71750
	06 Jan 1992	06 Feb 1992	Not used	167990	71750
	10 Feb 1992	11 Mar 1992	Not used	167990	71750
Lough Mahon	06 Dec 1991	08 Jan 1992	Data invalid	175225	70400
	09 Jan 1992	06 Feb 1992	-	175225	70400
	10 Feb 1992	14 Mar 1992	-	175225	70400
Pfizer Jetty	06 Dec 1991	08 Jan 1992	Data invalid	177550	65225
	10 Jan 1992	26 Jan 1992	-	177550	65225
	08 Feb 1992	13 Mar 1992	-	177550	65225
Belvelly	06 Dec 1991	07 Jan 1992	-	183830	69580
	07 Jan 1992	08 Feb 1992	-	183830	69580
	08 Feb 1992	11 Mar 1992	-	183830	69580
Fort Camden	09 Dec 1991	08 Jan 1992	-	180870	62000
	09 Jan1992	07 Feb 1992	-	180870	62000
	07 Feb 1992	11 Mar 1992	-	180870	62000

Table 2-2 List of Water Level Gauges

Site	From	To	Comments
Spit Bank	08 Dec 1991	14 Feb 1992	4m above bed
Lough Mahon	15 Dec 1991	14 Feb 1992	2m above bed

Table 2-3 List of Current Speed and Direction Gauges

A comprehensive quality-assurance of the dataset was undertaken. From this it was apparent that there were a number of erroneous readings in the water level time-series. One example is illustrated in Fig. 2.5 below. The recorded surface elevation shows large oscillations occurring during high tides. These are physically unrealistic and these data have been rejected.

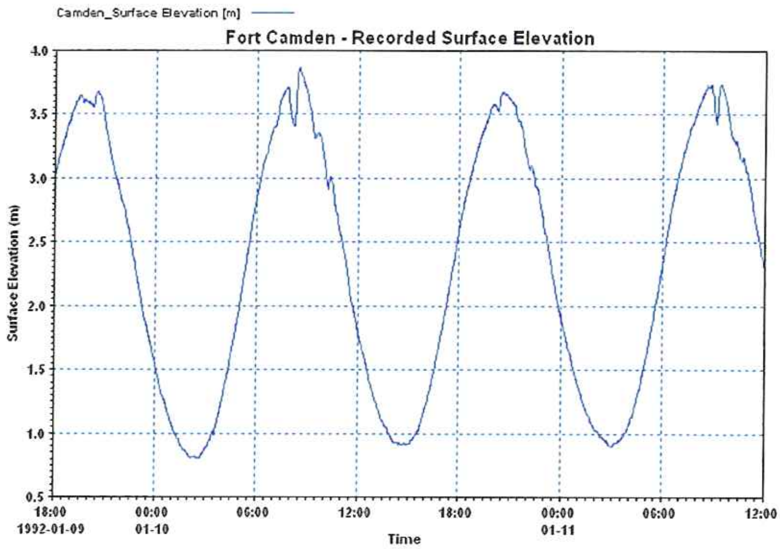

Fig. 2.5 Erroneous Fort Camden Recorded Data

Errors of this type occur in a number of the recorded time-series and at different periods. Such datasets were deemed to be unsatisfactory and were discarded.

The quality-assurance also indicated an error with the 'zero' mark on two of the gauges, Pfizer and Belvelly. The problem with the Pfizer gauge is highlighted in Fig. 2.6. The figure plots the recorded data for a spring tide at Fort Camden against the recorded data from the Pfizer Jetty. The Pfizer gauge 'bottoms out' at low tide due to the incorrect positioning of the gauge; when the water level drops below the level of the zero, the gauge reading stays constant.

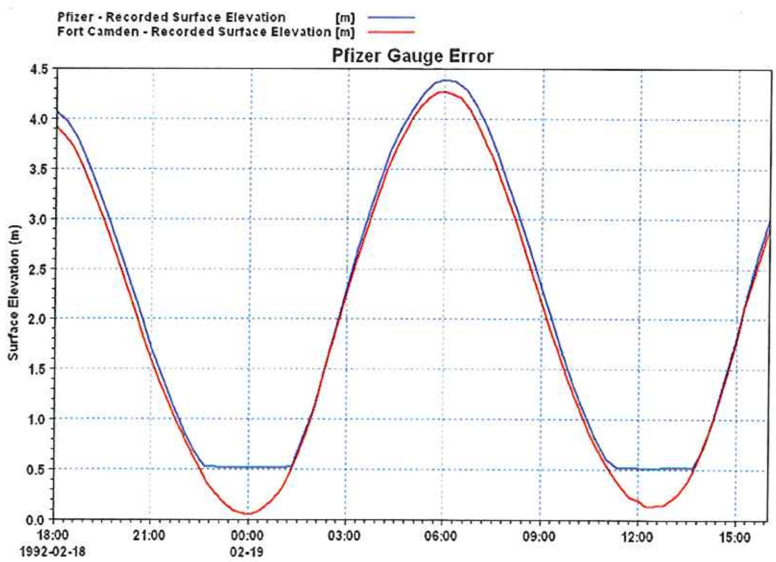

Fig. 2.6 Error with the Pfizer Gauge

A further error was associated with the Belvelly Gauge. When plotted against the other recorded data the water levels of the Belvelly time-series appeared to be at too high an elevation. Irish Hydrodata confirmed that there was a constant error of 12cm in the data and advised that all elevations in the dataset be shifted down by this amount.

2.2.6 Water Level & Current Speed Direction Recordings – 1993

Irish Hydrodata also measured water level and current measurements in 1993 as part of the investigation into the siting of the outfall for the Midleton Sewage Treatment Plant. This dataset was used in the calibration and validation of the hydrodynamic model. Fig. 2.7 shows the location of the gauges and Table 2-4 contains their Irish national grid coordinates and dates of deployment. This dataset provided additional measurements in the main area of interest in the study. Unfortunately, no recordings were taken at Roches Point during this campaign and so the extent of the hydrodynamic model had to be adjusted to make use of this dataset in model calibration and validation. Fig. 2.7 shows the adjusted model domain. We can see from the figure that the recorded data at East Ferry acts as the boundary condition of the model. The model extends up as far as Midleton and over to the Belvelly Bridge. The calibration and validation of this model is described in the following chapter.

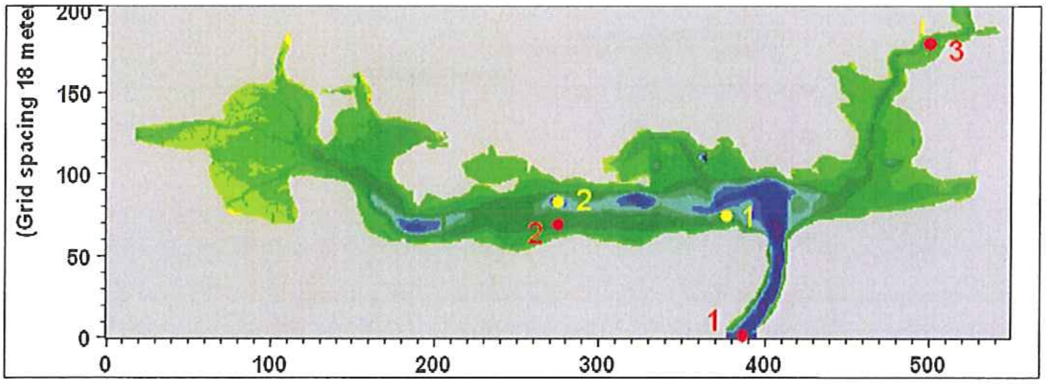

Fig. 2.7 Location of gauges for 1993 deployment. The red points are the location of the tide gauges. The yellow points are the locations of the current metres

Site	From	To	Comments
Water levels			
East Ferry	11/09/93	28/09/93	
Ashgrove Castle	11/09/93	13/10/93	
Midleton	11/09/93	13/10/93	
Currents			
Bagwell Hill	11/09/93	28/09/93	1.3m above seabed
Brown Island	11/09/93	28/09/93	1.3m above seabed

Table 2-4 List of 1993 hydrographic datasets

2.2.7 The POL CS3 model

The Applications Group at the Proudman Oceanographic Laboratory (POL), UK, supplies hindcasts of (a) tide-plus-surge, and (b) tide-only levels on a grid covering part of the North Atlantic Shelf at frequencies of 1 hour for (a) and 20 minutes for (b) respectively. The centre uses its POL CS3 model to provide the annual hindcast at the end of each calendar year. Hindcasts are available from 1992 onwards. The model makes use of meteorological data from the UK Met Office Operational Storm Surge Local Area Model (1992 to 1998) and the Mesoscale model (1999 onwards). The hindcasts from the POL CS3 Model use a combination of measured and modelled meteorological data. Surface elevations and currents in component form are provided at each grid point. The POL CS3 numerical model grid, which covers part of the North Atlantic Shelf, has a resolution of approximately 12km (Fig. 2.8). The level data has a relative accuracy of approximately 3% of the sea level range[49]. The absolute accuracy is unknown on the southern Irish Coast. A previous study (1997-2001)[50] of the Cashen Estuary in the outer Shannon showed that such data could provide very good boundary conditions for hydrodynamic models of Irish coastal waters. The Cashen/Feale model agreed with measurements within the estuarine network to within 10cm.

[49] Smith, J. A. (1994). The Operational Storm Surge Model Data Archive. Proudman Oceanographic Laboratory, Report, No 34, 34pp

[50] Martin, J., 2002, De-Watering the Lower Feale – "A Virtual Water World", *Ph.D. Thesis*, Department of Civil and Environmental Engineering, National University of Ireland, Cork

Two years of hindcast data (1992 & 2004) were purchased from POL for this project. Data from the three points closest to the mouth of Cork Harbour, which form a right-angle, were selected from the CS3 grid and used to drive the hydrodynamics of the 'Old Head' hydrodynamic model. The locations of these points relative to Cork Harbour are highlighted in Fig. 2.9.

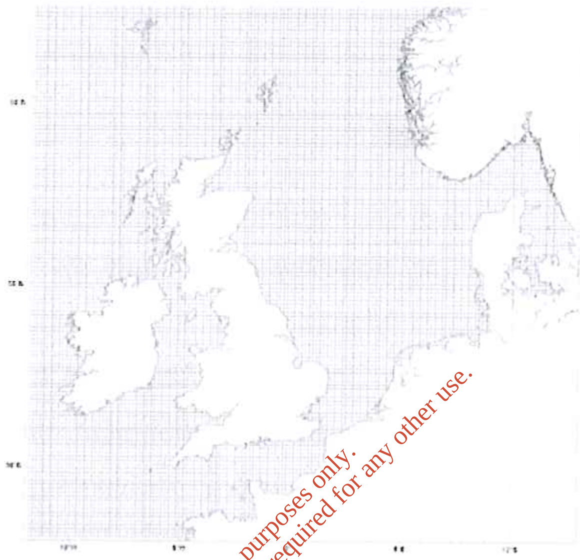

Fig. 2.8 CS3 grid (12km resolution)

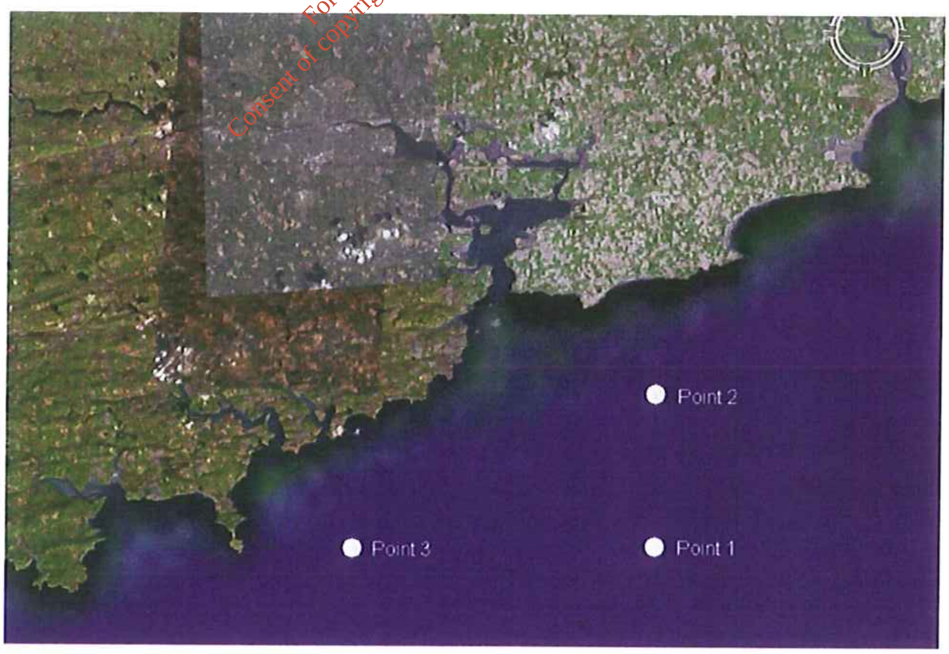

Fig. 2.9 Location of points on the CS3 grid used for the OH Hydrodynamic model boundary conditions (Image from Google Earth)

2.2.8 Quickbird high-resolution remotely sensed data

DigitalGlobe, owners of the Quickbird commercial earth-observation satellite, supplied remotely-sensed data of the harbour and its surrounding areas through their Irish agent ERA-Maptec. QuickBird collects the highest resolution imagery of the Earth that is commercially available. The satellite measures panchromatic images at 60-70 centimetre spatial resolution and mulitspectral images at a resolution of 2.4 and 2.8 metres. This dataset was used in the following ways:

- To identify houses around the North Channel of the Harbour in order to model possible discharges of sewage from these houses;
- To quality-assure the bathymetric data for those intertidal mudflats not in the DLR dataset. A number of adjustments were made to the bathymetric data as a result of this;
- To identify and find the Irish national grid coordinates of features such as the tidal holding tank at Rathcoursey and the oyster trestles in the North Channel and Outer Harbour.

2.2.9 Water Level Recordings from the Port of Cork

Water levels measurements from the Tivoli and Cobh gauges were obtained from the Port of Cork and used in the validation of the OH model.

2.2.10 River & Wind Files

River flows and wind influence the hydrodynamics of the estuary. Cork County Council, EPA, OPW and the ESB supplied measurements of flow in all the rivers discharging into Cork Harbour for 1992 and 2004.

The archive of the 1992 survey carried out by Irish Hydrodata Ltd contained the wind records at Cork Airport (Met Eireann), Roches Point (Met Eireann). and Ringmahon Point (Bord Gais/Cork Corporation). The 1992 survey report by Irish Hydrodata Ltd states that the Cork Airport and Roches Point datasets "show very similar wind patterns". It also states in reference to the Cork Airport and Ringmahon Point sites that there is "little difference between the sites". Consequently, we have relied on the data from Cork Airport exclusively.

2.2.11 Bridge Survey

Bridges exert an influence on the local hydrodynamics in the harbour by restricting the cross-sectional area available for currents and by increasing locally the resistance to flow. Cork County Council commissioned a survey of all relevant bridge openings in the harbour. The bridge at Belvelly is of particular importance and is discussed further in the following chapter.

2.2.12 Drawings of outfalls and sewer networks

Cork County Council provided engineering drawings of all the main outfalls in the harbour and the sewer network for Midleton. They pinpoint the exact location of the main outfalls of interest and also provide the length of the three multi-port diffusers at Carrigrennan, Rathcoursey, and just inside the Harbour Mouth. The model contains the appropriate number of identical sources at the grid points that fall along the line of each diffuser.

2.2.13 Population of Urban catchments

The 2002 census on the CSO website provided the population of each urban area from which the populations of relevant sewer catchments were determined. (http://www.cso.ie/census/Census2002Results.htm). The 1992 Main Drainage Report from EG Pettit Ltd allocates the sewer catchments of Cork City to the main outfalls at Kennedy Quay, Albert Quay, Tramore Valley and Lough Mahon.