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Fate and transport of particles in estuaries

Volume I: summary and conclusions

Science Report SC000002/SR1

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Steve Killeen

Head of Science

Executive Summary

1. Faecal indicator organisms in the aquatic environment (such as enterococci species of bacteria) readily associate with sediments. The transport of sediments in estuarine and coastal areas is therefore a mechanism by which faecal indicators can be conveyed from sources such as wastewater treatment works (WwTWs) and rivers. This transport can have a major polluting effect on nearby bathing waters and can determine whether the waters comply with relevant legislation. This research project investigates this effect in the context of the Severn estuary and Bristol Channel by developing a numerical hydrodynamic water quality model that incorporates a dynamic representation of bacterial decay.
2. The research project consisted of three interlinked components, each of which required the development of integrated approaches.
 - Estimating enterococci deposits from sewage sources and rivers.
 - Conducting experiments to determine enterococci mortality rates (expressed as T_{90}) and the degree of association of the organism with suspended sediments.
 - Developing a numerical hydrodynamic water quality model using data derived from the other elements of this project to incorporate both variable inputs and real-time decay rates for enterococci.
3. The project concentrated on enterococci due to its increasing importance as a regulatory indicator and the relatively small amount of information about this indicator in the literature.
4. To estimate the levels of enterococci flowing into the estuary from rivers, discharge data from the Environment Agency hydrometric network was combined with predicted enterococci concentrations at catchment outlets, which were derived from catchment land cover data. This modelling approach was calibrated with empirical 'ground truth' data collected from over 100 UK sub-catchments by a team from the Centre for Research into Environment and Health (CREH). The levels of enterococci being discharged into the estuary from WwTW final effluent sources were estimated using discharge data from the Environment Agency consents database and effluent quality data derived from previous CREH studies. Estimates were made for the 150-day period between 2 May 2001 and 29 September 2001.
5. Estimates from river sources suggested that 95 per cent of the enterococci input to the estuary was associated with high rates of flow caused by rainfall. Such conditions prevailed for 7–40 per cent of the study period, during which time 40 per cent of the total flow volume was discharged to the estuary. The largest proportional contributions to total enterococci levels are associated with the largest catchments such as the rivers Severn, Wye and Usk. During periods of high flow, the River Severn would account for approximately 25 per cent of the estimated enterococci input from river sources.
6. Similarly, the largest sewage-related enterococci inputs were associated with the largest WwTWs, such as those at Cardiff and Avonmouth. These two WwTWs generate over 46 per cent of the estimated effluent volume and at least half the estimated input of enterococci from WwTW final effluent sources.
7. Comparing the instantaneous loads from the WwTWs with those estimated for river sources suggests that during periods of dry weather (base flow) nine of the 10 largest enterococci inputs are from WwTWs. Cardiff and Avonmouth WwTWs represent the two largest contributors, followed by the River Severn (see upper map, page 8). During periods of high flow, the river sources become more dominant, providing eight of the 10 largest enterococci inputs. The River Severn represents the largest single source during periods of high flow, delivering enterococci at a rate that is an order of magnitude greater than from Cardiff WwTW (see centre map, page 8). Under both flow conditions, the top 10 contributors account for 75 per cent of the instantaneous load, although the combined base flow input is only 6 per cent of the combined high flow input.

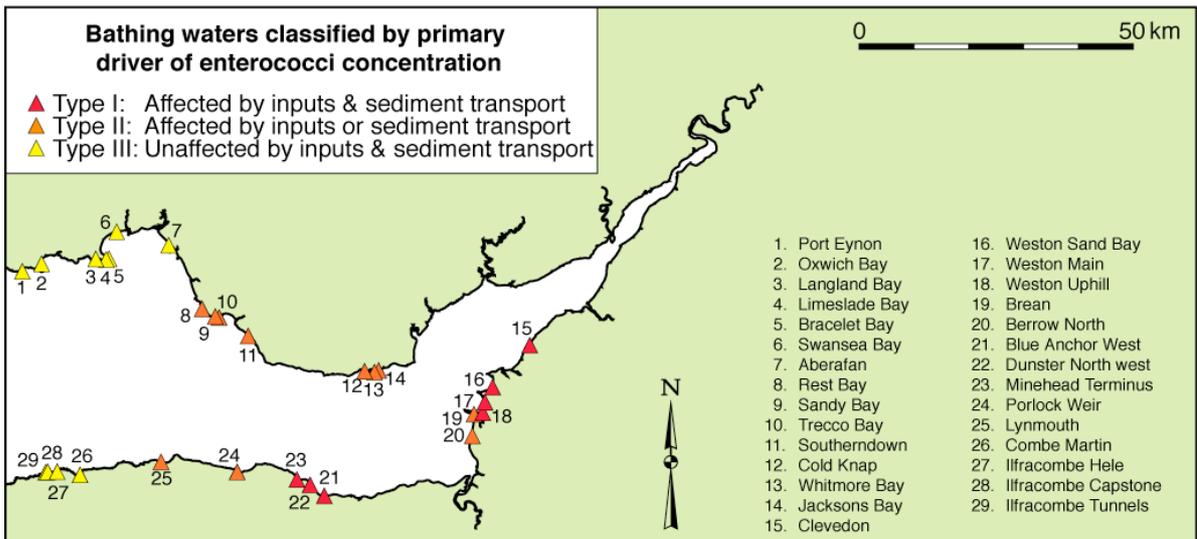
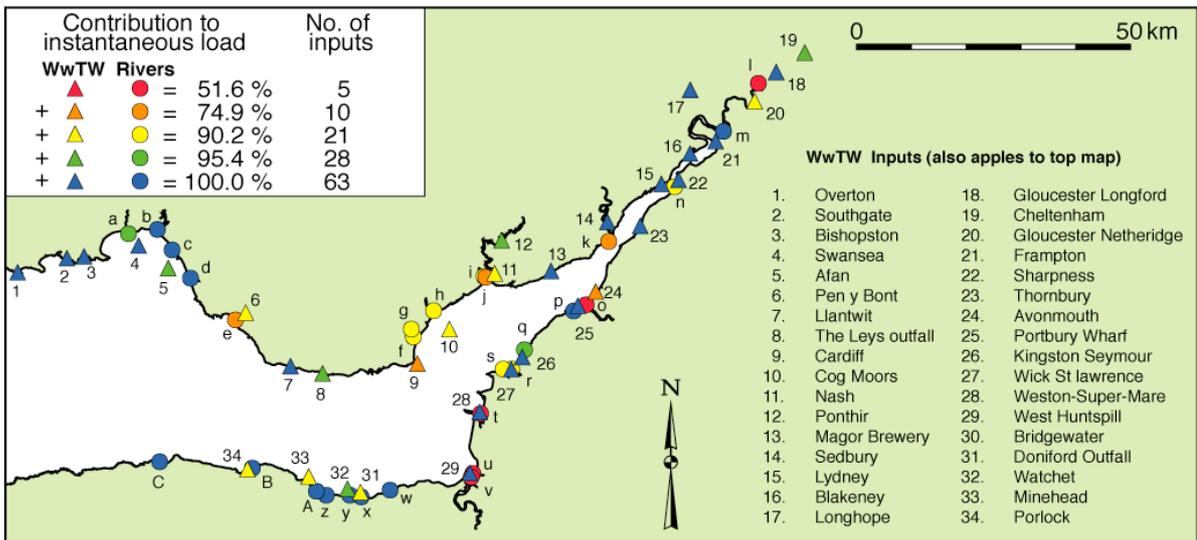
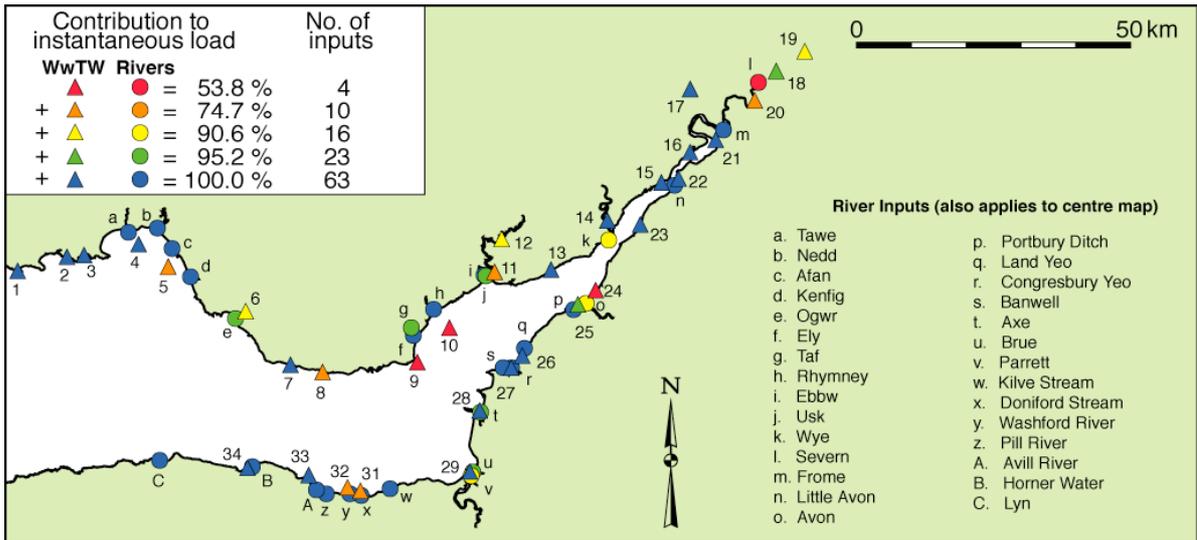
8. A range of microcosm experiments were conducted, with the bacteria either irradiated with simulated sunlight or kept in the dark, to investigate the decay of enterococci at three marine locations with relatively low turbidity (Langland Bay, Porthcawl and Minehead) and two higher turbidity inner estuary locations (Beachley and Weston-Super-Mare). High turbidity estuarine waters produced a mean irradiated T_{90} value of 39.5 hours. Low turbidity coastal waters produced a much shorter mean T_{90} value of 6.6 hours. In experiments where the bacteria received no light energy, high turbidity estuarine waters produced a longer mean T_{90} value of 65.1 hours, compared with a corresponding figure for low turbidity coastal waters of 24.8 hours. There was no observed re-growth of enterococci associated with suspended sediments at 15°C over periods of up to 48 hours.
9. Irradiated T_{90} values were correlated with salinity, turbidity and suspended solids. The results suggest that enterococci decay in irradiated experiments with turbidity >200 nephelometric turbidity units (NTU) is similar to decay observed under dark conditions.
10. Further experiments were conducted to investigate the association of enterococci with suspended solids. Higher enterococci counts were obtained by applying treatments to separate organisms from the sediments prior to membrane filtration. The best treatment involved agitating the sediments using a 'wrist shaker' for three minutes.
11. Experiments comparing stirred microcosms with others where suspended solids were allowed to settle demonstrated that enterococci concentrations decrease as the concentration of suspended solids and turbidity decrease. Hence, settling of sediments removes enterococci from the water column, in addition to its effects on microbial mortality. The fact that enterococci and suspended solids concentrations did not drop immediately upon initiation of the experiments suggests that enterococci are associated with finer particles (median diameter 5–14µm).
12. Mathematical functions relating T_{90} and turbidity for irradiated and dark conditions were developed from the microcosm experiments. In addition, functions relating microbial mortality to irradiation were developed from locally derived data. These functions allowed real-time variable T_{90} values to be incorporated within the numerical hydrodynamic model, which varied with the temporally and spatially modelled suspended solids concentrations and the pattern of solar radiation. This represents a significant refinement in the characterisation of microbial mortality in such models, which have in the past relied on constant daytime and night time T_{90} values.
13. Four days of site surveys were conducted at two strategic locations (Porthcawl and Minehead) to obtain calibration data for the numerical model. Data collected offshore included current velocity and direction profiles, global irradiation at the sea surface and downwelling photosynthetically-available radiation. Water quality data, including enterococci concentration, turbidity, concentration of suspended solids and particle size, were collected for survey points offshore, at near-shore bathing water compliance points, and for local sewage effluent and inputs from rivers.
14. The hydrodynamic calibration of water surface elevations, current speed and current direction showed good correlation between the predicted and measured values for tidal phasing in all four surveys. The accuracy of this model calibration was similar to other studies of the Bristol Channel.
15. The predictions generated by the numerical model indicate that enterococci concentrations in the Severn estuary and Bristol Channel are closely linked to both bacterial mortality and sediment transport processes. Enterococci disappear from the water column when the sediments are depositing. Concentrations of enterococci also vary in a cyclical manner in phase with the tidal oscillations and are derived, at many locations, principally from bed sediments.
16. Using the results from the model simulations, bathing water compliance locations were categorised according to the primary drivers of enterococci concentration (such as input from rivers/sewage sources and/or sediment transport). Of the 29 bathing waters considered, seven were affected by both inputs and sediment transport (including the three Weston-Super-Mare beaches), 11 were affected by either inputs or sediment transport, whilst the remaining 11 were not affected by either inputs or sediment transport. The 11 latter bathing waters included those situated along the coastline of the outer Bristol Channel (see lower map on page 8).

17. The levels of suspended solids generally had more impact on the predicted enterococci levels in the near-shore waters and less effect in the deeper, less turbid offshore waters. This implies that turbid bathing water compliance locations may be more susceptible to higher enterococci concentrations and, hence, more likely to exceed regulatory standards.
18. Far field effects of enterococci sources discharging to the estuary were explored by modelling the fate of plumes from the two largest river inputs (the rivers Severn and Wye) and the two largest WwTW inputs (Cardiff and Avonmouth) during high flow periods. Whilst these sources can distribute enterococci to most bathing waters, the discharges from all but Avonmouth WwTW were diluted and dispersed before reaching the bathing waters. Whereas, the discharge from Avonmouth WwTW affected the Clevedon and three Weston-Super-Mare beaches, with raised enterococci concentrations 8–16 hours after the start of the event.
19. Including sediment-related bacterial processes within the numerical model produces significantly different predictions than if the processes are excluded. Together with the improvements to enterococci T_{90} characterisation produced by the dynamic functions described above, these innovations have greatly improved the representation of microbial processes within the numerical hydrodynamic model.
20. The model is sensitive to the proportion of enterococci attached to sediments and the initial enterococci concentration of bed sediments. Both these factors are currently poorly characterised and the precision of the numerical model would be increased by obtaining further empirical field data in this area.

Top: Contribution (%) of inputs to the base flow instantaneous enterococci load

Centre: Contribution (%) of inputs to the high flow instantaneous enterococci load

Bottom: Bathing waters categorised by the main controlling factor of enterococci concentration



Report Context

The overall aim of this project is to assess the impact of distant sources of faecal indicator organisms, specifically enterococcal species of bacteria, on bathing beach compliance sites within a highly turbid and high energy estuarine environment. The final experimental design emerged after discussion with Environment Agency personnel and a project steering group that included water company and Scottish Environment Protection Agency (SEPA) personnel, as well as Environment Agency staff. The total project effort can be split into three principal tasks that almost form stand alone studies.

1. Estimating bacterial inputs to the estuary from rivers ($n=29$) and marine sources ($n=34$) using a modelling approach grounded in past Centre for Research into Environmental and Health (CREH) empirical studies, which involved 'ground truth' data on enterococci concentrations and land use from 100 subcatchments.
2. Defining decay rates of enterococci under highly turbid conditions by conducting some 40 microcosm experiments on water derived from characteristic sampling points in the Seven Estuary. These experiments were done under both simulated daylight and in the dark. In addition, investigating sediment characteristics by conducting settlement experiments.
3. Developing a hydrodynamic water quality model using data derived from 1 and 2 as inputs. The model incorporates both variable inputs and real-time decay rates for enterococci at key locations in the estuary; it was validated with empirical field data acquired during the summer of 2001.

Overall, the study presents the first attempt to estimate bacterial 'inputs' to a major estuary at a regional level, the first attempt to define and quantify the environmental controls on enterococci survival in estuarine waters and the first attempt to develop a coastal hydrodynamic water quality model that incorporates a dynamic 'real-time' T_{90} value for enterococci mortality rates.

The overall approach offers the potential for regional scale 'profiling' of recreational waters, as suggested by the World Health Organization (WHO, 2003) and the Council of the European Communities (CEC, 2002). It also allows for 'real time' prediction of water quality as a beach management tool, as suggested by the WHO (2003) and by the Department for Food, Environment and Rural Affairs in recent negotiations regarding the revision of EU Directive 76/160/EEC.

This volume (Volume I) addresses the overall objectives of the project by providing an overview, a summary of results and conclusions from the entire project. Volume II presents in detail the results of the first task (estimating enterococci inputs), Volume III presents the results of the second task (laboratory experiments) and Volume IV presents the results of the third task (numerical modelling).

This was an ambitious project from the outset and many lessons have been learned during its execution. These lessons, as well as identified research gaps, are also presented in this volume.

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1. Introduction

Investment in sewage treatment and control of sewage discharges in the vicinity of bathing waters by the water industry over the past 10 years has led to an improvement in compliance with the *Imperative* standard of the Bathing Waters Directive (BWD; 76/160/EEC). However, compliance with *Guideline* values has been more difficult to achieve. As more point sources (such as drains or sewage pipes) of bacterial pollution to the coastal environment are controlled, it has become increasingly apparent that there is an underlying level of contamination, which cannot be addressed by control of sewage discharges alone. This contamination largely relates to inputs from rivers (which can include sewage discharged from inland wastewater treatment works (WwTWs) and combined sewage overflows (CSOs)), agriculture and wildlife.

Concentrations of faecal indicator organisms, such as enterococcal bacteria, at bathing waters often display occasional peaks of contamination, which can threaten compliance, with the *Guideline* standards of the BWD. In many instances, these peaks are associated with episodes of increased river flow in response to rainfall. Many studies have demonstrated that, during such periods of high flow, bacterial loads from riverine sources can be considerably greater than during dry weather (base) flows (Crowther *et al.*, 2001; Crowther *et al.*, 2003; Kay *et al.*, 1999; Wyer *et al.*, 1995; Wyer *et al.*, 1996; Wyer *et al.*, 1997). Unless the problem of the continuing contamination from diffuse sources is understood, and programmes of work implemented to alleviate its effects, further improvements in compliance levels to meet the *Imperative* and *Guideline* values of the BWD may not be possible. This becomes particularly crucial in light of the tightening of bathing water quality standards, which are designed to protect public health, that has been proposed by the European Union (EU) (Council of the European Communities (CEC), 2002) and the World Health Organization (WHO, 2003).

The CEC (2002) and the WHO (2003) suggest a process of beach 'profiling' to ensure the total mix of point and diffuse source inputs are understood by the competent authorities. The CEC (2002) notes that the means of controlling this complex mix of potential sources is via the Water Framework Directive (WFD, EC/60/2000), which specifically addresses the integrated management of point and diffuse source pollution. Article 6 and Annex IV of the WFD require bathing waters identified under the BWD to be declared as 'protected areas'. Article 11 and Annex VI require a programme of 'basic measures' to be implemented to achieve the standard specified in directives such as the BWD. This study represents perhaps the first regional scale 'profiling' of a major European estuary and it provides estimates of the balance between point and diffuse pollution sources, both in terms of total inputs and the potential effects on bathing waters at compliance locations.

Bacteria associate readily with suspended solids in the environment and, as a result, contamination may shift from one site to another as sediments are transported. This may mean that sites that do not receive local sewage or riverine inputs are nevertheless at risk from contamination from further afield. Bacteria attached to suspended solids are not affected to the same extent as 'free swimming' bacteria

(those unattached to sediment particles) by ultra-violet (UV) irradiation. Thus the disinfecting effects of solar radiation are not as strong, and bacteria attached to suspended solids are able to survive for longer. This allows bacteria to travel much further and as a result the contaminating effects of a discharge are potentially much greater than had previously been suspected. Numerical models of bacterial contamination have generally treated bacteria as free-living (planktonic, 'free swimming') and although models describing sediment movement are available these have not been applied to the problem of modelling sediment associated bacteria. This may be due to the lack of information describing the relationships between bacteria and sediments in the coastal zone, including survival dynamics and regrowth, and the lack of credible bacterial input data from point and diffuse sources.

Over the past decade, much hard work has gone into reducing the discharge of sewage into the Severn Estuary by treatment facilities. An associated improvement in water quality has been seen at the bathing waters in the estuary. However, now that these waters are approaching *Guideline* status, it has become apparent that some are vulnerable to continuous low-level bacterial contamination, making it difficult for them to comply with the *Guideline* standards of the BWD. The estuary carries a large sediment load, much of which is generated by re-suspension as a result of the high energies within each tidal cycle. The distribution of the areas of sediment accumulation needs to be determined to see if bathing waters are at risk from faecal indicator bacteria associated with the sediment.

The purpose of this research project, therefore, has been to (i) determine the degree of association of enterococci with sediments, (ii) provide the Environment Agency with information on the transport of enterococci throughout the estuarine and coastal waters of the Severn Estuary and (iii) examine the impact of far field sources of enterococci on compliance with the *Guideline* standards of the BWD.

1.1 Objectives

1. To determine the extent to which enterococci associate with suspended solids.
2. To determine whether and how enterococci can be desorbed from suspended solids into the aquatic environment.
3. To determine whether there is some re-growth of enterococci associated with suspended solids.
4. To determine the half-life of bacteria associated with suspended solids and to model the transport of suspended solids through the Severn estuary.

1.2 Research Strategy

The final experimental design of the research project emerged after discussion with Environment Agency personnel and a project steering group including water company and Scottish Environment Protection Agency (SEPA) personnel, as well as Environment Agency staff. The Project Management Group agreed that the project should focus on enterococci due to (i) its increasing importance as a regulatory indicator (CEC, 2002; WHO, 2003; Kay *et al.*, 2004) and (ii) the relatively small amount of information on this indicator in the literature.

The overall goal of this research is to develop a robust numerical model capable of adequately describing sediment-related bacterial transport in order to identify the far-field effects of riverine and sewage sources of contamination on bathing water compliance locations along the Severn Estuary coast. To achieve this, and to meet the specific objectives relating to the association of enterococci with suspended sediments and the development of the numerical model described above, it was necessary to estimate the magnitude of enterococci inputs from riverine and point sources discharging to the Severn estuary and the Bristol Channel.

Thus, the total project effort can be split into three integrated studies used to define:

1. Estimating bacterial inputs to the estuary from rivers ($n=29$) and marine sources ($n=34$) using a modelling approach grounded in past Centre for Research into Environmental and Health (CREH) empirical studies, which involved 'ground truth' data on enterococci concentrations and land use from 100 subcatchments.
2. Defining decay rates of enterococci under highly turbid conditions by conducting some 40 microcosm experiments on water derived from characteristic sampling points in the Seven Estuary. These experiments were done under both simulated daylight and in the dark. In addition, investigating sediment characteristics by conducting settlement experiments.
3. Developing a hydrodynamic water quality model using data derived from 1 and 2 as inputs. The model incorporates both variable inputs and real-time decay rates for enterococci at key locations in the estuary; it was validated with empirical field data acquired during the summer of 2001.

Overall, the study presents the first attempt at estimating bacterial 'inputs' to a major estuary at a regional level, the first attempt to define and quantify the environmental controls on enterococci survival in estuarine waters and the first attempt to develop a coastal hydrodynamic water quality model that incorporates a dynamic 'real-time' T_{90} value for enterococci mortality rates. The overall approach offer the potential for regional scale 'profiling' of recreational waters as suggested by the WHO (2003) and and the CEC (2002). It also allows for 'real time' prediction of water quality as a beach management tool as suggested by the WHO (2003) and by the Department for Food, Environment and Rural Affairs (Defra) in recent negotiations regarding the revision of the BWD. It also provides the first regional scale examination of faecal indicator fluxes in an estuarine system, which could underpin the integrated management of point and diffuse source pollution as required under the WFD. This is

defined by the CEC (2002) as the mechanism by which bathing beaches should comply with new tighter standards (CEC, 2002, derived from WHO, 2003).

This was an ambitious project from the outset and many lessons have been learned in its execution. These lessons, as well as identified research gaps, are presented within this volume.

1.3 Report Structure

This volume (Volume I) summarises the overall objectives, research strategy, results and conclusions of this project. It draws together the different strands of the research undertaken to address the overall aims described above. It also discusses the gaps in current knowledge that were highlighted by this project and makes suggestions for further research.

Further volumes describe in detail the three principal strands of the research.

- Volume II describes the methods used to estimate enterococci inputs to the Severn estuary. An evaluation of such inputs is necessary to characterize boundary conditions for the hydrodynamic model developed as part of this project.
- Volume III describes laboratory microcosm experiments that were conducted to determine typical values for the time taken for enterococci concentrations to decay by 90 per cent (T_{90} (hours)) for the Severn estuary and to investigate the relationship between enterococci and sediments. Determining enterococci T_{90} values in a tidal estuarine environment allowed a dynamic T_{90} value to be developed for use within the hydrodynamic model. The association, or otherwise, of enterococci with sediments is an important factor in understanding the transport pathways of the organism. This volume also includes a literature review of previous studies that explored bacterial inactivation and sediment association, which were used to inform the development of the experimental protocols.
- Volume IV presents the numerical modelling of enterococci concentrations in the Severn estuary and at bathing water compliance locations. This volume details the methods developed for describing the fate of enterococci organisms, and the hydrodynamic and sedimentation processes that are the principal transport mechanisms for these organisms. The modelling uses the enterococci input data and the empirical formulae obtained from the field and analytical studies described in Volumes II and III.

2. Estimate of enterococci inputs from point and diffuse sources

Faecal indicator organisms can be deposited into the estuarine environment from human or animal sources (Booth *et al.*, 2003). The former would include effluents discharged to rivers, estuaries or the sea and spills from CSOs and/or storm tanks. The latter would include various agricultural activities. Previous CREH work for the Environment Agency, SEPA, the Scottish Executive and water companies, suggests a highly episodic and complex input pattern dominated by periods of high bacterial contamination following rainfall (Fewtrell *et al.*, 1998; Stapleton *et al.*, 1999; 2000a; 2000b; 2002; Wyer *et al.*, 1998a; 1998b; 1998c; 1999a; 1999b; 2001; 2003).

Acquiring empirical field data to characterize inputs at this scale was beyond the resources available to this project. Therefore, models relating bacterial concentrations to catchment land cover data were developed to predict enterococci concentrations at the outlets of the main river catchments that discharge into the Severn estuary. These predictions, which describe microbiological concentration during periods of high and low flow, are combined with hydrological data, collected by the Environment Agency from their network of hydrometric gauging stations, to derive estimates of bacterial fluxes from riverine diffuse sources (a combination of catchment diffuse sources and upstream inputs to rivers from human sources). Discharges of faecal indicator organisms from point sources – for example, wastewater treatment works' final effluents – are calculated by combining effluent bacterial concentrations acquired through past empirical studies (Stapleton *et al.*, 2002) with flow estimates from Environment Agency and water company data sources.

The regression models developed to predict enterococci concentrations in rivers draining into the Severn Estuary are based on the results of CREH empirical investigations of land use and faecal indicator concentrations during the May–September bathing season. These investigations covered a total of 131 subcatchments draining into six UK study areas: Staithes Beck, Yorkshire (Crowther *et al.*, 2002); Afon ('River') Nyfer, south-west Wales (Crowther *et al.*, 2002); Afon Ogwr, south Wales; River Irvine, west Scotland; Holland Brook, Essex; and Afon Rheidol/Afon Ystwyth, west Wales (Crowther *et al.*, 2003).

Land cover data for the Severn Estuary catchment were taken from the Landsat-derived Centre for Ecology and Hydrology (CEH) Land Cover Map of Great Britain for 1990, which provides data at a 25m cell resolution. These data were verified using field-by-field acquired data from the six CREH study areas and comparison with digital OS 1:50,000 map data. This verification ensured, for example, that areas of built-up land and woodland were properly categorised and delimited.

Enterococci deposits from the 29 main river inputs that discharge to the Severn Estuary (Figure 2.1) were based, where possible, on time series of discharge ($\text{m}^3 \text{s}^{-1}$) recorded at EA discharge gauging stations. In the absence of gauging station data, the time series was estimated using catchment area and discharge time series from

an adjacent catchment. Corresponding enterococci concentrations were based on geometric mean concentrations. These were estimated using the land-use water quality models, adjusted to reflect the discharge volumes, expressed as mm rainfall equivalent, and estimated for each catchment. The hourly discharge records for EA discharge monitoring stations were used to split total flow (Q_t) into two components: (i) base flow (Q_b) and (ii) rainfall induced high flow (Q_h) and enterococci loads were estimated for both flow conditions. This produced hourly time series of estimated enterococci organism load (second^{-1}) for each of the 29 river and stream inputs for the 150-day period between 9:00am GMT on 2 May 2001 and 8:00am GMT on 29 September 2001. These sequences were used as inputs to the hydrodynamic model of the Severn estuary.

These estimates suggest that just under 40 per cent of the total discharge volume (m^3) to the Severn estuary from riverine sources is associated with high flow conditions. The largest proportional contributions are associated with the largest catchments, such as the Severn, Wye and Usk. Individual inputs show variation in the proportion of discharge associated with high flow conditions: mean 28 per cent, range 12 per cent to 49 per cent. The highest proportions (> 44 per cent) are associated with the larger catchments. High flow duration also varied between inputs, ranging from 6.7 per cent to 40.1 per cent of the study period (mean 16.3 per cent). The longest durations (> 30 per cent) were again associated with the largest inputs.

Approximately 95 per cent of the estimated enterococci discharge from rivers to the estuary is associated with high flow conditions. As would be expected, the largest proportional contribution is from the largest catchment inputs, with the River Severn contributing over a quarter of the total estimated enterococci load to the estuary during periods of high flow. A summary of the proportional (per cent) base flow, high flow and total flow contribution for each input is provided in Table 2.1, whilst Figure 2.1 and Figure 2.2 show the contribution of each discharge source to the enterococci load during high flow. These show that high flow conditions dominate the estimated riverine enterococci flux for every catchment (mean 92.4 per cent, range 83.6 per cent–97.3 per cent).

The estimates of enterococci inputs from consented sewage effluent discharges to the Severn estuary (point sources of sewage effluent) were restricted to the main discharges with population equivalents (PEs) greater than 2,000. A total of 34 discharges with PE >2000 were identified, made up of 33 WwTW final effluents and one brewery effluent treatment plant. Where possible, the calculations were based on measured dry weather flow (DWF) values from 2001. Where such data were unavailable, consented flow values (DWF and maximum flow) from water company and Environment Agency consents databases were used. In the absence of defined discharge values, flow rates were estimated using a PE flow of 180 litres of effluent per PE day $^{-1}$ (taken from Water Quality Consents Manual EAS/2301 - Standard Flows to Full Treatment V2), with an added 50 per cent infiltration (from discussions with water company officials). Where maximum flow data were not available this value was assumed to be 3 x DWF.

Corresponding values for enterococci concentrations were based on microbial levels in effluent samples taken during previous CREH investigations and categorised by

the level of treatment (untreated, primary settled, biologically treated, disinfected and storm overflow). These studies included the catchments used to calibrate the land-use models, plus studies undertaken around Lake Windermere, Morecambe Bay, St. Bees/Seascale (Cumbria), the Ribble Estuary and Jersey. In total, over 1,200 individual values for bacterial levels, covering 111 WwTWs and continuous crude sewage discharges, were used to determine the characteristic enterococci concentrations of each treatment type (Stapleton *et al.*, 2002). The appropriate concentration was then assigned to each source based on the discharge type (final effluent or storm overflow) and treatment level specified in the consent details.

The lack of temporal flow records for the WwTWs means that loads from these sources can only be expressed as an instantaneous flux (organisms second⁻¹). The proportional contribution to the high flow load of each WwTW source is shown in Figure 2.1. The two main inputs of enterococci organisms to the Severn estuary from WwTW point sources came from Cardiff WwTW and Avonmouth WwTW final effluents. These two sources provide over 46 per cent of the estimated effluent volume and at least half of the estimated enterococci flux.

Comparing the instantaneous loads from the WwTWs and those estimated for riverine sources (Table 2.2) shows that, for base flow conditions, WwTWs contribute nine of the 10 largest base flow fluxes. Cardiff and Avonmouth WwTWs represent the two largest contributors during base flow conditions, followed by the River Severn, which occupies a high rank due to its large discharge rate rather than a high enterococci concentration (Table 2.2). During high flow conditions, the riverine sources become more dominant, representing eight of the 10 largest high flow fluxes. The River Severn represents the largest source during high flow conditions, with a flux an order of magnitude greater than the base flow flux from Cardiff WwTWs (Table 2.2). The Rivers Brue, Avon, Parrett, Axe and Wye all contribute larger instantaneous enterococci loads than the two largest WwTWs (Cardiff and Avonmouth; see Table 2.2). Under both flow conditions, the top 10 contributors represent 75 per cent of the estimated enterococci flux discharged into the estuary, although total base flow flux is only 6 per cent of the total high flow flux (Figure 2.4).

3. Laboratory experiments

The experimental protocol to determine the inactivation of enterococci in estuarine waters was developed in association with the Project Management Group and after conducting a literature review. Further experiments investigating the association of enterococci with sediments were also conducted. Two investigations were necessary here: first, a study identifying the optimum method for separating attached enterococci from sediments; and, second, a set of experiments designed to investigate relationships with suspended solids, turbidity and particle size.

3.1 Enterococci decay rates

The enterococci inactivation experiments used water collected from three outer Bristol Channel locations – Langland Bay, Porthcawl (both south Wales) and Minehead (Somerset) – and two inner estuary locations – Beachley Slip (below the old Severn road bridge) and Weston-Super-Mare. ‘Environmental’ concentrations of enterococci in the collected samples were found to be too low to generate decay functions. Thus, the water samples were seeded with washed crude sewage to achieve an initial concentration of approximately 1×10^4 cfu 100ml⁻¹. Experiments were conducted in pairs, with one dark and one irradiated microcosm, and water from each of the five sites was used on four separate occasions, giving a total of forty water bath microcosms. An artificial light source was used to replicate the correct solar spectrum and intensity observed in the period from 10.00am to 2.00pm between the beginning of July and the end of August at a latitude of 52° North. The light source emitted visible, UV-A and UV-B wavebands (400–700nm, 320–400nm, and 280–320nm, respectively).

The T_{90} values were derived from the regressions for each experiment and for data combined by location, and were calculated using all experimental data and excluding outlying results. T_{90} values using all experimental data, together with r^2 values, are presented in Table 3.1 and discussed below. The results excluding outlying data were similar, although r^2 values were generally greater.

Non-significant ($p > 0.05$) regression results (slope not significantly different from zero) were produced for dark conditions on five occasions: three for Beachley Slip and two for Weston-super-Mare (Table 3.1). The combined data regression for dark conditions at Beachley Slip was also non-significant. All other regression results were significant at $\alpha = 0.05$. To quantify the sole effects of radiation on inactivation, irradiated T_{90} values were adjusted using the dark T_{90} (Table 3.2). All significant relationships indicated a negative relationship between time and enterococci concentration (as time increased, enterococci concentration decreased), indicating bacterial death. No statistically significant positive relationships, indicative of regrowth, were produced. Thus, it is unlikely that regrowth of enterococci associated with suspended solids occurs at 15°C over the kind of timescales used in the experiments (up to 48 hours).

Shorter T_{90} values were observed in experiments using low turbidity marine water from the three outer Bristol Channel sites – Minehead (3.7–12.8 hours), Porthcawl (4.2–16.8 hours) and Llangland Bay (4.8–10.9 hours), than from the more turbid estuarine sites, namely Weston-super-Mare (14.2–113.9 hours) and Beachley Slip (27.0–54.2 hours). Combining the irradiated data from the low turbidity marine waters results in the following T_{90} decay rates: Llangland Bay – 6.8 hours, Porthcawl – 9.4 hours and Minehead – 9.7 hours (Table 3.1). Corresponding values for the turbid waters from Beachley and Weston-Super-Mare were 35.1 hours and 18.7 hours respectively (Table 3.1).

One-way analysis of variance (Anova) indicated that the irradiated mean T_{90} values for the three Bristol Channel sites were significantly different from the two more turbid estuarine sites ($p < 0.05$). The three outer sites displayed high practical salinities (mean values: Llangland Bay = 38.9; Porthcawl = 36.8; Minehead = 34.6) typical of marine conditions and turbidities of < 100 NTU (mean values: Llangland Bay = 30 NTU; Porthcawl = 25 NTU; Minehead = 56 NTU). Suspended solids concentrations were also relatively low at these sites (mean values $< 200 \text{ mg l}^{-1}$). This is in contrast to the two estuarine sites, which displayed lower salinities and greater turbidities and suspended solids concentrations (mean values: turbidity > 120 NTU; suspended solids $> 260 \text{ mg l}^{-1}$; salinity: Weston-Super-Mare=22.3, Beachley Slip=8.9). Multiple range tests to examine the significance of between-site differences in mean turbidity reveals two distinct groups. The three outer, marine sites show no significant differences between each other, with the two estuarine sites also showing no significant differences, but mean turbidity is significantly different between the estuarine and marine locations. This was not the case for the salinity data.

The data from (i) the low turbidity, marine, sites and (ii) the high turbidity estuarine sites were combined to calculate a separate T_{90} for each type of environment. For the marine category, the combined T_{90} for irradiated conditions was 8.8 hours ($r^2 = 48.8$ per cent), while, for the estuarine sites, the combined irradiated T_{90} was longer, at 22.5 hours ($r^2 = 53.7$ per cent).

The results from the non-irradiated, dark experiments suggest protracted survival of enterococci. Interestingly, the irradiated T_{90} decay rates in turbid waters from Beachley Slip and Weston-Super-Mare generally exceeded the dark T_{90} values in marine water from Llangland Bay (with the exception of experiment 1, which produced a T_{90} of 73.8 hours), Porthcawl and Minehead (Table 3.1). At the outer 'coastal' sites, dark T_{90} values ranged from 8.8 hours to 34.6 hours with one exception (Llangland Bay, experiment 1, which produced a T_{90} value of 73.8 hours). The estuarine sites displayed values of between 52.0 hours and 74.9 hours in the three experiments where significant decay was observed. However, in the remaining five experiments, which used water from the two estuarine sites, no significant bacterial decay was observed in the dark.

Combining the data from dark experiments by site generates the following T_{90} values from marine waters: Llangland Bay – 24.9 hours, Porthcawl – 29.7 hours, Minehead – 15.1 hours (Table 3.1). These contrast with a T_{90} of 54.6 hours using water from Weston-Super-Mare and no significant dark decay in experiments using water from Beachley Slip (Table 3.1). Combining data for the coastal and estuarine sites

resulted in an estimated T_{90} for dark conditions of 21.5 hours ($r^2=50.6$ per cent) at the coastal sites and 66.2 hours ($r^2=33.6$ per cent) at the estuarine sites.

Radiation-induced T_{90} values (irradiated T_{90} adjusted for decay in the dark) range between 4.9 hours and 113.9 hours (Table 3.2), although some irradiated T_{90} values could not be adjusted because there was no discernible bacterial death in the paired dark experiment. Again, the shortest T_{90} values were associated with the three coastal sites. A one-way Anova of mean adjusted T_{90} by site indicated that only the Langland Bay radiation-induced T_{90} was significantly different from the two estuarine sites.

Relationships between the environmental parameters and T_{90} were investigated following appropriate data transformations to ensure normality. Statistically significant Pearson correlations ($p<0.05$) were evident between T_{90} and practical salinity, total dissolved solids, turbidity, conductivity and suspended solids. Practical salinity was inversely related to T_{90} , whilst turbidity and suspended solids displayed positive relationships. This suggests that, in the context of the Severn Estuary and Bristol Channel, enterococci are more resistant to deactivation at locations exhibiting decreased salinity, and elevated levels of turbidity and/or suspended solids concentrations. Statistically significant relationships with turbidity and salinity (also total dissolved solids and conductivity) were present for the dark T_{90} experiments, although the relationships were weaker. Again salinity was negatively correlated with T_{90} , whilst turbidity was positively correlated. This indicates that the deactivation effects of salinity are also present in the dark and that suspended sediments continue to offer a degree of protection.

Stepwise multiple regression analysis was used to explore the relationships between environmental parameters and bacterial decay rates. Separate regressions were performed for irradiated, radiation-induced and dark data sets. A statistically significant relationship was identified in each case, but it should be noted that the regression analyses predicting 'irradiated' T_{90} produced residuals that were not normally distributed. Turbidity was the independent variable entered for the 'irradiated' and 'radiation induced' T_{90} values. A statistically significant relationship between conductivity and dark T_{90} was identified although the coefficient of determination was relatively low ($r^2 = 28.1$ per cent). The inclusion of conductivity rather than turbidity is interesting because, in the dark, the relative predictive power of the chemical parameters would increase in the absence of any protective shading by particulates. The hydrodynamic modelling (Volume IV) employs a dynamic T_{90} function based on turbidity. It was therefore necessary to develop relationships between turbidity and dark T_{90} values. To generate this function, turbidity was forced into the regression equations. After a single atypical result was omitted from the analysis, a statistically significant relationship was identified for dark T_{90} with a r^2 value of 46.9 per cent.

The relationships between irradiated and dark T_{90} values with suspended solids and turbidity are shown in Figure 3.1. Turbidity was related to suspended solids using regression analysis ($p<0.05$, $r^2=82.3$ per cent). Figure 3.1 shows that irradiated and dark T_{90} values intersect at $T_{90} = 52.6$ hours, suspended sediment concentration = $1,738.5\text{mg l}^{-1}$ and turbidity = 207.2 NTU. Whilst empirical data to define the functional forms above this intersection in Figure 3.1 are sparse, the plot does suggest that

above approximately 200 NTU there is little difference in irradiated and dark T_{90} values for the same water environment. It is perhaps also worth noting that at turbidities >200 NTU, around 99 per cent of the incident radiation is absorbed in the first centimetre of the optical path through the water column (Joyce *et al.*, 1996). This would support the suggestion from the empirical data (Figure 3.1) that radiation effects are likely to be minimal above this turbidity threshold.

These results are in line with comparable findings in the international literature, but reveal much higher turbidities than commonly encountered in such experiments. The highest turbidity reported in the reviewed literature was 35 NTU. This suggests that studies using, for example, filter sterilised seawater in microcosms might significantly overestimate bacterial mortality (resulting in lower T_{90} values). This could generate optimistic predictions of faecal indicator concentrations, with potential implications for modelling compliance with BWD standards and the likely public health risk.

The constant irradiation used throughout the irradiated experiments allowed estimates to be made of the energy dose required to inactivate 90 per cent of organisms (D_{90}). The D_{90} values for total irradiation ($MW\ m^{-2}$), UV-A ($kW\ m^{-2}$), UV-B ($kW\ m^{-2}$) and biologically weighted UV-B using the DNA damage action spectrum ($kW\ m^{-2}$) are shown in Table 3.3. Since irradiance throughout the experiments was constant, the D_{90} patterns of for the various wavebands are similar to those described for the T_{90} data (lower D_{90} values at the three outer Bristol Channel sites and higher D_{90} values at Weston-super-Mare and Beachley slip). The 'within site' and 'combined site' (marine/estuarine) D_{90} values, presented in Table 3.3 for the various wavebands, are linear functions of the T_{90} values. The estimated D_{90} values at the various wavebands for the threshold T_{90} values, which were identified where the suspended solids concentration and turbidity are such that decay is the same under irradiated and dark conditions, are also shown in Table 3.3.

3.2 Association with sediments

Suspended and inter-tidal sediment was collected from Beachley Slip and Weston-Super-Mare for experiments investigating the association of enterococci with sediments. Experiments were conducted using the natural enterococci concentrations within each sample, as preliminary tests indicated sufficient numbers were present. The three outer estuary sites of Langland Bay, Porthcawl and Minehead were excluded due to the low levels of suspended solids and background enterococci concentrations observed at these sites.

The membrane filtration test normally employed to enumerate faecal indicator organism concentrations in bathing water compliance samples, and utilised in the enterococci T_{90} microcosm experiments described above, records both free-living and sediment attached organisms and does not discriminate between the two. However, in the case of organisms attached to sediment particles, only one colony will grow irrespective of whether there is either a single organism attached or several. Furthermore, enterococci commonly form chains of organisms that produce a single colony forming unit. Thus, if the enterococci plate count is to reflect sanitary significance, enterococci cells should be separated from particulates and individual

organisms should be counted. The literature review failed to highlight any preferred method, with the efficacy of each treatment being largely dependent on the type of sediment being analysed. Therefore, tests were carried out to identify the optimum method of separating enterococci from sediments.

Four methods were applied over seven time intervals: (i) stomaching; (ii) vortexing; (iii) mechanical wrist-shaking; and (iv) sonicating using an ultrasonic bath. The time intervals tested were 30, 60, 120, 180, 300 and 600 seconds, whilst a control with no treatment was also included.

Enterococci concentrations in the inter-tidal sediment from Weston-Super-Mare ranged between $10,000 \text{ cfu } 100\text{g}^{-1}$ and $63,333 \text{ cfu } 100\text{g}^{-1}$. A water sample taken at the same time yielded a much lower concentration of $82 \text{ cfu } 100\text{ml}^{-1}$. The wrist-shaker consistently produced the greatest enterococci concentration at any given time-interval and was the only treatment method to produce concentrations that exceeded the concentration in the control sample for all treatment times. The results suggested that a mixing time of 180 to 600 seconds on the wrist shaker gave the most reliable results and a time of 180 seconds (3 minutes) was used for further tests. The concentration of enterococci in the Beachley Slip inter-tidal sediment varied between the limit of detection ($<3,333 \text{ cfu } 100\text{g}^{-1}$) and $10,000 \text{ cfu } 100\text{g}^{-1}$. The various treatments had little effect on the enterococci concentration and concentrations were generally similar to the control sample. The estuarine water sample, which was also treated using the wrist-shaker, yielded an enterococci concentration of $144 \text{ cfu } 100\text{ml}^{-1}$.

Of particular importance in developing the numerical model for the Severn estuary is the proportion of enterococci in the water column that are attached to sediments. In the absence of studies describing such ratios, experiments were carried out to investigate the hypothesis that enterococci are associated with suspended solids and to find out whether they attach specifically to certain particle size fractions. The experiments were based on a modified version of the pipette method for determining particle size through sedimentation. This method uses Stoke's Law to calculate settlement velocity and to infer particle size at specific depths during a period of settlement. Each experiment comprises two incubated microcosms containing 4.5 litre aliquots of the sample, one of which is allowed to settle whilst the other is continuously mixed to ensure complete suspension of the sediments. The results from the settled sample can then be compared with the mixed sample, which acts as a control. A maximum duration of six hours settlement was selected because estuarine tidal dynamics are unlikely to result in slack water for longer periods.

The results from the four settlement experiments, together with the corresponding control data, are shown in Figure 3.2. The results from the four experiments all show the same general trend, with enterococci, turbidity and suspended solids concentrations in the stirred control samples varying little over the duration of the experiments (Figure 3.2a–d).

In the microcosms allowed to settle, after an initial period of relatively stable concentrations, enterococci, turbidity and suspended solids concentrations displayed noticeable decreases. In all experiments, enterococci concentrations decreased from concentrations similar to the stirred control samples to concentrations of less

than 100 cfu 100ml⁻¹ (Figure 3.2e–h). Enterococci and turbidity concentrations in the Weston-Super-Mare sample displayed significant decreases after 34.14 minutes (predicted particle diameter <7.8µm), whilst suspended solids decreased after 8.33 minutes (predicted particle diameter <15.6µm) (Figure 3.2e). The predicted particle size diameter associated with the start of the decline in enterococci concentrations (or the marked break point in the enterococci decline in experiments three and four), varied between 3.9µm and 31.2µm.

Determining whether enterococci are preferentially attached to particles of a particular size, however, is more difficult. The results of the particle size analysis indicate median particle size in the range 8–14µm in the Weston-Super-Mare sample and 5–10µm in the Beachley Slip samples. However, an analysis of particle size showed that the median particle size did not decrease in accordance with Stoke's Law. Nevertheless, some experiments did show an increase in the proportions of finer material over time, a shift away from the distribution of the settled sediment and a decrease in maximum particle size around the same time as the enterococci concentrations began to decrease significantly. The samples collected from the stirred control microcosms varied very little over the duration of the experiments and were similar to the settled sediment from the settlement experiments.

The deviation of settled particle size away from that predicted by Stoke's Law may be due to several factors. The pipette method for estimating particle size would normally include drying, removal of organic material and use of a chemical dispersant to reduce the potential for flocculation. However, since this would destroy the enterococci organisms, these stages could not be included. Thus, the particle size distribution may be affected by the presence of organic material in suspension with the sediments, whilst biofilms (including the presence of attached enterococci) are likely to affect the density and buoyancy of the particles. It is also possible that particles formed flocs, which would increase particle size, although these would not settle in accordance with Stoke's Law.

Concentrations of enterococci in all the settled sediments that were sampled at the end of the experiments were over an order of magnitude greater than the initial concentrations in the overlying water, which is consistent with the findings of other studies. Thus, it is clear that the decrease in enterococci associated with the decline in suspended sediment and turbidity, which was observed during the 'bench scale' settlement experiments, results in a concentration of enterococci in settled sediments. This suggests that enterococci are attached to sediments rather than being 'free-swimming'.

Organisms appeared to be associated with sediments with a median particle size of 5–14µm which, is in broad accord with the findings of other researchers. Given that transport velocities for such particles are low when compared to the velocities experienced in the Severn Estuary, sediments with attached bacteria are likely to remain in suspension for almost the entire tidal cycle. This may be of particular importance in the context of rainfall mobilising sediments in river channels and over the diurnal (daytime) and spring-neap tidal cycles.

4. Numerical modelling

A conceptual model for enteric bacterial transport in natural waters was developed as an aid to developing the governing equations of enteric bacterial transport associated with sediment erosion and deposition (Figure 4.1). Bacteria in natural waters can be considered to exist in two forms, either as free-living (or planktonic) bacteria within the water column or attached to suspended particles. The free-living bacteria are transported by currents, whilst the attached bacteria are transported with suspended particles. The latter could settle out when the suspended particles are deposited, whilst the occurrence of increased turbulence can re-suspend the particles into the overlying water column with the bacteria still attached.

New mathematical equations were derived from the conceptual model, in which the source and sink terms are represented in the standard one-dimensional (1-D) and two-dimensional (2-D) governing equations formulated for numerical model algorithms. These new formulations are incorporated into an integrated 2-D and 1-D model to predict the hydrodynamic processes, sediment concentration distributions and enterococci concentrations in the coastal and estuarine waters of the Severn estuary and Bristol Channel. Firstly, the model computes the 'sediment-attached' enterococci loss due to deposition and the enterococci increase due to re-suspension in separate sub-models. The total enterococci disappearance rate includes both the mortality rate and the deposition rate. Secondly, the model assumes that the enterococci decay rate (T_{90}) varies with sunlight irradiance and the concentration of suspended solids (SS), whilst the received dose of light radiation is reduced by any increase in the SS concentration. The SS concentration in this model therefore affects the bacterial concentration through two processes: (i) sedimentation/re-suspension and (ii) attenuation of bactericidal irradiance.

The study area covers receiving waters from an integrated catchment area of up to 15,000 km², including a number of bays, rivers and the main estuary. The model domain extends from the seaward boundary of the outer Bristol Channel (between Hartland Point and Stackpole Head) to the tidal limit of the River Severn at Haw Bridge. This area is divided into two modelling domains. The 2-D modelling domain primarily covers the Bristol Channel and the 1-D modelling domain includes the Severn Estuary up to the tidal limit of the River Severn at Haw Bridge. The 1-D and 2-D domains overlap in the area between the M4 Severn Bridge (the new Severn Bridge) and the M48 Bridge (the old Severn Bridge). The model simulation time was for a period of 300 hours, commencing at 5.30pm on 20 July 2001 and finishing at 5.30am on 2 August 2001. This timescale was chosen to cover the period of the model calibration field surveys.

The model incorporates estimates for enterococci inputs from the 29 rivers and 34 point source effluent discharges from WwTWs and one brewery (see Section 2 and Volume II). The model also draws on the empirical relationships for enterococci-sediment association and enterococci T_{90} values that were developed from the laboratory experiments (see Section 3 and Volume III).

Dedicated field surveys were carried out to provide calibration data for the model. These surveys, carried out at Porthcawl and Minehead, provided data for offshore areas, bathing water compliance locations and local riverine and sewage inputs. Data collected offshore included water depth, current velocity and direction profiles, global irradiation received at the sea surface, downwelling photosynthetically-available radiation and wind direction. Water quality data describing enterococci concentration, turbidity, suspended solids concentration, particle size, conductivity, practical salinity and total dissolved solids were collected for all survey points. Two surveys over a single tidal cycle were undertaken at each location, comprising hourly samples. In addition, half-hourly samples were collected at one offshore site.

Details of the coefficients and initial values used in this element of the study, together with parameters relating to enterococci, are given in Table 4.1. These were derived from the microcosm and settlement experiments described in Section 3 and Volume III of this report, as well as from the data generated by the calibration field surveys and from literature sources.

The hydrodynamic calibration of water surface elevations, current speed and current direction showed that the correlation between the predicted and measured data is very good for tidal phasing for all four surveys. The prediction of the water depths and current directions closely agreed with the site survey data. The current speed predictions also showed good agreement with the measured data, except at the South Wales site where the model slightly (and consistently) underestimated the magnitude of fluid speed during the ebb tide. The level of accuracy of this model calibration was similar to other studies of the Bristol Channel (Lin and Falconer, 2001).

Sediment transport in the estuary was governed by the tidal currents and varied both diurnally and over the spring-neap cycle. During spring tides, sediment resuspension was the dominant process, driven by the relatively high tidal currents. During neap tides, when tidal current velocities were lower, sediment deposition was more common.

The predicted results for enterococci concentration at bathing water compliance points displayed the following general trends: (i) the enterococci concentration varies with the periodicity of the tidal currents (causing micro-organisms to flow in and out of the basin); (ii) the peak enterococci concentration at each compliance point was determined by their distances from the riverine and point sources of the enterococci; and (iii) the timing of peak concentration at each site was unique for each site, being dependent on factors such as distance from source and local tidal velocities and direction.

The bathing water compliance locations within the Severn estuary and Bristol Channel were divided into three types, dependant on the main factors controlling enterococci concentrations.

- Type I sites are affected by both riverine inputs /sewage outfalls and sediment transport/deposition.
- Type II sites are affected by either riverine inputs /sewage outfalls or sediment transport/deposition.

- Type III sites are not affected by riverine inputs /sewage outfalls or sediment transport/deposition.

The bathing waters falling into each category are shown in Table 4.2 and Figure 4.2.

A sensitivity analysis was conducted to test the effect of the model's key assumptions on the predicted enterococci results. The effect of sediment-associated enterococci transport, assuming no bacterial decay, was considered by comparing enterococci transport by advection and dispersion (flow) only with transport by flow and sediment transport flux. This indicated that enterococci concentrations at most compliance locations would continue to increase under the 'flow only' transport scenario. However, when attachment to sediments and sediment deposition/suspension are included with the flow-based transport the enterococci concentrations at bathing water compliance points are determined by factors such as the spring-neap tidal cycle and areas of net deposition/erosion. For example, concentrations may be greater than predicted using the flow transport only model during spring tides when there is a net resuspension of sediments and concentrations may be lower during neap tides when there may be a net deposition of sediments.

The effect of including sediment-associated enterococci transport with bacterial decay processes was also considered, again by comparing flow transport only with combined flow and sediment transport processes. Thus, the flow transport only model takes into account only the enterococci that are present in the water column as free-living bacteria, which are subject to related decay processes. It does not include the addition of bacteria arising from re-suspension of the bed sediments. The model that includes sediment transport processes refers to the total enterococci concentration, thereby including both the free-living bacteria in the water column and the addition of bacteria released into the water column from the re-suspension of bed sediments and the partitioning of the bacteria into the water column. During this process, the enterococci will move with the sediments and are also subject to decay processes. These comparisons indicated that enterococci concentrations were again elevated when transport of sediments and associated bacteria are included in the model predictions (Figure 4.3).

Model predictions to test the sensitivity of the initial concentration of enterococci in the bed sediment across the domain (set at $1,000 \text{ cfu g}^{-1}$) suggested that this can be an important factor in determining enterococci concentrations in the water column in areas of erosion (resuspension). However, it is not as significant in areas of net deposition. Few data exist describing enterococci concentrations in the Severn Estuary and this represents a serious gap in the knowledge base. Concentrations in bed sediments analysed during the course of this study at Weston-super-Mare and Beachley Slip indicated concentrations of between 3 cfu g^{-1} and $1,088 \text{ cfu g}^{-1}$.

The model is also sensitive to the proportion of total enterococci attached to sediments in areas of deposition, with a greater proportion of attached bacteria leading to greater numbers of organisms settling out. However, in areas of resuspension, the model is less sensitive to this factor, with concentrations in the water column being governed largely by the concentration in bed sediments.

The far-field effects of rainfall-induced high flow enterococci inputs on compliance at bathing water monitoring points were investigated by looking at the two largest riverine inputs, namely the rivers Severn and Wye, and the two largest sewage inputs, namely Cardiff and Avonmouth WwTWs. The largest high flow event on the River Severn and corresponding events for the other three locations were individually modelled, assuming that no enterococci were discharged from any other source. Each simulation was run for a duration of 360 hours, with a period of base flow preceding each event to allow the model to stabilise and with base flow conditions prevailing after cessation of the event to allow the high flow plume to disperse within the model domain. Throughout the simulations, a bed sediment enterococci concentration of 100cfu g^{-1} was used.

The results of the model simulations show that despite the distance of the inputs from the Rivers Severn and Wye and the distance of Cardiff WwTW from bathing water compliance points, each input contributes enterococci to at least some of the bathing waters along the Severn estuary–Bristol Channel coast. For example, the effect of the plume from Cardiff WwTW appears as far west as Ilfracombe on the southern shore of the Bristol Channel and the Gower peninsula on the northern site, albeit at low concentrations. The plumes from the two rivers do not extend as far into the Bristol Channel before concentrations decrease to zero, although they still contribute to enterococci concentrations at many compliance points. Generally, the high flow event from these three inputs was not obvious by the time the plumes had reached the bathing water compliance points, due to a high degree of dispersion within the estuary.

The modelling results suggest a greater impact from the Avonmouth WwTW effluent due to its proximity to some compliance locations. It was estimated that the plume would reach the beaches at Clevedon and Weston-Super-Mare (3 beaches) within a relatively short time, and the high flow event produced a noticeable increase in enterococci concentrations between eight and 17 hours after the start of the event. The model results also suggest that the plume from this input may also affect the majority of bathing waters in the Severn estuary and Bristol Channel, although again at lower levels (the impact of the high flow event being buffered by the effect of dilution and dispersion). The likely effect of the Avonmouth WwTW effluent on enterococci concentrations at neighbouring compliance locations could be further clarified by incorporating discharge time series for the effluent and detailed monitoring of enterococci concentrations in the effluent. Any storm overflow from the works should also be included in such a survey.

5. Conclusions

The estimates of enterococci loads discharged to the Severn estuary and Bristol Channel from diffuse riverine and point source WwTW effluents from 2 May 2001 to 29 September 2001 show inputs to be dominated by the diffuse riverine sources, which account for over 79 per cent of the high flow instantaneous load.

Approximately 95 per cent of the riverine enterococci load is discharged during high flow conditions. These high flow events represented approximately 40 per cent of the total discharge volume from rivers to the Severn estuary and Bristol Channel, and such conditions prevailed for 7–40 per cent of the study period. Thus, to significantly reduce enterococci levels in the area programmes should target sources of diffuse pollution within the riverine catchments. The WFD provides a regulatory framework for the control of diffuse bacterial pollution (CEC, 2000). Article 6 and Annex IV require bathing waters identified under the BWD to be declared as ‘protected areas’ and Article 11 and Annex VI require a programme of ‘basic measures’ to be implemented to achieve the standard specified in directives such as the BWD.

The largest WwTW sources of enterococci into the basin were Cardiff and Avonmouth WwTWs. These two works, together with nine others (Cog Moors, Watchet, Nash, Afan, Gloucester Netheridge, Ponthir and Cheltenham WwTWs and the Doniford and Leys outfalls), contribute over 75 per cent of the base flow instantaneous enterococci load. Thus, under base flow conditions, it is clear that sewage-related point sources are responsible for discharging the majority of the background enterococci contamination. However, the estimates described herein were based on rudimentary flow data available in the Environment Agency consents database and average enterococci concentrations taken from CREH empirical studies. Diurnal flow patterns and response to rainfall will vary between plants and the quality of final effluents is also likely to vary. To further enhance the precision of these estimates it would be necessary to monitor temporal flow patterns and to collect bacterial concentration data for final effluents. In addition, intermittent discharges from overflows such as storm tanks and CSOs, which were not accounted for in the estimates due to lack of data, would also need to be included.

The microcosm experiments that were conducted to establish enterococci T_{90} values in estuarine waters suggest that T_{90} values in dark experiments with low turbidity marine water may be shorter than those in irradiated experiments using highly turbid estuarine waters. This observation may be due to the salinity and related ecological differences between the water types studied. However, organisms attached to sediments were partially protected from bacterial inactivation processes, which may explain why the irradiated T_{90} values in turbid waters were longer than dark T_{90} values in low turbidity waters.

Turbidity was identified as the dominant predictor variable for T_{90} if irradiance and temperature are held constant. Above approximately 200 NTU, results from irradiated and dark experiments do not differ in the degree of observed enterococci mortality. However, it should also be noted that there was no significant decay during some microcosm experiments with water from the estuarine sites, even when turbidity was below this threshold.

Experiments investigating the association of enterococci with suspended solids demonstrated that enterococci concentrations decrease as the concentration of suspended solids and levels of turbidity decrease through settlement. Hence, settlement of sediments out of the water column represents another process for removing enterococci from the water column, in addition to the effects of microbial mortality. The attachment of bacteria to a mobile or semi-mobile solid phase has important implications for their transport. Bacteria that adhere to particles are no longer buoyant and have the potential to settle out with particulates or to begin moving again as flow velocities increase. The preferential adsorption of bacteria onto fine particles is particularly important in the context of bathing water compliance and the impact of potential sources of pollution, since particle size determines the movement of attached enterococci. This is because finer particles provide a greater surface area available for attachment of bacteria per unit mass and remain in suspension for longer.

The empirical relationships derived from the microcosm experiments allowed functions relating T_{90} and turbidity to be generated for irradiated and dark conditions. Thus, it was possible to generate T_{90} values within the numerical model that varied with the time- and spatially-dependent suspended solids concentrations. These functions were combined with published functions relating microbial mortality to irradiation in order to reflect more accurately the variation in this parameter with the diurnal pattern of sunlight intensity (based on local irradiation records).

This approach to calculating a variable T_{90} within a hydrodynamic model represents a significant improvement in the representation of bacterial mortality, which, at best, was previously represented in such models by constant values for daylight or night-time across the whole model domain. In essence, this new approach allows T_{90} to vary spatially and temporally whilst taking into account the prevailing conditions. These comprise the amount of sunlight received at the water surface and the level of turbidity, which is the main driving factor determining how much irradiation is received by organisms within the water column.

The predictions generated by the numerical model indicate that enterococci concentrations in the Severn estuary and Bristol Channel are closely linked to both bacterial mortality and sediment transport processes. In this estuarine environment, enterococci disappearance is evident when the sediments are depositing, with enterococci concentrations varying in a cyclical manner in phase with the tidal oscillations and being derived, at many locations, principally from bed sediments. The predictions allowed the bathing water compliance locations to be categorised according to the primary drivers of enterococci concentration (input from riverine/sewage sources and/or sediment transport). This will help the Environment Agency to identify better remediation strategies.

The model simulations designed to assess the far-field impacts of inputs from Cardiff and Avonmouth WWTWs and the Rivers Severn and Wye, over a high flow event, suggest that these sources can all contribute to enterococci concentrations at bathing water compliance locations along the Severn estuary and Bristol Channel coast. Furthermore, the high flow event scenario for Avonmouth WWTW produces a noticeable increase in concentrations at bathing waters situated close to the discharge (such as Clevedon and the three Weston-Super-Mare beaches). Thus the

model suggests that far-field sources are likely to contribute to enterococci contamination at bathing water compliance points.

Calibrating the model and testing the sensitivity of some of its main assumptions highlighted further key points.

First, including sediment-related bacterial processes within the numerical model generates predictions that are significantly different from those produced when these processes are omitted. The magnitude of these differences are related to both diurnal and lunar tidal cycles. This suggests that previous modelling efforts may not adequately characterise true bacterial concentrations within the estuarine environment. This has important implications for pollution control strategies, which often rely on numerical models to provide information on effluent plumes and environmental impacts.

Second, the concentration of suspended solids generally had more effect on the predicted enterococci levels in the near-shore waters and less effect on levels in the deeper offshore waters. This is particularly relevant in terms of complying with the BWD (CEC, 1976) and implies that turbid bathing water compliance locations may be more susceptible to higher enterococci concentrations, and hence more prone to exceeding regulatory standards.

Finally, the model is sensitive to the concentration of enterococci in bed sediments and the proportion of the total enterococci population attached to sediments. Few data exist describing the concentration of enterococci in bed sediments of the Severn estuary and Bristol Channel, and it was necessary to assume a concentration based on the data collected for this study, which was limited in its extent. The experiments investigating the association of enterococci with sediments demonstrated that a relatively high proportion of the total population is associated with suspended sediments, although it was not possible to characterise an exact proportion. Collecting additional data describing these two elements will further enhance the accuracy of the numerical model.

6. Further Research

The estimates of enterococci loads from WwTW final effluent sources described above were based on daily flow rates. These flow data provide only a guide to the likely flows from each WwTW. The lack of temporal data describing flows from these discharges meant that it was only possible to provide estimates of instantaneous enterococci delivery. Furthermore, it was not possible to calculate how enterococci concentrations changed over time during the study period. Thus, the numerical model simulations of the far-field effects of WwTW discharges were based on constant flow rates for the base flow and high flow periods. To improve the characterisation of enterococci deposits from WwTWs it would be necessary to obtain hourly discharge data at each of the inputs.

During this study, it was not possible to characterize intermittent discharges, such as CSOs and storm tank overflows, due to the lack of flow data describing spill events. The numerical model does not therefore include such inputs. This lack of flow data represents a significant gap in the knowledge base and highlights a limitation in the methods used to estimate absolute bacterial flux. However, it was not considered to be a fatal flaw to the aims of this project, which sought to assess the impact on bathing beach compliance of far-field inputs to the estuary. Nevertheless, research into storm overflow inputs would provide a more accurate representation of faecal indicator organism discharges to the riverine, estuarine and coastal environments of the Severn estuary/Bristol Channel area. Research by CREH has shown that storm overflow spills can contribute episodic pulses of faecal indicator organisms, which can be far in excess of those contributed by riverine or WwTW final effluent sources. Depending on the relative position of CSOs and other sources, these episodic inputs may precede the inputs from diffuse riverine sources and this may have implications for bathing water compliance.

The land cover-water quality modelling used to estimate enterococci concentrations at the tidal limits of the riverine catchments used the CEH land cover map for 1990. An updated version of the map for 2000 is now available and reassessing the predicted enterococci concentrations with the more recent land cover data would better reflect the current situation. To improve further the ability of the land cover models to reflect recent changes to land cover, new remotely sensed data sets, such as the SPOT5 5m resolution satellite imagery, could be investigated for determining land-cover.

A number of key assumptions were made in developing the model. Specifically, the model assumes no bacterial decay within the bed sediments and a constant initial bed enterococci concentration at all locations. The importance of this model compartment suggests that further work on (i) defining enterococci concentrations in bed sediments, as well as their regional and spatial heterogeneity and (ii) conducting further investigations into the proportion of the total enterococci population attached to sediments in the water column would be fruitful areas of investigation to enhance the predictive capacity of the model in the estuarine environment. The current model is sensitive to these factors under certain conditions and conducting investigations to

increase the precision of the estimates provided herein would improve confidence in the model's predictions.

The numerical model developed for this study is perhaps the first of its kind to incorporate sediment-associated bacterial transport processes and dynamic T_{90} values. The model shows that it is possible to incorporate such dynamic factors and further refinement of the model should be pursued to build on the success of this project. A model with finer resolution could be developed as enhanced computer processing power becomes available. Improved bathymetric and hydrodynamic data would allow more accurate representation of the hydrodynamic features of the channel and estuary. The models could be further improved as more information becomes available relating to the research requirements described above, such as bed sediment bacterial concentration and characteristics. Together with advances in numerical modelling techniques, these new data would allow the model to predict more accurately changes in bacterial concentrations at specific compliance monitoring sites.

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References

Booth, A. M., Hagedorn, C., Graves, A. K., Hagedorn, S. C. & Mentz, K. H., 2003. Sources of fecal pollution in Virginia's Blackwater River, *Journal of Environmental Engineering-Asce*, 129, 547–552.

Council of the European Communities, 1976. Council Directive 76/160/EEC of 8 December 1975 concerning the quality of bathing water. *Official Journal of the European Communities*, **L31**, 1–7.

Council of the European Communities, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, **L327**, 1–72.

Council of the European Communities, 2002. *Proposal of the European Parliament and of the Council concerning the quality of bathing waters*. Report No: COM(2002) 581 final 2002/0254 (COD).

Crowther, J., Kay, D. and Wyer, M. D., 2001. Relationships between microbial water quality and environmental conditions in coastal recreational waters: The Fylde coast, UK. *Water Research*, **35**(17), 4029–4038.

Crowther, J., Kay, D. and Wyer, M. D., 2002. Faecal indicator concentrations in waters draining lowland pastoral catchments in the UK: relationships with land use and farming practices. *Water Research*, **36**(7), 1725–1734.

Crowther, J., Wyer, M. D., Bradford, M., Kay, D., Francis, C. A. and Knisel, W. G., 2003. Modelling faecal indicator concentrations in large rural catchments using land use and topographic data. *Journal of Applied Microbiology*, **94**(6), 962–973.

Fewtrell, L., Kay, D., Wyer, M. D., Crowther, J., Carbo, P. and Mitchell, G. (1998). *Faecal Indicator Budgets Discharging to the Ribble Estuary*. Centre for Research into Environment and Health, University of Leeds.

Joyce, T. M., McGuigan, K. G., Elmore-Meegan, M. and Conroy, R. M., 1996. Inactivation of faecal bacteria in drinking water by solar heating. *Applied and Environmental Microbiology*, **62**, 399–402.

Kay, D., Wyer, M. D., Crowther, J., O'Neill, J. G., Jackson, G., Fleisher, J. M. and Fewtrell, L., 1999. Changing standards and catchment sources of faecal indicators in nearshore bathing waters. In: S. Trudgill, D. Walling and B. Webb, eds. *Water Quality Processes and Policy*. Chichester: Wiley, 47–64.

Stapleton, C. M., Wilkinson, J., Wyer, M. D., Fewtrell, L. and Kay, D., 1999. *Sescale and St. Bees bathing waters bacterial impact study*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Stapleton, C. M., Kay, D., Chudley, J., Fewtrell, L., Wilkinson, J. and Wyer, M., 2000a. *Morecambe Bay bathing waters bacterial impact study*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Stapleton, C. M., Wilkinson, J., Kay, D., Fewtrell, L. and Wyer, M., 2000b. *Lake Windermere bathing waters bacterial impact study*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Stapleton, C. M., Wyer, M. D. and Kay, D., 2002. *Assessment of point and diffuse sources of faecal indicators in the Ribble catchment. Phase I: scoping and desk study*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

WHO, 2003. *Guidelines for safe recreational-water environments Volume 1: coastal and fresh-waters*. World Health Organisation. Geneva, Switzerland.

Wyer, M. D., Kay, D., Jackson, G. F., Dawson, H. M., Yeo, J. and Tanguy, L., 1995. Indicator organism sources and coastal water-quality - a catchment study on the island of Jersey. *Journal of Applied Bacteriology*, **78**(3), 290–296.

Wyer, M. D., Kay, D., Dawson, H. M., Jackson, G. F., Jones, F., Yeo, J. and Whittle, J., 1996. Delivery of microbial indicator organisms to coastal waters from catchment sources. *Water Science and Technology*, **33**(2), 37–50.

Wyer, M. D., O'Neill, G., Kay, D., Crowther, J., Jackson, G. F. and Fewtrell, L., 1997. Non-outfall sources of faecal indicator organisms affecting the compliance of coastal waters with Directive 76/160/EEC. *Water Science and Technology*, **35**(11–12), 151–156.

Wyer, M. D., Kay, D., Crowther, J., Whittle, J., Spence, A., Huen, V., Wilson, C., Carbo, P. and Newsome, J., 1998a. Faecal-indicator budgets for recreational coastal waters: a catchment approach. *Journal of the Chartered Institution of Water and Environmental Management*, **12**(6), 414–424.

Wyer, M. D., Crowther, J. and Kay, D., 1998b. *Faecal indicator organism sources and budgets for the Ogwr catchment, south Wales*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Wyer, M. D., Crowther, J. and Kay, D., 1998c. *Faecal indicator organism sources and budgets for the Nyfer catchment, south Wales*. Environment Agency R&D Technical Report E61.

Wyer, M. D., Crowther, J., Kay, D., Stapleton, C. and Wilkinson, J., 1999a. *Faecal indicator organism sources and budgets for the Tendring peninsula, Essex*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Wyer, M. D., Crowther, J., Kay, D. and Fewtrell, L., 1999b. *Faecal indicator organism sources and budgets for the Irvine and Girvan catchments, Ayrshire*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Wyer, M. D., Kay, D., Stapleton, C., Francis, C. A., Watkins, J. and Rushby, L., 2001. *Faecal indicator organism sources and budgets for Irvine Bay, Ayrshire. Report to West of Scotland Water, the Scottish Environment Protection Agency, South Ayrshire Council and North Ayrshire Council*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Wyer, M. D., Stapleton, C., Crowther, J., Kay, D., Bradford, M., Humphrey, N., Francis, C. A. and Watkins, J., 2003. *Assessment of point and diffuse sources of faecal indicators in the Ribble catchment: Phase II: budget studies and land-cover water quality modelling*. Centre for Research into Environment and Health, University of Wales, Aberystwyth.

Tables

Table 2.1:

Summary of proportional (%) contributions of estimated enterococci loads for the 29 Severn Estuary riverine inputs during a 150 day period between 2 May 2001 and 29 September 2001

Input no. and Catchment	Total enterococci load (organisms) from which proportions are calculated: 1.71×10^{17}		
	Base flow (%)	High flow (%)	Total (%)
12 Severn	1.79	30.81	32.60
11 Wye	0.43	11.68	12.11
21 Brue	0.28	9.84	10.12
15 Avon	0.73	9.27	10.00
10 Usk	0.25	8.08	8.33
22 Parrett	0.47	6.85	7.32
20 Axe	0.13	4.43	4.56
05 Ogwr	0.16	2.63	2.78
06 Ely	0.09	1.37	1.46
07 Taf	0.18	1.26	1.44
08 Rhymney	0.11	1.21	1.33
09 Ebbw	0.11	1.16	1.26
17 Land Yeo	0.05	1.18	1.24
01 Tawe	0.06	0.71	0.77
19 Banwell	0.06	0.64	0.70
14 Little Avon	0.04	0.61	0.65
13 Frome	0.08	0.50	0.58
18 Congresbury Yeo	0.03	0.54	0.58
02 Nedd	0.05	0.44	0.48
04 Kenfig	0.03	0.34	0.36
16 Portbury Ditch	0.02	0.34	0.36
29 Lyn	0.01	0.24	0.24
03 Afan	0.03	0.16	0.19
27 Avill River	0.01	0.17	0.19
24 Doniford Stream	0.02	0.16	0.17
25 Washford River	0.01	0.10	0.11
28 Horner Water	<0.01	0.03	0.04
26 Pill River	<0.01	0.02	0.02
23 Kilve Stream	<0.01	0.01	0.01
Total	5.22	94.78	100.00

Table 2.2:

Base flow and high flow instantaneous enterococci loads (organisms second⁻¹) to the Severn estuary and Bristol Channel from riverine and WwTW sources

Source	Base flow load ¹ (orgs. s ⁻¹)	Source	High flow load ² (orgs. s ⁻¹)
Cardiff WwTW	1.08x10 ⁹	Severn	1.33x10 ¹⁰
Avonmouth WwTW	7.38x10 ⁸	Brue	1.03x10 ¹⁰
Severn	3.39x10 ⁸	Avon	5.47x10 ⁹
Cog Moors WwTW	3.01x10 ⁸	Parrett	5.34x10 ⁹
Watchet WwTW/Outfall	2.21x10 ⁸	Axe	4.62x10 ⁹
Doniford Outfall	2.04x10 ⁸	Wye	4.45x10 ⁹
Nash WwTW	2.01x10 ⁸	Avonmouth WwTW	4.28x10 ⁹
Afan WwTW	1.76x10 ⁸	Cardiff WwTW	3.51x10 ⁹
Gloucester Netheridge WwTW	1.49x10 ⁸	Ogwr	2.77x10 ⁹
The Leys outfall, Aberthaw	1.24x10 ⁸	Usk	2.66x10 ⁹
Avon	1.24x10 ⁸	Ely	1.31x10 ⁹
Cheltenham WwTW	1.22x10 ⁸	Banwell	1.25x10 ⁹
Ponthir WwTW	1.14x10 ⁸	Cog Moors WwTW	1.24x10 ⁹
Wye	8.71x10 ⁷	Taf	1.20x10 ⁹
Penybont WwTW	7.99x10 ⁷	Rhymney	1.15x10 ⁹
Parrett	7.41x10 ⁷	Penybont WwTW	1.11x10 ⁹
Usk	5.44x10 ⁷	Congresbury Yeo	1.07x10 ⁹
Brue	4.20x10 ⁷	Ebbw	8.67x10 ⁸
Taf	2.73x10 ⁷	Nash WwTW	8.21x10 ⁸
Ogwr	2.37x10 ⁷	Little Avon	8.04x10 ⁸
Gloucester Longford WwTW	2.26x10 ⁷	Gloucester Netheridge WwTW	7.05x10 ⁸
Portbury Wharf WwTW/Outfall	2.15x10 ⁷	Afan WwTW	6.99x10 ⁸
Axe	2.03x10 ⁷	Tawe	6.73x10 ⁸
Lydney	2.00x10 ⁷	Land Yeo	6.22x10 ⁸
Rhymney	1.75x10 ⁷	Ponthir WwTW	5.14x10 ⁸
Ebbw	1.72x10 ⁷	The Leys outfall, Aberthaw	5.09x10 ⁸
Thornbury WwTW	1.53x10 ⁷	Cheltenham WwTW	5.03x10 ⁸
Ely	1.35x10 ⁷	Watchet WwTW/Outfall	4.61x10 ⁸
Frome	1.30x10 ⁷	Doniford Outfall	4.18x10 ⁸
Blakeney	1.30x10 ⁷	Kenfig	4.14x10 ⁸
Magor Brewery Effluent Plant	1.16x10 ⁷	Nedd	3.78x10 ⁸
32 other riverine & WwTW inputs each discharging less than	1.00x10 ⁷	Frome	3.55x10 ⁸
		Avill River	2.27x10 ⁸
		Afan	1.95x10 ⁸
		Portbury Ditch	1.78x10 ⁸
		Doniford Stream	1.77x10 ⁸
		Lyn	1.76x10 ⁸
		Washford River	1.36x10 ⁸
		Portbury Wharf WwTW/Outfall	1.25x10 ⁸
		Gloucester Longford WwTW	1.19x10 ⁸
		23 other riverine & WwTW inputs each discharging less than	1.00x10 ⁸

¹ Base flow load in riverine sources, dry weather flow load in WwTW sources

² High flow load in riverine sources, maximum flow load in WwTW sources
(refer to Volume II for more details)

Table 3.1:

T₉₀ values (hours) for enterococci in irradiated and non-irradiated environmental waters estimated using unadjusted data from each experiment, and combined data from all four experiments at each sample site (the table also shows the adjusted r^2 for the regression equation used to determine the T₉₀)

Location		Experiment 1		Experiment 2		Experiment 3		Experiment 4		Combined	
		T ₉₀	r^2								
Langland Bay	Irradiated	10.9	64.7	4.8	76.5	7.5	93.4	5.4	91.3	6.8	63.8
	Dark	73.8	20.1	19.9	71.8	28.8	81.2	18.7	85.5	24.9	57.5
Porthcawl	Irradiated	16.8	69.5	5.1	92.9	4.2	92.5	8.8	61.2	9.4	41.5
	Dark	25.8	81.1	34.6	83.9	31.2	71.6	30.8	80.5	29.7	60.1
Beachley Slip	Irradiated	27.0	74.4	54.2	51.0	44.1	36.5	32.0	76.0	35.1	58.2
	Dark	74.9	25.1	n.s.	—	n.s.	—	n.s.	—	n.s.	—
Weston-s-Mare	Irradiated	113.9	17.4	46.5	27.2	26.6	89.2	14.2	86.8	18.7	57.2
	Dark	n.s.	—	n.s.	—	68.5	43.4	52.0	77.4	54.6	62.7
Minehead	Irradiated	5.0	67.8	8.2	93.4	12.8	64.8	3.7	96.1	9.5	46.7
	Dark	18.0	88.4	12.5	84.6	31.9	79.2	8.8	95.5	15.1	60.3

n.s. not significant: slope of regression line not significantly different to zero (no significant mortality)

Table 3.2:

T₉₀ values (hours) for enterococci attributable to the effects of radiation¹

Location	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Langland Bay	12.9	6.4	11.9	7.5
Porthcawl	47.9	5.9	4.9	12.3
Beachley Slip	42.2	54.2†	44.1 ²	32.0†
Weston-s-Mare	113.9†	46.5†	43.5	19.5
Minehead	6.9	23.5	21.5	6.6

¹ Note that the T₉₀ attributable to the effects of radiation is not just the bactericidal effect of radiation, it also includes factors such as shielding by particles, and increased chemical reactions and biological activity stimulated by radiation

² T₉₀ values not adjusted due to no bacterial mortality during dark experiments

Table 3.3:

Estimated D₉₀ values using combined data from each site and for coastal/estuarine water types* (the range of D₉₀s estimated using data from the individual experiments is shown in brackets)

Location	Waveband			
	Total (MW m ⁻²)	UV-A (kW m ⁻²)	UV-B (kW m ⁻²)	Biologically Weighted UV-B† (kW m ⁻²)
Langland Bay	6.4 (4.5-10.2)	127.6 (90.2-204.9)	27.0 (19.1-43.3)	7.8 (5.5-12.6)
Porthcawl	8.8 (3.9-15.7)	176.2 (78.7-313.8)	37.3 (16.6-66.4)	10.8 (4.8-19.3)
Beachley Slip	32.9 (25.3-50.7)	657.2 (505.3-1013.9)	139.0 (106.9-214.5)	40.4 (31.1-62.4)
Weston-s-Mare	17.5 (13.3-106.7)	350.0 (265.0-2133.1)	74.0 (56.3-451.2)	21.5 (16.4-131.3)
Minehead	8.9 (3.5-12.0)	177.4 (70.2-240.3)	37.5 (14.8-50.8)	10.9 (4.3-14.8)
Coastal ¹	8.2	164.7	34.8	10.1
Estuarine ²	21.1	421.6	89.2	25.9
Threshold ³	49.2	984.7	208.3	60.6

¹ Coastal: Langland Bay, Porthcawl and Minehead. Estuarine: Beachley Slip and Weston-super-Mare

² Weighted using the DNA damage action spectrum.

³ Threshold: This is the estimated D₉₀ at the point where suspended solids concentration/turbidity is replicating dark conditions

Table 4.1: Boundary condition parameters used in model simulations

Parameter	Value
Initial non-cohesive suspended sediment concentration	2 mg l ⁻¹
Initial cohesive suspended sediment concentration	2 mg l ⁻¹
Coarse sediment particle diameter:	
D ₁₆	0.026mm
D ₅₀	0.058mm
D ₈₄	0.126mm
D ₉₀	0.150mm
Average size of cohesive flocs	0.010 - 0.063mm
Critical shear stress for deposition of cohesive particles	0.1 N m ⁻²
Critical shear stress for erosion of cohesive particles	2.0 N m ⁻²
% of total enterococci population attached to sediments ¹	80% (20%, 50%)
Initial enterococci concentration in bed sediments*	1,000 cfu g ⁻¹ (10 cfu 100ml ⁻¹ , 100 cfu 100ml ⁻¹)
Initial enterococci concentration in water column	0 cfu 100ml ⁻¹
Enterococci decay rate in water column	Time variable, determined by suspended sediment concentration and irradiation
Enterococci decay rate in bed sediments	No decay

¹ A sensitivity analysis was undertaken to test the effect of this assumption on model predictions (values tested during this analysis are indicated in brackets)

Table 4.2:

Bathing water compliance points in the Severn estuary and Bristol Channel categorised by the main controlling factor of enterococci concentration

Type I Beaches affected by both riverine inputs /sewage outfalls <u>and</u> sediment entrainment	Type II Beaches affected by either riverine inputs /sewage outfalls <u>or</u> sediment entrainment	Type III Beaches <u>not</u> affected by riverine inputs /sewage outfalls or sediment entrainment
Mean enterococci concentration: 83–155 cfu 100ml ⁻¹	Mean enterococci concentration: 13–57 cfu 100ml ⁻¹	Mean enterococci concentration: <1–10 cfu 100ml ⁻¹
Max. enterococci concentration: 400–697 cfu 100ml ⁻¹	Max. enterococci concentration: 141–380 cfu 100ml ⁻¹	Max. enterococci concentration: 7–66 cfu 100ml ⁻¹
Clevedon Beach	Berrow north of Unity Farm	Ilfracome Hele
Minehead Terminus	Brean	Combe Martin
Blue Anchor West	Cold Knap Barry	Ilfracombe Tunnels Beach
Dunster North West	Whitmore Bay Barry	Ilfracombe Capstone
Weston-s-mare Sand Bay	Jackson Bay Barry	Swansea Bay
Weston Main	Southerndown	Langland Bay
Weston-s-Mare Uphill Slipway	Porlock Weir	Limeslade Bay
	Lynmouth	Bracelet Bay
	Rest Bay Porthcawl	Port Eynon Bay
	Sandy Bay Porthcawl	Oxwich Bay
	Trecco Bay Porthcawl	Aberafan

Figures

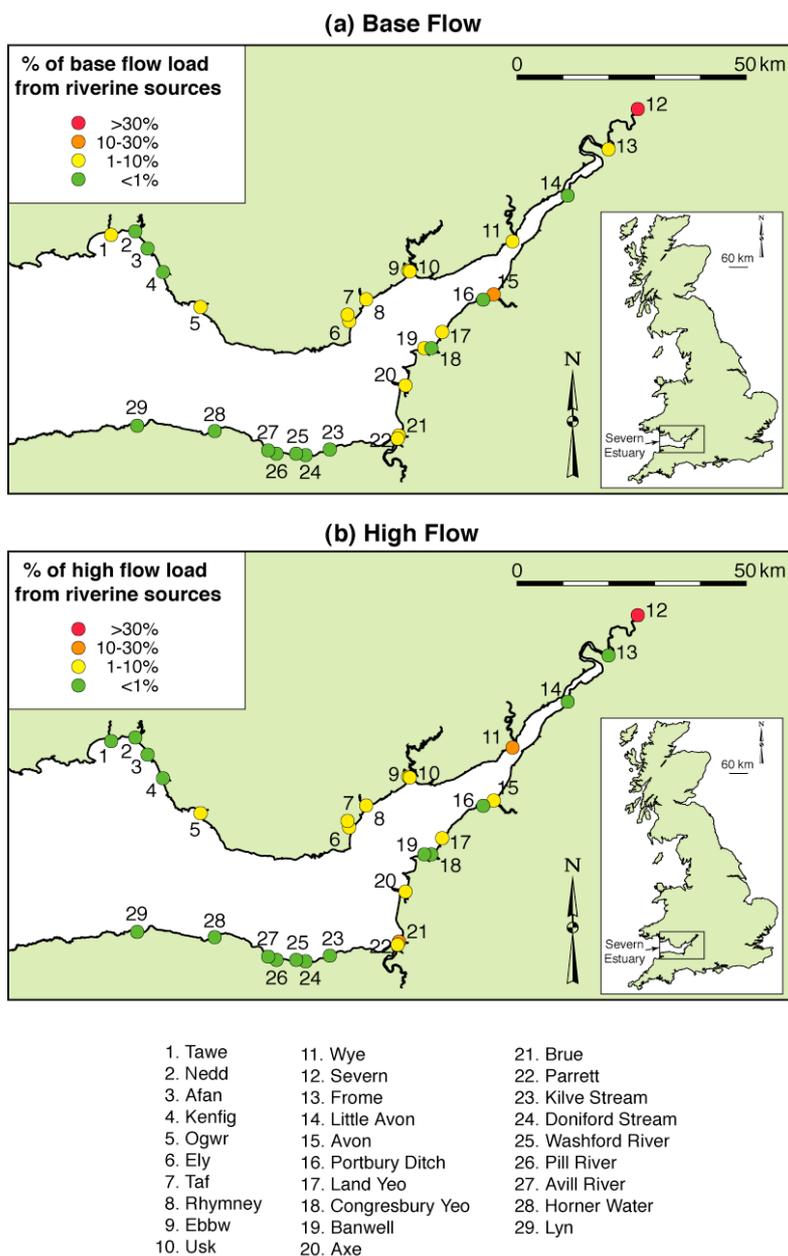


Figure 2.1:

Proportional contribution of main riverine inputs to the riverine enterococci load discharged to the Severn estuary and Bristol Channel: (a) Base flow (combined base flow load represents 5% of total load); (b) High Flow (combined high flow load represents 95% of total load)

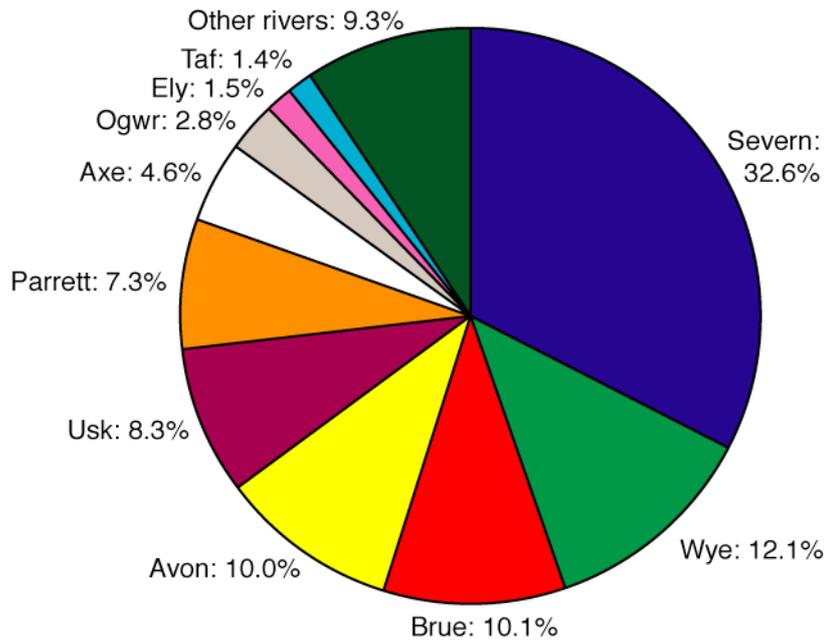
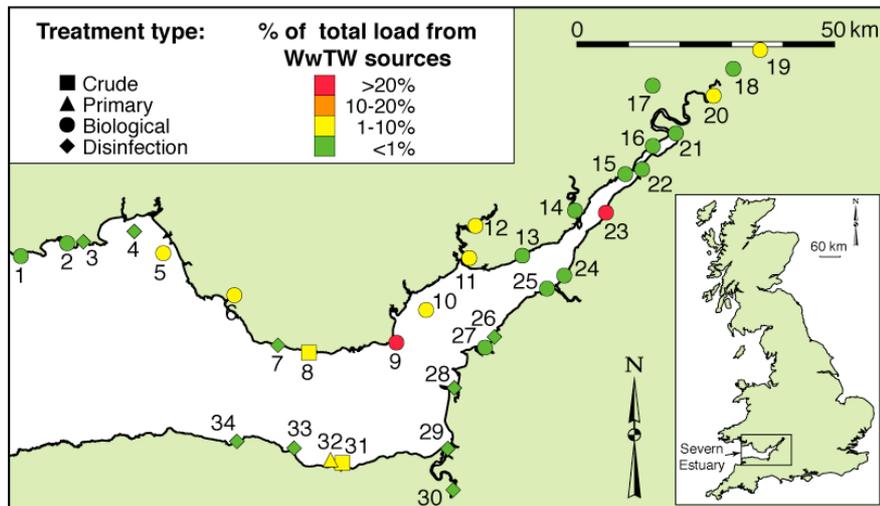
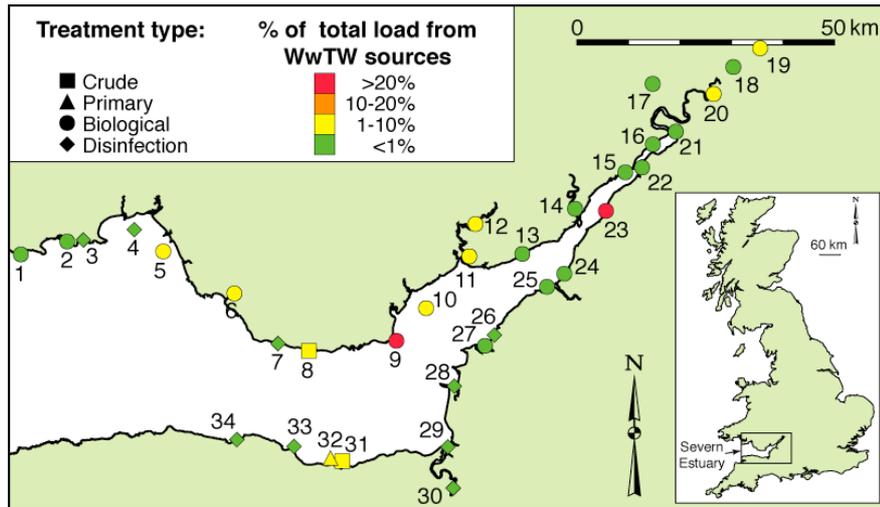


Figure 2.2:

Proportions of high flow enterococci loads discharged by riverine inputs to the Severn estuary and Bristol Channel during the period 2 May 2001 to 29 September 2001



- | | | |
|---------------------|--------------------------------|----------------------------|
| 1. Overton WwTW | 13. Magor Brewery | 25. Portbury Wharf WwTW |
| 2. Southgate WwTW | 14. Sedbury WwTW | 26. Kingston Seymour WwTW |
| 3. Bishopston WwTW | 15. Lydney WwTW | 27. Wick St Lawrence WwTW |
| 4. Swansea WwTW | 16. Blakeney WwTW | 28. Weston-Super-Mare WwTW |
| 5. Afan WwTW | 17. Longhope WwTW | 29. West Huntspill WwTW |
| 6. Pen y Bont WwTW | 18. Gloucester Longford WwTW | 30. Bridgewater WwTW |
| 7. Llantwit WwTW | 19. Cheltenham WwTW | 31. Doniford Outfall |
| 8. The Leys outfall | 20. Gloucester Netheridge WwTW | 32. Watchet WwTW |
| 9. Cardiff WwTW | 21. Frampton WwTW | 33. Minehead WwTW |
| 10. Cog Moors WwTW | 22. Sharpness WwTW | 34. Porlock WwTW |
| 11. Nash WwTW | 23. Thornbury WwTW | |
| 12. Ponthir WwTW | 24. Avonmouth WwTW | |

Figure 2.3:

Treatment type and proportional contribution of main WwTW inputs to the instantaneous enterococci load discharged to the Severn estuary and Bristol Channel: (a) base flow (dry weather flow); (b) high flow (maximum flow)

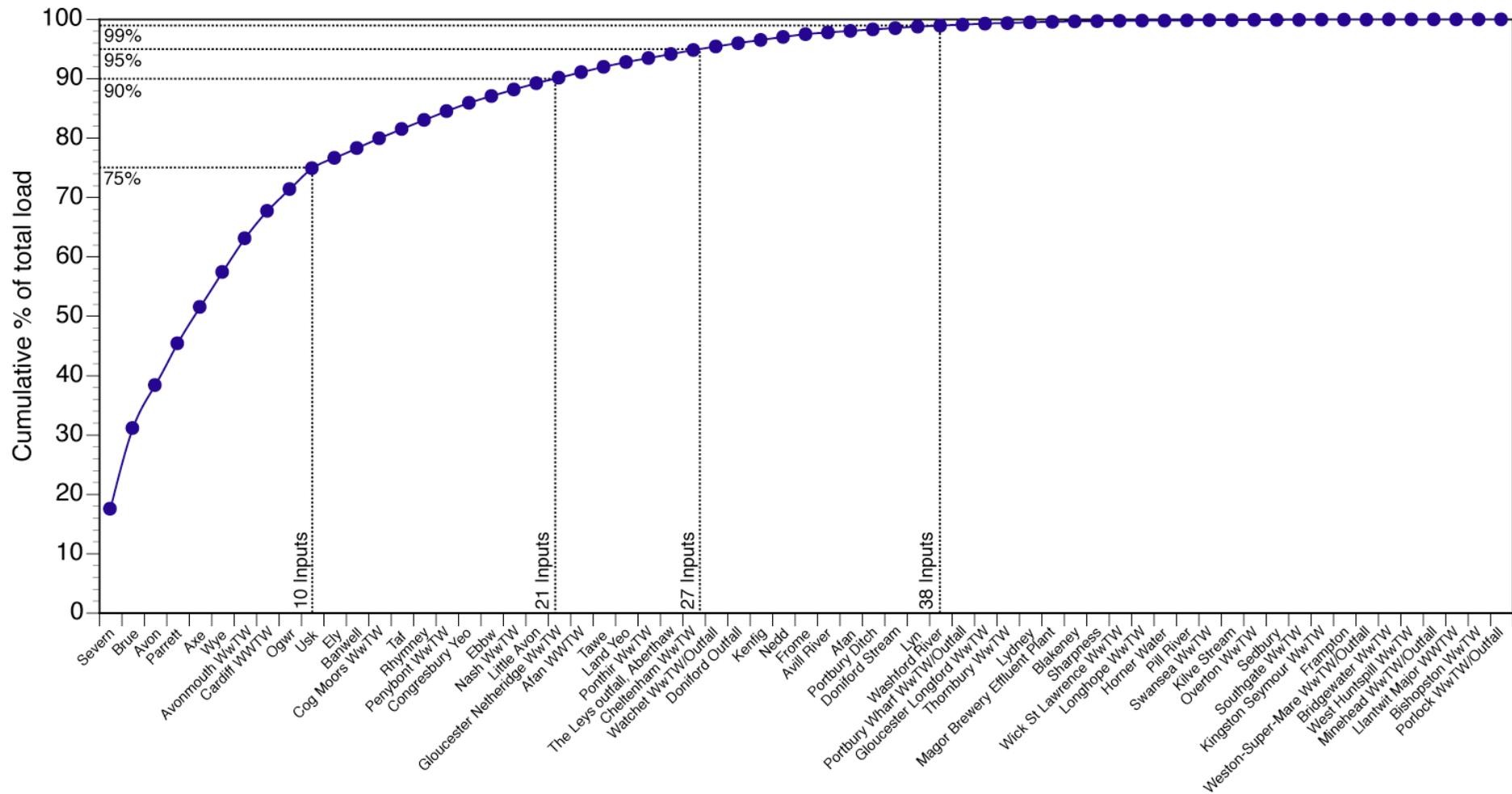


Figure 2.4: Cumulative percentage of total high flow instantaneous enterococci load discharged to the Severn estuary and Bristol Channel from riverine and WwTW sources

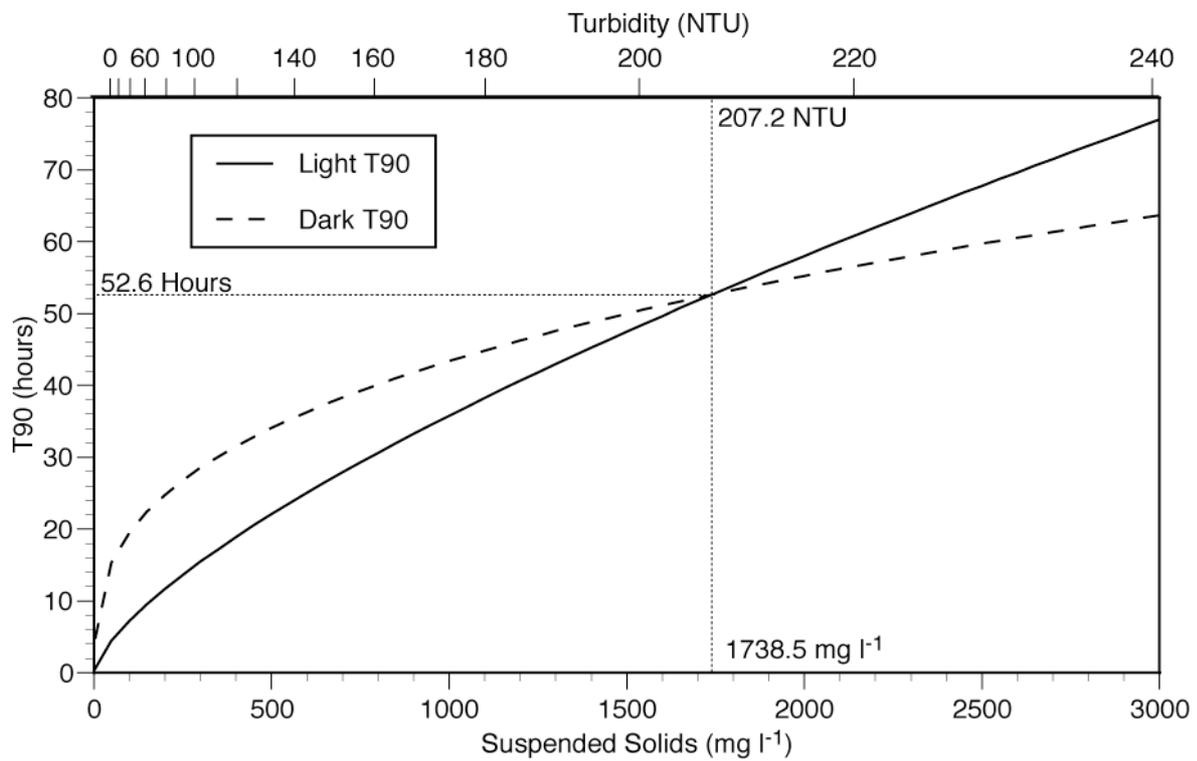


Figure 3.1:

Relationships between irradiated and dark T₉₀ with suspended solids/turbidity estimated using all data from the microcosm experiments

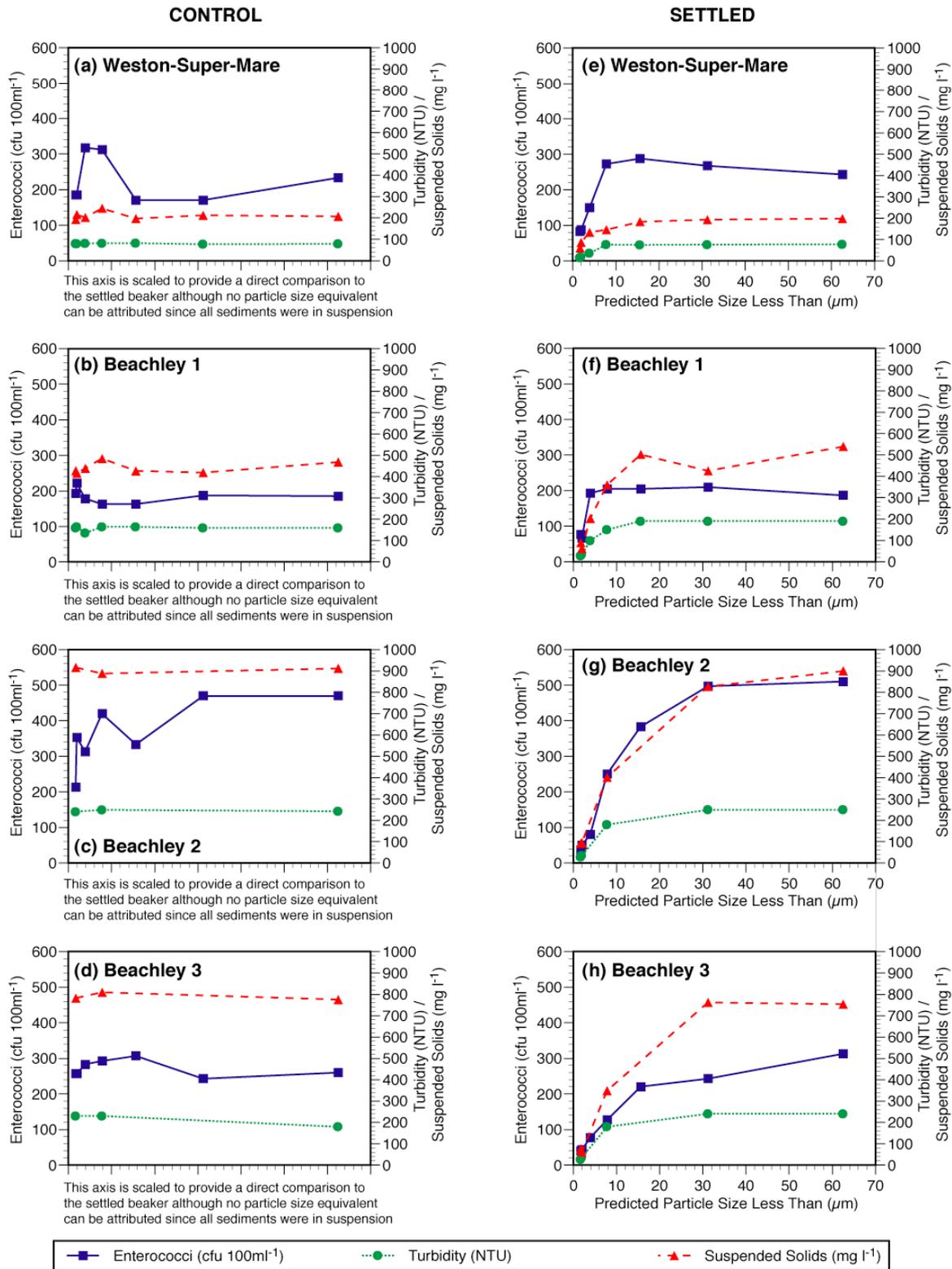


Figure 3.2:

Enterococci (cfu 100ml⁻¹), turbidity (NTU) and suspended solid concentrations (mg l⁻¹) plotted against predicted particle size (estimated using Stoke's Law) from the four sediment settlement experiments: (a-d) stirred controls; (e-h) settled samples

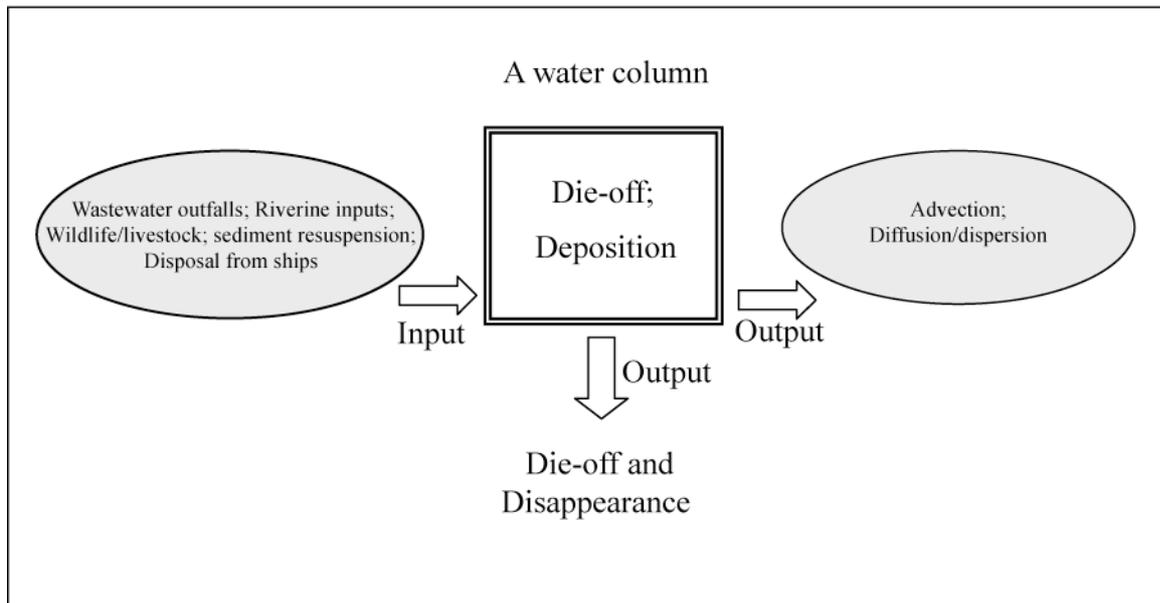
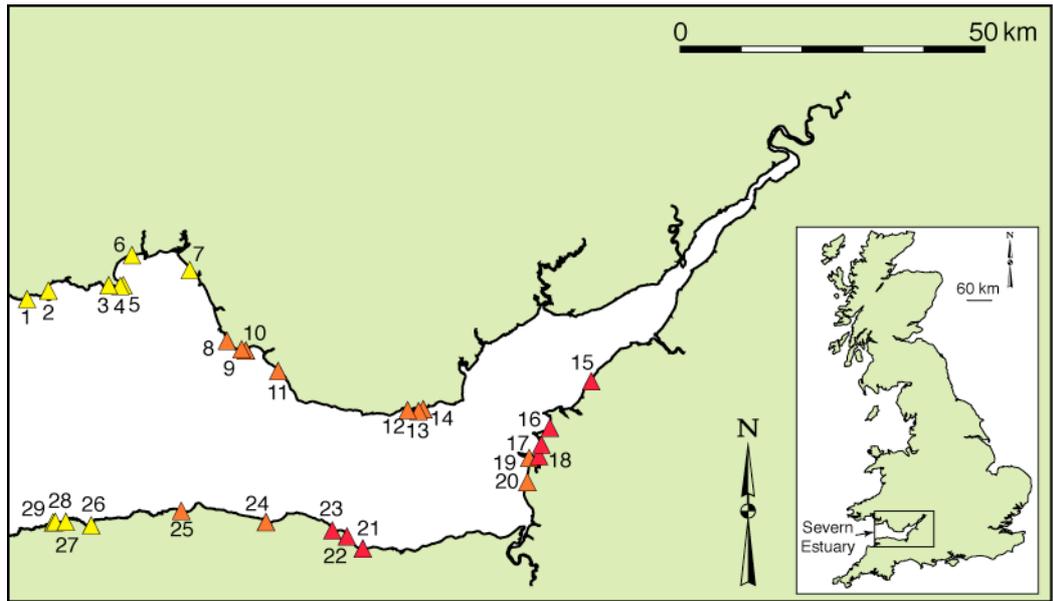


Figure 4.1:

Conceptual model of faecal indicator organism transport in natural waters



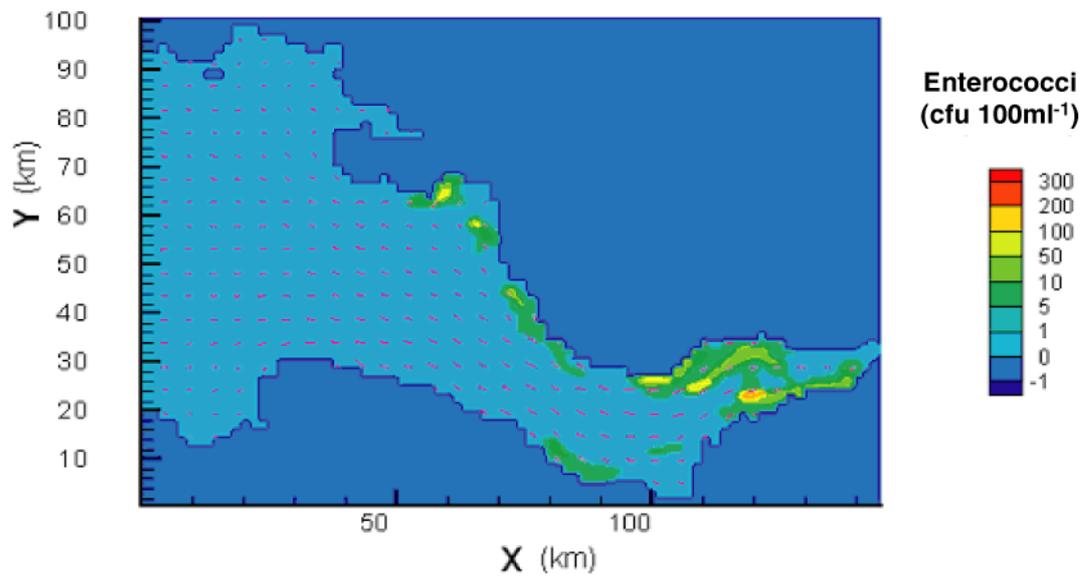
Bathing waters classified by primary driver of enterococci concentration

- ▲ Type I: Affected by inputs & sediment transport
- ▲ Type II: Affected by inputs or sediment transport
- ▲ Type III: Unaffected by inputs & sediment transport

- | | | |
|------------------|---------------------|-------------------------|
| 1. Port Eynon | 11. Southerndown | 21. Blue Anchor West |
| 2. Oxwich Bay | 12. Cold Knap | 22. Dunster North west |
| 3. Langland Bay | 13. Whitmore Bay | 23. Minehead Terminus |
| 4. Limeslade Bay | 14. Jacksons Bay | 24. Porlock Weir |
| 5. Bracelet Bay | 15. Clevedon | 25. Lynmouth |
| 6. Swansea Bay | 16. Weston Sand Bay | 26. Combe Martin |
| 7. Aberafan | 17. Weston Main | 27. Ilfracombe Hele |
| 8. Rest Bay | 18. Weston Uphill | 28. Ilfracombe Capstone |
| 9. Sandy Bay | 19. Brean | 29. Ilfracombe Tunnels |
| 10. Trecco Bay | 20. Berrow North | |

Figure 4.2:
Bathing water compliance points in the Severn estuary and Bristol Channel categorised by the main controlling factor of enterococci concentration during base flow conditions

(a) Predicted concentration (cfu 100ml⁻¹) assuming transport of non-sediment associated enterococci only.



(b) Predicted concentration (cfu 100ml⁻¹) including transport of non-sediment associated enterococci.

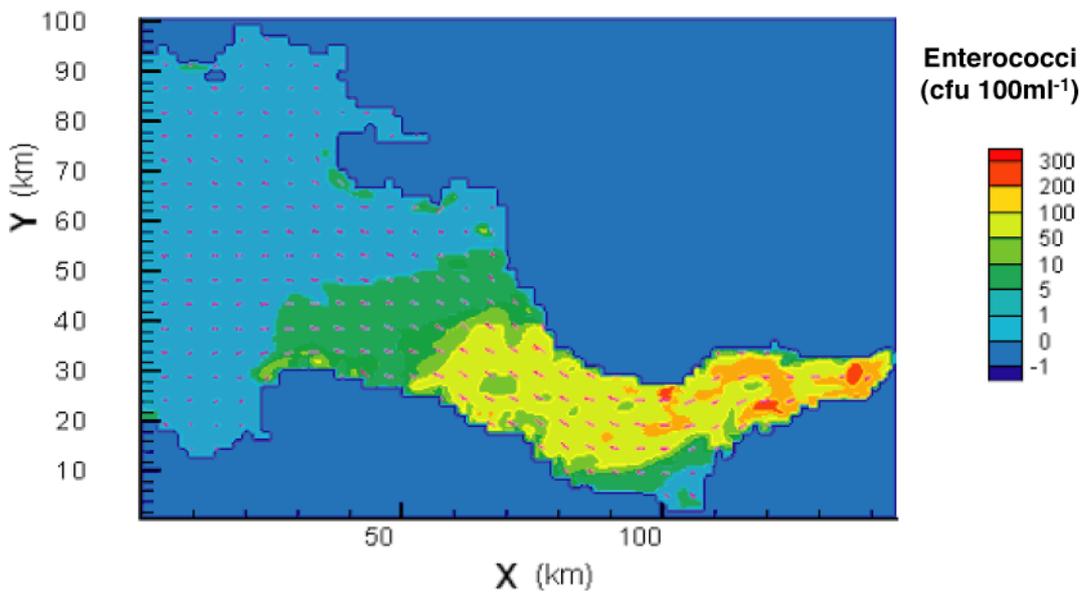


Figure 4.3:

Spring tide mid-ebb enterococci concentrations (cfu 100ml⁻¹) in the outer Severn estuary and Bristol Channel predicted assuming (a) transport of non-sediment associated ('free-living') enterococci only; and (b) transport of 'free living' and sediment-associated enterococci

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