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Achieving EU Standards in Recreational Waters

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Maritime Ireland / Wales INTERREG Report NO.6
Measure 1.3: Protection of the Marine and Coastal Environment and Marine Emergency Planning

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Maritime (Ireland / Wales) INTERREG Programme- Building Bridges.

Maritime Ireland / Wales INTERREG
1994 - 1999

Achieving EU Standards in Recreational Waters

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Maritime Ireland / Wales INTERREG Report No. 6

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Maritime (Ireland/Wales) INTERREG Programme 1994 - 1999

The EU Maritime (Ireland /Wales) INTERREG II Programme (1994 – 1999) was established to:

1. promote the creation and development of networks of co-operation across the common maritime border.
2. assist the eligible border region of Wales and Ireland to overcome development problems which arise from its relative isolation within the European Union.

These aims are to be achieved through the upgrading of major transport and other economic linkages in a way that will benefit the constituent populations and in a manner compatible with the protection and sustainability of the environment. The Maritime INTERREG area includes the coastlines of counties Meath, Dublin, Wicklow, Wexford and Waterford on the Irish side and Gwynedd, Ceredigion, Pembrokeshire and Carmarthenshire on the Welsh side and the sea area in between.

In order to achieve its strategic objectives the programme is divided into two Areas:

Sub-Programme 1:	**Maritime Development:** transport, environment and related infrastructure (59 mEuro)
Sub-Programme 2:	**General Economic Development:** Economic growth, tourism, culture, human resource development (24.9 mEuro)

The Marine and Coastal Environment Protection and Marine Emergency Planning Measure (1.3) has a total budget of 5.33 mEuro of which 3.395 mEuro is provided under the European Development Fund. EU aid rates are 75% (Ireland) and 50% (Wales).

The specific aims of Sub-Programme 1.3 are:

- to promote the transfer of information between the designated areas.
- to establish an in-depth profile of marine/coastal areas for conservation of habitat/species.
- to explore, survey, investigate, chart the marine resource to provide a management framework.
- to develop an integrated coastal zone management system.
- to improve marine environmental contacts and co-operation.
- to promote the sustainable development of the region.
- to improve nature conservation.

Joint Working Group

The Joint Working Group, established to oversee the implementation of Measure, consists of 5 Irish and 5 Welsh representatives.

Irish representation:	Department of the Marine & Natural Resources, Department of the Environment & Local Government, Department of Transport, Energy & Communications, Local Authority and Marine Institute.
Welsh representation:	National Assembly for Wales, Countryside Council for Wales, National Trust, Local Authority (Dyfed), Local Authority (Gwynedd).

This Report series is designed to provide information on the results of projects funded under Measure 1.3. Protection of the Marine & Coastal Environment and Marine Emergency Planning.

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Overview

In the interest of public health and amenity, the quality of bathing waters is controlled by the European Union Bathing Water Directive (1976); the well-known Blue Flag scheme is associated with this. The Directive regulates — among other parameters — the numbers of "indicator bacteria" permitted in the water; these microorganisms themselves are not an apparently significant risk to health, but they act as indicators that sewage-derived pathogenic organisms that cause illness may be present. Coastal and freshwater bathing areas are monitored regularly during the bathing season for compliance with the Directive, and the published annual reports attract much public and news-media attention.

Substantial high-cost improvements to sewerage management infrastructure have been made by Local Authorities both in Ireland and Wales aimed at achieving better compliance with bathing water standards. Nevertheless, there have been continuing episodic failures to meet the indicator-bacteria standards. Recent research in the United Kingdom has indicated that substantial quantities of the offending indicator bacteria may be conveyed in surface water runoff from the catchments of rivers and small streams in response to rainfall events. There have been indications too that the use to which land in a catchment is put (pasture, forestry, urban, and so on) is reflected in the levels of indicator bacteria contributed by the land to water.

Two principal questions arise:-

1. Are failures to meet microbial water-quality standards for bathing areas due to rainfall-related runoff from adjacent catchments?

2. If so, is this effect related to land uses in the catchments?

This report gives an account of work addressing these issues conducted in the Afon Rheidol and Afon Ystwyth catchments in north Ceredigion, Wales and in the Dargle catchment in north Co. Wicklow, Ireland. The catchments in both areas drain to the sea through harbour outlets close to bathing beaches, and the beaches have had imperfect compliance with the Bathing Water Directive in the past.

The study had three main components:-

(a) A retrospective study involving collection and statistical analysis of past bacteriological water-quality data, rainfall and other related environmental parameters, with a view to identifying the reasons for past bathing water-quality compliance failures.

(b) Preparation of indicator-bacteria "budgets" to show the numbers of indicator bacteria coming from all types of catchment sources which might impact on bathing water quality. Budget preparation required water sampling to enumerate indicator bacteria, water-flow measurements to quantify the amounts of runoff from the catchment, and field surveys to classify land use. Frequent microbiological sampling and flow measurements were carried out both in quiescent weather conditions with low river flow, and in high-rainfall conditions when there was high runoff and river flow. Indicator-bacteria budgets then were prepared for "low-flow" and "high-flow" conditions, and their impact on bathing water quality was examined.

(c) Development of statistical models relating the impacts of land use and rainfall to river water quality within the catchment.

A brief overview of the main findings now follows. Note that a comprehensive, detailed summary is given at the end of this Report.

(a) Retrospective Study

Examination of past records for Wales showed that after improvements were made to the sewerage infrastructure at Aberystwyth, there was significant improvement in microbial water quality. Nevertheless, the beaches at Aberystwyth still failed to achieve overall compliance with the indicator-bacteria criteria necessary for “blue flag” status. Moreover, the water quality of these bathing sites showed marked dependence on prevailing environmental conditions. For the beaches at Bray, an association between high-rainfall events and compliance failure was immediately evident from past records.

(b) Indicator-bacteria “Budgets” and Beach Compliance

Rivers and streams in the Dargle and Rheidol/Ystwyth catchments showed an increase in indicator-bacteria concentrations (typically by an order of magnitude) in response to rainfall. Water samples from Aberystwyth and Bray beaches showed elevated indicator-bacteria concentrations, in excess of those specified in standards of the Bathing Water Directive during wet-weather conditions, when loadings from the catchments were greatest. The Kilmacanogue stream, a tributary to the Dargle, was an exception to this, as its mean concentration during low-flow (dry-weather) conditions was greater than during high-flow conditions.

The Afon Ystwyth during high-flow conditions and the Tan-y-cae combined sewer outfall (CSO) were the dominant contributors of the indicator-bacteria load to nearshore waters at Aberystwyth. The introduction of ultraviolet disinfection of the sewage effluent at Aberystwyth has reduced the load from that source by more than 95%.

The above general weather-related pattern was particularly pronounced at Aberystwyth south beach, which is closest to the river outlet at Aberystwyth harbour. Thus, despite the dramatic reduction in indicator-bacteria load achieved by sewage effluent disinfection at Aberystwyth the remaining high-flow load from the Afon Ystwyth and Tan-y-cae CSO was enough to produce “fail” conditions. At Aberystwyth north beach, which is remote from the river outlet at Aberystwyth harbour, the indicator-bacteria load was dominated during high-flow conditions by the Nant Penglais stream that discharges directly onto the beach. Failure to meet microbial water-quality standards at the north beach may have related to the load from this stream and close proximity to the bathing-water compliance monitoring site.

Turning to the Dargle catchment, most of the indicator-bacteria load originating upstream of Bray harbour in high-flow conditions, was from the Enniskerry outfall and the Dargle river itself. A lesser, but still highly significant contribution, was provided by the Swan and Glencullen rivers. In low-flow conditions the Enniskerry outfall was the biggest contributor with the Dargle and Kilmacanogue rivers also major contributors. Generally the

Enniskerry outfall contributed more bacteria than the entire Dargle catchment upstream of that outfall. During the ten-day period of intensive high-flow analysis, the Bray storm overflow contributed slightly more bacteria during a total of seven hours discharge than the rest of the Dargle catchment contributed over the entire ten-day period and was the major source of bacteria. At Bray harbour, microbial water quality was poor even during dry-weather conditions and it deteriorated greatly during rainfall events when the geometric means for the three categories of indicator bacteria all increased by about one order of magnitude.

Bray south beach showed deterioration in water quality in response to rainfall events. The geometric means for total coliforms and faecal coliforms increased by about one order of magnitude and there was about an approximately three-fold increase for faecal streptococci. There was a strong indication that the Bray storm overflow was associated with this. If the compliance of Bray south beach with the EU Bathing Water Directive was to be judged on the results obtained during this study, it would have failed to comply with both the *Guideline* and the *Imperative* criteria in 1999 and with the *Guideline* criteria in 2000.

The Kilruddery stream, which discharges directly onto Bray south beach, showed poor microbial water quality in dry-weather conditions and grave deterioration in this was evident in rainfall conditions. These preliminary observations created concern about the impact of the stream on bathing-water quality at Bray south beach.

(c) Statistical Modelling

For the Afon Rheidol and Ystwyth catchments, regression modelling showed that the proportion of improved pasture in subcatchments was the dominant predictor of indicator-bacteria concentrations in rivers and streams in high-flow conditions. At low flow the most significant predictor was the proportion of built-up land. A series of highly significant multivariate regression models associating water quality with land use were produced for the Welsh catchments under low- and high-flow conditions. The models, based on lumped subcatchment land-use data, land use in buffer strips around the stream network, and land use in various zones upstream of each stream sampling point, typically explained over 70% of the variance in indicator-bacteria concentrations.

For the Dargle catchment, there was a strong and consistent positive correlation between the proportion of built-up land and the concentrations of indicator bacteria. These correlations were slightly stronger for non-storm periods than for storm periods. A definite curvilinear relationship between indicator-bacterial concentrations and the proportion of built-up land was established and indicated a distinct gradual fall-off in the rate of increase of the indicator-bacteria concentrations with increasing proportion of built-up land. This was interpreted as perhaps reflecting an improvement in the control of seepage of sewage from higher built-up land densities. A significant negative correlation emerged between indicator-bacteria concentrations and the proportion of forest. Regression equations relating land-use categories with indicator-bacteria concentrations explained approximately 50% of the variance in the concentrations.

Implications and Remediation Potential

At Aberystwyth reduction in the spill from the Tan-y-cae CSO would provide a significant reduction in the indicator-bacteria load discharging to nearshore waters. Likewise, improved control of storm overflow from Bray would reduce the impact of high-flow conditions on the microbial pollution of Bray south beach. The remaining indicator-bacteria load from the Dargle catchment would still be substantial, bearing in mind the loading from urban streams and from the Enniskerry outfall. However, the impact of remedial measures on bathing area compliance would be difficult to predict with acceptable scientific certainty without detailed hydrodynamic and tracer studies. Such studies could also be used to examine the impact of local stream inputs to Aberystwyth north beach and to Bray south beach and to point to appropriate remedial measures.

In conclusion, this study demonstrated that the microbial water quality of bathing areas was vulnerable to rainfall-related runoff from adjacent rivers in a manner that related to the patterns of catchment land use. The study gave further support to the conclusions of earlier studies for the UK, and importantly, tested their applicability outside the UK in a second member state, introducing a new multidisciplinary research team and a fresh approach to this area of research. It built on the previous UK studies in other important ways. For example, it contributed to the mixture of catchment types that have been investigated, furnishing additional mixtures of land use, important to the development of a broadly-applicable statistical model yielding valuable insights for the management of this source of bathing-water pollution.

Abbreviations

mS: micro-Siemens
AS: activated sludge
BFI: base flow index
cfu: colony-forming units
CREH: Centre for Research into Environment and Health
CSO: combined sewer outfall
DC/WW: Dwr Cymru/Welsh Water
DED: District Electoral Division
DTM: digital terrain model
EA: Environmental Agency
EC: European Community, and also Enterococci
EEC: European Economic Community
EPA: Environmental Protection Agency
EU: European Union
FC: faecal coliforms
FS: faecal streptococci
GIS: geographical information system
GM: geometric mean
GMT: Greenwich mean time
ha: hectare
hr: hour
IGER: Institute of Grassland and Environmental Research
km: kilometre
l: litre
log$_{10}$: logarithm to the base ten
m: metre
MAX: maximum
MIN: minimum
mm: millimetre
n: number of samples
NGR: national grid reference
O.D.: ordnance datum
OS: Ordnance Survey
REP: Rural Environment Protection
s: second
SD: standard deviation
SPSS: statistical package for the social sciences
STP: sewage treatment plant
TC: total coliforms
UK: United Kingdom
UV: ultraviolet
WCC: Wicklow County Council
WwTW: waste water treatment works
WWW: world wide web

1 Introduction

This report has two main components. The first examines relationships between bathing water compliance monitoring data (faecal indicator organism concentrations) collected by the Environment Agency (EA) in Wales and Local Authorities in Ireland and antecedent environmental conditions. Data describing environmental conditions include river discharge and meteorological records. Relationships between environmental descriptors and faecal indicator organism concentrations at four north Ceredigion beaches (Aberystwyth North, Aberystwyth South, Clarach and Borth) in Wales are explored using a statistical modelling approach developed for investigations of the Fylde coast (north-west England) (Crowther *et al.*, 1999a, 1999b, 2001) and the Ayrshire coast (west Scotland) (Kay *et al.*, 1998). Also, faecal indicator organism concentrations and rainfall amounts are correlated for three beach sites at Bray, Co. Wicklow, Ireland.

The second component presents the results of a detailed investigation of faecal indicator sources and budgets for the Afon Rheidol and Afon Ystwyth catchments discharging to the north Ceredigion coast at Aberystwyth in Wales and the Dargle catchment discharging to the Co. Wicklow coast at Bray in Ireland. This investigation explores: (i) the budgets of faecal indicator organisms from sewage and riverine sources, and (ii) relationships between land use and faecal indicator organism concentrations within the river catchments. The latter aspect of the study aims to focus on potential catchment derived sources of faecal pollution which may contribute to compliance failures against EC Directive 76/160/EEC standards at the adjacent beaches. Similar catchment investigations by CREH in the United Kingdom have examined faecal indicator organism sources and budgets in the following areas: the Island of Jersey (Wyer *et al.*, 1994, 1996a), the Staithes Beck catchment (North Yorkshire) (Wyer *et al.*, 1996b, 1998b), the Afon Nyfer catchment (Pembrokeshire) (Wyer *et al.*, 1997a, 1998b), the Afon Ogwr catchment (south Wales) (Wyer *et al.*, 1998a), the Holland Brook (Clacton) catchment (Essex) (Wyer *et al.*, 1999a) and the River Irvine and Water of Girvan catchments, Ayrshire (Wyer *et al.*, 1999b). The current study aims to contribute further to generic modelling of relationships between land use and water quality based on data from these studies.

2 Retrospective investigation of relationships between environmental conditions and faecal indicator concentrations

The aim of this section of the study is to investigate variations in enteric bacterial concentrations in coastal bathing waters and their relationship with environmental conditions at, and immediately prior to the time of sampling over the number of years for which appropriate records are available. The principal objectives were: (i) to investigate inter-site variations in concentrations of total coliforms (TC), faecal coliforms (FC) and enterococci (EC) and in rates of compliance with Directive 76/160/EEC *Imperative* concentrations (10,000 and 2,000 cfu 100 ml^{-1}, respectively, for TC and FC) and *Guide* concentrations (500, 100 and 100 cfu 100 ml^{-1}, respectively, for TC, FC and EC) (EEC, 1976), and (ii) to establish whether there are significant statistical relationships between microbial water quality and environmental conditions at, and immediately prior to, the time of sampling.

2.1 The four north Ceredigion beaches in Wales

Data for four monitoring points north of the Afon Ystwyth/Rheidol outlet in Aberystwyth Harbour over the six years 1993-1998 was investigated. The monitoring points are Aberystwyth South (EA bathing water reference: 38800; ngr: SN579814), Aberystwyth North (38900; SN583822), Clarach (38920; SN586837) and Borth (39000; SN606901) (Figure 2.1). The environmental parameters investigated are river discharge to the coastal zone (based on data for the Afon Ystwyth at Pont Llolwyn), daily rainfall, 3-hourly wind direction and mean daily wind speed, daily sunshine (meteorological data from the IGER station at Gogerddan, ngr: SN627835) and tidal conditions. The approach adopted is the same as in recent studies of the Cumbrian and Fylde coasts (Crowther *et al.*, 1999a, 1999b; Kay *et al.*, 1998, Crowther *et al.*, 2001). The study also enables an assessment to be made of the impact on bathing water quality of the Aberystwyth waste water treatment works (completed in April 1995) and improvements to the sewerage infrastructure in the Clarach catchment (completed in January 1996). This additional objective, then, was to determine whether there has been a significant change in bathing water quality since completion of the sewerage schemes.

2.1.1 Data limitations and methods of analysis

2.1.1.1 Limitations of microbial data

It should be noted at the outset that the microbial data available for the four monitoring points are not ideal in that on many occasions absolute enumerations were not made (i.e. a ‘less than’ or ‘greater than’ value was recorded). Thus, of the 482 enumerations made for each of the three microbial determinands, the numbers of samples for which the values were recorded as being ‘less than’ for TC, FC and EC were 57, 105 and 55, respectively. Corresponding figures for ‘greater than’ values were 1, 0 and 5. Values in the ‘greater than’ category are particularly problematic, as there is no consistency in the concentration beyond which no absolute determinations were made. As in previous studies, the latter data have been eliminated in determining mean concentrations for the individual sites, and in the correlation, regression and t-test analyses undertaken. For the ‘less than’ values, the detection limit values have been used. This leads to some clustering within the data (particularly at 1, 10 and 100 cfu 100 ml^{-1}) and a potential over-estimation of the mean concentrations, but is considered preferable to eliminating such high proportions of data at the lower end of the concentration range.

In all cases where a ‘greater than’ value has been recorded, the figure exceeds the EC *Imperative* concentrations for TC and FC and the *Guide* concentration for EC. These values have therefore been included in calculating rates of compliance.

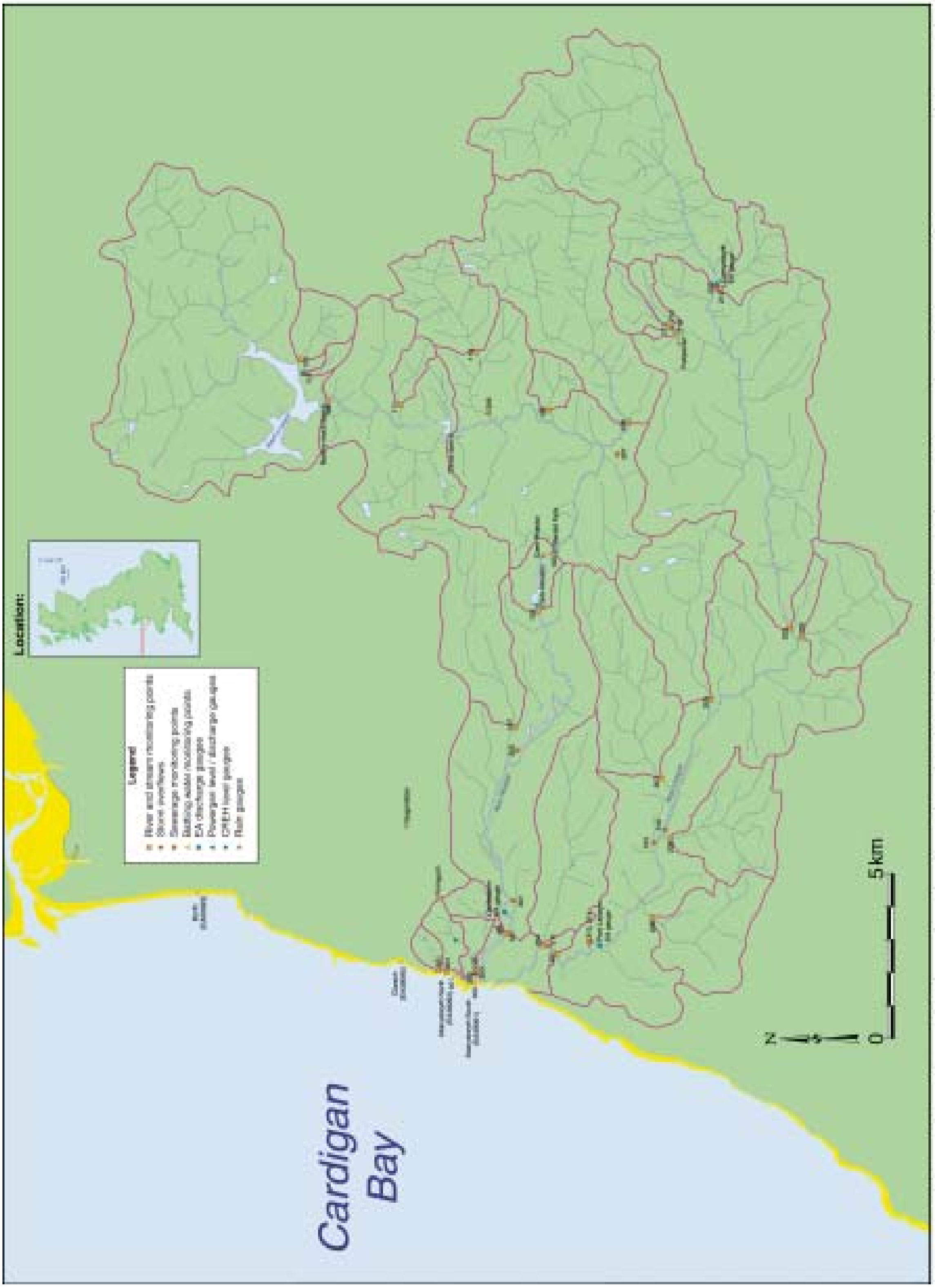


Figure 2.1. Location of monitoring sites in the Afon Rheidol/Afon Ystwyth catchment (based on Ordnance Survey map information)

Data for the monitoring point at Clarach, which is located south of the Afon Clarach, are available only for 1993-5 and 1998 bathing seasons. In fact, Clarach South beach was not identified officially until 1998. In 1996 and 1997 samples were taken at a different sampling point (SN585840) to the north of the river, which is here referred to as 'Clarach North'. Unfortunately, no record was made of the time of sampling at Clarach North, and data are therefore lacking for tidal conditions at the time of sampling. Because of the smaller sample size and other data limitations, only a more restricted programme of statistical analysis has been possible for the Clarach data.

2.1.1.2 Selection of environmental parameters

Previous studies (Fewtrell *et al.*, 1998; Wyer *et al.*, 1996a, 1996b, 1997a, 1997b, 1997c, 1998a, 1998b, 1999a, 1999b) have clearly established two key non-outfall sources of microbial organisms to coastal waters: (i) CSO discharges from coastal towns; and (ii) streams/rivers. Microbial loadings from both these sources increase very markedly following rainfall. In addition, it is well established that enteric bacteria die off more rapidly when waters are exposed to direct sunlight. Previous modelling studies have also identified wind and tidal conditions as significant factors affecting microbial concentrations in coastal bathing waters (Crowther *et al.*, 1999a, 1999b; Kay *et al.*, 1998). Attention therefore focused upon rainfall, river discharges, hours of sunshine, wind direction, wind speed and tidal conditions. In the case of the wind direction, the proportion of time with winds from the following directions was used in the analysis: 165-15° (onshore), 105-285° (south) and 165-255° (southwest). Data for all these parameters were obtained for the day of sampling (referred to as 'day 1') and for each of the two days prior to sampling ('day 2' and 'day 3').

2.1.1.3 Value and limitations of discharge data

Previous studies have demonstrated that rivers are potentially important sources of faecal indicator organisms (Fewtrell *et al.*, 1998; Wyer *et al.*, 1996a, 1996b, 1997a, 1997b, 1997c, 1998a, 1998b, 1999a, 1999b). In addition, however, river flow is likely to exhibit strong covariance with discharges to the coastal zone from sources for which routine data are not available, such as smaller streams, WwTW effluent and CSOs. In view of this, and the obvious covariance with weather conditions, any relationships between river discharge and microbial concentrations in sea water cannot be assumed to infer causality. However, if relationships do exist, these undoubtedly demonstrate that antecedent environmental conditions do play a significant role in influencing coastal bathing water quality. In previous studies a range of rivers with different-sized catchments and different response rates to rainfall have been included, so as to increases the chances of successfully detecting a relationship with antecedent environmental conditions, if one exists. Unfortunately, the only complete set of river discharge data for the study period is for the Afon Ystwyth, which has a relatively large catchment. It should be noted, therefore, that flows which have a more flashy response to rainfall (e.g. smaller rivers and CSOs) are poorly represented in the present data set.

2.1.1.4 General approaches to statistical analysis

Throughout the study, microbial concentrations have been expressed as $\log_{10}$ values. Mean values are expressed as 10^x, where x is the mean of the $\log_{10}$ transformed values, i.e.

geometric mean (GM). Student's t-test has been used to establish whether there are statistically significant differences in GM microbial concentrations between pairs of data sets (e.g. to establish whether there are significant differences in GM microbial concentrations according to whether or not rainfall occurred in various antecedent time periods prior to sampling).

Two approaches were adopted to investigate possible relationships between $\log_{10}$ enteric bacterial concentrations in bathing waters and the various environmental parameters. First, stepwise multiple regression analysis (as detailed below) was undertaken to establish the extent to which variations in enteric microbial concentrations can be predicted from river discharge, sunshine, wind speed, wind direction and tidal conditions. Unfortunately, antecedent rainfall could not be included in the multiple regression analysis because of the high proportion of zero values for this variable. The effects of antecedent rainfall were therefore investigated separately. In this second approach, t-tests were undertaken to establish if there are significant differences in microbial concentrations according to whether or not rainfall occurred in various antecedent time periods. In addition, the t-tests were repeated with the data split according to whether or not ≥5.0 mm of rain fell prior to sampling, in order to establish whether the amount of rainfall is a critical factor. Rainfall amounts of <5.0 mm, for example, may be insufficient to cause a marked hydrological response in the major rivers, but may be sufficient to affect volumes of flow in the sewerage infrastructure.

All the statistical tests were assessed at $\alpha = 0.05$ (i.e. 95% confidence level).

2.1.1.5 Multiple regression analysis

GM TC, FC and EC concentrations were used as dependent variables (y), predicted by independent, or predictor, variables (x_i), which were the various environmental parameters. The statistical distribution of each independent variable was examined and $\log_{10}$ transformations applied in cases where skewness exceeded a value of 1.0. The transformation was used to reduce skew in the data and improve parametricity, thereby enhancing the distribution of residual values (i.e. deviation between actual value and that predicted by a model).

These variables were used to examine multivariate relationships between the environmental and water quality data, of the form:

$$y = a1\ x1 + \ a2\ x2\ .....\ a_i\ x_i + b \pm u \quad \text{where:}$$

a = slope (change in y per unit change in x)
b = intercept (y at $x = 0$)
u = stochastic disturbance or random error term

The strength of any relationship was assessed from the coefficient of determination (r^2), which indicates the proportion (expressed as a percentage) of variance in y explained by the independent variables in the model. The modelling was undertaken using the SPSS forward selection stepwise procedure (SPSS, 1988). The entry of variables to an equation was controlled using a tolerance value to limit multicollinearity between independent variables. This excluded all predictor variables which have an explained variance of ≥50% with predictor variables already entered in the model (i.e. strongly inter-correlated predictor variables ar excluded). All values of r^2 derived from regression models were adjusted for degrees of freedom, accounting for the number of variables in the equation (Minitab, 1995). Regression models should conform to assumptions of parametricity, an important assump-tion being that residual values should be normally distributed. This was assessed by visual inspection of normal probability plots of standardised residuals.

2.1.2 Environmental conditions during the retrospective study period

Rainfall and sunshine data for the six bathing reveal marked variations in the total figures from year to year, with 1995 and 1996 standing out clearly as drier (rainfall: 227.2 and 306.2 mm, respectively) and sunnier summers (sunshine: 1143.4 and 1113.4 hours). In view of the fact that lower rates of compliance are more likely in wetter summers, because of higher flows in the sewerage system and greater runoff from land, the contrasts in weather conditions over the study could potentially preclude meaningful comparisons of microbial data before and after completion of the new sewerage infrastructure. Fortunately, however, rainfall and sunshine totals for the wetter summers of 1993 and 1994 are very similar to those of 1997 and 1998. Data for these four years have therefore been used in assessing the impact of the new sewerage infrastructure schemes.

2.1.3 Enteric bacterial concentrations during the retrospective study period

2.1.3.1 Overall summary and comparison of microbial concentrations before and after completion of new sewerage schemes

Annual summaries of the microbial concentrations for each of the sites are presented in Figure 2.2. These results highlight the very marked temporal variability in the concentrations of TC, FC and EC that occur at the individual monitoring points, with all three determinands typically having maximum concentrations which are 100 to 1000 times higher than the minimum values recorded. In 1993/4, the highest GM concentrations were recorded at Aberystwyth South (TC and EC: 9.3×10^2 and 5.7×10^1 cfu 100 ml^{-1}, respectively) and Clarach (FC: 2.5×10^2 cfu 100 ml^{-1}), and the lowest at Borth.

The results of the t-tests show a highly significant reduction in the GM concentrations of all three determinands at Aberystwyth South following completion of the new sewerage infrastructure. For TC, the reduction is by an order of magnitude (from 9.3×10^2 to 9.2×10^1 cfu 100 ml^{-1}). There are also highly significant reductions in TC and EC at Aberystwyth North. These results suggest that the new sewerage infrastructure has improved bathing water quality at these sites. There is also marked reduction in GM TC at Clarach (from 8.4×10^2 in 1993/4 to 3.2×10^2 cfu 100 ml^{-1} in 1998), and had data been available for 1997 then the difference may well have been statistically significant. However, the overall level of improvement achieved at Clarach is less than at the two Aberystwyth sites. Indeed, in 1998, which is the year for which comparable data are available, Clarach had the highest GM concentrations for all three determinands. The fact that no significant differences were recorded at Borth is assumed to reflect the low GM concentrations at this site in 1993/4 and its greater distance from the new sewerage schemes.

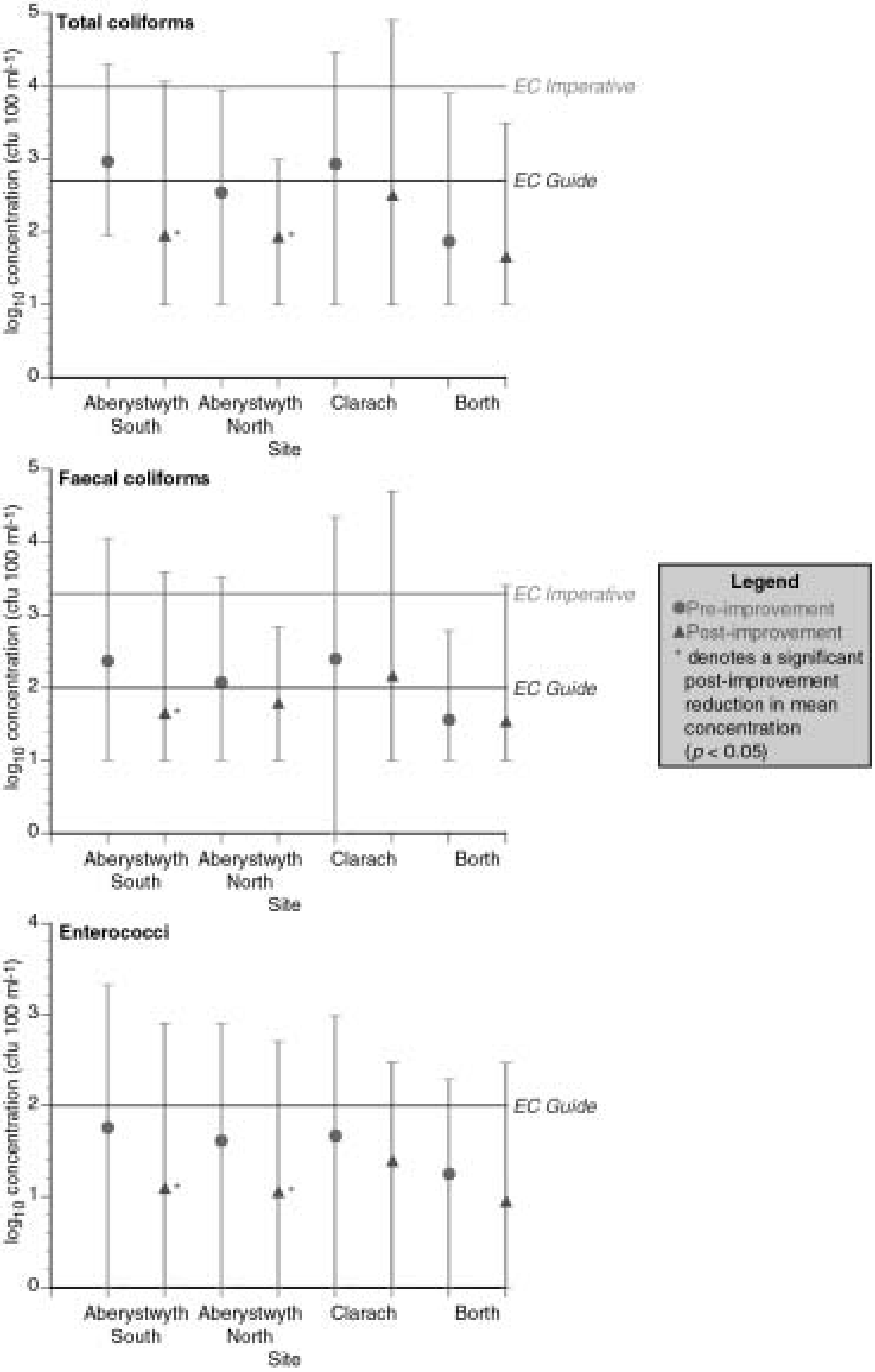


Figure 2.2. Mean and range of $\log_{10}$ transformed faecal indicator concentrations (cfu 100ml^{-1}) (excluding 'greater than' values) at Aberystwyth, Clarach and Borth beaches before and after improvements to the sewerage infrastructure.

2.1.3.2 Rates of compliance before and after completion of the new sewerage infrastructure

Aberystwyth North and Borth were already achieving 95% compliance in 1993/4. At Aberystwyth South and Clarach water quality in years 1993 and 1994 failed to meet this target, but has done so in the years since completion of the sewerage infrastructure.

In terms of *Guide* concentrations, Aberystwyth South, Aberystwyth North and Clarach all show an increase in percentage compliance in 1997/8 compared with 1993/4. In the case of the two Aberystwyth sites, the results for TC and EC in 1997 and 1998 achieved the required 80% compliance, though the results for FC fall short of this, especially at Aberystwyth North, where compliance in 1997 and 1998 was 60%. Despite a marked reduction in GM concentrations at Clarach, the beach failed to achieve 80% compliance in respect of any of the microbial determinands in 1998 (or in 1997 at Clarach North). Again, the main problem occurs with FC, which achieved only 35% compliance in 1998. Borth has consistently achieved 80% compliance for TC and EC since 1996. The results for FC are, however, less consistent, with only 65% compliance being achieved in 1998.

2.1.3.3 Inter-relationships between TC, FC and EC concentrations

The concentrations of the three faecal indicator organisms are strongly inter-correlated. The strongest relationships ($p<0.0001$) at each site are between $\log_{10}$ TC and FC concentrations, with correlation coefficients as high as 0.9266 (at Clarach). The fact that there are weaker relationships with EC suggests that this determinand may be affected, at least partially, by different factors than TC and FC. This finding is in keeping with the results from previous studies.

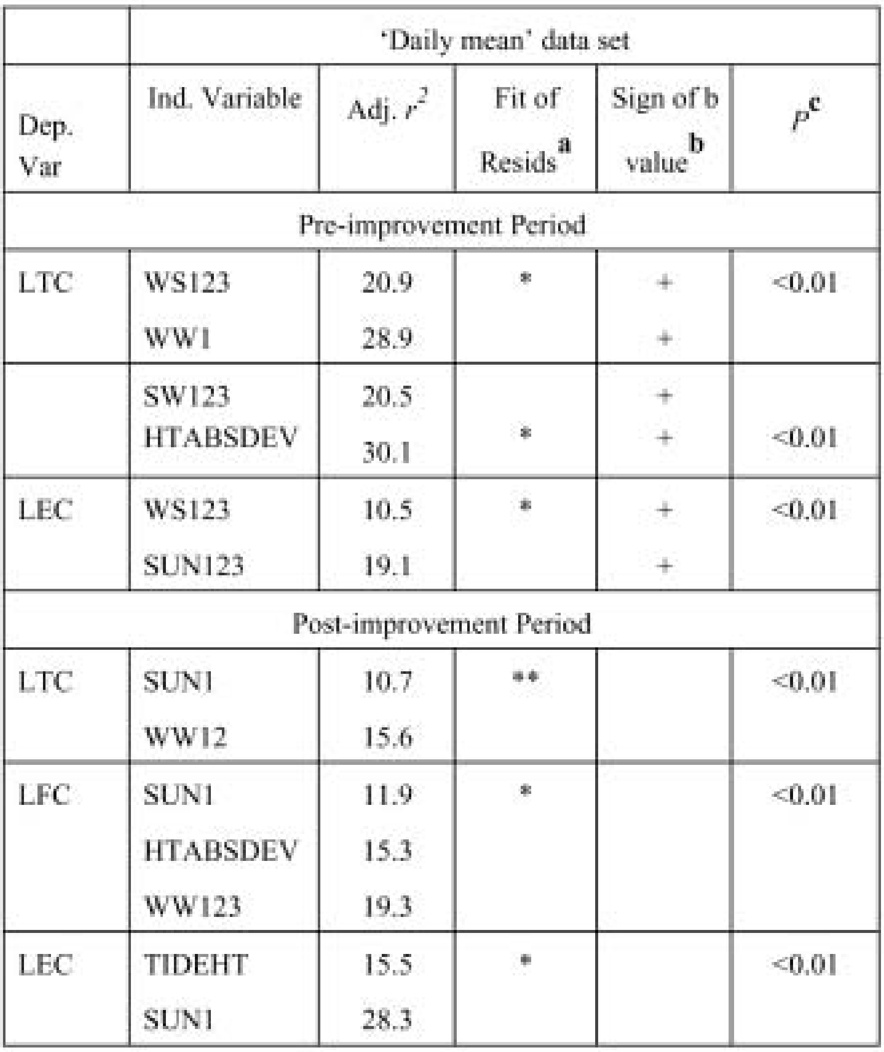
2.1.4 Relationships between microbial concentrations and environmental parameters

2.1.4.1 Results of regression analysis

Table 2.1 provides a summary of multiple regression results predicting enteric bacterial concentrations at the Aberystwyth South compliance point. Full predictor descriptions, as well as analyses for three adjacent compliance points are presented in the full report (Wyer et al., 2000). This analysis has been completed for the pre-improvement and post-improvement periods.

It is perhaps worth noting that the results from Aberystwyth exhibit lower r^2 values than previous work in Scotland and the North West of the UK. However, the coliform parameters do show a decrease in explained variance after completion of the sewage treatment scheme.

Table 2.1. A multiple regression analysis to predict faecal indicator concentrations at the Aberystwyth South compliance point.



	'Daily mean' data set				
Dep. Var	Ind. Variable	Adj. r^2	Fit of Resids[a]	Sign of b value[b]	P^c
Pre-improvement Period					
LTC	WS123	20.9	*	+	<0.01
	WW1	28.9		+	
	SW123	20.5		+	
	HTABSDEV	30.1	*	+	<0.01
LEC	WS123	10.5	*	+	<0.01
	SUN123	19.1		+	
Post-improvement Period					
LTC	SUN1	10.7	**		<0.01
	WW12	15.6			
LFC	SUN1	11.9	*		<0.01
	HTABSDEV	15.3			
	WW123	19.3			
LEC	TIDEHT	15.5	*		<0.01
	SUN1	28.3			

LTC: Log_{10} Total coliforms
LFC: Log_{10} Faecal coliforms
LFS: Log_{10} Faecal streptococci
WS123:mean wind speed on days d1 (sampling day), d2 (previous day) and d3 (two days previously)
WW1: proportion of wind from the west on d1
HTABSDEV: Time of sampling in relation to nearest high tide
SUN123: Sunshine hours on days d1, d2 and d3
SUN1; Sunshine hours on day d1
WW12; Proportion of wind from the west on days d1 and d2
WW123 Proportion of wind from the west on days d1, d2 and d3
TIDEHT; Height of the tide (m) at the time of sampling

Note a: Fit of standardised residuals to normal plot:
**: good fit
*: acceptable fit
b: This indicates whether the relationship is positive (+) or negative (-).
c: Significance stated at α=0.01 (99% confidence level).

2.2 Bray beach sites, Co. Wicklow, Ireland

A review of retrospective beach compliance results (1989-1998) and meteorological records was undertaken. Indicator-bacteria levels found for water samples taken during this period at Bray south beach, Co. Wicklow, Ireland (Figure 2.3), at the south end of the promenade opposite Dawson's Amusements (O32752180), at the north end opposite the former National Aquarium building (O32732184) and at Bray north beach (O32682194) were obtained from Wicklow County Council. The daily (9.00 am – 9.00 am) rainfall amounts (mm) recorded at Kilmalin (near Enniskerry village) were obtained from Met Eireann (Irish meteorological service).

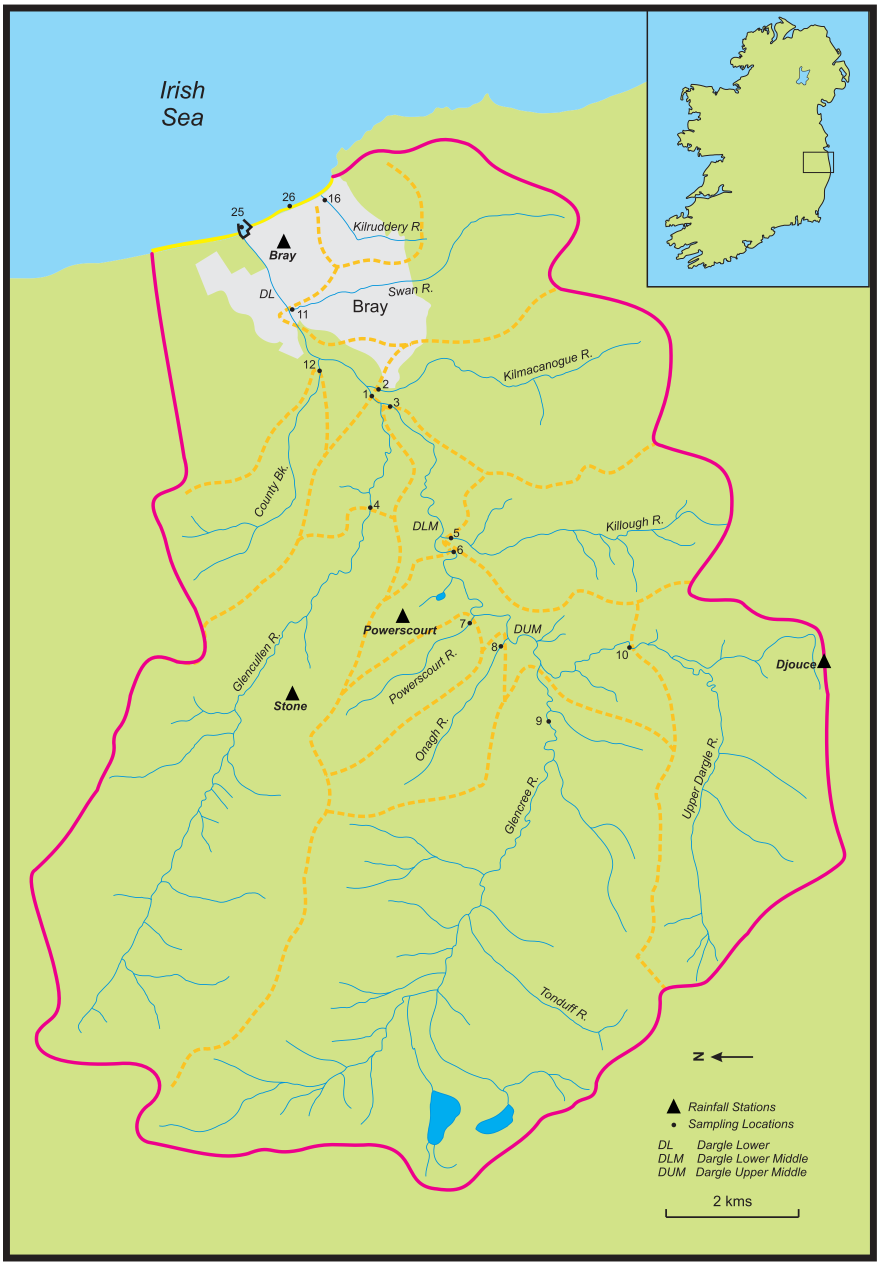


Figure 2.3. The Dargle catchment and its subcatchments, Co. Wicklow, Ireland, showing Bray harbour and beach which face eastwards. The locations of rain gauges and water-quality sampling stations are shown.

2.2.1 General approaches to statistical analysis

Microbial concentrations have been expressed as $\log_{10}$ values. The mean of these logarithms can be described also as the logarithm of the geometric mean of the bacteriological concentrations and its antilogarithm gives the geometric mean (GM). Values below the lower limit of detection were changed to the value 1 to facilitate calculation of GM values; this procedure has negligible impact on the GM values, and also to allow investigation of Pearson's parametric correlations.

Unfortunately, no record was made of the time of beach sampling. Therefore little environmental data could be associated with the beach compliance data. Because of these limitations, it has been possible to investigate the impact of only a single environmental parameter, antecedent rainfall, and this with only moderate certainty. Microbial samples had been taken routinely in the morning time, as close to high tide as time constraints allowed. However, the daily aggregated rainfall was recorded from 09.00 hr on the record date to 09.00 hr on the following day. So, a rainfall record dated the day of sampling gave the amount of rain which occurred sometime between 09.00 hr on the sampling day until 09.00 hr on the day following. A record dated the day prior to the sampling day related to some period from 09.00 hr on the previous day until 09.00 hr on the sampling day; a record dated two days previously related similarly. Uncertainty about the period of rainfall and its coincidence with time of beach sampling prevented definitive analysis of the association between rainfall and microbiological water quality. However, the use of simple scatter-plots has yielded a useful perspective (2.2.3).

2.2.2 Enteric bacterial concentrations during the retrospective study period

Annual geometric mean (GM) microbial concentrations for each of the sites are presented in Figures 2.4 to 2.6. These results highlight the very marked temporal variability in the concentrations of TC, FC and FS that occur at the individual monitoring points along Bray beach. All three determinands typically have maximum concentrations which are 1 to 2 orders of magnitude higher than the minimum values recorded. The highest GM concentrations recorded were in 1989 at Bray north beach (TC and EC: 1697 and 980 cfu $(100\ \mathrm{ml})^{-1}$, respectively) and in 1998 at Bray north beach (FC: 23 cfu $(100\ \mathrm{ml})^{-1}$).

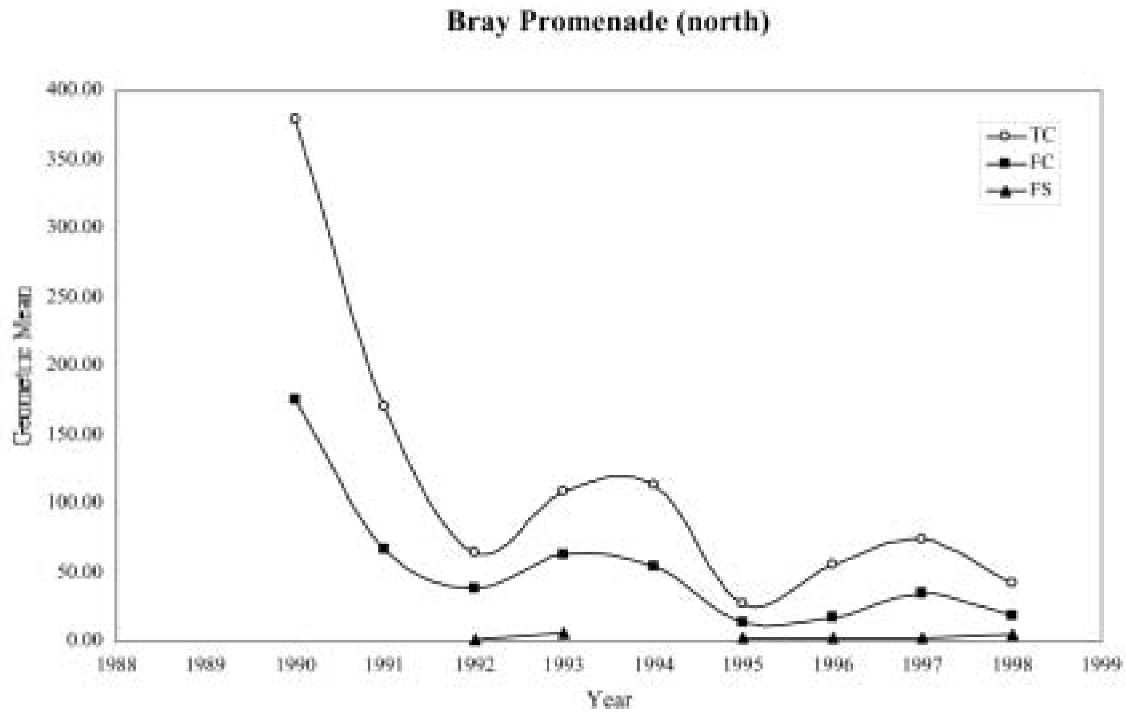


Figure 2.4. Annual geometric mean indicator organism levels for Bray Promenade (north) in the period 1990 to 1998 (TC: total coliforms, FC: faecal coliforms, FS: faecal streptococci (enterococci)).

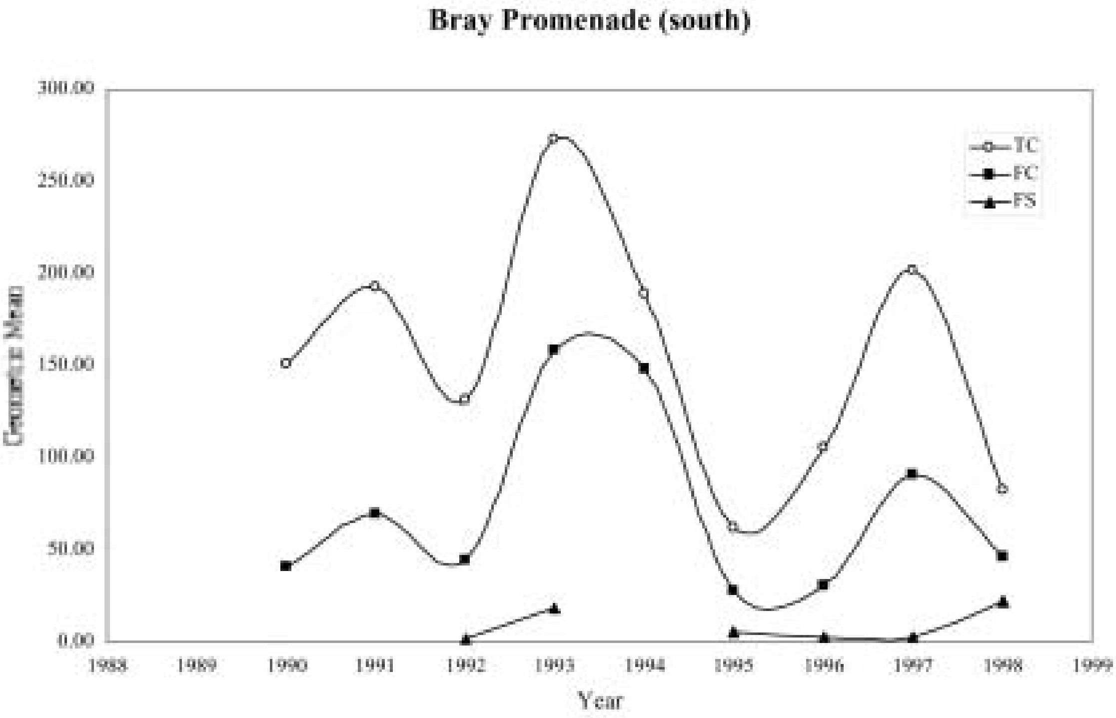


Figure 2.5. Annual geometric mean indicator organism levels for Bray Promenade (south) in the period 1990 to 1998 (TC: total coliforms, FC: faecal coliforms, FS: faecal streptococci (enterococci)).

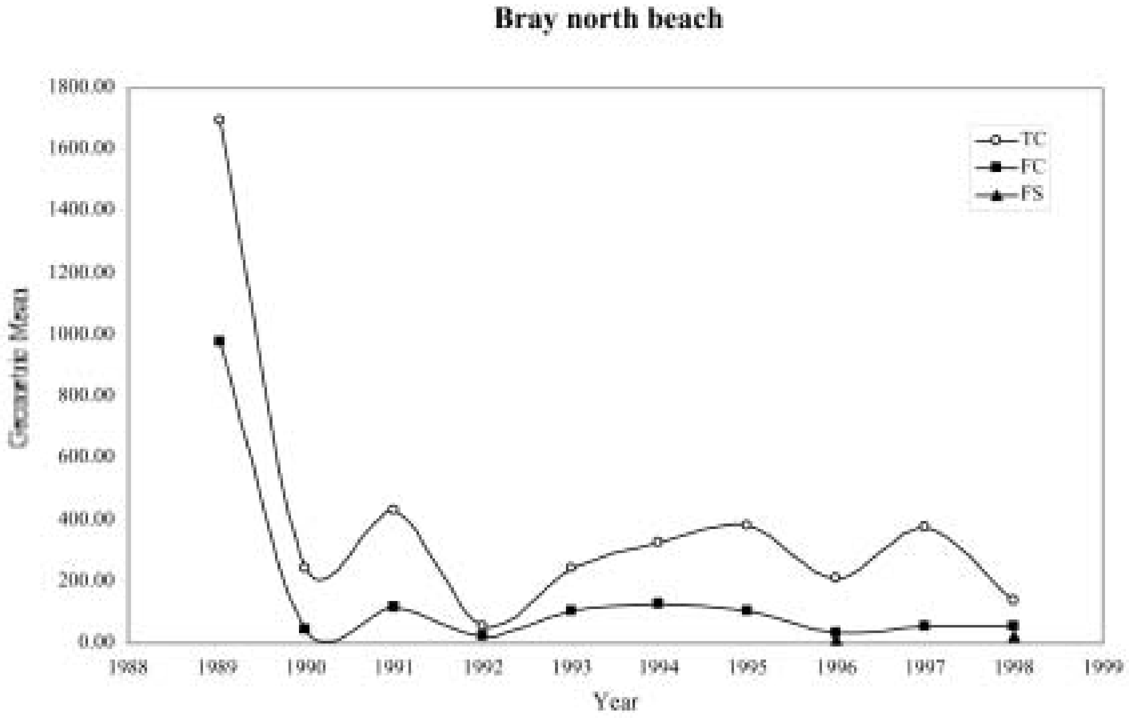


Figure 2.6. Annual geometric mean indicator organism levels for Bray north beach in the period 1989 to 1998 (TC: total coliforms, FC: faecal coliforms, FS: faecal streptococci (enterococci)).

The lowest recorded means were at Bray Promenade (north) in 1995 (TC and FC: 27 and 13 cfu 100 ml^{-1} respectively) and at Bray Promenade (south) (FC: 2 cfu 100 ml^{-1}). High levels of TC and FC were found in 1989 at north beach that is adjacent to Bray harbour into which the town sewage was then discharged. At that time the present sewage pumping station had not been commissioned; sewage is currently pumped one kilometre offshore and storm overflow is discharged at the outside of the north harbour pier.

2.2.2.1 Rates of compliance

Bray promenade south failed to comply with the EC Directive (76/160/EEC) *Imperative* standard in 1993, 1994 and 1995 and Bray promenade north in 1990. Bray north beach failed to comply with the *Imperative* standard in 1991 and 1993. None of the beaches complied with the *Guideline* standard during the period 1989-1998. Faecal streptococci data was available from 1993 onwards for Bray promenade north and south, but almost none for Bray north beach. Interestingly, although failing the *Guideline* standard for the other indicator organisms, these beaches complied with the standard for faecal streptococci in 1996 and 1997. North promenade complied with this standard also in 1998, and south promenade also in 1995. Had they been judged on this indicator alone, these two Bray beaches would have been significantly more compliant for the years when faecal streptococci were enumerated.

2.2.2.2 Inter-relationships between TC, FC and EC concentrations

The concentrations of the three faecal indicator organisms were strongly inter-correlated. The strongest relationship ($p<0.0001$) at each site was between $\log_{10}$ TC and $\log_{10}$ FC concentrations, with a correlation coefficient as high as 0.9159 for these concentrations at Bray promenade south. These correlations are evident in the trends displayed in Figures 2.4-2.6 above. Correlations with FS were weaker; this result is in agreement with the results from other studies.

2.2.3 Relationships between microbial concentrations and environmental parameters

The levels of total coliforms and faecal coliforms almost always exceeded EU Guideline levels at the three sampling sites at Bray Beach when rainfall in the 24 hour period prior to 09.00 hr on the sampling day was more than 15 mm (Figures 2.7-2.9). These levels sometimes exceeded the EU *Imperative* level; faecal streptococci levels were close to or sometimes exceeded the *Imperative* level. These observations demonstrate a *prima facie* association between high-rainfall events and failure in hygiene standards at the Bray beach sites. This is considered to be a substantial insight already revealed at this early stage of the project. It is important to point out that the data show a considerable scatter overall, indicating other contributing factors in addition to rainfall.

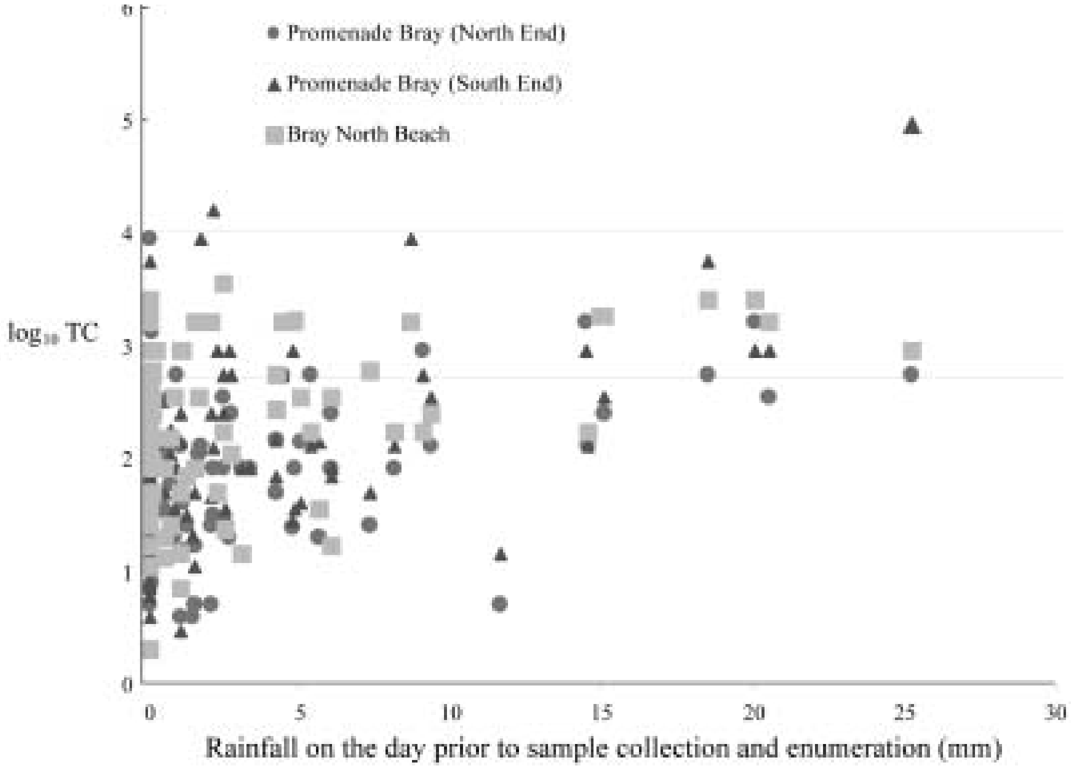


Figure 2.7. Log_{10} transformed total coliforms levels (cfu $(100\ \text{ml})^{-1}$) in samples taken at three sites on Bray beach are plotted against the corresponding total rainfall (mm) recorded at Kilmalin between 09.00 hr on the day when the samples were collected and 09.00 hr on the previous day. Horizontal lines show the EU Guideline and Imperative levels.

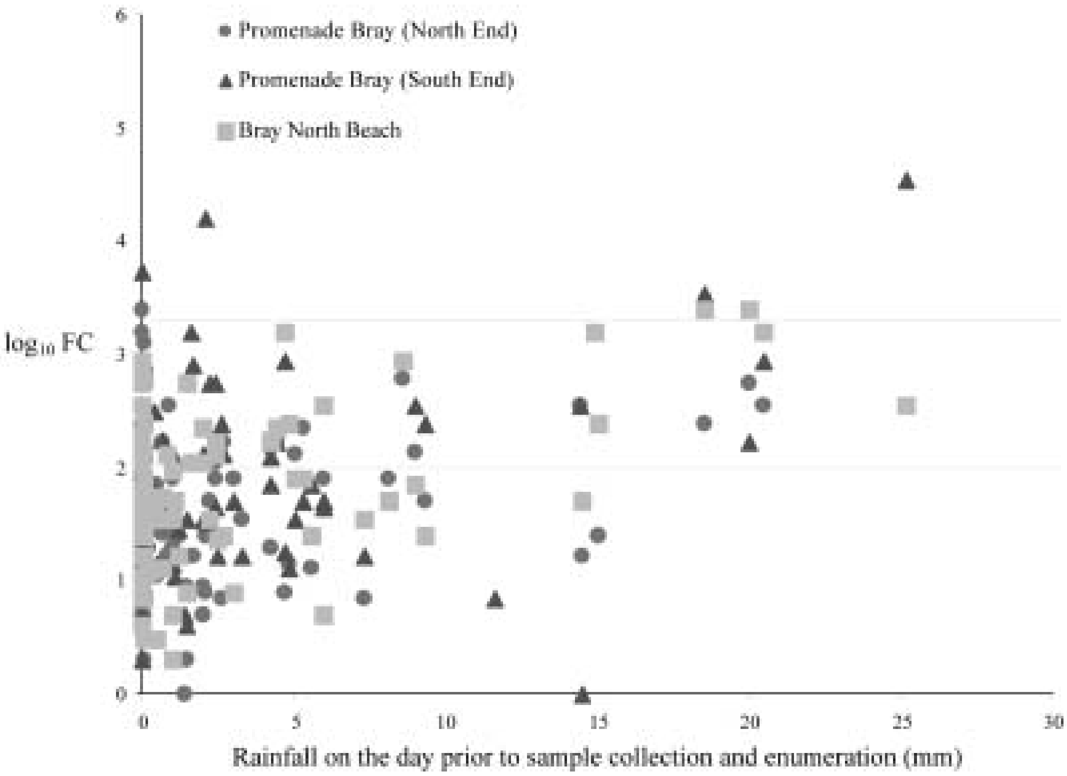


Figure 2.8. Log_{10} transformed faecal coliforms levels (cfu (100 ml)$^{-1}$) in samples taken at three sites on Bray beach are plotted against the corresponding total rainfall (mm) recorded at Kilmalin between 09.00 hr on the day when the samples were collected and 09.00 hr on the previous day. Horizontal lines show the EU Guideline and Imperative levels.

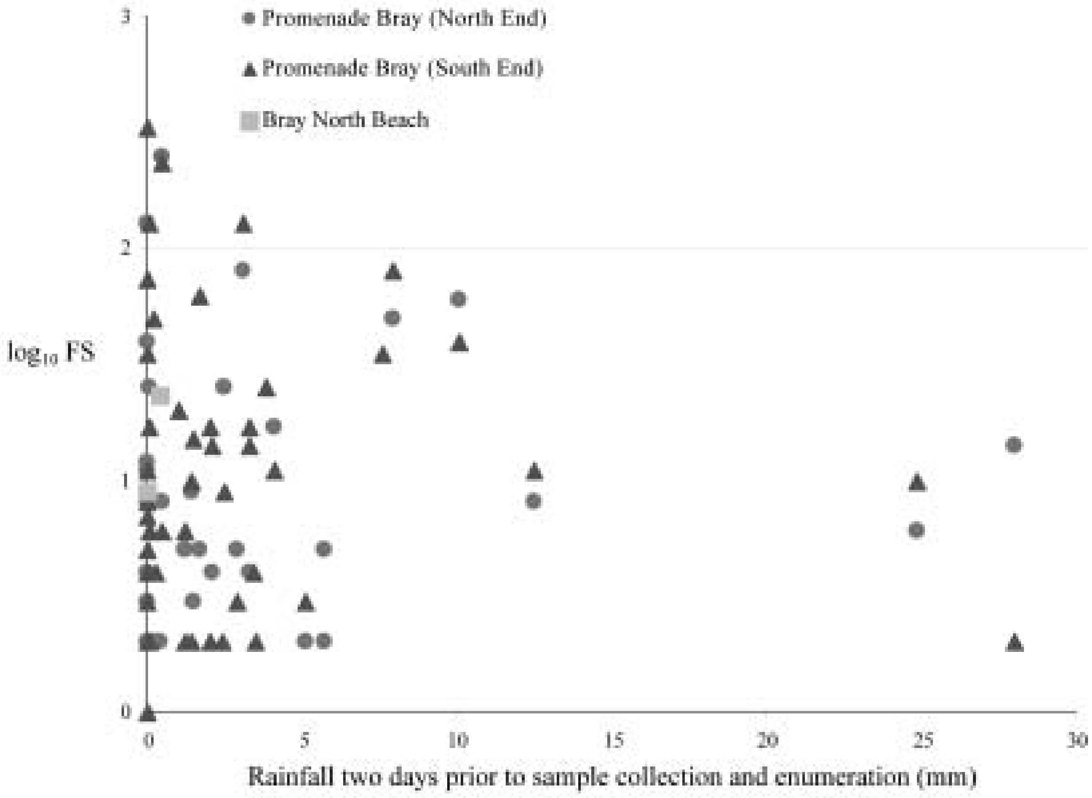


Figure 2.9. Log_{10} transformed faecal streptococci levels (cfu (100 ml)$^{-1}$) in samples taken at three sites on Bray beach are plotted against the corresponding total rainfall (mm) recorded at Kilmalin between 09.00 hr on the day when the samples were collected and 09.00 hr on the previous day. The horizontal line shows the EU Guideline level.

3 Faecal indicator sources, budgets and land-use relationships

This study has three main elements. The first examines the estimation of indicator organism, namely, total coliforms (TC), faecal coliforms (FC) and enterococci (faecal streptococci) (EC) budgets for the catchment system. Budget estimate studies include: (i) comparisons of contributions from riverine sources and inputs from sewage and (ii) an assessment the potential impact of sewage treatment scenarios. The second element assesses interactions between land use in the study catchment and river and stream water quality. The final focus is on marine faecal indicator organism concentrations at adjacent identified beach monitoring locations.

3.1 The study catchments

3.1.1 Wales: the Afon Rheidol and Afon Ystwyth catchments, north Ceredigion

The catchments of the Afon Rheidol and the Afon Ystwyth cover an area of 377 km^2 in north Ceredigion, the main rivers discharging to the coast via the harbour at Aberystwyth (Figure 2.1). The Afon Rheidol system (186 km^2) drains the northern part of the study area, flowing westwards from headwaters on the flanks of Pumlumon (maximum elevation 752 m

O.D. at Pumlumon Fawr (NGR: SN 789869)). The Afon Ystwyth system (191 km^2) flows westwards draining the southern part of the study catchment (maximum elevation 610 m O.D. at Pen y Garn (NGR: SN 798771)). With the exception of the town of Aberystwyth at the western margin of the catchment, the study area contains little urbanized land. In this respect, the catchment area is broadly similar to previous rural/pastoral study catchments (e.g. Staithes Beck and the Afon Nyfer) with a mixture of improved pasture in the lower reaches and unimproved pasture and moorland in headwater areas. However, the Rheidol/Ystwyth catchments contain more extensive areas of conifer plantation, similar to areas of the Ogwr and Irvine study catchments. In addition to the main river catchments, the study area incorporates two small stream systems (Nant Lover's Dingle and Nant Penglais, total area 2km^2) which drain directly to the north beach at Aberystwyth.

The Rheidol and Ystwyth catchments contrast markedly in terms of hydrology. Upstream of Cwm Rheidol (11 km inland) the discharge in the Afon Rheidol is managed for power generation via a series of reservoir impoundments. The first, and largest, is Nant-y-moch reservoir in the headwaters of the catchment (Figure 2.1). The second impoundment is 3km downstream at Dinas. The final impoundment, downstream of the confluence of the Afon Rheidol and Afon Mynach, is at Cwm Rheidol. The impact of such a highly managed hydrological regime on faecal indicator organism budgets has not been explored in previous studies. The hydrology of the Afon Ystwyth system is not managed and responds naturally to rainfall events. The two adjacent rivers systems therefore provide an interesting comparison in terms of faecal indicator loading estimates.

The sewage from Aberystwyth and environs (population equivalent 28,300) receives secondary (activated sludge (AS)) treatment and ultraviolet disinfection at the waste water treatment works (WwTW) at Glanyrafon (Figure 2.1). This plant discharges to the Afon Rheidol. With the exception of the island of Jersey, previous budget studies have concentrated on systems with a crude sewage discharge to sea (e.g. Staithes, Nyfer, Clacton, Irvine and Girvan) or a secondary treated effluent (e.g. Ogwr) without disinfection.

3.1.2 Ireland: the Dargle catchment, Co. Wicklow

The Dargle catchment is located just south of the Dublin-Dun Laoghaire urban area, at the northern end of the Wicklow Mountains. The catchment covers 133.4 km^2 and contains two major tributaries - the Glencullen and the Glencree, and discharges to the coast via the harbour at Bray. The harbour is located at the north end of the main recreation beach. At the south end of this beach the Kilruddery catchment discharges via a drain. Statistics for this catchment are treated separately although it is included in the overall map. Within the Dargle catchment there are 14 subcatchments (Figure 2.3). There is an inland mountain perimeter, with several large valleys converging on the gently dissected lowland plateau.

Bray is a very rapidly growing town with a population at the 1996 census of ca. 26,000. Enniskerry, Glencullen and Kilmacanogue are villages with populations of 1,300, 1,000 and 800 respectively and attract large numbers of weekend trippers from Dublin. The total population in the catchment is ca. 57,000 of which ca. 28,000 live outside the four towns/villages above. The upland region with blanket peat heathlands and *quasi* natural grasslands is extensively grazed at low stocking densities and contrasts with the climatically benign and fertile lowlands which, outside the built areas, are intensively farmed for sheep, crops and cattle.

During the past 10 years in the catchment agriculture, dominantly sheep rearing with some cattle and arable cropping, has markedly intensified and many fields especially on the upland periphery of the main lowland farming area have been re-improved. Surburban expansion has occurred not only around the edges of Bray, Enniskery and Glencullen but also in the spread of detached houses throughout the eastern part of the catchment. Most of these individual residences have their own sewage disposal system.

3.2 Data collection

3.2.1 Wales

3.2.1.1 Discharge, rainfall, stream and reservoir level

The catchments of the Afon Rheidol and Afon Ystwyth have a network of river flow gauging stations operated by the EA (Figure 2.1). The Afon Ystwyth catchment has telemetric gauging stations (Telegen 1150) at two locations on the main river: Cwmystwyth near the headwaters (NGR: SN791737) and Pont Llolwyn (NGR: SN591774), 5.25 km inland from the harbour outlet. Discharge in the Afon Rheidol is monitored at the EA gauging station at Llanbadarn (NGR: SN 601804), 3 km inland from the harbour outlet. Telemetric access to fifteen minute interval river level data (m) from sites on the Afon Ystwyth was available throughout the study. Hourly discharge data ($m^3 s^{-1}$) for the duration of the study (53 days (1272 hours) from 09:00 hrs GMT 2nd August 1999 to 08:00 hrs GMT 23rd September 1999) were available. Further discharge data for the Afon Rheidol system were available from PowerGen in the form of chart records. This information included discharge records ($m^3 s^{-1}$) for the river input to Cwm Rheidol reservoir at Rheidol Falls (site 103, Figure 2.1) plus the output from Dinas and Nant-y-moch reservoirs. Estimates of output discharge ($m^3 s^{-1}$) to the Afon Rheidol from Cwm Rheidol reservoir were calculated from power generation and reservoir level records in consultation with Paul Miller at Cwm Rheidol power station. Reservoir level charts (m) were also available for the three impoundments. Hourly rainfall records were available for three EA gauges in the study catchment at: Pwll Peiran (NGR: SN 773749) in the Afon Ystwyth catchment, Cwm Rheidol (NGR: SN 709792) in the Afon Rheidol catchment and at Frongoch (NGR: SN 605825) just north of Aberystwyth. Further rainfall records were available from the IGER meteorological station at Gogerddan just outside the catchment boundary, north east of Aberystwyth (NGR: SN 627835).

Additional stream level monitoring equipment (A. Ott type X recorders) and stage boards were installed at sites on three streams in the study catchment: in the upper Rheidol system, on the Nant Maesnant-fach (site 112, Figure 2.1) in the upper Ystwyth system, on the Nant Peiran (site 211/212, Figure 2.1), and on Nant Penglais, in the University of Wales Aberystwyth grounds (Figure 2.1). These recorders were used as visual aids for sampling during hydrograph response and for categorization of samples into base flow and high-flow event groups. Stage boards or metre rules were installed at most of the remaining stream sampling locations shown in Figure 2.1. Charts from stage recorders and PowerGen archives were digitized, appended and interpolated to produce corresponding hourly records of stream or reservoir level or river discharge during the study period.

Separation of river flow records into base flow and high-flow components, and derivation of base flow indices (BFI) (Base flow (Q_b) = BFI x Total flow (Q_t)) for the study period were achieved by detailed examination of individual hydrograph events. In the case of the Afon Rheidol the high-flow component derived from power generation rather than natural events.

Hourly discharge data ($l\ s^{-1}$) for final effluent from Aberystwyth WwTW were obtained from operational records supplied by Dr Cymru/Welsh Water (DC/WW). High-flow and base flow components of sewage discharge were separated by close inspection of hourly values in relation to an average dry weather flow cycle based on 19 ‘dry’ days when sewage flow was not appreciably affected by rainfall.

3.2.1.2 Sampling and analysis

River and stream water samples were taken at 13 locations in each of the two main river catchments (Afon Rheidol catchment: sites 101-113, Afon Ystwyth catchment: sites 201-213, Figure 2.1). Water samples were also taken from two streams discharging to the sea across Aberystwyth North beach (sites 501 and 601, Figure 2.1). Samples of treated final effluent were taken at Aberystwyth WwTW (site 301, Figure 2.1). Samples were also taken from the Tan-y-cae pumping station CSO discharging to the Afon Rheidol at Aberystwyth harbour (site 302, Figure 2.1). The final effluent from six small DC/WW WwTWs in the study area was also sampled (sites 305, 307, 309, 311, 313 and 315; Figure 2.1).

River and stream sampling in the main catchments included a series of subcatchment sites. These included sequences on the main rivers: four sites on the Afon Rheidol from the tidal limit at Pont Pen-y-bont (site 101, Figure 2.1), upstream to the outlet from Nant-y-moch reservoir (site 104, Figure 2.1), and three sites on the Afon Ystwyth from the closest accessible site to the tidal limit at Pont Tanycastell (site 201, Figure 2.1), upstream to the headwaters near the Cwmystwyth EA gauge (site 203, Figure 2.1). Sampling sites included tributaries of the main rivers downstream of sites 101 and 201 (i.e. sites 105, 106 and 204, Figure 2.1). The remaining stream sampling points were selected to reflect the range of land-use types in the catchment area, for input to the land use-water quality modelling exercise. For example, tributaries draining to sites 111 to 113 were predominantly unimproved moorland catchments, typical of the upper Rheidol, whilst sites 210 to 212 were highly afforested. Subcatchment tributaries draining to sites 205 to 208 had areas with high proportions of improved pasture, typical of the lower reaches of the study catchment.

Marine water-quality sampling was undertaken at the two identified EA sites likely to be affected by adjacent faecal indicator inputs: Aberystwyth North beach (site 401, Figure 2.1) and Aberystwyth South beach (site 402, Figure 2.1). Whenever possible, marine water samples were taken offshore in one metre depth of water and approximately 30 cm below the water surface. During extreme weather or dangerous tidal conditions, marine samples were recovered remotely from the shore using a net landing rod and laboratory clamp.

Water and effluent samples for bacterial analysis were taken aseptically using 150 ml sterile disposable plastic containers (Media Disposables™). A larger volume (250 ml) was taken at one site on each sampling run for quality control duplicate analysis. The volumes of sample required for analysis were determined from a trial run. Samples were stored in the dark inside a cool box during transport to the CREH mobile laboratory situated at

Aberystwyth WwTW.

Indicator organism enumerations (colony forming units (cfu) 100 ml^{-1}) followed standard UK methods based on membrane filtration (HMSO, 1994). TC enumerations were performed at two or three sample dilutions. FC and EC enumerations employed at least two sample dilutions and triplicate filtration to enhance measurement precision. A complete duplicate analysis was carried out on one sample collected during each sampling run for quality control purposes. The majority (96.7%) of microbiological plates were prepared within six hours (mean: 3.5 hours) of sample collection and always within 8.7 hours.

A total of 806 samples were taken for TC, FC and EC analysis. Valid results were obtained from all samples for TC and FC and 805 samples (99.88%) for EC. The single invalid result was due a laboratory accident. Paired t-tests were used to compare duplicate bacteriological analyses of control samples with corresponding sample results. The results showed no significant differences between sample and duplicate analyses for all three bacterial parameters. River and stream water samples were also analysed for pH, conductivity (µS cm^{-1}), total dissolved solids (TDS) (mg l^{-1}) and turbidity (NTU) in the laboratory, and the field temperature of streams was recorded at the time of sampling. With the exception of conductivity, these parameters were also measured in marine samples.

3.2.1.3 Land use

Detailed field-by-field mapping of land use for the entire catchment area of the Afon Rheidol and Afon Ystwyth (37,933 ha) was undertaken during June 1999. The classification scheme used is the same as in previous CREH investigations in the Staithes, Nyfer, Ogwr, Holland Brook and Irvine catchments. The land-use information was entered into a Geographical Information System (GIS), based on the OS Landline (1:10,000 scale) digital map, using ERDAS Imagine software. In previous work, land use-water-quality modelling was based only upon the overall percentage of different land-use types within different subcatchments (termed ‘lumped’ modelling). However, in the present study the distribution of land use within the subcatchments has also been taken into account (i.e. ‘distributed’ modelling). In this respect, two different data sets have been produced: (i) the percentages of different land use within a 50 m ‘buffer strip’ along the line of mapped watercourses; and (ii) the percentages within certain pre-defined overland flow distances of stream sampling points. In the latter case, land use within the designated distances was sampled on a 50 m grid coinciding with the digital terrain model (detailed below).

It should be noted that, whilst land use was mapped for the whole of the study area, the land use of reservoir catchments which are located within the subcatchment of a particular stream water sampling point is defined as being ‘reservoir catchment’ in the land use-water-quality modelling work undertaken. The reason for this is that concentrations of faecal indicator organisms decrease substantially within reservoirs as a consequence of die-off and sedimentation. In the present study, reservoirs were defined, somewhat arbitrarily, as being water bodies along stream courses that have an area of ≥0.1 ha. In total, 21 were identified, the largest being Nant-y-moch Reservoir in the headwaters of the Afon Rheidol.

3.2.1.4 Watercourses, drainage divides and topography

Watercourses mapped on the hydrology layer of the OS Landline digital map were used to delimit the 50 m buffer strips. The drainage divides of the subcatchments of the 28 stream sampling points and of the reservoir catchments were mostly defined using contours and spot height data from 1:25,000 OS topographic maps. The only exceptions were those subcatchments which included the built up area of Aberystwyth. Here, the divides were defined by the EA (Hannah Wilkinson, personal communication) on the basis of the known road drainage systems.

Additional topographic data were obtained using the Ordnance Survey Land-Form PANORAMA digital terrain model (DTM). This provides a grid of height values at 50 m intervals, which have been mathematically interpolated from 1:50,000 scale contour data (10 m contour interval, with ±3.0 m contour height accuracy). Using ARC/INFO software, the DTM has been used to generate data on this 50 m grid of hillslope gradient and the overland flow distance to the subcatchment outlet. Four difficulties arise when using DTMs at this relatively coarse scale to produce flow paths and drainage divides. First, anomalous ‘sinks’ may occur along the lines of the valley floors. Here, such features have been ‘filled’ using standard procedures within ARC/INFO. Second, in relatively small flat subcatchments, the flow networks generated may bear little resemblance to the known drainage. Problems of this type were encountered in subcatchments 105, 212 and 601, and in these cases the Euclidian distance to the sampling point was used instead of the overland flow distance. Thirdly, particularly in subcatchments with a wide, flat valley floor, the stream outlet generated by the model may be displaced slightly from the 50 m grid point closest to the actual sampling point (i.e. it occurs at a nearby point on the valley floor). Finally, the subcatchment and reservoir boundaries generated by the model do not coincide exactly with those defined from the 1:25,000 topographic map, and relatively small numbers of points around the edges drain across the divides. Such points have been excluded from the flow distance analysis. Although these various problems cause some inconsistency and inaccuracy in the flow length data, the consequences are considered negligible, particularly in view of the wide (1 km) flow distance bands from the sampling points that have been used in the distributed land-use modelling.

3.2.2 Ireland

3.2.2.1 Rainfall

In contrast to the Welsh catchment, prior to this project, the Irish catchment, Dargle, was very sparsely gauged. Some daily rainfall data are collected but, given its small size and its short flood response time, better temporal resolution of measured rainfall was indicated. Three RainLog tipping-bucket automatic recording raingauges were installed within the rural part of the catchment, (i) near Djouce Wood, (ii) in Powerscourt Demesne and (iii) at a Stone Quarry in Glencullen valley (Figure 2.3). A fourth was located at the sewage pumping station in Bray. These have a resolution (bucket capacity) of 0.2 mm and record the time and date of every bucket tip. The sites were chosen to give a distribution covering a range of altitudes, and both north-south and east-west axes within the catchment to establish any spatial variation in the overall rainfall pattern. FORTRAN programs were written to extract rainfall time series for any specified time-interval, e.g. daily, hourly, minutely etc. from the recorded data. As expected there is considerable variation in rainfall amounts with altitude, decreasing from west to east. The totals recorded during the period 22 July 2000 to 13 Nov 2000 were Djouce (618 mm), Stone Quarry (534 mm) and Powerscourt Demesne (515 mm). The correlation of daily rainfall totals between Stone Quarry (Glencullen valley) and Powerscourt Demesne (Dargle valley) was quite close (Figure 3.1). The correlation between the higher Djouce values and the others was still good but with more scatter for the higher rainfall amounts (Figure 3.2).

3.2.2.2 Water levels and flows

With the exception of a single water level recorder at Glencullen Bridge there were no operational water level recording stations. Thus the project had to start the hydrometric programme *ab initio*. Ten Ott Thalimedes automatic recording water level recorders were installed. In all, 12 different sites were used (Table 3.1). Some recorders were moved from their original sites during the course of the project as circumstances demanded. Two Ott Opthalimedes bubble water level recorders were available as back-up. All instruments recorded water levels to a precision of 1 mm and, for the period of study, were set to record the water level every minute. At other times they were set to record at 5 or 10 minute intervals.

The sites were chosen with a number of objectives in mind. They had to be secure and safely accessible at all times, day or night, as water samples were to be taken at each location, particularly during high-flow events. They also had to offer a reasonable prospect of establishing a rating relationship between water levels and high flows. In addition, the catchment of each water level recorder had to offer a different range of land uses, so that the resulting data would allow the relationship between land use and bacteria concentrations to be examined. In effect, each catchment defines a different experimental set-up and a major objective of this study is to compare the outcomes from these different “experiments”. The sites chosen reflect a balance between these objectives. Accessibility and safety requirements often dictated the choice of sites near existing bridges. Accurate measurement of low flows was not a priority and was not feasible within the parameters of this project as it requires the construction of control structures in the channels. During the course of the project, it was discovered that some of the originally-chosen sites were unsuitable. The Tinnahinch Bridge site was in one arch of a three arched bridge and tree trunks lodged against the bridge piers caused different water levels up-stream of each of the arches. The recorder was moved to a different site. At the N11 site, the gauge float sat on the bed of the channel during low flows and frequently became stuck, so did not rise during high flows. This recorder was also relocated.

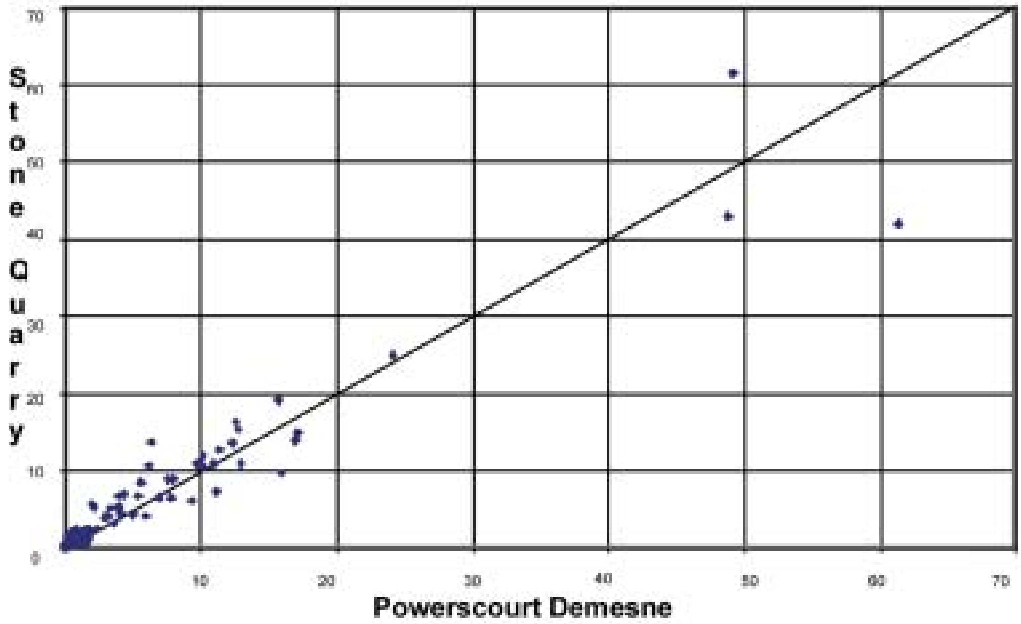


Figure 3.1. Correlation of daily rainfall in middle Dargle catchment (Powerscourt) with middle Glencullen catchment (Stone Quarry).

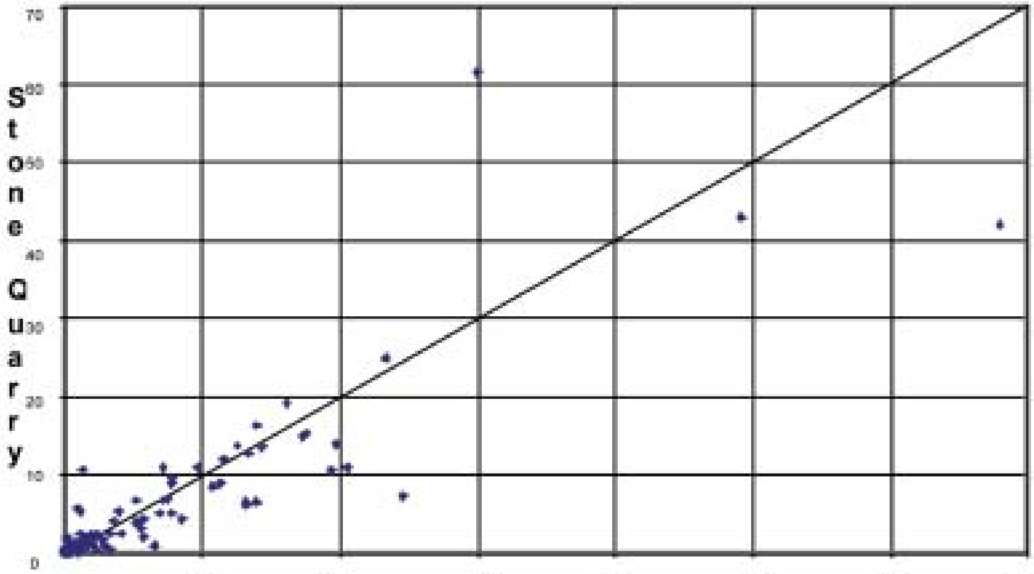
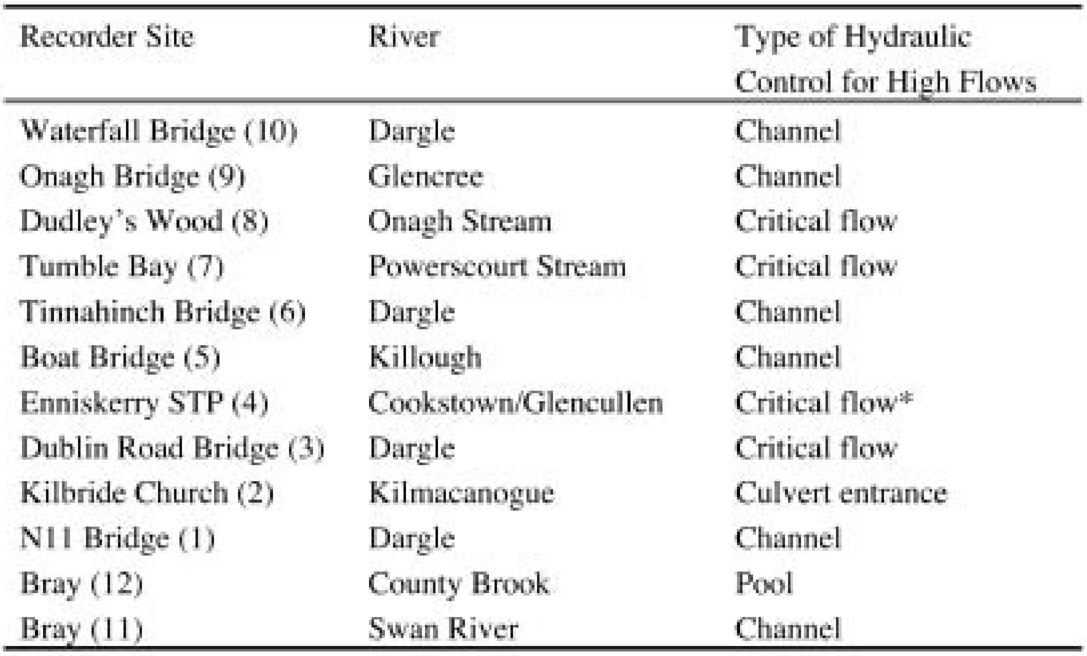


Figure 3.2. Correlation of daily rainfall in upper catchment (Djouce) with middle (Stone Quarry).

Table 3.1. Water level recorder sites. Nearest water-quality sampling locations are shown in parenthesis (see Figure 2.3).



Recorder Site	River	Type of Hydraulic Control for High Flows
Waterfall Bridge (10)	Dargle	Channel
Onagh Bridge (9)	Glencree	Channel
Dudley's Wood (8)	Onagh Stream	Critical flow
Tumble Bay (7)	Powerscourt Stream	Critical flow
Tinnahinch Bridge (6)	Dargle	Channel
Boat Bridge (5)	Killough	Channel
Enniskerry STP (4)	Cookstown/Glencullen	Critical flow*
Dublin Road Bridge (3)	Dargle	Critical flow
Kilbride Church (2)	Kilmacanogue	Culvert entrance
N11 Bridge (1)	Dargle	Channel
Bray (12)	County Brook	Pool
Bray (11)	Swan River	Channel

* This was not obvious from a visual inspection, however it matched the flow gauging and modelling more closely than an equation based on uniform flow.

Over the relatively short duration of the project, it was not expected that reliable rating relationships between water levels and discharges could be established at each of the sites. This takes many years and requires spot gauging at a wide range of different flows. Such work has begun during this project and will be continued by UCD. For the purposes of this project, preliminary rating relationships were established by surveying the channel in the vicinity of the gauge and for some distance downstream and using a steady-flow computer program (HECRAS) to simulate water levels for different discharges through the reach. This establishes first estimates of a rating relationship which can be refined as more spot-flow measurements are taken with a current meter for medium-range flows and a fluorimeter for high flows. The spot-flow measurements taken as part of this study were used to help calibrate the rating relationships. The preliminary rating curves are very sensitive to the choice of Manning's coefficient for the reaches and of the downstream boundary conditions. A number of the gauging sites offered a reasonable expectation of producing critical flow conditions a short distance downstream of the site during high flows, while "uniform" flow sections were assumed at other sites. The gauge on the Kilmacanogue site is just upstream of a culvert entrance which is expected to offer an inlet control during high flows.

3.2.2.3 Sampling and analysis

Water and effluent samples for bacterial analysis were taken aseptically using 500 ml sterile Schott Duran bottles. Samples were stored in the dark inside a cool box during transport to the laboratory. Indicator organism enumerations followed standard UK methods based on membrane filtration (HMSO, 1994). Total coliforms (TC) enumerations were performed by undertaking a single analysis for three different sample volumes. Both faecal coliforms (FC) and faecal streptococci (FS) enumerations employed triplicate filtration of two different sample volumes so as to enhance measurement precision (Fleisher and McFadden, 1980). Duplicate analysis were carried out on some samples collected during a few sampling runs for quality control purposes. The majority (~85%) of microbiological plates were analysed within six hours (typically within 5 hours) of sample collection and always inside 8 hours.

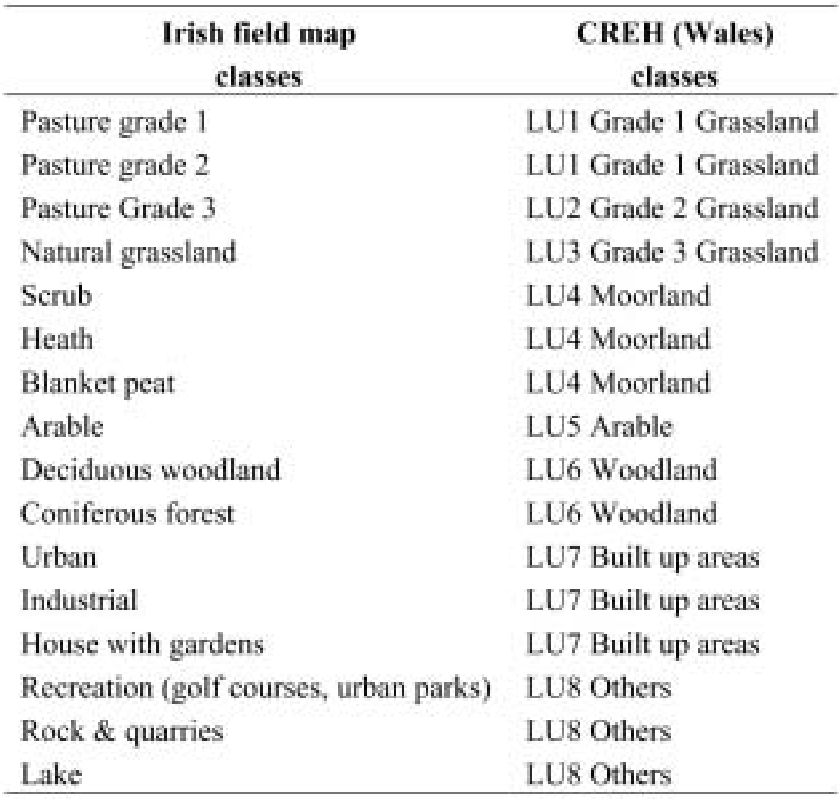
The volumes of sample required for membrane filtration were determined from a trial run. A total of 343 water samples were collected for analysis. Absolute enumerations were made for 338 (98.5%) for TC, 341 (99.4%) for FC and 336 (98.0%) for FS. One FC and two FS results were indefinite (<33); these samples were collected during one of the earliest excursions when the microbial levels for dry weather conditions had not yet been properly established. One FS sample was judged to be below the limit of detection (<3) on the basis that no cfus were found for triplicate 10 ml filtrations. Indefinite results were obtained for three TC, one FC and four FS during one excursion when higher than expected microbial levels (>200000, >2000, >2000 respectively) occurred after rainfall. There were two TC invalid results attributed to laboratory manipulative error. Temperature (^{o}C), pH, conductivity (mS cm^{-1}), salinity (SAL) and dissolved oxygen (DO; mg l^{-1}) were measured at the time of sampling in dry weather conditions.

For total coliforms, plate counts of not more than 200 cfus were multiplied up by the appropriate volume factor to recover the result as cfu (100 ml)$^{-1}$; then the results for the different volumes filtered were averaged to give a weighted average. For faecal coliforms and faecal streptococci, counts ranging between 20 and 80 (i.e. 21 to 79 inclusive) found for a volume filtered in triplicate were averaged and multiplied up by the appropriate volume factor to obtain the result. Where both sets of triplicate counts were outside of the range, the set of recorded counts for the highest volume filtered was averaged and multiplied up by the appropriate volume factor to obtain the result. (Had triplicate counts been obtained in range for two volumes filtered, the set of counts recorded for the highest volume filtered would have been averaged and multiplied up by the appropriate factor to obtain the result.)

3.2.2.4 Land use

Land cover in the catchment was mapped during the summers of 1999 and 2000 field by field onto 1/10560 Ordnance Survey Maps (1908 and 1934 editions). This was assisted where necessary by digital analysis of a Landsat image (acquired September 1997) and cross checked from farmer and landowner interviews. Forests and woodlands extents were obtained from the National Forestry Inventory (Coillte 1999). Field mapping identified 16 generic classes and the land cover map was digitised into an ARC/VIEW GIS data base. These classes have been re-grouped into the CREH classification (Table 3.2) and are portrayed in Figure 3.3.

Table 3.2. Relationship of Ireland and Wales land-use classification.



Irish field map classes	CREH (Wales) classes
Pasture grade 1	LU1 Grade 1 Grassland
Pasture grade 2	LU1 Grade 1 Grassland
Pasture Grade 3	LU2 Grade 2 Grassland
Natural grassland	LU3 Grade 3 Grassland
Scrub	LU4 Moorland
Heath	LU4 Moorland
Blanket peat	LU4 Moorland
Arable	LU5 Arable
Deciduous woodland	LU6 Woodland
Coniferous forest	LU6 Woodland
Urban	LU7 Built up areas
Industrial	LU7 Built up areas
House with gardens	LU7 Built up areas
Recreation (golf courses, urban parks)	LU8 Others
Rock & quarries	LU8 Others
Lake	LU8 Others

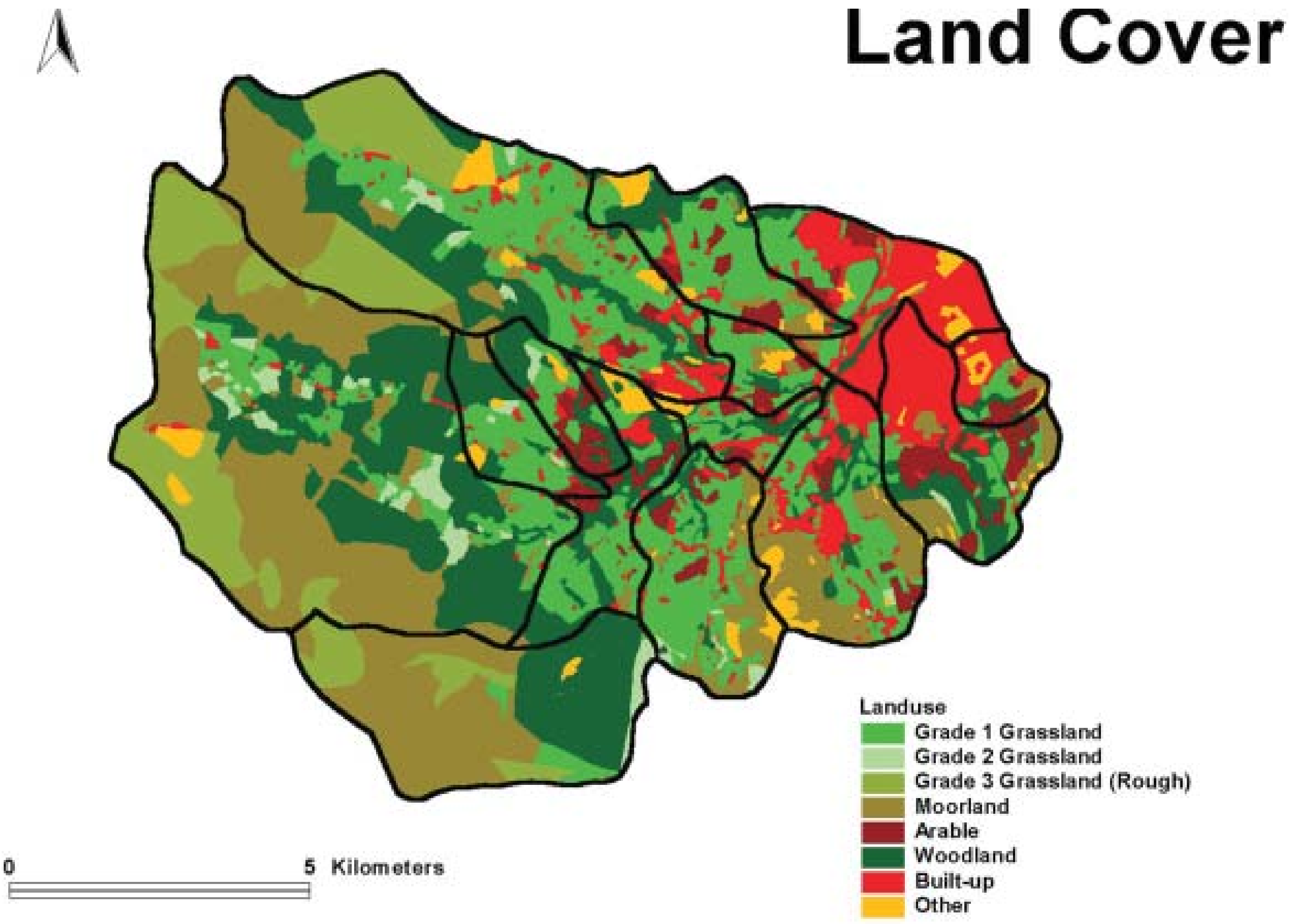


Figure 3.3. Land-use map of the Dargle catchment.

Information on farming practises was obtained from various sources including farmers and from Teagasc. Additional statistical data on agricultural was obtained from:

(i) The Central Statistics Office relating to the 1991 National Census of Agriculture. Data was supplied on a District Electoral Division (DED) basis but as the catchment falls into 6 DEDs and some DEDs extend beyond the catchment it is not possible to accurately apportion data to particular subcatchments or to farm holdings. The information includes: number of farms classified by farm size, area under crops, number of farms classified by type of farm and numbers of livestock. Neither the Department for Agriculture nor the Central Statistics Office is permitted to supply data on an individual farm basis or on any scale other than the DED. The accuracy and reporting dates do not permit this data to be used in this project's analyses.

(ii) The Department for Agriculture relating to farmer participation in the REP Scheme (Dowling, 1994). This data is available only on a county basis and is entirely confidential at a farmer level. It was not available for this project.

3.2.2.5 Farming in the Dargle catchment

Farming in the catchment consists of mostly dry stock, particularly sheep. Specialist sheep farming is carried out mainly on the highly intensive farms in the lowlands but also in the upland regions of the catchment. Estimates of sheep number are approximately 4000. Estimates of cattle in the catchment are 180-200 and cattle grazing is limited to the improved grassland/pastures. Areas of tillage are common in the lowland subcatchments. Many farmers in the catchment have diversified their farming practices: forestry, agri-tourism, horse breeding, and commercial egg production.

There is a high farmer participation in the REP Scheme. The REP scheme limits stocking rates on grassland, requires codes of practice relating to collection, storage and disposal of animal manures, to run off, to land spreading of slurry and farm yard manure, to grazing practises in relation to water supplies and stream courses and to stocking densities. Grassland management plans are followed to optimise the protection of habitats, minimise overgrazing and soil erosion, and prevent nutrient enrichment of surface waters. Overwintering stocking densities are prescribed.

3.3 Statistical analysis (Wales)

For the purposes of statistical analyses, samples where no organisms were detected were recorded as the detection limit value. In the case of bacterial parameters the detection limits were: TC 10 cfu 100 ml^{-1}, FC and EC 3 cfu 100 ml^{-1}. The distribution of microbial concentrations found in stream, sewage effluent and sea water samples, taken under base flow and high-flow conditions, showed a closer approximation to normality when $\log_{10}$ transformed. All microbial concentration data were, therefore, $\log_{10}$ transformed prior to statistical analysis. The MINITAB (Minitab, 1995; Ryan and Joiner, 1994) and SPSS (SPSS, 1988) packages were used for statistical analyses. Descriptive statistics were used to characterize the distribution of bacterial concentrations at each sampling location. These statistics include the geometric mean (GM), the standard deviation (SD) of $\log_{10}$ transformed concentrations, the 95% confidence for the mean and the range of values at each site. The significance of differences between GM concentrations was examined using Student's t-test or analysis of variance (ANOVA) to compare the means of $\log_{10}$ transformed concentrations. Where two GM values were compared, e.g. comparing GM values between two sites or flow conditions, the t-test was employed.

ANOVA was used where comparisons involved more than two groups, for example in assessing the significance of differences in GM values between a group of stream monitoring sites, with Tukey's honest significant difference (HSD) multiple range test used to examine significant differences between individual groups. General Linear Model (GLM) ANOVA was used for multivariate comparisons, e.g. between sites and flow conditions. This technique also allows assessment of interaction between factors.

Land use-water-quality relationships were examined using multiple regression analysis. Measures describing water quality at sampling locations (e.g. mean, maximum and minimum $\log_{10}$ transformed base flow and high-flow concentrations) were used as dependent variables (y), predicted by independent, or predictor, variables (x_i), which were the % areas of subcatchments in each land-use class or combinations of land-use classes. The statistical distribution of each independent variable was examined and $\log_{10}$ transformations applied in cases where skewness exceeded unity, producing data more appropriate for the regression analysis.

These variables were used to examine multivariate relationships between land use and water quality, of the form:

$$y = a_1 x_1 + a_2 x_2 \ldots\ldots a_i x_i + b \pm u \quad \text{where:} \qquad \mathbf{3.1}$$

y = water-quality measure (mean, maximum or minimum $\log_{10}$ transformed concentration at base flow or high flow)
x_i = % areas of subcatchments in each land-use class or combinations of land-use classes
a = slope (change in y per unit change in x)
b = intercept (y at $x = 0$)
u = stochastic disturbance or random error term

The strength of relationships was assessed from the coefficient of determination (r^2) expressed as a percentage (i.e. amount of variance in the dependent variable, y, explained by the independent variables, x_i, in the equation). The modelling was undertaken using the SPSS forward selection stepwise procedure (SPSS, 1988). The entry of variables to an equation was controlled using: (i) a significance criteria value of 0.2 and (ii) a tolerance value to limit multicollinearity between independent variables in the model to those with non-significant which have an explained variance of less than 50% with predictor variables already entered into the equation (i.e. to exclude significantly correlated independent variables). The latter exclusion criterion was resolved after determination of the independent variable most highly correlated with the dependent variable of interest. All values of r^2 derived from regression models were adjusted for degrees of freedom, accounting for the number of variables in the equation (Minitab, 1995). The quality of regression models was further assessed by examining the statistical distribution of residual values (deviations between actual values of y from those predicted by the model).

Regression models should conform to assumptions of parametricity, an important assumption being that residual values should be normally distributed. This was assessed by visual inspection of normal probability plots of standardized residuals.

All statistical tests were assessed at $\alpha = 0.05$ (i.e. 95% confidence level or 5% significance level) by comparing p, the calculated probability at which the null hypothesis for a particular test is accepted, to α. Rejection of the null hypothesis (e.g. that two means are not different from each other or that a regression line slope is not different from zero) and acceptance of the alternative hypothesis (e.g. that two means are different from each other or that a regression line slope is different from zero) occurs when $p < \alpha$ (i.e. $p < 0.05$).

3.4 Faecal indicator organism budgets

3.4.1 Wales

Budget calculations were made using data sets from selected sites to examine the faecal indicator inputs from riverine sources and sewage effluent discharges to the adjacent coastal waters. The relative proportions (%) of sources contributing to the budgets were calculated as follows:

(i) The load (L (organisms)) of each indicator organism was calculated for each source (i) for base flow (b) and high-flow (h) discharge components during the study period:

$L_{ib} = Q_{ib} \ x \ C_{ib}$ **3.2**

$L_{ih} = Q_{ih} \ x \ C_{ih}$ **3.3**

where:

Q = flow (m^3) during the study period
C = geometric mean (GM) concentration (per m^3).

(ii) Total load (L_{it}(organisms)) from each source was calculated as:

$L_{it} = L_{ib} + L_{ih}$ **3.4**

(iii) The total load (Ls (organisms)) from all sources is given by:

$L_s = S \ L_{it}$ **3.5**

(iv) Proportional contributions (PC_{ix} (%)) from each source (i) associated with each flow component (x (base flow, high-flow or total flow) for each study were finally calculated as:

$PC_{ix} = (L_{ix} / L_s) \ x \ 100$ **3.6**

Similar calculations were performed for discharge data. The results were then plotted as a series of pie charts. Modification of the budgets by changing effluent quality enabled the effects of a range of treatment options to be explored.

3.4.1.1 Monitoring sites

Budgets were derived for sources discharging to coastal waters near Aberystwythduring the 53 day study period. Data from the following sites were available for calculation of faecal indicator organism budgets for inputs to the coast near Aberystwyth:

(i)	Aberystwyth WwTW – UV disinfected final effluent (site 301)	Discharge and quality
(ii)	Afon Rheidol catchment	
	Afon Rheidol at Llanbadarn	Discharge
	Afon Rheidol at Pont pen y bont (site 101)	Quality
	Plas Crug ditch catchment (site 105)	Quality
	Nant Padarn catchment (site 106)	Quality
(ii)	Afon Ystwyth catchment	
	Afon Ystwyth at Pont Llolwyn	Discharge
	Afon Ystwyth at Pont Tanycastell (site 201)	Quality
	Nant Paith catchment (site 204)	Quality
(iv)	North beach catchments	
	Nant Lover’s Dingle catchment (site 501)	Quality
	Nant Penglais catchment (site 601)	Quality

3.4.1.2 Discharge from riverine sources

Complete hourly discharge records (m^3 s^{-1}) for the two main rivers discharging to Aberystwyth harbour were available from EA and PowerGen records. Detailed analysis of the hydrograph records for the Afon Ystwyth at Cwm Ystwyth and at Pont Llolwyn, 25 km downstream, showed peak discharge to occur approximately 6 hours later (average of 15 events) at the downstream site. This suggested an hydrograph peak travel time of approximately 4.1 km hr^{-1} along this reach of the Afon Ystwyth. This hydrograph peak travel time was used to adjust the discharge record for Pont Llolwyn gauge to estimate the temporal pattern of discharge at Pont Tanycastell (site 201), 2.5 km downstream of the gauging station. Using the total rainfall at Pwll Peiran gauge (218.2 mm) (Figure 2.1) as an estimate of rainfall input to the catchment to Pont Llolwyn gauge (area 169.6 km^2) suggested that total runoff from the Afon Ystwyth during the study period represented by 21.51% of the total rainfall input. This figure was used to estimate the additional runoff to the Afon Ystwyth generated in the catchment area between Pont Llolwyn and Pont Tanycastell. This additional runoff (approximately 4.8% of the total estimate) was assumed to have proportionally the same temporal distribution as that of the estimated temporal record for this site. The resulting hourly estimates of discharge at Pont Tanycastell (site 201) were split into base flow, dry weather, and high-flow, wet-weather, components by detailed analysis of each hydrograph event. Dry weather, base flow discharge was typically 1 m^3 s^{-1}. Maximum discharge during the study period exceeded 16 m^3 s^{-1}.

Detailed analysis of the hourly records for the Afon Rheidol at Cwm Rheidol dam (derived from PowerGen data) and at the Llanbadarn gauge (13 km downstream) suggested that all major events on this river during the study period were the result of power generation releases. Discharge peaks arrived at Llanbadarn gauge approximately 4.7 hours (average of 25 events) after peak discharge at Cwm Rheidol dam, suggesting a hydrograph peak travel time of 2.8 km hr^{-1} along this reach of the Afon Rheidol. This travel time was applied to the hourly record for Llanbadarn gauge to produce an estimated hourly discharge record for the Afon Rheidol at Pont Pen-y-Bont (site 101), 0.75 km downstream. This discharge record was not adjusted further as there are no major stream inputs to the river in this short reach. The record has also been split into base flow and high-flow, power generation components. This split was achieved by applying the cumulative discharge from Cwm Rheidol reservoir to the record for Pont Pen-y-Bont. Typical dry weather discharge in the Afon Rheidol at site 101 was approximately 2.7 m^3 s^{-1}. This discharge is maintained by a constant compensation flow of approximately 1.8 m^3 s^{-1} from the hydroelectric scheme, agreed with the EA, plus a natural background baseflow of 0.9 m^3 s^{-1} from the catchment downstream of Cwm Rheidol dam. This background discharge was taken into account when calculating the cumulative discharge at the Llanbadarn gauge to determine the finish of each event. Peak flow at site 101 during the study period was 10 m^3 s^{-1}.

Discharge from small stream inputs to the Afon Rheidol down stream of site 101 (Plas Crug Ditch (site 105) and Nant Padarn (site 106)), the Afon Ystwyth downstream of site 201 (Nant Paith (site 204)), and Aberystwyth North beach (Nant Lover’s Dingle (site 501) and Nant Penglais (site 601) was estimated proportionally using catchment area. For these estimates, discharge components were calculated for the areas of each catchment with urban and rural land use based on land-use survey data. For the urban areas of catchments, with a high proportion of impervious surfaces generating direct runoff, 90% of rainfall input was assumed to contribute to runoff (Shaw, 1994), all of which would contribute to high-flow events. For rural catchment areas, 21.51% of rainfall was assumed to contribute to runoff, 44.9% of which was assumed to contribute to high-flow events based on the figures for the Afon Ystwyth catchment outlined above. The rainfall input to these catchments during the study period was assumed to be 173.4 mm, from the nearest rain gauge at Frongoch (Figure 2.1).

3.4.1.3 Discharge from sewage sources

An average hourly dry weather sewage effluent flow cycle for Aberystwyth WwTW was calculated for 21 dry days when discharge was not affected by rainfall. Typical average hourly dry weather flow was approximately 0.084 m^3 s^{-1} (range: 0.046 to 0.123 m^3 s^{-1}). Typical maximum discharge during event conditions was between 0.20 and 0.22 m^3 s^{-1}.

Discharge from the overflow at Tan-y-cae storm retention tanks could not be measured during the study period due to logistical problems. The Tan-y-cae tanks provide 4,700 m^3 of storage and the system was designed to produce less than one spill per bathing season. Estimated “worst case” peak discharge from this CSO is approximately 0.8 $m^3 s^{-1}$. Overflow from the system was observed, and sampled, during two events during the study period. However, there were considerable periods, at high tidal states, when the CSO outlet was submerged and not accessible for observation or sampling. As faecal indicator organism concentrations in CSO discharges are high (i.e. dilute crude sewage), such sources can represent a relatively high proportion of total budget estimates of faecal indicator organisms in relation to their comparatively small contribution to total discharge. Estimates of the proportion of total sewage discharge from CSO systems in previous investigations suggest that the proportion of total sewage effluent volume discharged from CSO systems ranged from less than 1% percent (Staithes, North Yorkshire) to over 12% (Lletty Brongu, south Wales), with a mean around 5%. However, it was recognised that the value for the Lletty Brongu system was disproportionately high due to high infiltration rates and low storage capacity (which has since been increased). Discounting this result, previous studies suggested a mean value of 4% loss of total sewage volume via CSOs. This value was applied to the discharge data for Aberystwyth WwTW to provide an estimate of discharge from Tan-y-cae CSO during the study period. A sensitivity analysis of the impact of a range of CSO discharge volumes, ranging from zero to 10% of the total sewage volume, on the indicator organism loading from this source was also carried out.

3.4.1.4 River and effluent quality

The results of water quality the Afon Ystwyth at site 201 (Figure 3.4) showed a pattern of deterioration in water quality (i.e. increased faecal indicator concentrations) during high-flow event conditions. This pattern was also evident in the stream inputs downstream of the main river sites and the stream inputs to Aberystwyth North beach, and is similar to results from previous studies. The Afon Rheidol showed a different pattern, with little evidence of deterioration in water quality during the power generation events.

Faecal indicator concentrations in the final sewage effluent from the Aberystwyth WwTW (disinfected effluent) did not show any consistent pattern of increase or dilution in response to event conditions.

Statistical summaries of faecal indicator concentrations in river, stream and sewage effluent samples from the sites used to calculate faecal indicator budgets to coastal waters near Aberystwyth were prepared. These summaries show statistically significant elevations in the mean of $\log_{10}$ transformed faecal indicator concentrations at most of the river and stream sites in samples taken during event conditions compared to base flow conditions. Elevations in GM concentrations during high flows were typically at least an order of magnitude higher than GM base flow concentrations, and were most marked for EC. One exception was the Afon Rheidol at site 101 where no significant differences were found between the mean $\log_{10}$ transformed faecal indicator concentrations in samples taken at base flow and during power generation events.

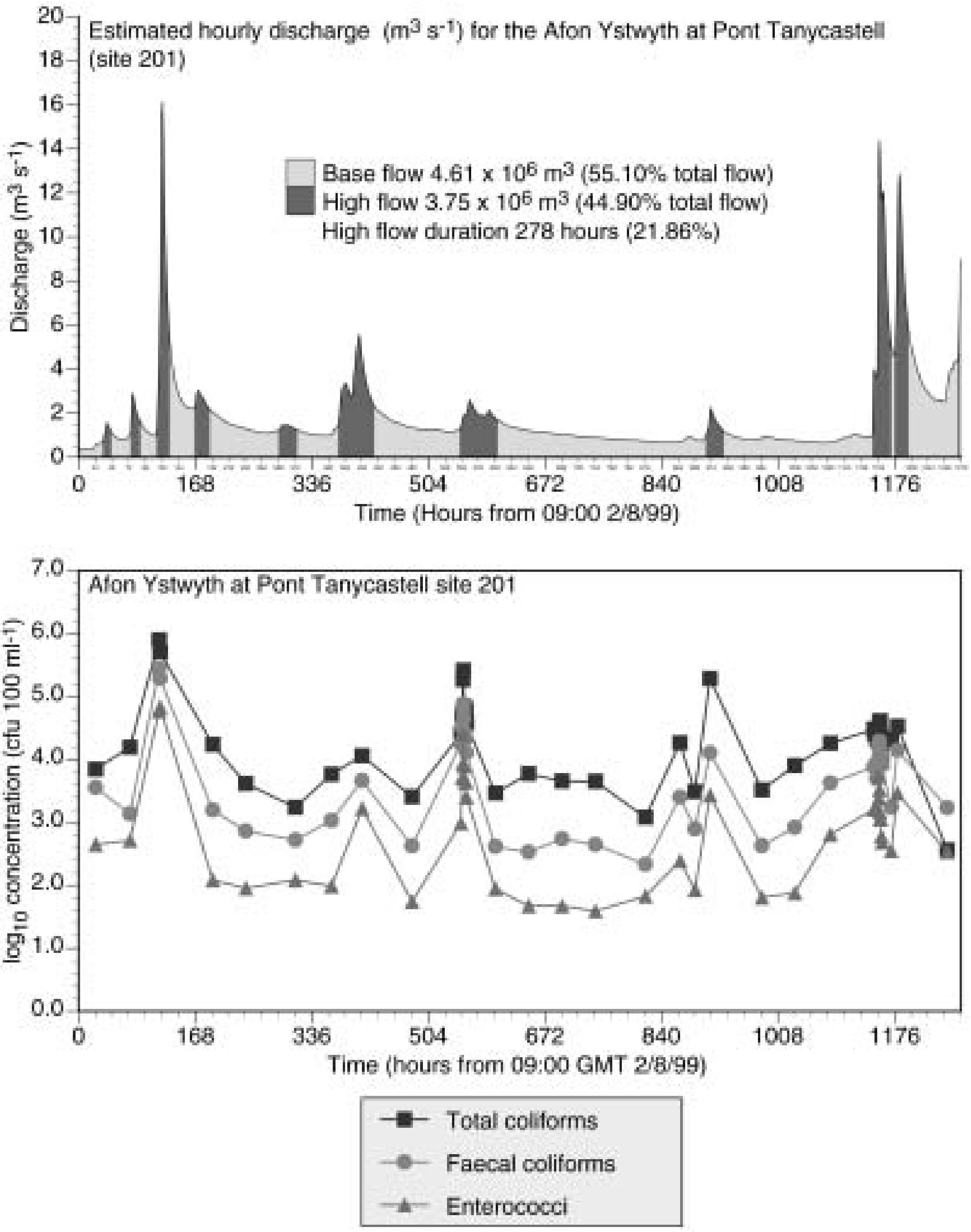


Figure 3.4. Estimated hourly discharges (m3 s^{-1}) and log$_{10}$ transformed faecal indicator concentrations (cfu 100 ml-1) in the Afon Ystwyth at Pont Tanycastell (site 201).

Indeed GM TC and FC concentrations at this site were slightly lower during power generation events, whilst GM EC concentrations were identical for base flow and event conditions. A further exception was the Plas Crug ditch site (site 105), which showed no significant difference in GM TC concentrations between flow conditions. Base flow TC concentrations at this site showed a particularly wide range ($7.9x10^3$ – $2.6x10^6$ cfu 100 ml^{-1}). Mean log$_{10}$ transformed concentrations of other faecal indicator organisms from site 105 showed a similar pattern to the other streams, with a statistically significant elevation in the GM concentration at high flow.

The GM concentrations in final effluent from Aberystwyth WwTW showed no significant difference between base and high flow. Indeed, GM concentrations in this effluent were lower than those found at all of the river and stream sites contributing to the budget estimates, including the Afon Rheidol to which the effluent discharges. The effluent from the Tan-y-cae CSO showed the highest GM faecal indicator concentrations of any of the budget input sites (TC: 9.8×10^6 cfu 100 ml^{-1}, FC: 2.1×10^6 cfu 100 ml^{-1} and EC: 4.1×10^5 cfu 100 ml^{-1}), typical of dilute crude sewage.

3.4.1.5 Budget results for inputs to the coast near Aberystwyth

The discharge budget (m^3) for input sources to Aberystwyth harbour, which discharges directly to coastal waters near Aberystwyth South beach, is dominated by river and stream inputs which provide over 98% of the total input. The Afon Rheidol provides the single greatest overall input (66.11%). Much of the remaining discharge (32.12%) derives from the Afon Ystwyth. The total discharge from sewage effluent is relatively small; less than 2% of the overall discharge estimate. The estimated input from the Tan-y-cae CSO, assuming a discharge of 4% of the total sewage flow, is extremely small; less than 0.1% of the total discharge.

The faecal indicator organism budgets show a contrasting pattern. Whilst the input of organisms is also dominated by riverine sources (TC 68.24%, FC 71.20% and EC 71.88%), the largest single source derives from the Afon Ystwyth during high-flow conditions (TC 33.20%, FC 55.84% and EC 46.74%), which provides 14.52% of the total discharge. The budget estimates also show a disproportionately high load, over 28%, associated with the small discharge from the Tan-y-cae CSO. This is due to the high faecal indicator organism concentrations in this input, and would be associated with high-flow conditions when loading from the Afon Ystwyth is greatest. In contrast, the faecal indicator input from the Aberystwyth WwTW is extremely small, less than 0.1%, due to the low faecal indicator organism concentrations in this disinfected effluent.

Sensitivity analysis for a range of CSO discharge scenarios indicates that while the discharge from the CSO contributes a small proportion of the total discharge (< 0.2%), the contribution of the CSO to faecal indicator load estimates increases rapidly. At the worst case examined, where Tan-y-cae CSO discharges 10% of the total sewage volume, the contribution to faecal indicator loads exceeds 45%. This analysis demonstrates the potential importance of relatively small inputs from highly contaminated sources to overall budget estimates. The contribution from the CSO becomes much less significant, providing less than 10% of the faecal indicator load, when spill volume is below 1% of the total sewage volume.

Discharge and faecal indicator inputs from the streams draining to Aberystwyth North beach represent a small proportion of the total budget estimates. These sources represent less than 1% of the total discharge from all sources examined and less than 10% of the corresponding faecal indicator organism budget estimates. However, these two faecal indicator sources may provide important local inputs to coastal waters at Aberystwyth North beach. The high-flow input from the Nant Penglais catchment to North beach dominates both the discharge and faecal indicator budgets from these sources. The high proportion of discharge estimated for Nant Penglais at high flow reflects the relatively high proportion of urban land use (44.78%) in this. This component provides over 90% of the estimated local faecal indicator input to the nearshore waters at Aberystwyth North beach.

Hourly faecal indicator budget patterns were constructed for the two main riverine sources at Aberystwyth harbour. The estimated hourly loading incorporates components for the small inputs downstream of sites 101 and 201. Discharge from these small catchments was assumed to behave temporally like the Afon Ystwyth. The temporal record for the two rivers at the harbour was adjusted to reflect the hydrograph peak travel as outlined in Section 3.4.1.2, the harbour outlet being 2.25 km downstream of site 101 and 2.75 km downstream of site 201. In the absence of a discharge record for the Tan-y-cae CSO, an hourly record for the overflow was estimated assuming: (i) flow from the CSO would only occur when discharge at Aberystwyth WwTW exceeded 0.15 $m^3 s^{-1}$ and (ii) flow from the CSO had the same temporal distribution as the corresponding final effluent discharge. As in the previous calculations, this record assumed 4% of total sewage volume was discharged via the CSO. Maximum estimated discharge from the CSO was less than 0.35 $m^3 s^{-1}$, which is below the theoretical maximum discharge for the structure of 0.82 $m^3 s^{-1}$. The results for faecal coliforms are shown in Figure 3.5, which also shows the hourly rainfall record at Cwm Rheidol. This figure shows that the temporal delivery of faecal indicator organisms is dominated by a series of episodic pulses associated with rainfall events. Periods of high delivery are dominated by the Afon Ystwyth, which may provide up to 80% of the instantaneous input. The estimated inputs from the CSO source appear to match the rainfall record quite closely, and this source might contribute significantly (in excess of 90% of the total load) especially during the early stages of events. A similar pattern was evident in a previous study of CSO inputs to the River Irvine (Wyer *et al.*, 1999b). During dry weather conditions, when absolute rates of delivery are minimal, the Afon Rheidol represents the dominant faecal indicator source. This reflects the relatively high base flow discharge from this source and small episodic inputs associated with elevated discharge during power generation events.

3.4.1.6 Treatment scenarios

The effects of improved sewage treatment at Aberystwyth were explored by modifying the budget estimates presented in the previous Section to examine scenarios for an untreated, crude effluent and an activated sludge (AS) treated effluent. For the crude effluent scenario, base and high-flow faecal indicator concentrations for Newport, Pembrokeshire were used to characterize effluent quality (Wyer *et al.*, 1998b). The CSO input was combined with the high-flow sewage effluent component in this scenario. For the AS treatment scenario, flow separation of sewage effluent was adjusted using results from a large AS plant in south Wales (Pen-y-Bont) (Wyer *et al.*, 1998a). The high-flow discharge component of treated effluent was considered as any hourly flow value exceeding the corresponding dry weather flow by 1.74 times. This threshold discharge was found to be the approximate value above which effluent quality from the AS plant at Pen-y-Bont deteriorated. This separation produced very similar results to that used for the current situation (Section 3.4.1.3). The effluent quality for this scenario was also based on the Pen-y-Bont AS plant (Wyer *et al.*, 1998a).

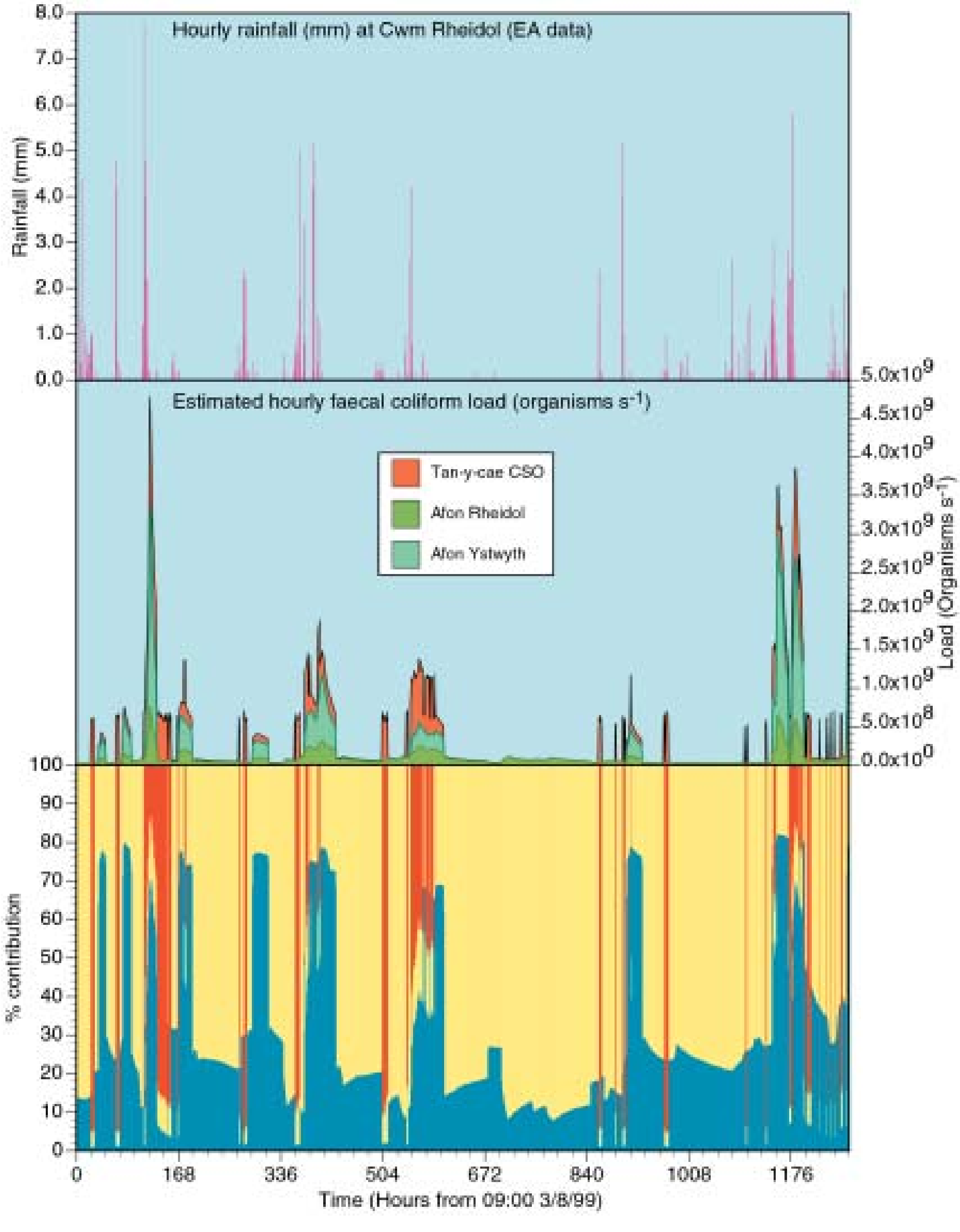
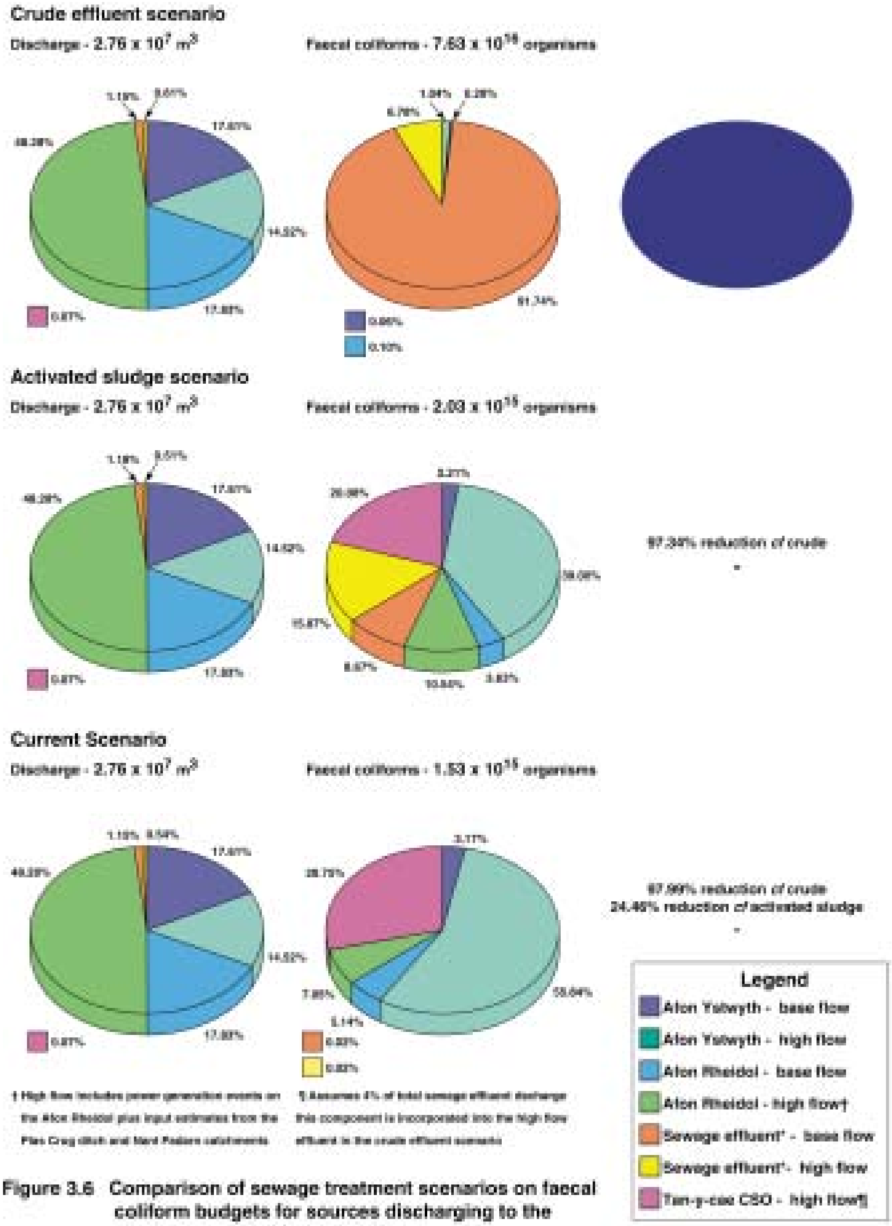


Figure 3.5. Hourly rainfall (mm) at Cwm Rheidol, estimated hourly faecal coliforms load at Aberystwyth harbour and proportional contribution (%) from three sources.

The results (summarised for faecal coliforms in Figure 3.6) indicate that activated sludge treatment at Aberystwyth has reduced faecal indicator budgets by over 93% in the case of total coliforms, and over 97% for faecal coliforms and for enterococci. The crude effluent scenario, which would have prevailed before the construction of the new WwTW, shows the budgets to be completely dominated by the sewage effluent discharge the base flow component of which provides the single largest source. The inclusion of UV disinfection at the works has provided a further reduction in the overall budgets to the point where faecal indicator load from the WwTW is comparatively negligible and riverine sources dominate faecal indicator budgets. The budget calculations suggest that treatment of sewage at Aberystwyth has reduced the faecal indicator load associated with the works by over 99.99%.



† High flow includes power generation events on the Afon Rheidol plus input estimates from the Plas Crug ditch and Nant Padarn catchments

¶ Assumes 4% of total sewage effluent discharge this component is incorporated into the high flow effluent in the crude effluent scenario

Figure 3.6 Comparison of sewage treatment scenarios on faecal coliform budgets for sources discharging to the coast near Aberystwyth harbour.

3.4.2 Ireland

Budget calculations were made to determine the inputs of faecal indicator bacteria to the sea at Bray.

(i) For any particular time at any particular gauging point, the delivery rate of organisms can be calculated as the product of the concentration and flow rate.

$$D_i(t) = Q_i(t)C_i(t)$$

where,

$D_i(t)$ is the delivery rate of organisms passing gauge number i;

$Q_i(t)$ is the discharge rate at gauge number i;

$C_i(t)$ is the concentration of organisms in the flow passing gauge number i.

(ii) The sum of the delivery rates for the various rivers, Dargle, Glencullen, Swan, Kilmacanogue River and the County Brook, added to the contribution from the Enniskerry outfall, gives the total catchment delivery to Bray.

(iii) The contribution of the Sewerage Treatment Plant at Enniskerry is calculated through a mass balance, i.e. by subtracting the delivery rates of other contributing catchments from the total delivery rate calculated from measurements at the N11 road bridge.

(iv) Contributions from the storm overflows from the sewage pumping station in Bray are calculated from an inspection of the pumping station records.

3.4.2.1 Summary of faecal organism measurements

Five separate sampling excursions were undertaken during the major storm period of the study, September 2000 and a total of 14 separate sampling excursions were made for non-storm periods during the preceding spring and summer. In each excursion the water was sampled at most of the gauging sites and at some additional sites and analysed as described in Section 3.2.2.3. Considerable care was exercised to ensure that the samples taken during storm periods included samples close to the peaks and also before and after the peak, on its rising and falling limbs. The timing of storm-period samples and the corresponding water-level is shown in Figure 3.7. The lag time, of approximately 4 hours, between the flood wave in the upper Dargle (at Waterfall Bridge) and the lower reaches (at Dublin Road Bridge) is clearly illustrated, as is the strong correlation between the flows from various subcatchments. Note that in this figure the water levels were adjusted to allow the record from each station to be clearly seen so as to illustrate the timing of the samples. Because of this and also because of the different channel geometries and slopes, this figure does not indicate the relative magnitudes of the individual flows.

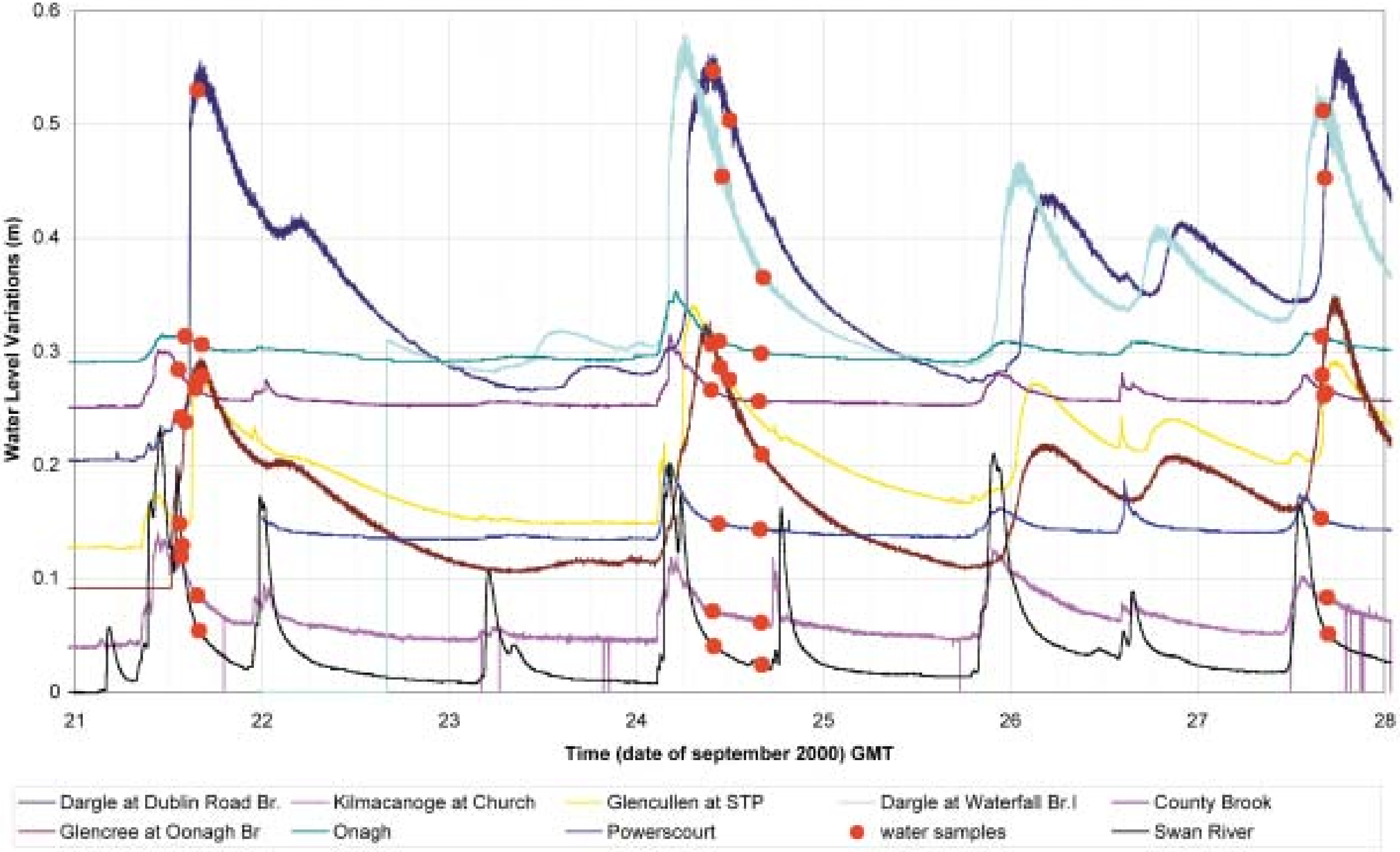


Figure 3.7. Timing of water quality sampling during storms.

The storm-period samples and the non-storm-period samples are grouped separately for the purpose of the analysis. The grouping is done by considering water levels, however some difficulties arise in determining what interval after a storm is required before the conditions can be considered non-storm. Tables 3.3 to 3.5 give a general overview of the sample statistics for each gauging site and for each type of organism. The concentrations in these Tables are given in units of colony forming units (cfu) per 100 ml, however thereafter for the subsequent analyses the logarithms (base 10) of these values are used. In the Tables the abbreviations TC, FC and FS refer to total coliforms, faecal coliforms and faecal streptococci, respectively. STP denotes Sewage Treatment Plant.

The summary tables point to the following important conclusions.

(i) None of the waters, even in the upper reaches of the catchment, is free of indicator bacteria.

(ii) The catchments seem to form three groups, “relatively clean” (first 5) and “relatively dirty” (last 5 + Killough) with two “intermediate” ones (Dargle at Dublin Road Bridge and Cookstown River (Glencullen) at Enniskerry STP).

(iii) Bacterial concentrations generally increase by an order of magnitude (and very occasionally by two orders of magnitude) during storm conditions, compared with non-storm conditions. This indicates that during storm conditions the increased numbers of organisms entering the water greatly outweigh any diluting effect of the additional runoff produced during the storm.

(iv) As a qualification to (iii), note that for total coliforms in the Kilmacanogue (Table 3.3) the mean decreases from 88031 cfu (100 ml)$^{-1}$ during non-storm conditions to 78728 cfu (100 ml)$^{-1}$ during the storm period measurements. However, this is not reflected in the measurement of faecal coliforms (Table 3.4), or for faecal streptococci (Table 3.5).

(v) There is considerable variation in bacterial concentrations for the same location and same type of conditions.

(vi) Maximum non-storm concentrations are greater than minimum storm concentrations for some sites, another indication of the great variability in the data and possibly of uncertainty in the duration of storm effects.

Table 3.3. Overall summary of results for total coliforms.

Conditions =>	Non-storm Conditions (cfu per 100 ml)			Storm Conditions (cfu per 100 ml)		
Location	Min TC	Max TC	Mean TC	Min TC	Max TC	Mean TC
Waterfall – North	235	1273	811	4200	35000	18331
Onagh (Glencree)	125	3700	976	1550	27000	8008
Onagh Stream	80	3200	1159	4950	12400	7750
Powerscourt Stream	205	3400	969	6200	103000	35117
Tinnahinch Bridge	175	2900	936	9533	39000	22017
Killough Bridge	200	8100	3806	20500	147000	87750
Dargle at Dublin Road Bridge	690	9050	4511	4400	41000	21742
Cookstown River at STP	2150	32000	11313	14767	52000	33550
Kilmacanogue at N11 Bridge	8500	430000	88031	11867	173000	78728
Dargle at N11 Bridge	3550	58000	25450	11750	198000	78458
County Brook (at Dargle)	2100	6950	4222	10900	128000	55317
Swan at Dargle	3300	149000	43265	53000	172000	122833
Harbour Mouth	1115	12050	7216	56000	270000	135417

Table 3.4. Overall summary of results for faecal coliforms.

Conditions =>	Non-storm Conditions (cfu per 100 ml)			Storm Conditions (cfu per 100 ml)		
Location	Min FC	Max FC	Mean FC	Min FC	Max FC	Mean FC
Waterfall - North	70	533	282	947	9133	4530
Onagh (Glencree)	37	853	236	613	3933	2050
Onagh Stream	7	613	235	1010	3767	2729
Powerscourt Stream	27	967	222	333	18233	5611
Tinnahinch Bridge	63	1013	327	973	10500	4862
Killough Bridge	57	4333	1043	9333	44000	24487
Dargle at Dublin Road Bridge	153	2267	935	960	17600	6702
Cookstown River at STP	187	1800	756	2967	7000	4395
Kilmacanogue at N11 Bridge	967	8567	5636	3367	25000	13567
Dargle at N11 Bridge	767	34000	7030	1800	98333	22750
County Brook (at Dargle)	667	4933	1721	2300	60667	18089
Swan at Dargle	667	12900	5522	10100	59333	22911
Harbour Mouth	267	3500	1934	4967	47667	17822

Table 3.5. Overall summary of faecal streptococci results.

Conditions =>	Non-storm Conditions (cfu per 100 ml)			Storm Conditions (cfu per 100 ml)		
Location	**Min FS**	**Max FS**	**Mean FS**	**Min FS**	**Max FS**	**Mean FS**
Waterfall - North	4	67	24	73	427	279
Onagh (Glencree)	7	357	115	230	1097	589
Onagh Stream	10	813	151	2100	5200	3327
Powerscourt Stream	0	1447	282	367	14533	4256
Tinnahinch Bridge	15	1327	244	410	5167	1491
Killough Bridge	3	3067	509	6000	44700	27213
Dargle at Dublin Road Bridge	67	1867	520	583	4433	2307
Cookstown River at STP	23	797	170	667	3533	1628
Kilmacanogue at N11 Bridge	360	3833	1566	3033	25167	13889
Dargle at N11 Bridge	223	15433	2387	667	10300	4606
County Brook (at Dargle)	233	1043	527	3433	14700	9253
Swan at Dargle	263	11767	2357	3933	23433	12800
Harbour Mouth	100	1573	592	1900	12233	6567

3.4.2.2 Budget calculations

The bacterial budget calculations are completed in two stages. In the first stage we estimate the amount and sources of bacteria in the Dargle reaching Bray from upstream sources, including the Swan and County Brook which enter at Bray. In the second stage we compare these with the contribution at Bray from the storm overflow from the sewage pumping station.

Stage 1: Upstream sources of indicator bacteria at Bray

The budget estimates are summarised in Figure 3.8 for storm conditions and in Figure 3.9 for low-flow conditions. The distributions are sensitive to the relative magnitudes of the flows in all the rivers rather than individual values. Low-flow measurements were not available for the entire project period and the estimates of low flows at the end of August 2000 were used in estimating these budgets, which should be considered as very approximate.

For storm conditions, most of the bacterial load coming from upstream of Bray comes from the Enniskerry storm overflow (34% of total coliforms, 34% of faecal coliforms and 28% of faecal streptococci) and the Dargle itself (25% TC, 34% FC and 30% FS). A lesser, but still highly significant, contribution is provided by the Swan river (16% TC, 15% FC and 21% FS) and the Glencullen River (20% TC, 11% FC and 7% FS)

In non-storm conditions the bacterial load from upstream of Bray is approximately an order of magnitude lower for total coliforms than for storm conditions (Table 3.6). The Enniskerry outfall is the most serious contributor (43% TC, 61% FC and 34% FS) with the Dargle (22% TC, 19% FC and 40% FS) and the Kilmacanogue (29% TC, 15% FC, 17% FS) also major contributors.

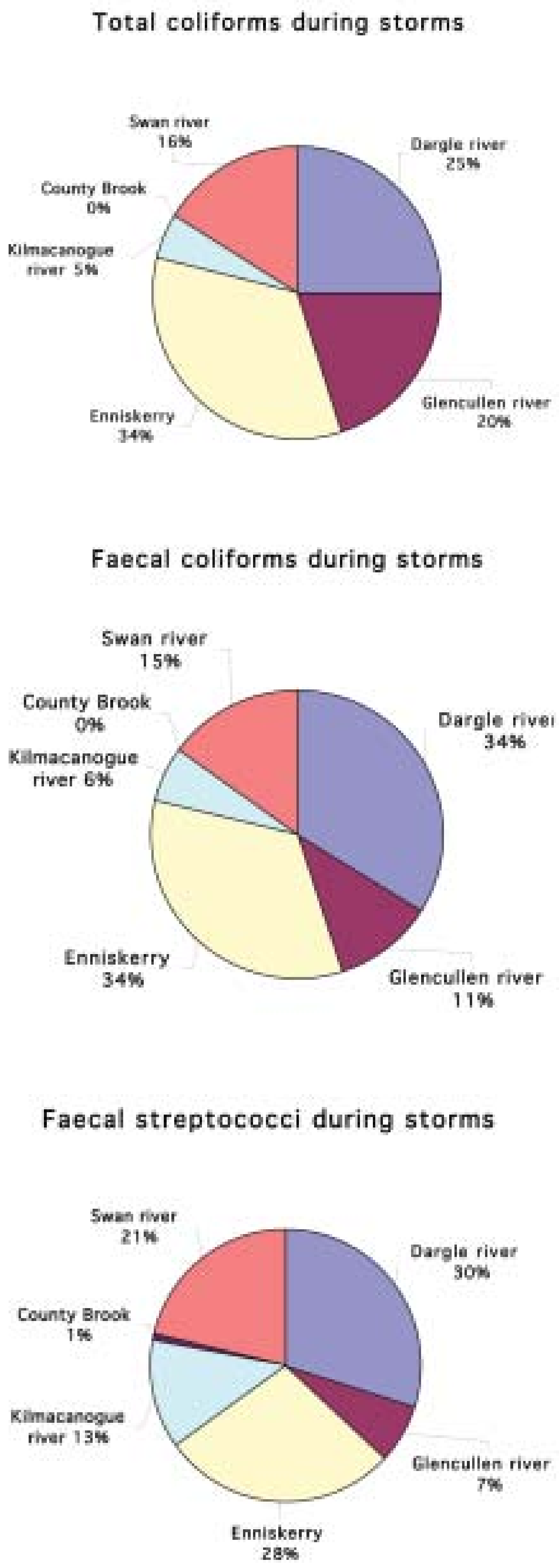


Figure 3.8. Upstream sources of indicator bacteria during storms.

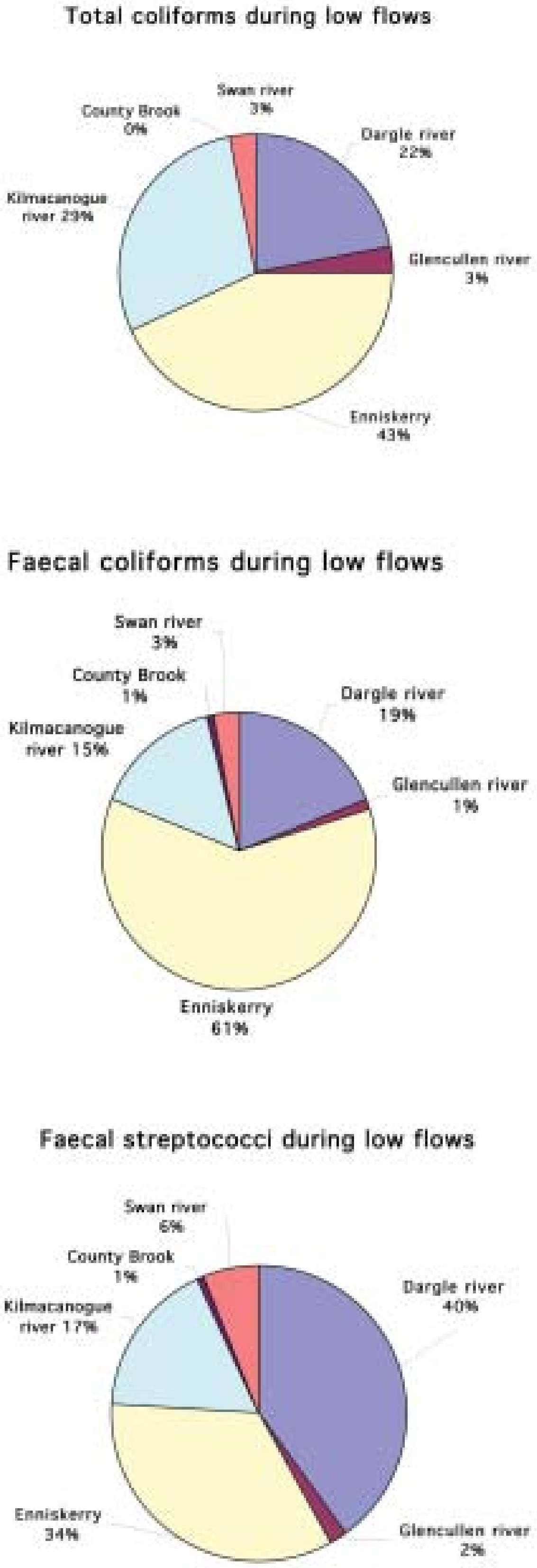


Figure 3.9. Upstream sources of indicator bacteria during low flows.

Thus the Enniskerry outfall and the Dargle itself are the major upstream sources of bacteria during both storms and non-storm periods. The Swan and Glencullen rivers also contribute significantly during storms and the Kilmacanogue during non-storm periods. The latter is particularly noteworthy, not only because of the high non-storm concentrations of organisms in the Kilmacanogue (some higher than for the storm periods) but also because it maintains its base flow during dry periods more so than the other rivers. There must be considerable storage available in the catchment for this to happen and this may also be a factor influencing the high non-storm concentrations in that flow.

Table 3.6 shows the total loads estimated as millions of cfu passing through Bray per second.

Table 3.6. Total indicator-bacteria load from upstream passing through Bray.

	Million cfu per second		
	TC	**FC**	**FS**
Storm	2706	708	190
Non-storm	322	39	8

Stage 2: Additional indicator-bacteria input from Bray storm overflow

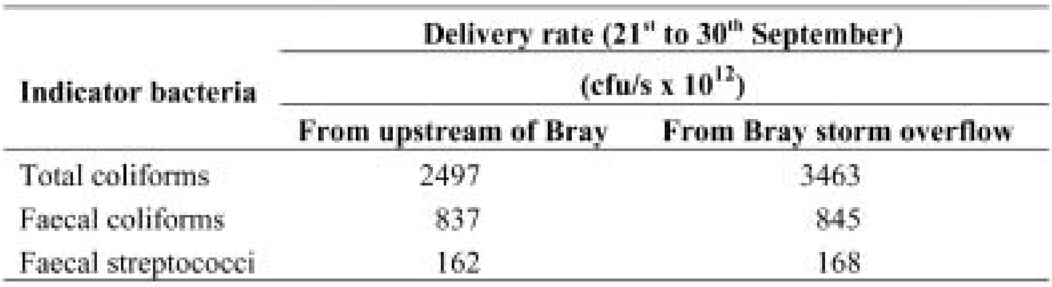
During storm periods when the substantial surface water run off from Bray is combined with sewage, the storage capacity of the sewage pumping station in Bray may be exceeded and the surplus "storm overflow" is pumped into the sea at the northern outer side of Bray harbour wall. Storm pumping may occur for only a short period of time, but during this time a mixture of raw sewage and storm water with a very high bacterial content is discharged. Samples of this material were taken on a number of occasions and analysed. Averaging (time weighted) the resulting concentrations and multiplying by the storm pump discharge capacity gives the potential bacterial delivery rates. The storm pump potential delivery rates are one to two orders of magnitude greater than the combined upstream delivery rates (Table 3.7).

Table 3.7. Potential bacterial delivery rates in storm conditions.

Indicator bacteria	**Delivery rate (all storm periods) (cfu/s x 10^6)**	
	From upstream of Bray	**From Bray storm overflow**
Total coliforms	2706	134850
Faecal coliforms	708	32902
Faecal streptococci	190	6529

However this is not the full picture and exaggerates the actual contribution of the storm overflow. This is because, while the pumping station can discharge storm overflow with very high numbers of bacteria, it actually does so only for short periods of time, when the inflow threatens to exceed storage capacity. A fairer comparison is to estimate the actual contribution of each source over a period of time. This is done here for the ten-day period 21st to 30th September 2000 inclusive. In this 240 hour period the pumping station pumped for a total of 7.13 hours. The results are shown in Table 3.8.

Table 3.8. Amounts of indicator bacteria delivered in storm conditions during the period 21st to 30th September 2000.



Indicator bacteria	**Delivery rate (21st to 30th September) (cfu/s x 10^{12})**	
	From upstream of Bray	**From Bray storm overflow**
Total coliforms	2497	3463
Faecal coliforms	837	845
Faecal streptococci	162	168

Remarkably, the amounts contributed by upstream sources for faecal coliforms and faecal streptococci (which included Enniskerry storm overflow) were very close to the total contribution from the Bray storm overflow. In the period 21st to 30th September 2000, the catchment contributed less total coliforms (2497 cfu x 10^{12}) than the Bray storm overflow (3463 x 10^{12}). The latter delivered slightly more total coliforms and slightly less faecal streptococci. Care must be taken in interpreting these results, since in addition to the uncertainties in the determination of bacterial concentrations and of river flow rates, the bacteria are delivered in quite different temporal distributions. The bacteria load delivered from the Bray storm overflow is delivered in high concentrations over short periods of time, while the delivery from upstream sources, while similar in total amount, occurs at lower concentrations over much longer times. The former may stress the assimilative capacity of the receiving water more so than the latter. It is worth noting that the total of 7.13 hours pumping included a single period of 3.3 hours continuous pumping which delivered in that short time 46% of the total bacterial output from the pumping station, which could possibly be input to the sea during one tidal cycle.

3.5 Land use-water-quality relationships

3.5.1 Wales

3.5.1.1 Potential sources and flow paths of faecal indicator organisms within the Afon Rheidol and Afon Ystwyth catchments

Topography, soils and hydrology

The catchments are developed on Silurian and Ordovician shales and mudstones, with a generally thin and patchy drift cover. The land rises to an altitude of 752 m at the summit of Pumlumon Fawr (Plynlimon) in the headwaters of the Afon Rheidol, some 20 km from the Cardigan Bay coast. On the whole, the catchment has quite steep slopes, with only 30.11% being < 5°. Some of the steepest slopes are concentrated along the middle reaches of the two main valleys and their tributaries, particularly near Pontarfynach (Devil's Bridge) in the Rheidol catchment and Pont-rhyd-y-groes in the Ystwyth catchment.

For the most part, the soils are well-drained, and range from brown earths (Denbigh 1 association) on the lower ground in the western half of the catchments, through brown podzols (Manod association), to podzols (Hafren association) on the higher ground (Rudeforth *et al.*, 1984). Gleys (Cegin and Wilcocks 1 associations) occur in localised areas, mostly on flatter land along the lower altitude interfluves on some of the more poorly drained valley floors.

On the basis of the geology, topography and soils, it might be anticipated that two river systems would be quite responsive to rainfall events, through a combination of throughflow on the steeper slopes and saturated overland flow in the areas of impeded drainage. However, flow variations in the Afon Rheidol are moderated by the various reservoir impoundments, notably the Nant-y-moch and Dinas Reservoirs, and are also strongly affected by the regular discharges of water from the Cwm Rheidol hydroelectric power station. Indeed, through the study period, the Afon Rheidol showed no clear response to rainfall events at either Pen-y-bont (site 101), the subcatchment of which comprises 78.95% of land upstream of reservoirs (i.e. 'reservoir catchment'), or at Cwm Rheidol (102) and Nant-y-moch Dam (104), which are located immediately downstream of impoundments. Only at Rheidol Falls (103), the subcatchment of which includes a smaller proportion (61.72%) of reservoir catchment, was it possible to make a clear high-flow separation following rainfall events. While there are several reservoirs within the Afon Ystwyth catchment, their subcatchments are too small to have a major impact upon the hydrological response, and base flow/high-flow separations could be made for all the monitoring points on the Afon Ystwyth and its tributaries.

Land use

The land-use map generated for the Afon Rheidol and Ystwyth catchments is presented in Figure 3.10, and an overall summary of the land-use data is given in Table 3.9. The lower land is dominated by highly improved, intensively used grassland, which accounts for 33.46% of the total land area. This land is used for dairy cattle, beef cattle and sheep. As has been demonstrated in previous CREH studies, these improved grasslands and

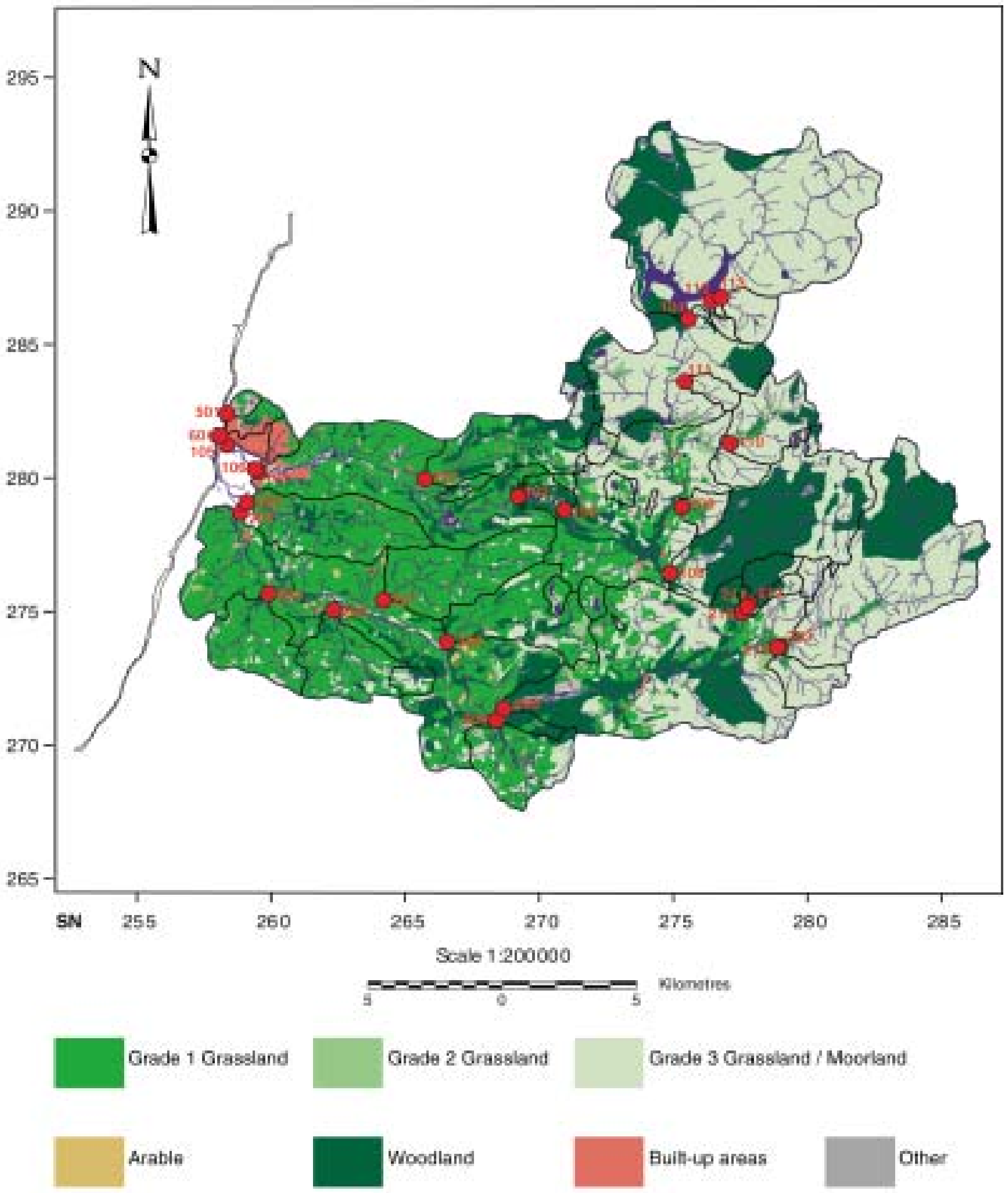
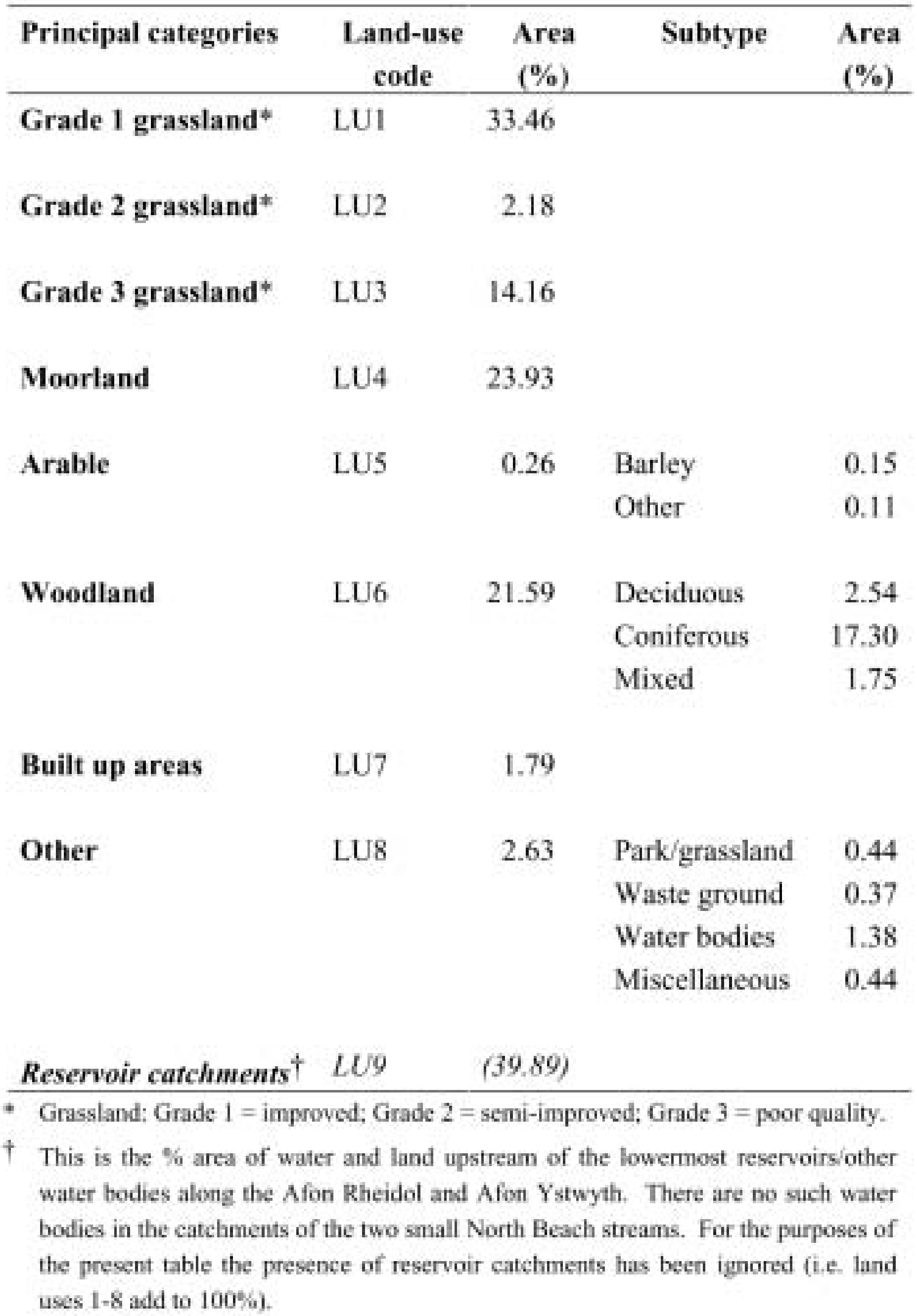


Figure 3.10. Land-use map of the Afon Rheidol and Afon Ystwyth catchments.

Table 3.9. Summary of land-use data for the Afon Rheidol and Afon Ystwyth catchments (total area = 37,933 ha).



Principal categories	Land-use code	Area (%)	Subtype	Area (%)
Grade 1 grassland*	LU1	33.46		
Grade 2 grassland*	LU2	2.18		
Grade 3 grassland*	LU3	14.16		
Moorland	LU4	23.93		
Arable	LU5	0.26	Barley	0.15
			Other	0.11
Woodland	LU6	21.59	Deciduous	2.54
			Coniferous	17.30
			Mixed	1.75
Built up areas	LU7	1.79		
Other	LU8	2.63	Park/grassland	0.44
			Waste ground	0.37
			Water bodies	1.38
			Miscellaneous	0.44
Reservoir catchments †	*LU9*	*(39.89)*		

* Grassland: Grade 1 = improved; Grade 2 = semi-improved; Grade 3 = poor quality.

† This is the % area of water and land upstream of the lowermost reservoirs/other water bodies along the Afon Rheidol and Afon Ystwyth. There are no such water bodies in the catchments of the two small North Beach streams. For the purposes of the present table the presence of reservoir catchments has been ignored (i.e. land uses 1-8 add to 100%).

associated farm yards/buildings represent potentially significant sources of faecal indicator organisms, through faecal inputs to land and watercourses from grazing animals, the spreading of animal wastes (slurry and farmyard manure), runoff from yards, etc. Quite high proportions of land comprise poor quality grassland (14.16%) and moorland (23.93%), both of which are mostly used for extensive sheep grazing; and conifer plantations. In previous studies, areas dominated by these land-use types have generally been associated with relatively low faecal indicator concentrations.

The proportion of built up land is very small (1.79%), with the majority of this being concentrated in Aberystwyth. Throughout the remainder of the catchments there are numerous isolated villages, hamlets and houses, with associated sewage treatment facilities and these represent potential sources of sewage-derived faecal indicator organisms. According to Environment Agency records there are 18 waste water treatment works within the two catchments, ranging from the activated sludge/UV disinfection plant at Aberystwyth (with maximum population equivalent of 28,300) to small septic tank/percolating filter systems at Pont-rhyd-y-groes and Ysbyty Ysytwyth (both with population equivalents of 40). The effluent from six of these small treatment systems, three in each main catchment, was monitored for faecal indicator organisms on a weekly basis. Analysis of variance revealed that the effluent from Pontarfynach WwTW (site 307) had significantly lower GM faecal indicator organism concentrations (e.g. 4.1×10^2 FC 100 ml^{-1}) than the remaining works. In contrast, GM faecal indicator organism concentrations in the effluent from Ponterwyd WwTW were significantly elevated compared to all other works examined (e.g. 1.4×10^7 FC 100 ml^{-1}). This pattern reflects the level of treatment at these works, the modern plant at Pontarfynach has a final stage reed bed which has a positive effect in reducing faecal indicator concentrations whilst Ponterwyd was in a poor state of repair, with the percolating filter not operating at the time of the study. GM faecal indicator organism concentrations in effluent from Capel Bangor and the three works in the Ystwyth catchment were statistically similar (e.g. $1.4 – 8.1 \times 10^5$ FC 100 ml^{-1}). In addition to the treatment works are also 48 consented discharges for treated sewage, including six caravan parks (maximum population equivalent 1132), and 10 for emergency crude/storm sewage, as well as numerous very small discharges (<5 m^3 day^{-1}), which do not require a consent.

Land-use data for the 28 subcatchments are presented in Table 3.10. These reveal marked variations in the proportions of different land uses. For example, several of the subcatchments in the headwaters have no areas of highly improved grassland, whereas six of the Afon Ystwyth tributaries have >50% highly improved grassland (maximum, 90.35% in subcatchment 207). Also, three of the subcatchments comprise >50% woodland (maximum, 87.50% in 211), most of which comprises conifer plantations; and three of the subcatchments draining the Aberystwyth area have very high proportions of built up land (100.0% in 105, 70.06% in 106 and 45.17% in 601). Built up land is one of the key land-use variables, and the presence of a very small number of subcatchments with such high proportions of built up land is somewhat unfortunate from a modelling point of view since the results will tend to be strongly influenced by a small number of sites.

Table 3.11 presents data on land use within 50 m of watercourses in the 28 subcatchments, which have been used in part of the distributed modelling. Correlation analysis shows that there are very strong relationships between the percentage of different land-use types within the subcatchments as a whole, and that defined by the 50 m buffer strips. Apart from arable (LU5), which is a very minor land use in the study area, all of the correlation coefficients are >0.900, and in many cases >0.950. Despite these strong relationships, comparison of Tables 3.10 and 3.11 reveals some interesting differences between the two data sets. For example, in subcatchment 207 (Afon Llanfiangel), which is one of the more intensively farmed lowland subcatchments (90.35% improved pasture overall), the buffer strip data show a reduction in the percentage of improved pasture (to 79.50%) and increases in the proportions of semi-improved grassland, neglected grassland, woodland, built up and other. Subcatchment 213 (Nant Milwyn), one of the headwater tributaries of the Afon Ystwyth, displays a different pattern. In this case, there are

Table 3.10. Total land area and percentage area of principal land-use types in the 28 subcatchments investigated in the Afon Rheidol and Afon Ystwyth catchments.

Subcatchment and Area (ha)		LU1 (%)	LU2 (%)	LU3 (%)	LU4 (%)	LU5 (%)	LU6 (%)	LU7 (%)	LU8 (%)	LU9 (%)
Afon Rheidol										
101	18319.52	13.13	0.34	1.27	0.01	0.03	4.06	0.60	0.89	79.66
102	14397.69	0.06	0.00	0.00	0.00	0.00	0.07	0.01	0.01	99.86
103	14162.03	7.01	1.31	7.79	6.15	0.00	13.04	0.28	0.47	63.95
104	5552.11	0.00	0.00	0.59	0.00	0.00	0.12	0.00	0.01	99.28
Rheidol tributaries										
105	120.02	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00
106	142.31	28.50	0.00	0.00	0.00	0.00	0.00	70.06	1.44	0.00
107	1337.27	41.93	3.32	9.51	0.18	0.00	33.36	1.10	1.26	9.34
108	2405.85	0.90	0.30	7.35	29.07	0.00	58.68	0.04	0.29	3.37
109	207.32	30.38	2.71	30.95	34.36	0.00	1.52	0.01	0.07	0.00
110	747.66	4.54	6.17	29.46	41.94	0.00	13.16	0.22	4.52	0.00
111	158.03	0.00	0.00	36.71	63.24	0.00	0.04	0.00	0.00	0.00
112	66.57	0.00	0.00	39.52	55.11	0.00	5.36	0.00	0.00	0.00
113	315.18	0.00	0.00	6.59	93.02	0.00	0.40	0.00	0.00	0.00
Afon Ystwyth										
201	17847.29	42.82	1.94	13.05	15.60	0.50	20.62	1.04	1.50	2.92
202	8458.09	11.45	1.86	18.22	32.71	0.01	30.27	0.49	1.74	3.25
203	3209.74	1.59	0.47	2.74	61.61	0.00	28.56	0.07	0.83	4.12
Ystwyth tributaries										
204	1250.68	83.42	2.10	1.86	0.00	0.43	9.55	2.42	0.21	0.00
205	838.49	86.56	0.49	6.79	0.00	0.61	3.75	1.26	0.53	0.00
206	846.98	79.27	0.72	10.34	0.00	0.00	7.36	1.88	0.42	0.00
207	1261.97	90.35	2.03	4.01	0.00	0.22	2.39	0.80	0.19	0.00
208	1217.62	62.81	5.02	12.39	0.00	0.00	9.96	0.48	1.19	8.14
209	863.15	55.49	2.59	24.67	2.88	0.40	11.74	0.83	1.40	0.00
210	370.67	2.89	0.00	15.42	8.20	0.00	71.96	0.06	1.47	0.00
211	226.02	1.05	0.00	1.47	9.98	0.00	87.50	0.00	0.00	0.00
212	113.16	0.00	0.00	46.84	6.94	0.00	43.78	0.02	2.43	0.00
213	366.82	3.47	0.50	14.08	80.80	0.00	0.74	0.20	0.20	0.00
Rheidol/Ystwyth catchment total										
Total	37933.00	33.46	2.18	14.16	23.93	0.26	21.59	1.79	2.63	39.89
North Beach streams										
501	89.51	37.26	0.00	0.00	0.00	0.00	0.00	5.63	57.11	0.00
601	163.24	40.82	0.00	0.00	0.00	0.00	8.48	45.17	5.54	0.00

increased proportions of improved grassland, neglected grassland, woodland and built up land within the buffer strip, and a marked reduction in the proportion of moorland (from 80.80% to 69.03%). The findings in both these subcatchments are consistent with what might be expected in these contrasted landscapes: in subcatchments dominated by better land, the principal areas where land use is likely to be more mixed (with woodland, semi-improved grassland, etc.) are adjacent to watercourses; whereas in upland catchments, the lower land close to streams is more likely to have higher proportions of improved grassland and neglected grassland (i.e. grassland which has been enclosed/improved at some time in the past), compared with moorland.

3.5.1.2 River and stream water-quality monitoring results

Apart from the two sampling points (102 and 104) on the Afon Rheidol, which are located downstream of impoundments, and the Afon Rheidol at Pen-y-bont (101), which is strongly affected by the effects of the impoundments, the monitoring points display very wide temporal variations in faecal indicator concentrations and show increases in response to rainfall events. All these sites (i.e. excluding 101, 102 and 104) show a statistically significant elevation in GM FC concentrations at high flow compared to base flow. The majority of sites also show significant elevations in GM TC and EC, the only exceptions being Plas Crug Ditch (105) for TC and Afon Melindwr (107) for EC. The striking feature of the latter site is the unusually high GM EC concentration (1.0×10^{4} cfu $100ml^{-1}$). Local Environment Agency monitoring since the present study suggests that the high concentrations may relate to leakage from local septic tank systems (Hannah Wilkinson, pers. comm.). Statistical summaries of the faecal coliforms data are given in Figure 3.11 for the Afon Rheidol and Afon Ystwyth catchments, and the North Beach streams.

Similar elevations in GM faecal indicator concentrations following rainfall events have been recorded in previous CREH studies. They are attributable to a combination of increased surface runoff, an extension of the stream network into the contributing areas, and entrainment of organisms from stream bed sources, all of which increase the numbers of organisms entering watercourses, and increased stream flow velocities and turbidity, which reduce the opportunities for die-off (through exposure to UV light) and sedimentation along the length of the watercourse.

3.5.1.3 Inter-subcatchment variability in microbial water quality

There are substantial differences in GM faecal indicator concentrations between the various sites, both under base flow and high-flow conditions, and these may provide valuable insights into the relative contributions made by different land-use types to the microbial loadings within the two catchments. The results from each of the main groupings of sites are presented below. Clearly, because of the combined effects of higher discharges and elevated concentrations of faecal indicator organisms, high-flow conditions are critical in affecting the loadings of catchment-derived bacteria delivered to the coastal zone. Attention in the following sections therefore focuses primarily upon the high-flow data.

Afon Rheidol (sites 101-104)

As noted in Section 3.5.1.1, because of the reservoir impoundments and regulation of flow from the Cwm Rheidol Reservoir, sites 101, 102 and 104 display no clear hydrograph response to rainfall and no base flow/high-flow separation is possible. Nonetheless, the results for these sites are important in providing some insight into the magnitude of reduction in faecal indicator concentrations that can occur within such impoundments. In the case of Nant-y-moch (site 104), for example, the water issuing from the reservoir has very low

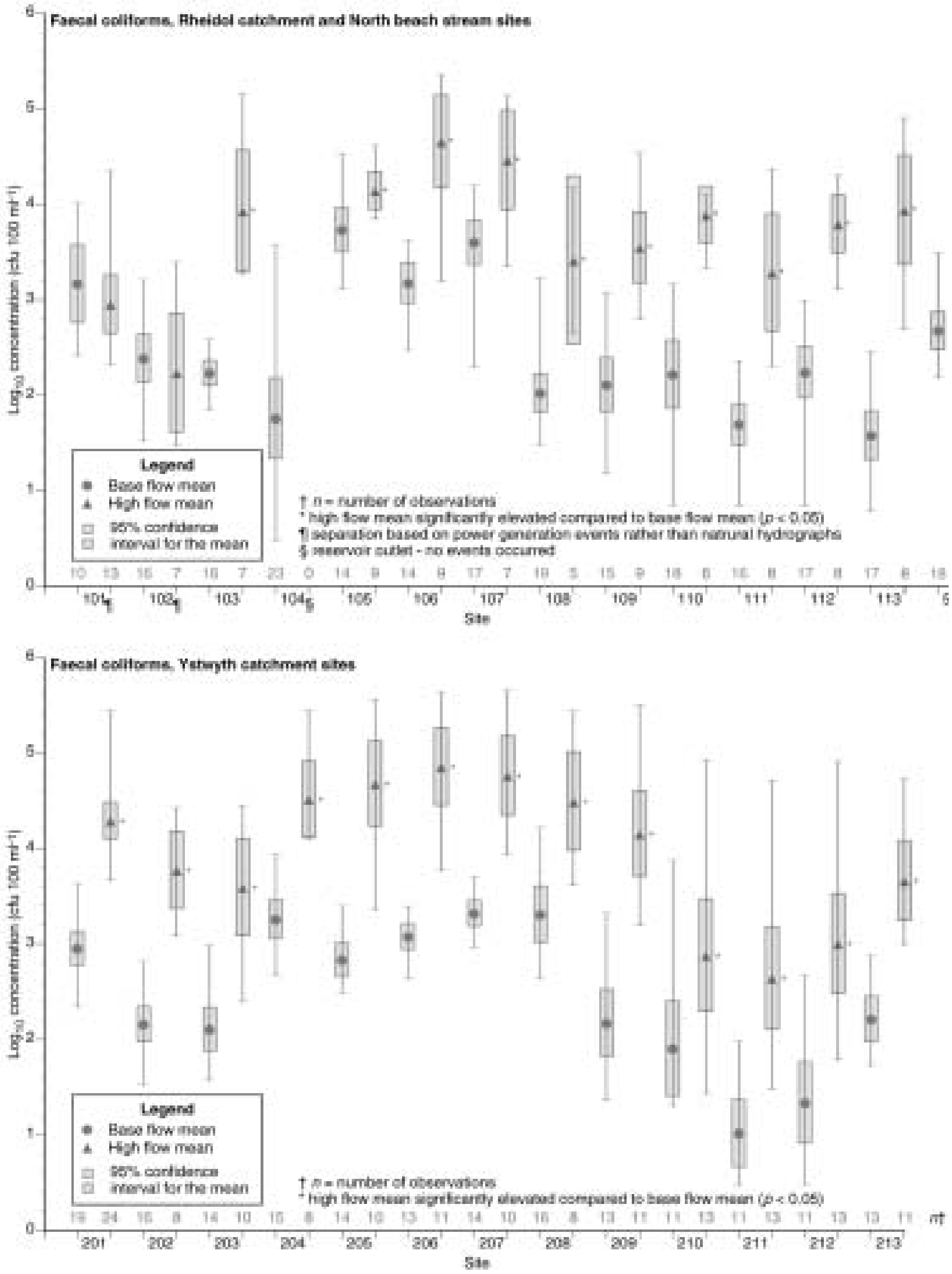


Figure 3.11. Mean, range and 95% confidence interval of $\log_{10}$ transformed faecal coliforms concentrations (cfu 100 ml^{-1}) in samples from sites in the Afon Rheidol and Afon Ystwyth catchments and the North Beach streams.

GM FC and EC concentrations ($5.6x10^1$ and $9.5x10^0$ cfu 100 ml^{-1}, respectively), which are of the same order of magnitude as the lowest GM base flow concentrations recorded at the other sites studied. These figures compare, for example, with high-flow GM concentrations of $6.1x10^3$ and $4.6x10^2$ cfu 100 ml^{-1}, respectively, recorded in the Nant-y-moch stream (site 113), which discharges into Nant-y-moch Reservoir close to the dam. Although the GM TC concentration at site 104 is also relatively low ($4.8x10^3$ cfu 100 ml^{-1}), the effects of impoundment upon this parameter would appear, on present evidence, to be less marked. Clearly, a detailed budget investigation of the principal tributaries entering the reservoir would be needed in order to obtain an accurate measure of the impact of the impoundment.

In the case of the Cwm Rheidol Reservoir, the average water retention times are likely to be much shorter than in the Nant-y-moch Reservoir. The water is, however, shallower, which will allow greater exposure to UV light in the water column. Unfortunately, because of discharges from the power station, the difference in faecal indicator concentrations between Rheidol Falls (103) and the reservoir outlet (102) cannot be used to quantify the change in faecal indicator concentrations through the reservoir. However, the fact that the GM TC, FC and EC concentrations at site 102 ($1.1x10^3$, $2.1x10^2$ and $1.4x10^1$ cfu 100 ml^{-1}, respectively) are more than an order of magnitude less than the high-flow GM concentrations at site 103 ($1.7x10^4$, $8.3x10^3$ and $8.1x10^2$ cfu 100 ml^{-1}, respectively), does indicate a substantial reduction through the reservoir system. It should be noted that the high-flow values recorded at Rheidol Falls are relatively low compared with many of the other sites sampled. This is probably attributable to the high proportion of land (63.95%) within the subcatchment that is upstream of reservoirs.

GM TC, FC and EC concentrations recorded at Pont Pen-y-bont (site 101), the lowest monitoring point on the Afon Rheidol, are all relatively low ($9.4x10^3$, $1.1x10^3$ and $1.2x10^2$ cfu 100 ml^{-1}, respectively). While these figures are about an order of magnitude higher than those recorded at site 102, presumably as a result of agricultural and sewage-derived inputs in the lower reaches of the catchment, the GM TC and FC concentrations are only a little higher, and the GM EC concentration is lower, than the base flow GM concentrations recorded at Pont Tanycastell (site 201), the lowest monitoring point on the Afon Ystwyth. These results appear to confirm the assumed impact of the reservoir impoundments upon faecal indicator concentrations.

Afon Rheidol tributaries (sites 105-113)

The two tributaries which drain part of Aberystwyth, Plas Crug Ditch (site 105) and Nant Padarn (106), both include very high proportions of built up land within their subcatchments (100.0% and 70.06%, respectively). Under high-flow conditions GM TC, FC and EC concentrations are higher at the latter site ($8.7x10^4$, $4.4x10^4$ and $2.2x10^4$ cfu 100 ml^{-1}, respectively). Although these concentrations are quite high, only the figure for EC stands out as being at the higher end of the range recorded in the study as a whole, and this might be related to the fact that most of the remainder of this subcatchment (28.50%) comprises highly improved grassland. These results show that the built-up areas represent a significant source of faecal indicator organisms, possibly as a result of street drainage, cross-connections and leakage from the sewerage system.

Of the other tributaries, only the Afon Melindwr (site 107) has >1.0% built up land (1.10%), and only the Afon Melindwr and Nant Ysbyty Cynfyn (site 109) have substantial proportions of highly improved grassland (41.93 and 30.38%, respectively). The Afon Melindwr displays quite high GM TC, FC and EC concentrations at high flow, but stands out particularly because of the exceptionally high GM EC concentration (1.0×10^4 cfu 100 ml^{-1}) recorded under base flow conditions. The source of the EC is the subject of further investigation by the local Environment Agency (Hannah Wilkinson, Pers. Comm). Nant Ysbyty Cynfyn, on the other hand, has much lower GM concentrations, particularly of FC and EC (3.4×10^3 and 6.7×10^2 cfu 100 ml^{-1}, respectively).

The remainder of the Afon Rheidol tributaries sampled largely comprise neglected grassland, moorland and conifer plantations, in varying proportions, and these exhibit only low to moderate GM concentrations under high-flow conditions.

Afon Ystwyth (sites 201-203)

The three monitoring points on the Afon Ystwyth show a progressive increase in high-flow GM TC, FC and EC concentrations from the headwaters monitoring point at Cwmystwyth (Site 203), through Pont Llanafan (202), to the lowermost point at Pont Tanycastell (201). The differences between sites 203 and 201 are most marked for FC (which increases from 3.8×10^3 to 1.9×10^4 cfu 100 ml^{-1}) and EC (from 4.6×10^2 to 3.3×10^3 cfu 100 ml^{-1}). These results appear to reflect an increase in the proportion of highly improved grassland (from 1.59 to 42.82%) and built up land (from 0.07 to 1.04%) from site 203 to site 201.

Afon Ystwyth tributaries (sites 204-213)

The subcatchments of four of the Afon Ystwyth tributaries that were monitored in the lower, western half of the catchment comprise very high proportions of highly improved grassland: Rhydyfelin stream (site 204), 83.42%; Afon Fâd (205), 86.56%; Nant Adail (206), 79.27%; and Nant Llanfiangel (207), 90.35%. Very high GM TC, FC and EC concentrations were recorded under high-flow conditions for the latter three sites. Indeed, the figures recorded for Nant Adail (1.6×10^5, 7.0×10^4 and 2.3×10^4 cfu 100 ml^{-1}, respectively) are the highest recorded in the study.

At the other extreme, are three small upland subcatchments, the Nant Peiran (site 210), Nant Hylles (211) and Nant Perfedd (212), which comprise high proportions of conifer plantations (71.96, 87.50 and 43.78%, respectively), with virtually all the remaining land being poor quality grassland and moorland. High-flow GM FC and EC concentrations at these sites were the lowest recorded in the study, with minima of 4.3×10^2 and 1.2×10^2 cfu 100 ml^{-1}, respectively. The figures for TC were also among the lowest recorded.

These results from the Afon Ystwyth tributaries appear to confirm the strong association between faecal indicator concentrations and highly improved grassland (positive) and conifer plantations (negative) observed in the previous CREH studies.

Streams discharging to Aberystwyth North beach

The small subcatchments of the two streams discharging to Aberystwyth North beach differ quite markedly in character. Nant Lover's Dingle (site 501) includes only a small proportion of built up land on the northern edge of Aberystwyth (5.63%), and is dominated by a golf course (57.11%) and highly improved grassland (37.26%). Moderately high GM faecal indicator concentrations were recorded at this site under high-flow conditions.

Nant Penglais (site 601), on the other hand, largely comprises built up land (45.17%) and highly improved grassland (40.82%). In this case, the high-flow GM TC, FC and EC concentrations are at the top end of the range ($1.1x10^5$, $6.5x10^4$ and $1.8x10^4$ cfu 100 ml^{-1}, respectively). The difference in water quality between these two streams would seem to be attributable to contrasts in land use.

3.5.1.4 Background to the correlation and multiple regression analysis

As in the previous studies, bivariate Pearson product moment correlation analysis and stepwise multiple regression analysis were undertaken on the subcatchment data in order to model the way in which faecal indicator concentrations in stream waters are related to land use. In the analyses undertaken, the water-quality variables (dependent variables) investigated were the GM TC, FC and EC concentrations under both base flow and high-flow conditions. The three monitoring points along the Afon Rheidol (sites 101, 102 and 104) for which no rainfall-related base flow/high separation could be made were excluded from the analysis. Analysis has been undertaken on data from the remaining subcatchments (n = 25).

The independent (predictor) variable sets used are based on the percentage area of different land-use types within the whole, or selected parts, of individual subcatchments. All independent variables that displayed a skewness value greater than 1.00 were $\log_{10}$ transformed (with 1 being added to such values to overcome the problem of transforming zero values) prior to analysis to improve residual parametricity. These are indicated by the preface "LG" in the code names used. In addition, all variables with ≥25% of cases with zero values were excluded from the analysis. Clearly, some of the independent variables are multicollinear. Rather than eliminating such variables at the outset of the regression analysis, the full set of variables was examined at step 1 so as to identify the most strongly correlated variable. In order to reduce multicollinearity, all independent variables which have an r value of ≥0.707 (i.e. where r^2 ≥50%) with a variable already entered into the regression equation are excluded from subsequent steps. On a small number of occasions the most strongly correlated variable exhibited a negative relationship with the faecal indicator concentration. Since one of the main aims of the regression modelling was to identify the likely sources of microbial organisms, in these cases the most strongly correlated variable with a positive b value was 'forced' into the regression in step 1.

Three different approaches were used to investigate relationships between land use and water quality in the Afon Rheidol and Afon Ystwyth catchments (as detailed below). These are referred to as 'lumped catchment modelling', 'buffer strip modelling' and 'surface flow distance modelling'. The latter two approaches, which were not used in the previous CREH studies, provide a means of investigating and developing ('distributed') models that take into account the distribution of land use within subcatchments.

Lumped catchment modelling

The lumped catchment modelling is based on the overall percentage cover of different land-use types within each subcatchment. The variables used include some of the original land-use categories (e.g. LU1, LU6 and LU7), together with some groupings of these, e.g.improved/semi-improved grassland (LU1+2); and rough grazing (LU3+4). In addition, subcatchment area is included as a variable. Details of the variables used in the lumped catchment (and buffer strip) modelling are presented in Table 3.12. As in previous studies, the modelling uses a combination of Pearson correlation (r) and stepwise multiple regression analyses.

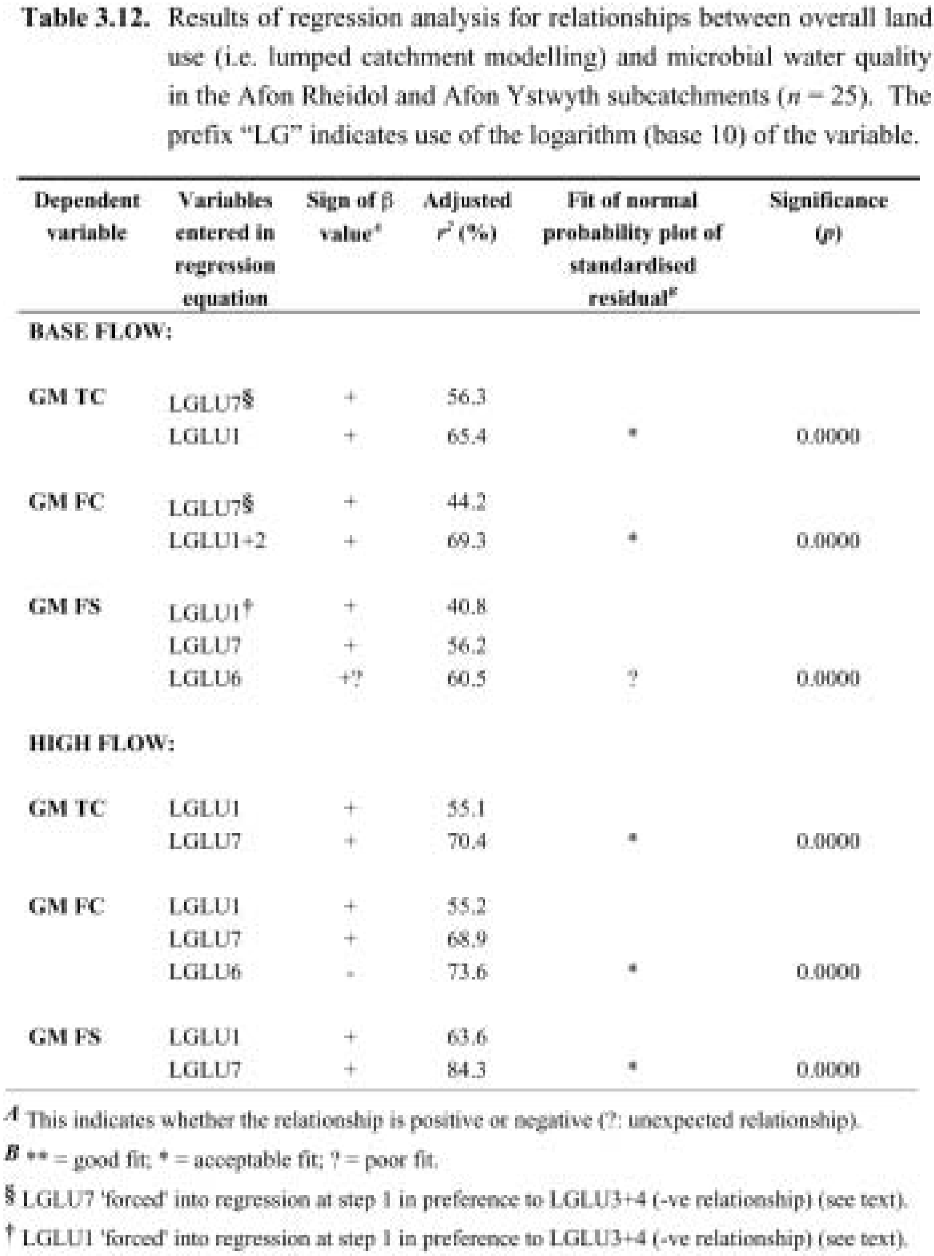


Table 3.12. Results of regression analysis for relationships between overall land use (i.e. lumped catchment modelling) and microbial water quality in the Afon Rheidol and Afon Ystwyth subcatchments (n = 25). The prefix "LG" indicates use of the logarithm (base 10) of the variable.

Dependent variable	Variables entered in regression equation	Sign of β value^A	Adjusted r^2 (%)	Fit of normal probability plot of standardised residual^B	Significance (p)
BASE FLOW:					
GM TC	LGLU7§	+	56.3		
	LGLU1	+	65.4	*	0.0000
GM FC	LGLU7§	+	44.2		
	LGLU1+2	+	69.3	*	0.0000
GM FS	LGLU1†	+	40.8		
	LGLU7	+	56.2		
	LGLU6	+?	60.5	?	0.0000
HIGH FLOW:					
GM TC	LGLU1	+	55.1		
	LGLU7	+	70.4	*	0.0000
GM FC	LGLU1	+	55.2		
	LGLU7	+	68.9		
	LGLU6	-	73.6	*	0.0000
GM FS	LGLU1	+	63.6		
	LGLU7	+	84.3	*	0.0000

^{A} This indicates whether the relationship is positive or negative (?: unexpected relationship).

^{B} ** = good fit; * = acceptable fit; ? = poor fit.

§ LGLU7 'forced' into regression at step 1 in preference to LGLU3+4 (-ve relationship) (see text).

† LGLU1 'forced' into regression at step 1 in preference to LGLU3+4 (-ve relationship) (see text).

Buffer strip modelling

It is well established that the numbers of enteric bacteria in faecal material deposited on ground surfaces can decline rapidly (as a result of exposure to UV light, desiccation, etc.) unless conditions for survival are particularly favourable. Clearly, many local factors affect the survival and transport of such bacteria on slopes, including the moisture regime at the ground surface, hydrological flow paths (overland flow, soil matrix throughflow, etc.) and hillslope gradient. However, other things being equal, the closer a given faecal input is to a watercourse, then the greater will be the chance of faecal indicator organisms entering that watercourse. On this basis, land use adjacent to streams and rivers would seem likely to be more critical in affecting microbial water quality than overall land use within a catchment. In order to investigate this, modelling was undertaken based on land use within 50 m of watercourses, as identified on the OS 1:10,000 scale topographic maps. The approach adopted is identical to that used in the lumped catchment modelling, and this allows direct comparisons to be made between the two.

It should be noted that there are very strong correlations between the percentages of different types of the land use within the buffer strips and those in the subcatchments as a whole. As a consequence, any differences between the lumped catchment and buffer strip models are likely to be relatively small. This is unfortunate, and does, to some extent, undermine the potential value of this aspect of the study. Ideally, the buffer strips would have been different in character, thereby enabling the effects of land use adjacent to streams to be more clearly isolated.

Surface flow distance modelling

In addition to the die-off of faecal indicator organisms on ground surfaces and within soils, it should also be recognised that once these organisms enter watercourses they are subject to continued die-off, through exposure to UV light, and to processes of sedimentation and re-suspension. Clearly, the chance of organisms surviving their passage down a given watercourse will be greater under high flow than base flow conditions, simply because of the shorter transit time at higher velocities; reduced chance of exposure to UV light in deeper and more turbid waters; and the less likelihood of sedimentation. Also, other things being equal, the shorter the flow distance, then the greater will be the chance of survival. Little, however, is known about the actual rates of die-off along natural watercourses. If rates of in-channel die-off are sufficient to affect appreciably the microbial concentrations in stream and river waters, then this is something that will need to be taken into account in developing models to predict microbial water quality accurately from land-use data.

In the present study, a first attempt has been made to investigate the effects of flow distance. The assumption underlying the approach adopted is that, if there is significant die-off along watercourses, then microbial water quality will be more strongly influenced by faecal indicator sources closer to the monitoring point than those at greater distance (i.e. land use closer to the monitoring point will be a better predictor of water quality than that for the subcatchment as a whole). In order to test this, relationships between GM faecal indicator concentrations and the proportion of certain land-use types within different surface flow distances of the monitoring points have been undertaken using correlation analysis. The distance bands used are <1, <2, <3, <4, <5, <10, <20, <30 and <40 km from the water monitoring point. The land uses/groupings used were those which appeared from the lumped catchment and buffer strip modelling to be most closely associated with elevated microbial concentrations, i.e. LU1, LU1+LU2 and LU7. In addition, a fourth variable, the percentage area of LU1+LU2 below 250 m altitude and with a gradient of ≥5°, was included in order to investigate the significance of topographic factors. These particular criteria were chosen with view to including only improved/semi-improved grassland at relatively low altitudes, which will tend to be more intensively used, and on sloping ground, which is more likely to favour surface runoff.

Since the subcatchments studies differ so much in size, and include a number of relatively small subcatchments, the land-use data for the smaller subcatchments only change through the first few distance bands, and thereafter remain constant. While this is, undoubtedly, an inherent limitation of the present study, it was felt that if surface flow distance is a significant factor in affecting microbial water quality, then some indication of this would be evident in the analytical results.

3.5.1.5 Lumped catchment modelling

Base flow conditions

The correlation analysis reveals highly significant relationships between the GM TC, FC and EC concentrations and four of the five land-use variables investigated. In all cases, the relationship is positive for those land uses (e.g. improved pasture and built up land) which represent likely sources of elevated faecal indicator concentrations, and negative for poor quality grassland/moorland, which previous studies have indicated as being sources of relatively clean waters. Interestingly, built up land (LGLU7) exhibits the strongest positive relationship with GM TC (r = 0.762, p<0.001) and FC (r = 0.682, p<0.001), but is weaker for EC (r = 0.562, p<0.01); whereas, for improved grassland (LGLU1) and improved/semi-improved grassland (LGLU1+2), the pattern is reversed with the stronger relationships being with EC (e.g. LGLU1+2: r = 0.636, p<0.01).

Highly significant regression models (Table 3.12 above) have been developed for all three microbial determinands, with the levels of explained variance ranging from 60.5% (EC) to 69.3% (FC). For TC and FC, built up land is entered first, followed by one of the improved grassland variables; whereas for EC this order is reversed.

These results suggest that: (i) built up areas are relatively important sources of TC (and to a lesser extent FC) and (ii) improved pastures are more important for EC under base flow conditions.

It should also be noted that there are no significant correlations with catchment size, either under base flow or high-flow conditions, nor is catchment size entered as a variable in the regression analyses.

High-flow conditions

Under high-flow conditions, improved pasture (LGLU1) exhibits the strongest positive relationships with all three microbial determinands: TC (r = 0.755, p<0.001), FC (r = 0.756, p<0.001) and EC (r = 0.807, p<0.001). Similar correlation coefficients were recorded for LGLU1+2. There are also highly significant, though weaker, relationships with built up land (+ve) and poor quality grassland/moorland (-ve).

Highly significant regression models, with high levels of explained variance, have been developed for all three determinands: TC (70.4%), FC (73.6%) and EC (84.3%). In each case, LGLU1 (+ve) is entered first, followed by LGLU7 (+ve). For illustration, a plot of the bivariate relationship between GM FC and the percentage area of improved grassland is presented in Figure 3.12. Woodland (LGLU6), with a negative *b* value, is also entered in the model for FC.

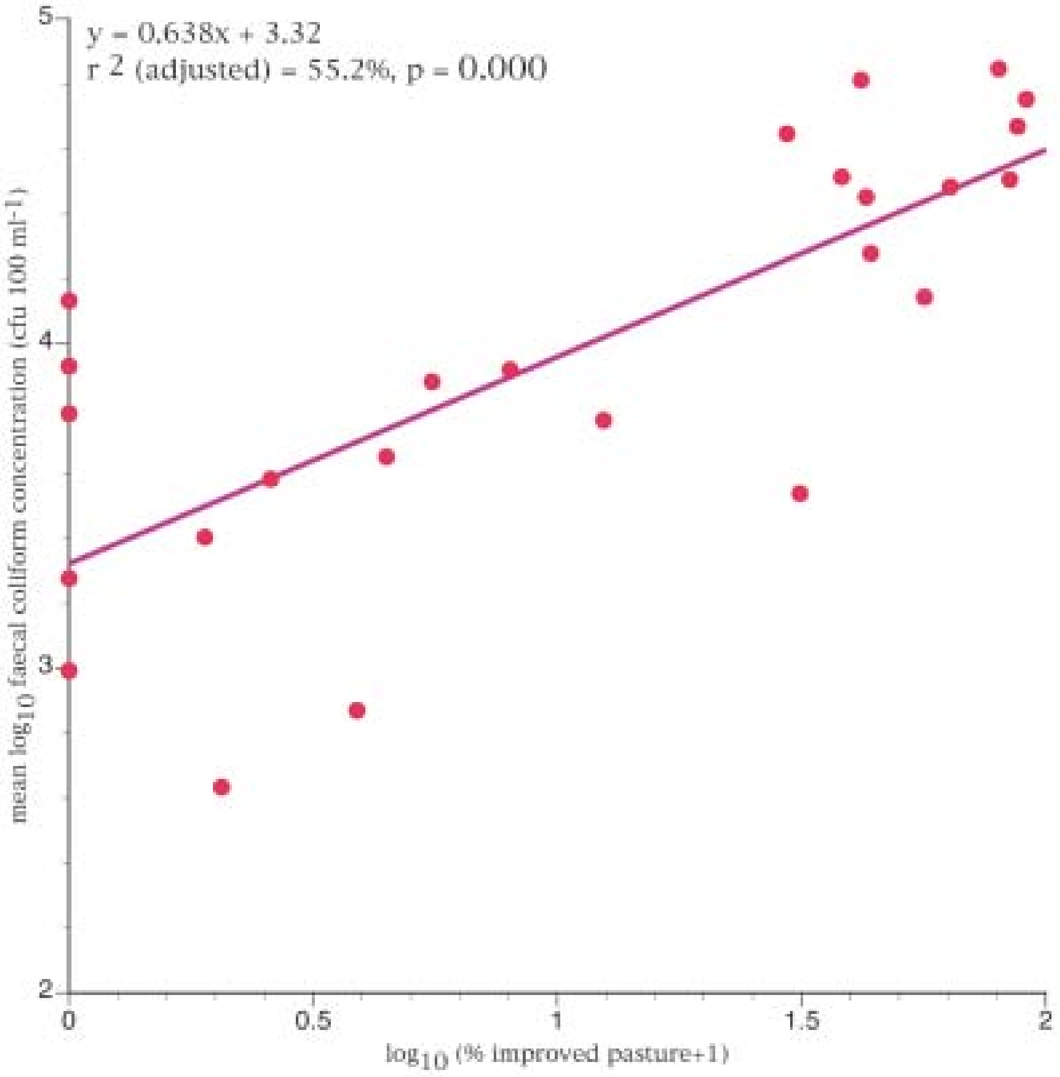


Figure 3.12. Plot of bivariate relationship between $\log_{10}$ (percentage area of improved grassland (LU+1) and mean $\log_{10}$ faecal coliforms concentration (cfu 100 ml $^{-1}$) within the subcatchments (n = 25).

3.5.1.6 Buffer strip modelling

Base flow conditions

The results of the correlation and regression analyses for relationships between land use within 50 m of water courses (i.e. buffer strip) and microbial water quality are very similar to those from the lumped catchment modelling. There are only two notable differences. First, the (-ve) correlations with LGLU3+4 (i.e. poor quality grassland + moorland) are consistently weaker. This is probably attributable to the fact that the variability of the percentage of this particular land-use grouping across the 25 subcatchments is less for the buffer strips than for the subcatchments as a whole, as a result of greater proportions of LU3 land along watercourses in the more lowland subcatchments and smaller proportions of LU3+LU4 land adjacent to streams in the upland subcatchments.

The second difference is that the (+ve) correlations with LGLU7 (built up land) are consistently slightly stronger in the buffer strip modelling. This may reflect the fact that built up land within close proximity of watercourses represents a more significant source of faecal indicator organisms in stream waters than built up land further away. On the other hand, it may be attributable to the fact that the variability of the percentage of built up land is greater for the buffer strips than for the subcatchments as a whole. This is simply because some of the subcatchments have no built up land at all, and in the case of the majority that do have built up land, then the percentage in the buffer strip is generally higher than in the subcatchment as a whole. Caution must, therefore, be exercised in interpreting these results, particularly in view of the fact that the models are likely to be strongly influenced by the small number of subcatchments which have high proportions of built up land.

High-flow conditions

The buffer strip modelling for high-flow conditions also produced very similar results to the lumped catchment modelling. A small improvement has been achieved in the explained variance of the regression models for each of the determinands: TC (71.2%), FC (76.4%) and EC (84.9%).

Discussion

As noted earlier, there are very strong correlations between land use in the buffer strips and in the 25 subcatchments as a whole, and the same would undoubtedly apply to almost all other rural catchments in the UK. It is not surprising, therefore, that the differences between the results of the lumped catchment and buffer strip modelling are quite small. Unfortunately, because of this, the present results cannot be used as a basis for evaluating the likely effectiveness of land-use control measures, such as a reduction in intensity of grazing and/or limiting the spreading of livestock wastes on land adjacent to streams. Realistically, the only way in which such an assessment can be made is through detailed, field-scale microbial budget studies.

The fact that somewhat stronger correlations with built up land are achieved in the buffer strip modelling may indicate that built up areas close to watercourses are of particular significance. However, as noted above, the results relating to the built up land do need to be treated with some circumspection.

3.5.1.7 Surface flow distance modelling

Since none of the catchments include points with surface flow distances in excess of 40 km, the results for the variables for flow distances <40 km, in fact, cover the entire areas of all the subcatchments (i.e. they are equivalent to the data used in the lumped catchment modelling). The correlation coefficients for the <40 km data sets are therefore virtually identical to those for the lumped catchment modelling, and any slight differences are attributable to the fact that the distance flow analysis is based on the sampling of land use on a 50 m grid, and that some points around the edge of individual subcatchments had to be excluded because the surface flow paths generated from the DTM crossed subcatchment boundaries (See Section 3.2.1.4).

Base flow

As in the case of the lumped catchment and buffer strip modelling, under base flow conditions the strongest (+ve) relationships at base flow are with built up land (LGLU7). What is striking about the results for LGLU7 is that the correlation coefficients are highest for land use within a 1 km surface flow distance of the monitoring point, and fall off progressively as the width of the band increases. For example, the coefficient for GM FC ranges from 0.872 (at <1 km) to 0.761 (<40 km). In the case of built up land, it would appear therefore that the actual distribution of this particular land use is important in affecting water quality. However, as with the results from the buffer strip modelling it should be recognised that within these subcatchments built up land is more likely to occur closer to the monitoring point, and this will inevitably increase the variability of the proportion of built up land within the <1 km distance band.

For the three improved grassland-related variables there is again a progressive change in the correlation coefficient with an increase in the surface flow distance band, but the pattern is reversed, with the strongest relationship being with the widest band. This tends to imply that surface flow distance is not an important factor in relation to faecal indicator organisms associated with these sources.

The other point to note is that the results obtained for improved/semi-improved grassland at an altitude of <250 m and gradient of ≥5˚ (LGLU1+2AG) does not give an improved correlation compared with LGLU1+2. This suggests that these particular topographic thresholds are not significant in affecting the supply of faecal indicator organisms to watercourses.

The regression models generated for GM TC, FC and EC show a considerable increase in the percentage explained variance compared with the lumped catchment and buffer strip modelling, with values of 77.7, 78.8 and 66.4%, respectively. These improvements are directly attributable to the greater strength of the relationship with the proportion of built up land within 1 km of the monitoring point, compared with built up land in the subcatchments as a whole.

High flow

At high flow, the improved grassland-related variables emerge as being more important than built up land, which is consistent with the lumped catchment modelling. Otherwise, the trends in the results closely parallel those recorded for base flow conditions.

The regression models for GM TC, FC and EC achieve high levels of explained variance of 74.4%, 72.5% and 85.7%, respectively. In all three cases, the level of explained variance achieved is slightly higher than for the equivalent land-use variables (i.e. LGLU1 and LGLU7) in the lumped catchment and buffer strip models. In the latter two, however, woodland, which has not been included in the surface flow distance modelling, is also entered at step 3 for FC, and this gives a higher value overall.

Discussion

As noted above, the present study does not provide an ideal basis for investigating the effects of surface flow distances because of the wide range in subcatchment size, and the results obtained are somewhat equivocal. In the case of the improved grassland-related variables, which are the most important predictors of high-flow water quality, the results may suggest that flow distance is not an important factor in affecting microbial concentrations. This implies that there is little removal of faecal indicator organisms along water courses from die-off and sedimentation processes. This is supported by the fact that the lumped catchment modelling showed no significant relationship between GM, TC, FC and EC and catchment size (a negative relationship would be anticipated if die-off and sedimentation were key factors). At high flow, factors relating to microbial survival (e.g. high turbidity) and rapid transport (e.g. high stream velocity) may be more important.

On the other hand, the results relating to built up land, which is the dominant predictor of base flow water quality, suggest that distance is important. Certainly, a considerable improvement in the base flow models is achieved when the proportion of built up land within 1 km of monitoring points is used, rather than the overall percentage within the subcatchments.

It is unclear, on present evidence, why the results for built up land are different, and this merits further investigation in future studies. However, what is clear from these preliminary investigations is that improvements in modelling appear to be achievable using distributed land-use data.

3.5.1.8 Overview of modelling results

The modelling work undertaken clearly demonstrates that there are strong underlying relationships between land use and microbial water quality within the Afon Rheidol and Afon Ystwyth catchments. The results confirm trends that have been established in previous CREH catchment investigations. In general, somewhat higher levels of explanation are achieved under high flow, than base flow, conditions. This is assumed to reflect the fact that at times of high flow, following rainfall: (i) a much larger proportion of the catchment contributes surface runoff to channels; and (ii) there is less opportunity for in-channel die-off and sedimentation under deeper, high velocity, and more turbid conditions. The dominance of the improved grassland-related predictor variables at high flow is presumed also to be related to the catchment-wide impact of rainfall events.

Under base flow conditions, not only are the models generally weaker, but built up land is the dominant land-use variable. The most likely explanation of this is that built up areas represent a source of faecal indicator organisms from sewage-related sources that affects water quality under both high-flow and base flow conditions. However, it is only at low flow, when faecal inputs from agricultural land are limited, that these sources become dominant. At times of high flow the impact of inputs from built up land is ‘swamped’ by inputs from the remainder of the catchment.

3.5.2 Ireland

The land-use classifications used in the Irish study relate to the Welsh (CREH) classifications as set out in Table 3.2. The areas of land use for the Dargle catchment as a whole are given under the Welsh classifications in Table 3.13.

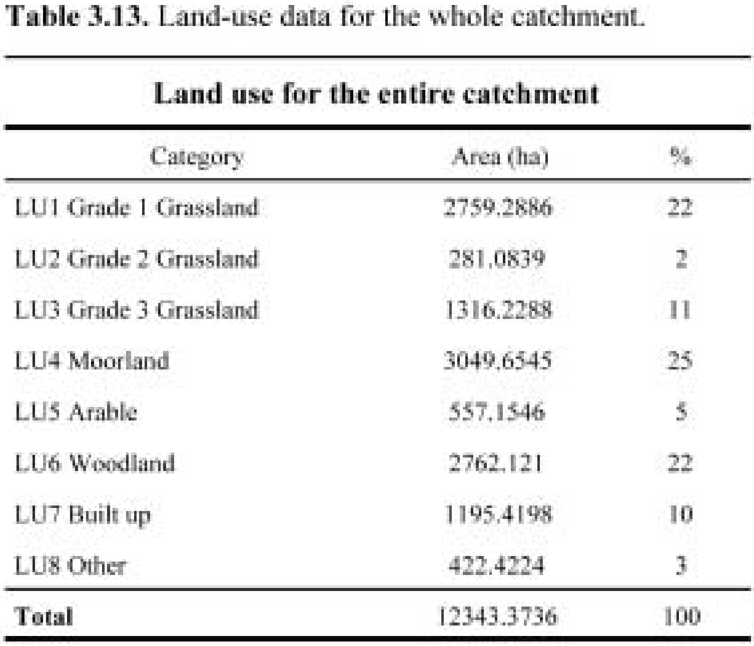


Table 3.13. Land-use data for the whole catchment.

Land use for the entire catchment

Category	Area (ha)	%
LU1 Grade 1 Grassland	2759.2886	22
LU2 Grade 2 Grassland	281.0839	2
LU3 Grade 3 Grassland	1316.2288	11
LU4 Moorland	3049.6545	25
LU5 Arable	557.1546	5
LU6 Woodland	2762.121	22
LU7 Built up	1195.4198	10
LU8 Other	422.4224	3
Total	12343.3736	100

For analysis of correlation with water quality the land use for each of the subcatchments was categorised at three different levels of detail: 3 classes, 6 classes and 8 classes as set out in the following Tables.

For each categorisation, the individual areas of each category of use were normalised to indicate the percentage of area of that land use in each subcatchment. These normalised data were used in the correlation and regression analysis described below. Tables 3.14 to 3.16 show the normalised land-use data.

Table 3.14. Distribution of land uses for classification no. 2 (3 categories).

	Percentage land use			Area
Subcatchment	**Pasture**	**Settlement**	**Other**	**(km)^2**
Waterfall - North	7.16	0.67	92.18	12.95
Onagh (Glencree)	12.94	0.78	86.28	33.87
Onagh Stream	45.54	3.28	51.18	3.34
Powerscourt Stream	28.77	5.49	65.74	2.69
Tinnahinch Bridge	16.79	2.19	81.02	52.85
Killough Bridge	53.83	5.97	40.20	7.27
Dargle at Dublin Road Bridge	21.41	3.23	75.36	60.12
Cookstown River at STP	28.58	8.62	62.80	24.05
Kilmacanogue at N11 Bridge	30.03	19.66	50.31	8.74
Dargle at N11 Bridge	24.40	6.05	69.55	86.17
County Brook (at Dargle)	48.30	11.78	39.92	5.51
Swan at Dargle	13.60	33.57	52.83	7.10
Harbour Mouth	24.76	10.93	64.31	114.15

Table 3.15. Distribution of land uses for classification no. 1 (6 categories).

Subcatchment	Percentage land use						Area $(km)^2$
	Arable	Buildings & grounds	Forest	Lake & rock	Pasture	Veg (non-agric)[a]	
Waterfall - North	0.00	0.67	29.70	0.00	7.16	62.47	12.95
Onagh (Glencree)	0.07	0.78	29.50	1.23	12.94	55.48	33.87
Onagh Stream	4.92	3.28	33.34	3.99	45.54	8.92	3.34
Powerscourt Stream	24.91	5.49	38.18	0.06	28.77	2.60	2.69
Tinnahinch Bridge	2.41	2.19	30.62	0.94	16.79	47.04	52.85
Killough Bridge	6.35	5.97	5.97	4.40	53.83	23.49	7.27
Dargle at Dublin Road Bridge	3.07	3.23	27.69	1.29	21.41	43.31	60.12
Cookstown River at STP	14.18	10.69	8.96	7.05	50.84	8.28	24.05
Dargle at N11 Bridge	2.85	4.78	25.58	1.29	23.88	41.62	86.17
Kilmacanogue at N11 Bridge	4.19	19.66	8.68	6.05	30.03	31.39	8.74
County Brook (at Dargle)	11.95	11.78	17.38	2.07	48.30	8.52	5.51
Swan at Dargle	16.54	33.57	20.38	1.27	13.60	14.64	7.10
Harbour Mouth	4.37	8.57	23.08	1.68	25.49	36.81	114.15

a: Non-agricultural vegetation.

Table 3.16. Distribution of land uses for the CREH classification (8 categories).

	Percentage land use								Area
Subcatchment	**Grass 1**	**Grass 2**	**Grass 3**	**Moor**	**Arable**	**Wood**	**Built up**	**Other**	**(km)^2**
Waterfall - North	4.26	2.90	14.41	48.06	0.00	29.70	0.18	0.49	12.95
Onagh (Glencree)	8.67	4.27	19.09	36.39	0.07	29.50	0.78	1.23	33.87
Onagh Stream	42.19	3.35	0.00	8.92	4.92	33.34	3.28	3.99	3.34
Powerscourt Stream	24.73	4.04	0.00	2.60	24.91	38.18	2.54	3.01	2.69
Tinnahinch Bridge	13.29	3.50	14.29	32.75	2.41	30.62	1.35	1.78	52.85
Killough Bridge	50.47	3.36	23.49	0.00	6.35	5.97	5.97	4.40	7.27
Dargle at Dublin Road Bridge	18.02	3.39	14.86	28.44	3.07	27.69	2.30	2.22	60.12
Cookstown River at STP	26.88	1.69	20.08	19.58	1.31	21.01	5.46	3.99	24.05
Dargle at N11 Bridge	21.00	2.88	15.89	25.73	2.85	25.58	3.29	2.78	86.17
Kilmacanogue at N11 Bridge	29.52	0.51	0.00	31.39	4.19	8.68	19.56	6.15	8.74
County Brook (at Dargle)	48.30	0.00	0.00	8.52	11.95	17.38	5.24	8.61	5.51
Swan at Dargle	12.58	1.02	0.00	14.64	16.54	20.38	33.22	1.62	7.10
Harbour Mouth	22.45	2.31	12.23	23.53	4.35	22.59	9.11	3.42	114.15

3.5.2.1 Correlation of indicator-bacteria concentrations with land-use classification 2 (3 categories)

The approach here is to start with the simplest analysis and assess its results before proceeding to more complex analyses. The simplest land-use classification is the Class 2 classification, which has three categories of land use, namely, Settlement, Pasture and Other. The bacterial samples are divided into two categories, those taken during non-storm (i.e. low-flow) conditions and those taken during storm conditions (higher flows). For each type of analysis (total coliforms, faecal coliforms and faecal streptococci) the correlation between the logarithm (base 10) of the bacterial cfu count and the percentage land use in the catchment was calculated for each sampling excursion. This gave 12 separate correlation coefficients for the non-storm events and 5 for the storm events. These were averaged for each type of condition and the coefficient of variation was calculated as the standard deviation of the values divided by their average. A low value of coefficient of variation indicates that the corresponding correlation was consistent through each sampling excursion. The results of this analysis are shown in Tables 3.17 through 3.22.

Non-storm events

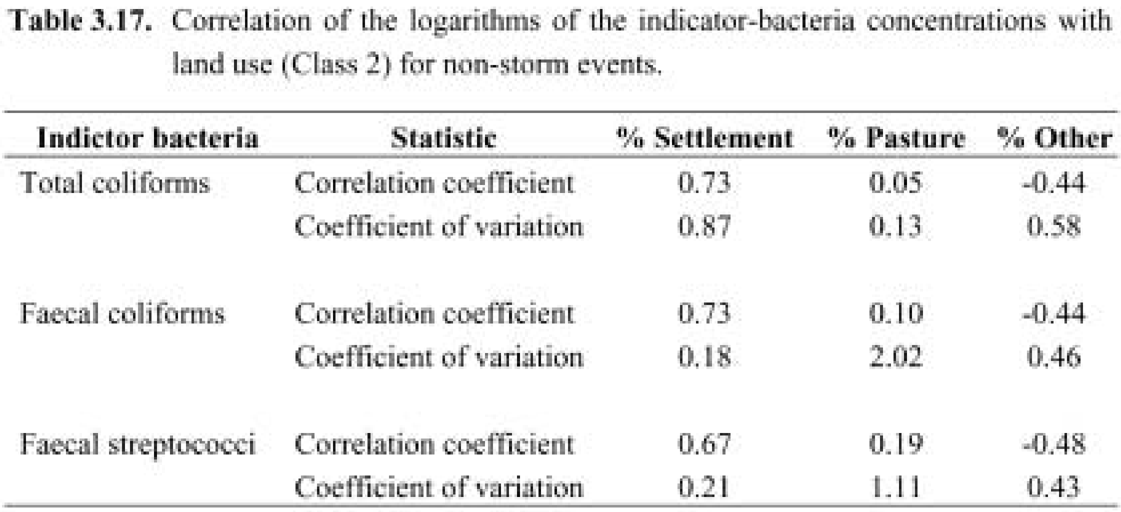


Table 3.17. Correlation of the logarithms of the indicator-bacteria concentrations with land use (Class 2) for non-storm events.

Indictor bacteria	Statistic	% Settlement	% Pasture	% Other
Total coliforms	Correlation coefficient	0.73	0.05	-0.44
	Coefficient of variation	0.87	0.13	0.58
Faecal coliforms	Correlation coefficient	0.73	0.10	-0.44
	Coefficient of variation	0.18	2.02	0.46
Faecal streptococci	Correlation coefficient	0.67	0.19	-0.48
	Coefficient of variation	0.21	1.11	0.43

The results for all three bacterial categories show very strong and consistent correlations with percentage settlement. The strongest correlation is that of total coliforms with % settlement, which is 0.73 with a coefficient of variation of 0.87. The “other” category represents all land uses which are not either settlement and pasture and includes forest, peat, moor. The negative sign of its correlation coefficient indicates that type of land use has a beneficial effect of concentrations, but there is considerable variability in the individual results, indicated by the relatively high coefficients of variation.

Storm events

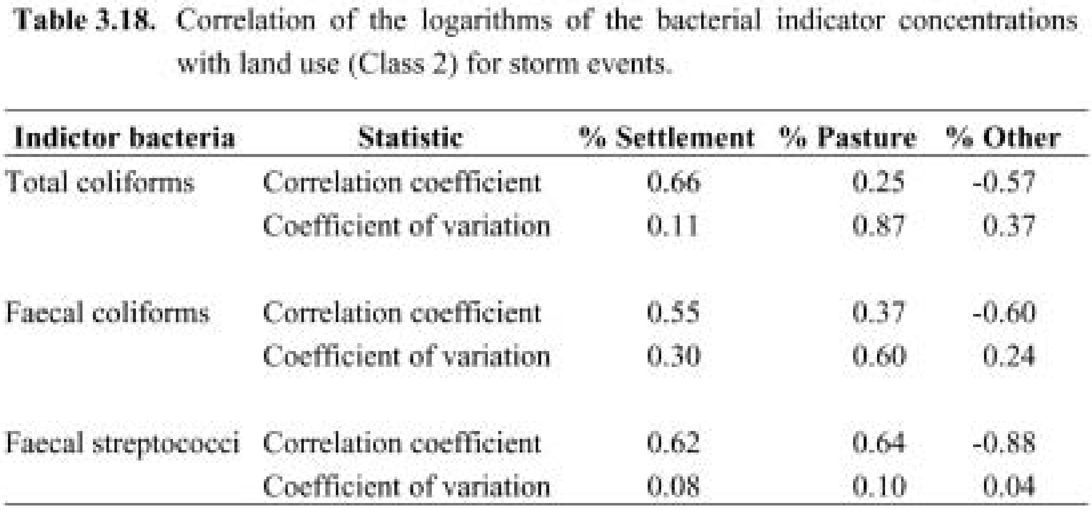


Table 3.18. Correlation of the logarithms of the bacterial indicator concentrations with land use (Class 2) for storm events.

Indictor bacteria	Statistic	% Settlement	% Pasture	% Other
Total coliforms	Correlation coefficient	0.66	0.25	-0.57
	Coefficient of variation	0.11	0.87	0.37
Faecal coliforms	Correlation coefficient	0.55	0.37	-0.60
	Coefficient of variation	0.30	0.60	0.24
Faecal streptococci	Correlation coefficient	0.62	0.64	-0.88
	Coefficient of variation	0.08	0.10	0.04

Again the relatively high and consistent correlation with settlement is apparent. In addition the negative correlation (beneficial effect) of the “other” land-use categories has become stronger and more consistent, i.e. lower coefficients of variation.

3.5.2.2 Correlation of indicator organism concentrations with land-use classification 1 (6 categories)

Using more detail in the land-use classification has the beneficial effect of isolating individual land-use effects. However, the correlations and regressions have more variability because of the limited amount of basic data and must be interpreted with care.

Non-storm events (Table 3.19)

The high correlation with settlement in the previous land use is continued with a high and consistent correlation with building in land-use classification no. 1. A weaker correlation with lakes and rock is apparent for total coliforms. The beneficial influence of forest is apparent through its negative correlation coefficient.

Storm events (Table 3.20)

The effect of building is also apparent during storms. However the effect of forest is stronger during the storm period than during non-storms. There is an unusually high correlation for pasture with faecal streptococci (0.5, Table 3.20).

Table 3.19. Correlation of the logarithms of indicator-bacteria concentrations with land use (Class 1) for non-storm events.

Indicator bacteria	Statistic	Arable	Building	Forest	Lake/rock	Pasture	Veg/non-ag[a]
Total coliforms	Correlation coefficient	0.12	0.77	-0.70	0.59	0.24	-0.25
	Coefficient of variation	1.39	0.12	0.18	0.29	0.90	0.51
Faecal coliforms	Correlation coefficient	0.02	0.74	-0.63	0.43	0.12	-0.12
	Coefficient of variation	4.20	0.18	0.23	0.28	1.15	1.15
Faecal streptococci	Correlation coefficient	0.21	0.65	-0.42	0.28	0.14	-0.27
	Coefficient of variation	1.07	0.21	0.52	0.65	1.40	0.78

a: Non-agricultural vegetation.

Table 3.20. Correlation of the logarithms of indicator-bacteria concentrations with land use (Class for storm events.

Indicator bacteria	Statistic	Arable	Building	Forest	Lake/rock	Pasture	Veg/non-ag[a]
Total coliforms	Correlation coefficient	0.40	0.66	-0.57	0.24	0.24	-0.39
	Coefficient of variation	0.43	0.1	0.24	0.69	0.72	0.48
Faecal coliforms	Correlation coefficient	0.16	0.54	-0.56	0.22	0.28	-0.26
	Coefficient of variation	1.70	0.31	0..08	0.51	0.57	0.69
Faecal streptococci	Correlation coefficient	0.35	0.61	-0.53	0.40	0.50	-0.58
	Coefficient of variation	0.40	0.08	0.19	0.14	0.25	0.14

a: Non-agricultural vegetation.

3.5.2.3 Correlations of indicator bacteria with CREH land-use classification (8 categories)

This classification has the largest number of categories (8) and is used here for comparison with the results of the Welsh team. Note from Table 3.16 that the amount of type 2 grassland in the Dargle catchment is quite small and so correlations with it may be spurious.

Non-storm events (Table 3.21)

The strong correlation with built up areas continues in this grouping with a slightly weaker negative correlation with woodland. There are high negative correlations with Grass type 2, but these must be suspect considering the small amount of this category in the catchment.

Storm events (Table 3.22)

For storm events, the high correlation with built up areas persists and the negative correlation with woodland strengthens, i.e. has a lower coefficient of variation. The moorland category has a negative correlation (beneficial effect) during storms, especially on faecal streptococci, i.e. viz. a correlation coefficient of –0.66 in Table 3.22 with a low coefficient of variation of 0.15.

3.5.2.4 Buffer strip modelling

Using the Ordnance Survey Map data there is, in the catchment, approximately 140 km of stream length. Using the GIS, the land cover was extracted for a 100 m wide zone flanking each stream (i.e. total buffer width is 200 m) for each catchment and upstream of each sampling point. The total catchment area is 12156 ha, the total buffer zone area is 2787 ha.

The percentage of each subcatchment taken up by the buffer zones varies from 5 to 31%. Most lie between 21 - 31%. The upper Glencree had the largest buffer at 31%, the urbanised Swan had 5%. The lower Dargle subcatchment and that of the Kilmacanogue were also low at 11%.

A comparison between the land covers in hectares and percentages for each whole subcatchment and its buffer land cover is presented in Tables 3.23 and 3.24.

The buffer zones show higher proportions of improved pasture and woodland than their associated catchments and lower proportions of rough grazing, moorland, arable, built up and other land covers.

With distance down the Dargle both buffer zones and whole catchments show similar trends: relative increases in grades 1 and 2 grassland, built and other types and relative decreases in poor quality grazing, and woodland. Absolute areas for all land cover classes in hectares, of course, increase in all cases.

Table 3.23. Subcatchment land-use areas (CREH classification) as percentages of the total subcatchment area. Totals are for all land area up-stream of sampling locations indicated.

Subcatchment(s)	Sampling location	Grassland grade 1	Grassland grade 2	Grassland grade 3	Moorland	Arable	Woodland	Built up	Other
Glencree	9	9	4	19	36	0	30	1	1
Dargle Upper	10	4	3	14	48	0	30	0	0
Powerscourt	7	25	4	0	3	25	38	3	3
Onagh	8	42	3	0	9	5	33	3	4
Dargle Upr. Middle	6	40	0	0	3	10	34	6	6
Total:	6	13	4	14	33	2	31	1	2
Killough	5	50	3	23	0	6	6	6	4
Dargle Lr. Middle	3	39	0	0	6	11	21	17	7
Total:	3	18	3	15	28	3	28	2	2
Upper Glencullen	4	27	2	20	20	1	21	5	4
Cookstown		51	0	0	8	14	9	11	7
Glencul'n/Cookst'n		29	2	19	19	2	20	6	4
Kilmacanogue	2	30	1	0	31	4	9	20	6
Total:	1	22	3	15	26	3	24	5	9
County Brook	12	48	0	0	9	12	17	5	9
Swan	11	13	1	0	15	17	20	33	2
Dargle Lower	25	23	0	0	4	6	6	55	7
Total:	25	22	2	12	24	4	23	9	3

Table 3.24. Subcatchment buffer zone land-use areas of as percentages of the total subcatchment buffer zone area. Totals are for all buffer zone area up-stream of sampling locations indicated.

Subcatchment(s)	Sampling location	Grassland grade 1	Grassland grade 2	Grassland grade 3	Moorland	Arable	Woodland	Built up	Other
Glencree	9	13	6	17	27	0	35	1	0
Dargle Upper	10	9	0	26	26	0	36	0	1
Powerscourt	7	15	3	0	4	13	51	4	9
Onagh	8	55	4	0	5	6	26	3	0
Dargle Upper Middle	6	36	0	0	0	10	51	2	0
Total:	6	17	4	16	22	2	37	1	1
Killough	5	53	2	0	13	9	16	5	1
Dargle Lower Middle	3	41	0	0	0	1	49	9	0
Total:	3	22	4	14	21	2	35	2	1
Upper Glencullen	4	29	3	7	20	0	33	4	4
Cookstown		46	0	0	2	5	36	11	0
Glencul'n/Cookst'n		30	2	6	19	0	33	4	4
Kilmacanogue	2	37	0	0	6	1	25	32	0
Total:	1	24	3	12	20	2	34	4	1

3.5.2.5 Correlations of indicator-bacteria concentrations with CREH land-use classification of 100 metre buffer strips (8 categories)

The percentage land use within a 100 m wide buffer strip on either side of the channels was calculated and correlated with the $\log_{10}$ bacterial concentrations. The average correlation coefficients and their coefficients of variation were calculated and are presented in Tables 3.25 and 3.26 below.

Non-storm events (Table 3.25)

The strong and consistent positive correlation with built up areas and negative correlation with grassland type 3 is apparent as is the additional strong, but not quite so consistent negative correlation (i.e. somewhat higher coefficients of variation) with woodland and moorland.

Storm events (Table 3.26)

For the storm events, the same strong and consistent positive correlation with built-up areas and negative correlation with grassland of type 2 and 3 is apparent. However, the influence of woodland and moorland has increased with strong and consistent negative correlations. The coefficients of variation for most estimates are much smaller than for the non-storm cases.

Comparing the original analysis of whole-catchment percentage land use, Tables 3.21 and 3.22 with the percentage land use in the buffer strips alone, Tables 3.25 and 3.26, showed that, overall, the whole-catchment land use was more closely related to the bacterial measurements than the buffer strip alone.

Table 3.25. Correlation of the logarithms of the indicator-bacteria concentrations with CREH land-use classification for non-storm events.

Indicator bacteria	Statistic	Grass 1	Grass 2	Grass 3	Moor	Arable	Wood	Built up	Other
Total coliforms	Correlation coefficient	0.14	-0.69	-0.20	-0.09	-0.10	-0.51	0.67	0.43
	Coefficient of variation	2.47	0.20	0.88	-0.06	2.34	0.89	0.28	0.76
Faecal coliforms	Correlation coefficient	0.08	-0.71	-0.24	-0.03	-0.09	-0.52	0.66	0.40
	Coefficient of variation	3.95	0.21	1.01	9.54	2.62	0.91	0.29	0.70
Faecal streptococci	Correlation coefficient	0.15	-0.46	-0.38	-0.25	0.15	-0.37	0.60	0.41
	Coefficient of variation	1.88	0.38	0.83	1.01	2.32	1.02	0.30	0.58

Table 3.26. Correlation of the logarithms of the indicator-bacteria concentrations with CREH land-use classification for storm events.

Indicator bacteria	Statistic	Grass 1	Grass 2	Grass 3	Moor	Arable	Wood	Built up	Other
Total coliforms	Correlation coefficient	0.08	-0.63	-0.46	-0.43	0.12	-0.56	0.57	0.23
	Coefficient of variation	3.71	0.19	0.34	0.31	1.25	0.29	0.15	1.15
Faecal coliforms	Correlation coefficient	0.26	-0.59	-0.43	-0.38	0.08	-0.66	0.48	0.09
	Coefficient of variation	1.19	0.38	0.33	0.60	2.39	0.16	0.35	4.81
Faecal streptococci	Correlation coefficient	0.50	-0.42	-0.82	-0.64	0.36	-0.64	0.50	0.18
	Coefficient of variation	0.18	0.25	0.10	0.18	0.32	0.16	0.17	1.37

3.5.2.6 Multiple linear regressions with land use

Multiple linear regressions were performed to examine the degree with which bacterial concentrations could be explained by land-use characteristics. This was done for the $\log_{10}$ of the concentrations in cfu (100 ml)$^{-1}$ with the data grouped into storm and non-storm sets as for the correlation analyses. The constant term in the regression is forced to zero as this generally gave more realistic equations for the land-use 1 and CREH land-use classifications. Because the land-use data are normalised as percentages, one land-use category is redundant in the regression since the sum of all categories must add to 100% for each subcatchment. This leads to multicollinearity problems in regression calculations if all categories are included in the regression. This is avoided by eliminating one category from the regression. There is no loss of generality, since the eliminated percentage land use is easily recovered from the percentages of the remaining categories. In all cases the significance of a coefficient estimate is assessed by as Student's t-test statistic at the 95% significance level.

Land-use classification 1 (6 categories) — storm events

The regression of total coliforms with five variables (arable, building, forest, pasture, nonag) explained approximately 50% of the variance in the data with an R^2 of 0.52. The resulting equation is

$$\log 10(TC) = 0.07\,Arable + 0.06\,Building + 0.02\,Forest + 0.05\,Pasture + 0.05\,nonag$$

Student's t-test statistic is calculated to assess if these estimates are statistically significant (i.e. different from zero) at the 95% confidence level. All are significant.

The regression for faecal coliforms had an R^2 of 0.40. The resulting equation is

$$\log 10(FC) = 0.04\,Arable + 0.06\,Building + 0.02\,Forest + 0.04\,Pasture + 0.04\,nonag$$

All the coefficients are statistically significant at the 95% confidence level.

The regression for faecal streptococci had an R^2 of 0.58. The resulting equation is

$$\log 10(FS) = 0.01\,Arable + 0.07\,Building + 0.03\,Forest + 0.05\,Pasture + 0.02\,nonag$$

The coefficient of Arable land is not statistically significant (95% level); all the others are.

Land-use classification 1 (6 categories) — non-storm events

The regression of total coliforms with five variables (eliminating lake & rock) explained approximately 50% of the variance in the data with an R^2 of 0.64. The resulting equation is

$$\log 10(TC) = 0.02\,Arable + 0.09\,Building + 0.01\,Forest + 0.04\,Pasture + 0.04\,nonag$$

Student's t-test statistic is calculated to assess if these estimates are statistically significant (i.e. different from zero) at the 95% confidence level. All are significant; however the coefficients for Arable land and Forest have the lowest statistics, 2.1 and 2.8 respectively, while those of the other variables are greater than 10.

The regression for faecal coliforms had an R^2 of 0.62. The resulting equation is

$$\log 10(FC) = 0.01\,Arable + 0.08\,Building + 0.01\,Forest + 0.03\,Pasture + 0.03\,nonag$$

The coefficients of Forest and Arable are not statistically significant (i.e. different from zero) at the 95% confidence level. All the other coefficients are statistically significant.

The regression for faecal streptococci had a very low R^2 of 0.36 so the equation is discarded.

The most significant general trend in the above figures is the strengthening of the Building variable as a predictor of bacterial concentration for the non-storm events compared with the storm events.

CREH land-use classification (8 categories) — storm events

The regression of total coliforms with seven variables (grass 1, grass 2, grass 3, moorland, arable, woodland and built up) explained more than 50% of the variance in the data with an R^2 of 0.55. The resulting equation is

$$\log 10(TC) = 0.05 grass1 - 0.07 grass2 + 0.06 grass3 + 0.05 moor + 0.08 arable + 0.03 wood + 0.06 built$$

The coefficient of grass 2 is not significant at the 95% confidence level, while all the other coefficients are.

The regression for faecal coliforms had an R^2 of 0.46 The resulting equation is

$$\log 10(FC) = 0.05 grass1 + 0.02 grass2 + 0.05 grass3 + 0.04 moor + 0.06 arable + 0.02 wood + 0.05 built$$

Again, the coefficient of grass 2 is not significant at the 95% confidence level, while all the other coefficients are.

The regression for faecal streptococci had an R^2 of 0.76. The resulting equation is

$$\log 10(FS) = 0.06\,grass1 + 0.14\,grass2 + 0.02\,grass3 + 0.03\,moor + 0.05\,arable + 0.06\,built$$

The coefficient of woodland was zero so it was removed from the equation. All coefficients in the equation are significant. Note the very high coefficient (0.13) for grass 2. This also has a very high coefficient of variation (0.059) and a low t-statistic (2.18).

CREH land-use classification (8 categories) — non-storm events

The regression of total coliforms with seven variables (eliminating the “other” category) explained approximately 60% of the variance in the data with an R^2 of 0.64. The resulting equation is, with all coefficients being significant.

$$\log 10(TC) = 0.04\,grass1 - 0.18\,grass2 + 0.05\,grass3 + 0.04\,moor + 0.03\,arable + 0.03\,wood + 0.08\,built$$

The regression for faecal coliforms had an R^2 of 0.64. The resulting equation is (all coefficients significant)

$$\log 10(FC) = 0.04\,grass1 - 0.16\,grass2 + 0.04\,grass3 + 0.04\,moor + 0.04\,arable + 0.01\,wood + 0.05\,built$$

The regression for faecal streptococci had an R^2 of 0.37 and the equation is discarded.

Land-use classification 2 (3 categories) — storm events

The regression of total coliforms and of faecal coliforms with two variables (settlement and other) gave R^2 values of 0.42 and 0.33 respectively and the resulting equations are discarded.

The regression for faecal streptococci had an R^2 of 0.70. The resulting equation is (all coefficients significant)

$$\log 10(FS) = 5.10 + 0.01\,settle - 0.03\,other$$

Land-use classification 2 (3 categories) — non-storm events

The regression for total coliforms gave an R^2 of 0.53 and the resulting equation is

$$\log 10(TC) = 3.34 + 0.05\,settle$$

However the coefficient of “other” was zero and is not significant and the variable was eliminated from the equation.

The regressions for faecal coliforms and faecal streptococci had low values of R^2, 0.48 and 0.37 respectively, and the resulting equations are not reported here.

Conclusions

Land use alone does not explain all of the variability in the bacteria data. It could not be expected to, since water-flow rates, intensity of precipitation and antecedent hydrological conditions, amongst other factors, must also influence the concentrations in the flow. However, many of the regression relationships with land use explain more than 50% of this variability and the values of the coefficients of the individual variables do indicate which types of land use have most influence and the sign of the coefficient indicates whether the influence is beneficial or detrimental.

Table 3.27 summarises the R^2 values for each of the regressions. The strongest relationships are those for total coliforms during non-storm periods and for faecal streptococci during storm periods.

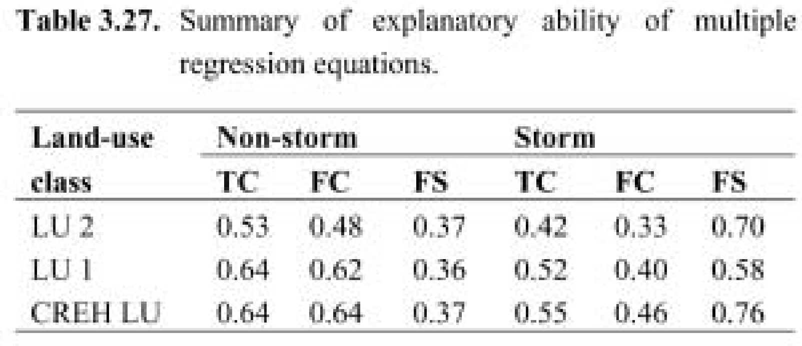


Table 3.27. Summary of explanatory ability of multiple regression equations.

Land-use class	Non-storm TC	Non-storm FC	Non-storm FS	Storm TC	Storm FC	Storm FS
LU 2	0.53	0.48	0.37	0.42	0.33	0.70
LU 1	0.64	0.62	0.36	0.52	0.40	0.58
CREH LU	0.64	0.64	0.37	0.55	0.46	0.76

3.5.2.7 Non-linear regressions with land use

The multiple regression analysis identified the land-use categories which significantly influenced the levels of indicator bacteria in the Dargle catchment but was necessarily confined to a search for linear relationships. Focussing on the significant land-use categories thus identified, a graphical analysis was undertaken to seek non-linear relationships.

The first phase of the graphical analysis employed the data for the “background” non-flood (non-storm-event) condition of the catchment and was restricted to sampling “Excursions” numbered 2 and 4 to 10, inclusive, and within those 8 excursions to those sampling stations which offered a rational basis for seeking correlations with the various land-use categories. The data on which the non-linear analyses were based are shown in Table 3.28. These excursions furnish an almost-uniform spread of bacteriological data, each point on the graphs representing an average of not less than 7 but usually 8 bacteriological measurements. The 12th station, “Dargle at N11 Bridge”, was considered to be arguably atypical in that its bacterial concentrations were affected by a major non-diffuse source, namely, the discharge of sewage from Enniskerry, a sizeable village. However, where convincing correlations were found when this station was omitted, the analysis was repeated to test the effect of including it. Although 6 further low-flow (dry weather) sampling excursions were undertaken, their data were omitted from the graphical analysis because these excursions omitted 3 of the 12 sampling stations employed by Excursions 2 and 4 to 10 of Table 3.28 and so would unduly bias the analysis.

Table 3.28. Bacterial counts for low-flow (dry weather) conditions - summary data.

Sampling Excursions 2, and 4 to 10, inclusive: 20 July to 8 September 1999										
Sampling Station	**Land Use**		**Total Coliforms (TC)**			**Faecal Coliforms (FC)**			**Faecal Streptococci (FS)**	
	% Pasture	**% Settlement**	**Average log TC***	**Number of Samples**	**St'd Dev'n**	**Average log FC**	**Number of Samples**	**St'd Dev'n**	**Average log FS**	**Number of Samples**	**St'd Dev'n**
Waterfall - North	7.2	0.7	2.9	8	0.2	2.4	8	0.2	1.4	8	0.3
Ouagh (Glencree)	12.9	0.8	3.0	8	0.3	2.4	8	0.2	2.1	8	0.3
Digby's Wood	45.5	3.3	2.8	8	0.5	2.3	7	0.5	1.9	8	0.6
Tumble Bay	28.8	5.5	3.0	8	0.3	2.2	8	0.5	2.2	7	0.6
Tinnahinch Bridge	16.8	2.2	3.0	8	0.2	2.6	8	0.3	2.4	8	0.4
Killough Bridge	53.8	6.0	3.6	8	0.3	3.1	8	0.3	2.7	8	0.4
Dargle at Dublin Road Bridge	21.4	3.2	3.7	8	0.2	3.0	8	0.2	2.6	8	0.4
Cookstown River at STP	28.6	8.6	4.0	7	0.4	2.9	8	0.2	2.3	8	0.3
Kilmacanogue at N11 Bridge	30.0	19.7	4.9	8	0.5	3.7	8	0.2	3.1	8	0.4
County Brook (at Dargle)	48.3	11.8	3.6	8	0.2	3.1	8	0.3	2.7	8	0.2
Swan at Dargle	13.6	33.6	4.6	8	0.3	3.6	8	0.4	3.1	8	0.5
Dargle at N11 Bridge	24.4	6.0	4.3	8	0.4	3.7	8	0.4	3.0	8	0.6

* "Average log TC" = average of the log to base 10 of the total coliform concentration, the latter being expressed as number of colony- forming units (cfu) per 100 ml of water sample. This value can also be described as the log of the geometric mean of the total coliform concentrations.
"Average log FC" and "Average log FS" are directly analogous to "Average log TC".

The second phase of the graphical analysis employed data gathered for the high-flow (storm-event) condition of the catchment, summarised in Table 3.29, embracing Excursions numbered 3 and 16 to 21, inclusive. It will be seen from this Table that these 7 excursions furnished an almost uniform spread of bacteriological data for all the 12 sampling stations employed in this preliminary search for correlations with land use, the averages being based on at least 6 but usually 7 bacteriological measurements. As with the low-flow data, the analysis firstly omitted the station “Dargle at N11 Bridge” until such time as a convincing correlation was obtained and then that station was included to test whether or not its inclusion weakened the correlation.

The analysis consistently produced definite correlations of the $\log_{10}$ of the bacterial concentrations with percentage settlement for total and faecal coliforms and faecal streptococci using both second-order-polynomial and “power” ($y = b\, x^c$) curves both for the low- and high-flow conditions. The correlations were strongest when the station “Dargle at N11 Bridge” was omitted. The inclusion of that station slightly weakened, but by no means obliterated, the correlations. Typical examples of the correlations obtained are shown in Figures 3.13 and 3.14. No special significance is to be attached the turn-down of the polynomial curve towards the right hand side of each graph. Instead, the significant feature of both the polynomial and power forms is that they identify a definite gradual fall-off in the rate of increase of $\log_{10}\{\text{bacterial concentration}\}$ with increasing percentage settlement which might reasonably be interpreted as reflecting an improvement in the control of leakage of sewage for higher settlement densities. All such correlations were absent when the percentage pasture was employed as the land-use category.

The percentage settlement employed heretofore represents the percentage of the area of each subcatchment under human settlement. Another approach to quantifying the settlement of each subcatchment with a view to assessing its influence on water quality involved determining the percentage of the area of a “buffer zone” delineated by a boundary 100 m from each side of the channel and under human settlement. However, no better insights were revealed by a graphical search for correlations between the bacterial concentrations and this buffer-zone settlement category than had been established using the non-restricted settlement category. The correlations continued to show the distinct fall-off in the rate of increase in the bacterial concentrations with increasing degree of settlement exposed by the earlier analyses.

Table 3.29. Bacterial counts for high-flow (storm-event) conditions - summary data.

Sampling Excursions 3, and 16 to 21, inclusive: 5 August 1999, and 10 to 27 September 2000										
Sampling Station	**Land Use**		**Total Coliforms (TC)**			**Faecal Coliforms (FC)**			**Faecal Streptococci (FS)**		
	% Pasture	**% Settlement**	**Average log TC***	**Number of Samples**	**St'd Dev'n**	**Average log FC**	**Number of Samples**	**St'd Dev'n**	**Average log FS**	**Number of Samples**	**St'd Dev'n**
Waterfall - North	7.2	0.7	4.1	7	0.4	3.5	7	0.4	2.3	7	0.4
Onagh (Glencree)	12.9	0.8	3.7	7	0.4	3.2	7	0.3	2.7	7	0.2
Digby's Wood	45.5	3.3	3.9	6	0.2	3.2	6	0.5	3.4	6	0.4
Tumble Bay	28.8	5.5	4.3	7	0.4	3.3	7	0.8	3.1	7	0.9
Tinnahinch Bridge	16.8	2.2	4.3	7	0.2	3.5	7	0.3	3.0	7	0.4
Killough Bridge	53.8	6.0	4.7	7	0.5	4.1	6	0.6	4.1	6	0.6
Dargle at Dublin Road Bridge	21.4	3.2	4.2	7	0.4	3.6	7	0.5	3.2	7	0.4
Cookstown River at STP	28.6	8.6	4.5	7	0.2	3.5	7	0.2	3.1	7	0.3
Kilmacanogue at N11 Bridge	30.0	19.7	4.7	7	0.4	4.0	7	0.3	4.0	7	0.3
County Brook (at Dargle)	48.3	11.8	4.6	7	0.3	3.9	7	0.6	3.7	6	0.5
Swan at Dargle	13.6	33.6	5.0	7	0.2	4.2	7	0.3	4.0	7	0.3
Dargle at N11 Bridge	24.4	6.0	4.7	7	0.4	3.9	7	0.5	3.4	7	0.5

* "Average log TC" = average of the log to base 10 of the total coliform concentration, the latter being expressed as number of colony- forming units (cfu) per 100 ml of water sample. This value can also be described as the log of the geometric mean of the total coliform concentrations.
"Average log FC" and "Average log FS" are directly analogous to "Average log TC".

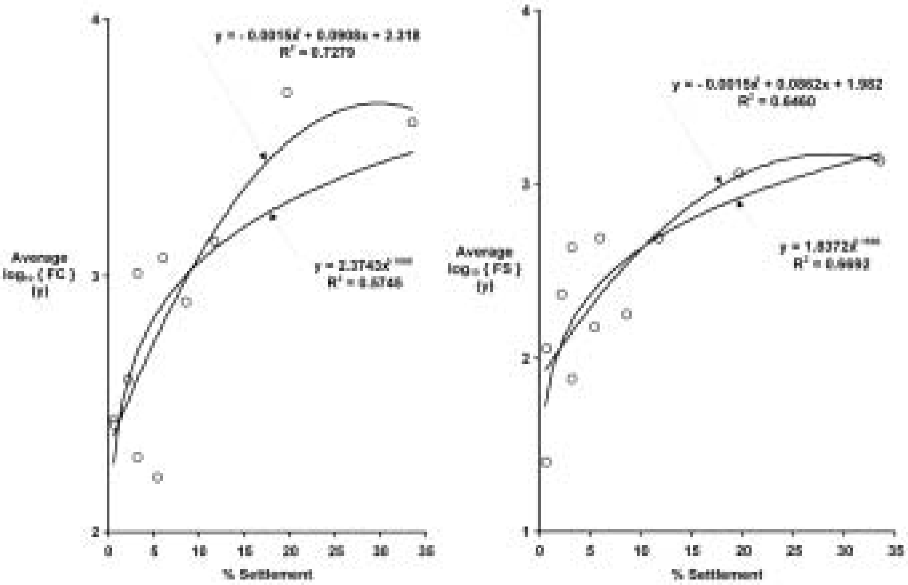


Figure 3.13. Illustrating non-linear correlations between the faecal coliform, or faecal streptococci, concentration and the percentage settlement of the catchment for the low-flow (dry weather) condition. Data from Table 3.28, excluding the station "Dargle at N11 Bridge". Bacterial concentrations are expressed as cfu per 100 ml.

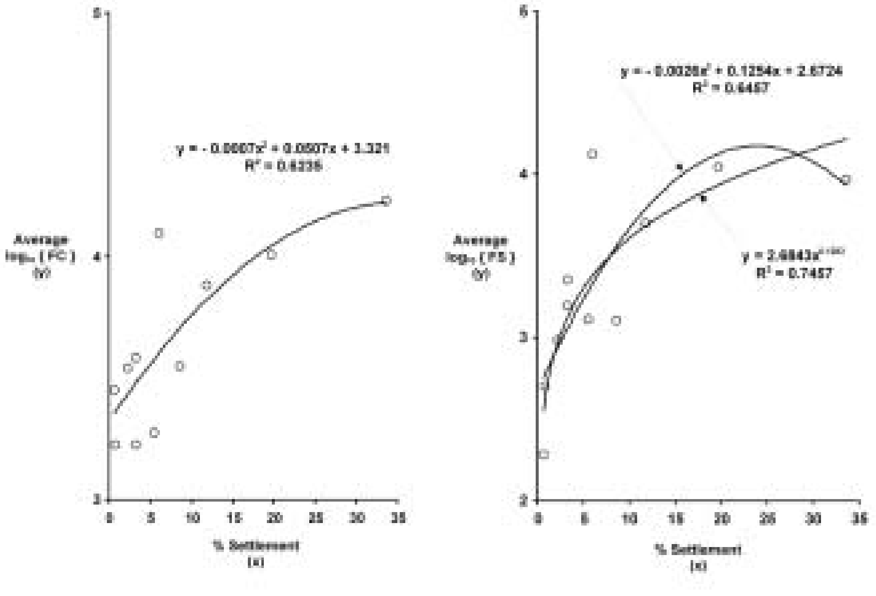


Figure 3.14. Illustrating non-linear correlations between the faecal coliform, or faecal streptococci, concentration and the percentage settlement of the catchment for the high-flow (storm-event) condition. Data from Table 3.29, excluding the station "Dargle at N11 Bridge". Bacterial concentrations are expressed as cfu per 100 ml.

3.6 Marine water quality

3.6.1 Wales

The results of marine water-quality monitoring at Aberystwyth North and South beaches during the study period are shown in Figures 3.15 and 3.16. These figures also include local hourly rainfall near North beach (Figure 3.15); the estimated discharge from the Afon Rheidol and Afon Ystwyth at Aberystwyth Harbour, close to South beach (Figure 3.16); the timing of CSO samples from Tan-y-cae and the concentrations used for compliance assessment in the EC Directive 76/160/EEC. Both beaches show a pattern of deterioration in water quality in response to rainfall events. This pattern is particularly marked at Aberystwyth South beach where TC and FC concentrations exceeded EC *Imperative* criteria (10,000 TC 100 ml^{-1}, 2,000 FC 100 ml^{-1}) on two occasions, both relating to high-flow event conditions (Figure 3.16) when the faecal indicator loading would be greatest (Figure 3.5). Interestingly, the Tan-y-cae CSO discharged during both events. After other events, water quality at South beach deteriorated sufficiently to exceed the EC *Guideline* criteria (500 TC 100 ml^{-1}, 100 FC, EC 100 ml^{-1}). At Aberystwyth North beach, the pattern of deterioration was less pronounced, with a single exceedence of the EC *Imperative* concentration for FC observed during the study period (Figure 3.15). This may reflect the proximity of the two beaches to the harbour outlet and major source of faecal indicators during hydrograph events. Any impact of this source at the more remote North beach may be attenuated and delayed by hydrodynamic conditions (e.g. tidal state, wind direction) during and after the event. However, the water-quality deterioration at North beach after rainfall is sufficient to exceed the EC *Guideline* concentrations. This may relate to local inputs of faecal indicators from the stream sources discharging directly to this beach, particularly Nant Penglais which provides the larger input closer to the compliance monitoring point. The contribution of such sources to compliance exceedence would require further tracer/hydrodynamic modelling studies.

The marine water-quality results (in terms of the number and proportion of results not exceeding each EC Directive compliance threshold specified for each of the faecal indicator organisms) show that Aberystwyth South beach would not comply with the *Imperative* criteria of 95% of samples below the specified TC and FC concentrations. The two *Imperative* compliance failures are related to high faecal indicator loading from the river system (3.5). The contribution of the Tan-y-cae CSO to such failures could only be ascertained by tracer and hydrodynamic modelling studies. The North beach results show compliance with *Imperative* criteria during the study period. Both beaches showed similar rates of compliance with EC *Guideline* criteria. The results in Figures 3.15 and 3.16 also suggest that exceedence of *Guideline* criteria can occur during dry weather conditions at both beaches. In some cases this may relate to relatively high residual concentrations of faecal indicators in the sea after input from events. At the North beach, such dry weather exceedence may relate to the relatively high concentrations of organisms in Nant Penglais evident even during dry weather.

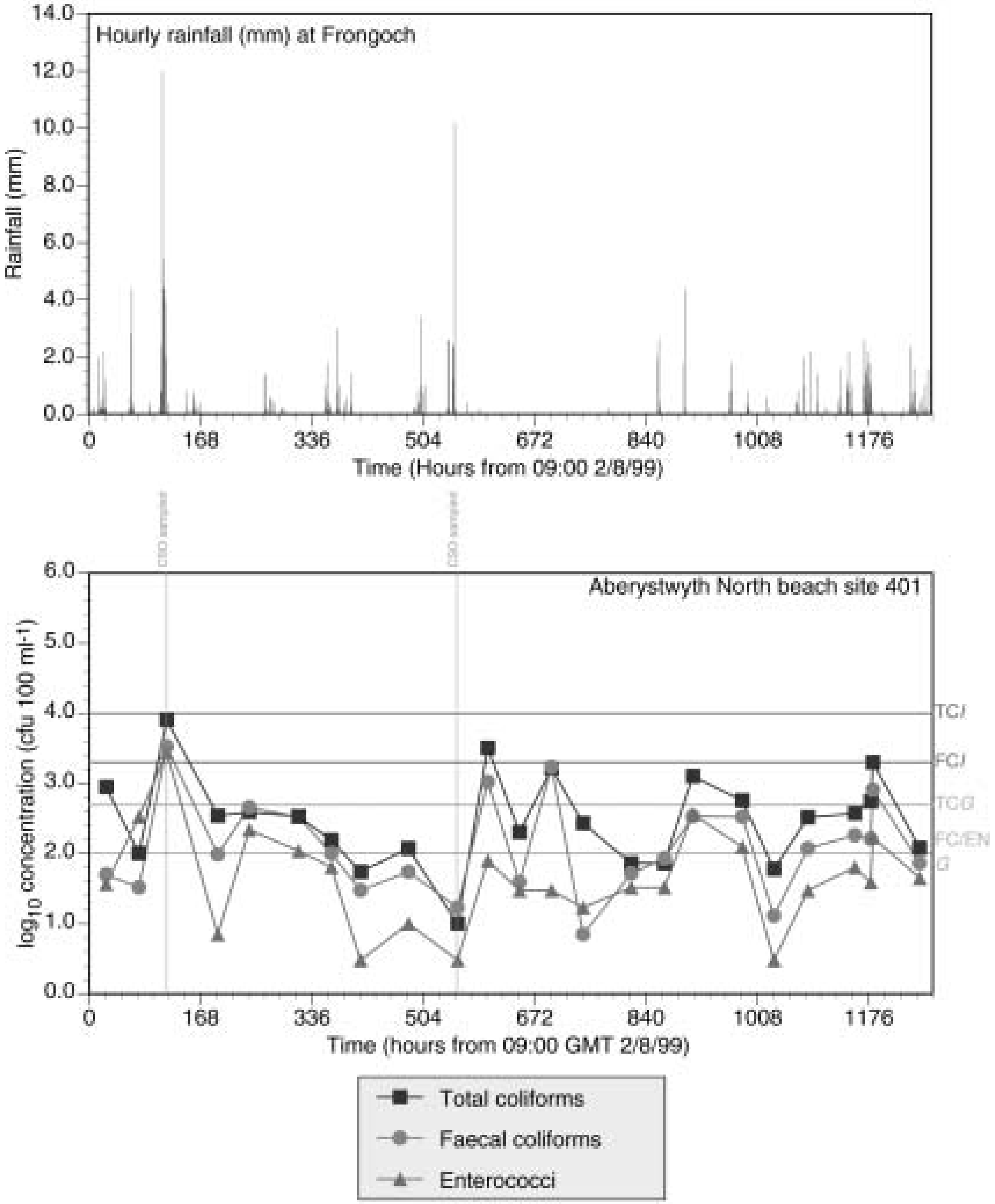


Figure 3.15. Rainfall (mm) at Frongach and $\log_{10}$ transformed faecal indicator concentrations (cfu 100 ml^{-1}) in marine samples from Aberystwyth North beach (site 401) during August and September 1999.

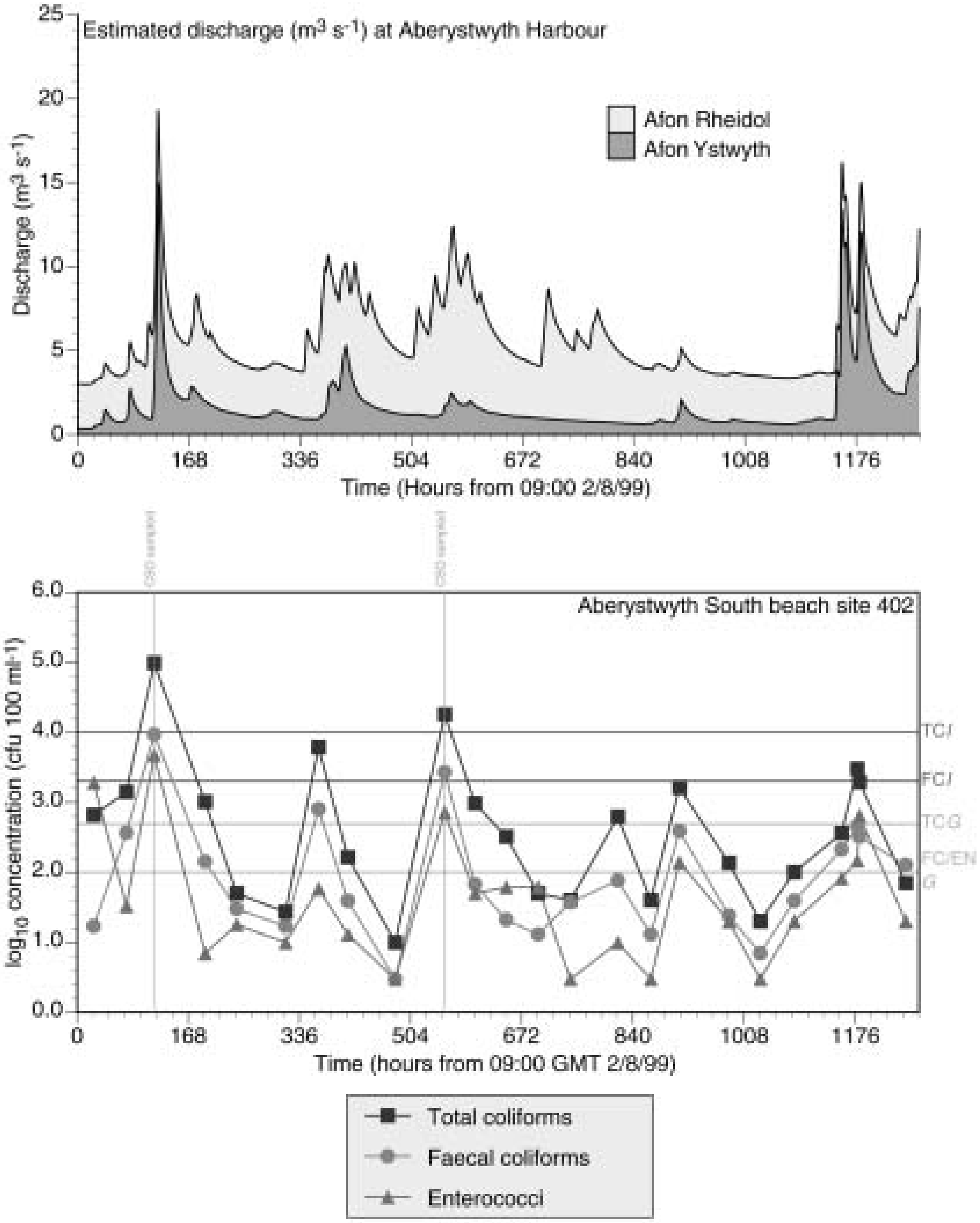


Figure 3.16. Estimated discharge (m^3 s^{-1}) at Aberystwyth harbour and $\log_{10}$ transformed faecal indicator concentrations (cfu 100 ml^{-1}) in marine samples from Aberystwyth South beach (site 402) during August and September 1999.

3.6.2 Ireland

3.6.2.1 Bray south and north beaches

The results of marine water-quality monitoring at Bray south beach at the National Aquarium site during the study period are shown in Table 3.30. The results were sorted according to whether the samples were taken during low-flow (no rainfall) or high-flow (rainfall) conditions, and the geometric means calculated. The results for 10th September 2000 were treated as high flow, because there was substantial rainfall in the catchment within the 24 hour period prior to sampling. The small number of results obtained for Bray north beach is displayed in Table 3.31, which is for low-flow conditions only.

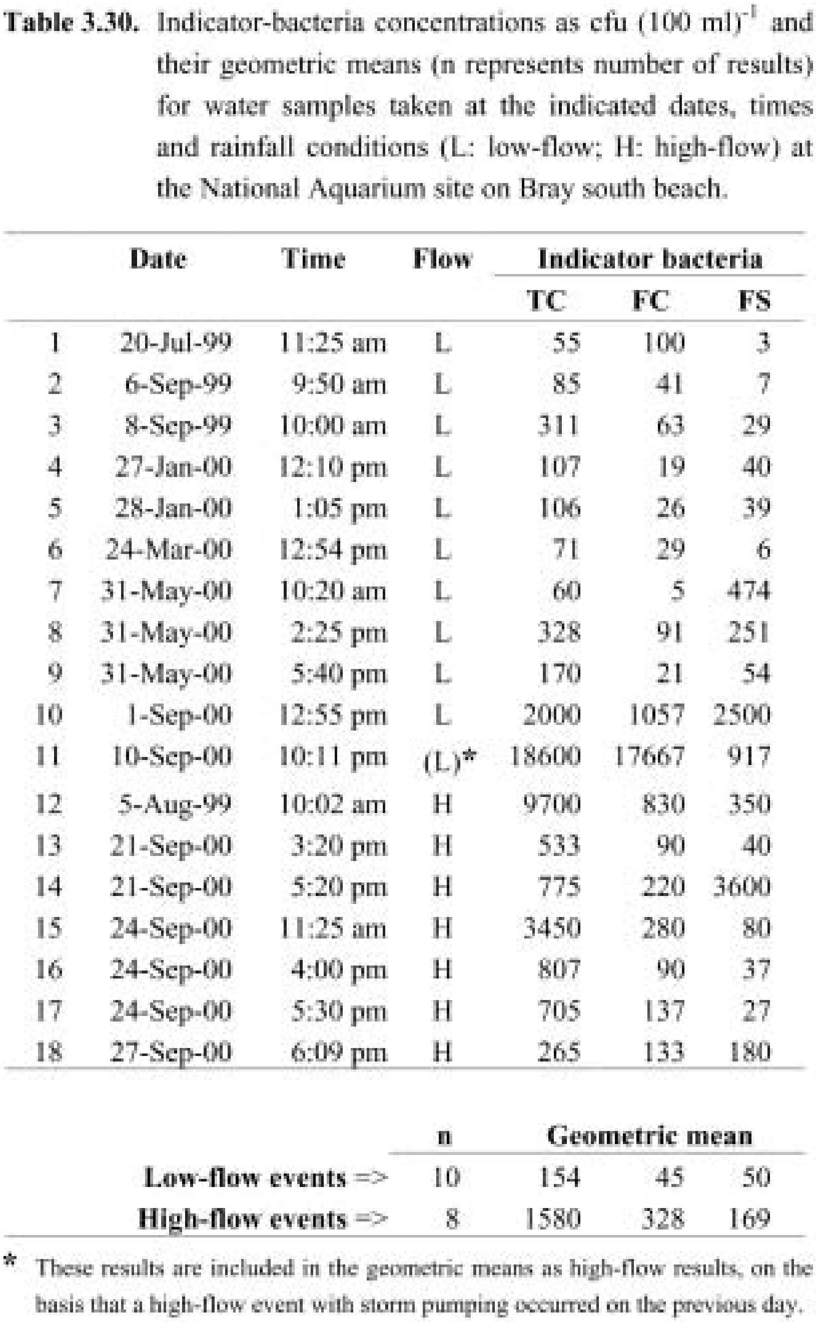


Table 3.30. Indicator-bacteria concentrations as cfu (100 ml)$^{-1}$ and their geometric means (n represents number of results) for water samples taken at the indicated dates, times and rainfall conditions (L: low-flow; H: high-flow) at the National Aquarium site on Bray south beach.

	Date	Time	Flow	Indicator bacteria		
				TC	FC	FS
1	20-Jul-99	11:25 am	L	55	100	3
2	6-Sep-99	9:50 am	L	85	41	7
3	8-Sep-99	10:00 am	L	311	63	29
4	27-Jan-00	12:10 pm	L	107	19	40
5	28-Jan-00	1:05 pm	L	106	26	39
6	24-Mar-00	12:54 pm	L	71	29	6
7	31-May-00	10:20 am	L	60	5	474
8	31-May-00	2:25 pm	L	328	91	251
9	31-May-00	5:40 pm	L	170	21	54
10	1-Sep-00	12:55 pm	L	2000	1057	2500
11	10-Sep-00	10:11 pm	(L)*	18600	17667	917
12	5-Aug-99	10:02 am	H	9700	830	350
13	21-Sep-00	3:20 pm	H	533	90	40
14	21-Sep-00	5:20 pm	H	775	220	3600
15	24-Sep-00	11:25 am	H	3450	280	80
16	24-Sep-00	4:00 pm	H	807	90	37
17	24-Sep-00	5:30 pm	H	705	137	27
18	27-Sep-00	6:09 pm	H	265	133	180

	n	Geometric mean		
Low-flow events =>	10	154	45	50
High-flow events =>	8	1580	328	169

* These results are included in the geometric means as high-flow results, on the basis that a high-flow event with storm pumping occurred on the previous day.

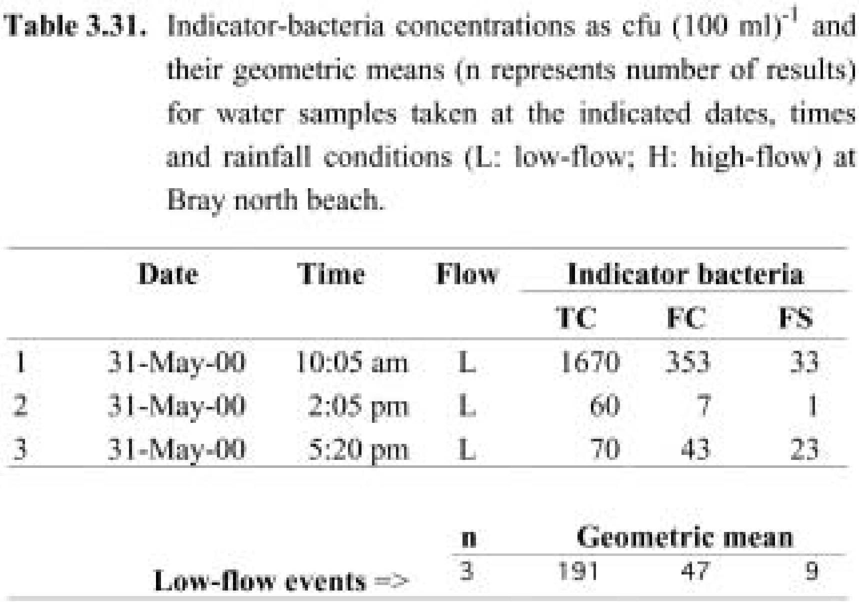


Table 3.31. Indicator-bacteria concentrations as cfu (100 ml)$^{-1}$ and their geometric means (n represents number of results) for water samples taken at the indicated dates, times and rainfall conditions (L: low-flow; H: high-flow) at Bray north beach.

	Date	Time	Flow	Indicator bacteria		
				TC	FC	FS
1	31-May-00	10:05 am	L	1670	353	33
2	31-May-00	2:05 pm	L	60	7	1
3	31-May-00	5:20 pm	L	70	43	23

	n	Geometric mean		
Low-flow events =>	3	191	47	9

Bray south beach showed deterioration in water quality coincident with rainfall events (Table 3.30); the geometric means for TC and FC increasing by about one order of magnitude, and there was about a three-fold increase for FS. Additionally, on all dates indicated as high flow, storm overflow was discharged at Bray pumping station. In particular, on August 5th 1999, the storm pumps were running at full capacity, responding to a break-in by the Dargle river to the foul sewer at Bray bridge (part of the sewerage system is routed under the river bed). Notably, the highest beach concentrations were found on 10th September 2000, the day following a storm overflow discharge. So, these results convey also a strong indication that storm pumping at Bray gave rise to microbial deterioration at Bray south beach. With regard to Bray north beach, only a few samples were taken in low-flow conditions (Table 3.31); it is no longer a designated beach under the EU Bathing Water Directive.

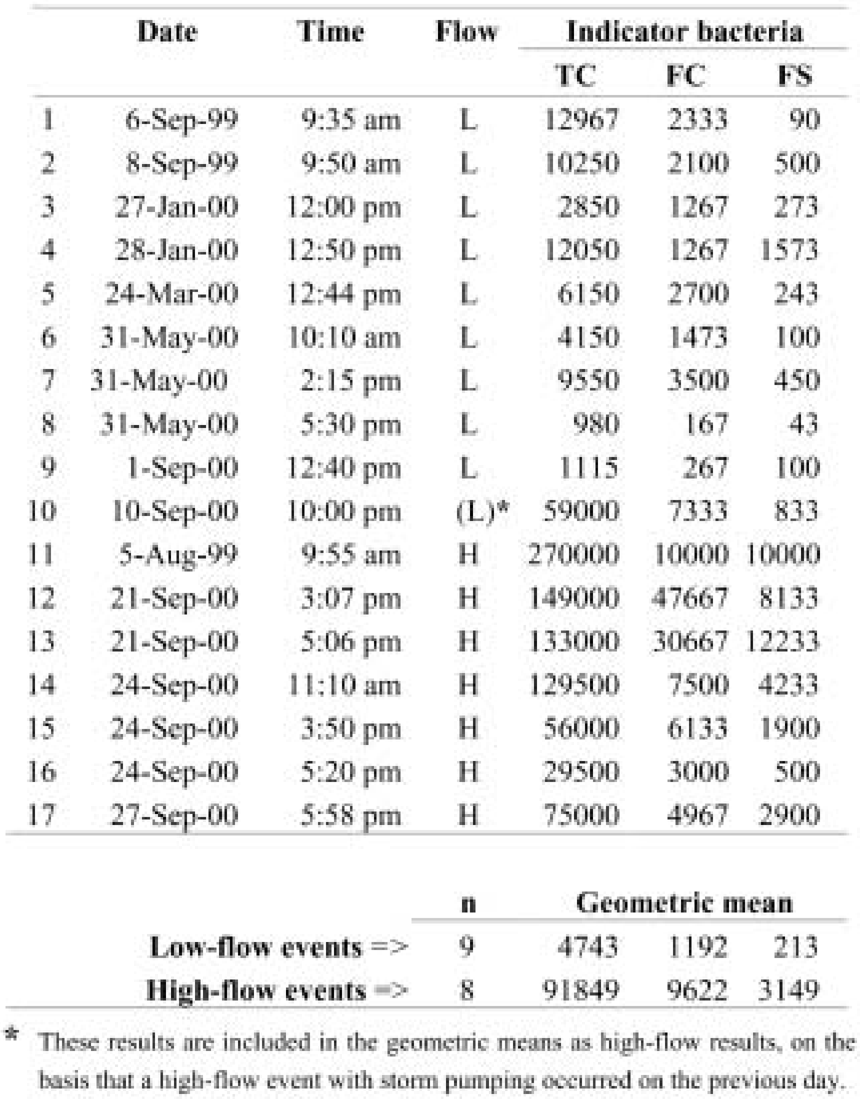
The repetitive sampling at Bray south beach on three of the dates was carried out to cover different states of tide; the results obtained varied substantially on each date. It is clear from this that detailed hydrological and hydrodynamic studies would be required to establish the detail of the association between rainfall events and beach microbial water quality.

If the compliance of Bray south beach with the EU Bathing Water Directive was to be judged on the results obtained during this study, it would have failed to comply with the *Guideline* and *Imperative* criteria in 1999. This failure was "by accident" though, because of the sewerage system malfunction on August 5th referred to above. It would have failed to comply with the *Guideline* criteria also in 2000 because of the exceedences on May 31st, notably during dry weather conditions.

3.6.2.2 Bray Harbour

Results for samples taken at the mouth of Bray Harbour are displayed in Table 3.32. The results were sorted according to whether the samples were taken during low-flow (no rainfall) or high-flow (rainfall) conditions, and the geometric means were calculated.

Table 3.32. Indicator-bacteria concentrations as cfu (100 ml)$^{-1}$ and their geometric means (n represents number of results) for water samples taken at the indicated dates, times and rainfall conditions (L: low-flow; H: high-flow) from the mouth of Bray Harbour.



	Date	Time	Flow	Indicator bacteria		
				TC	FC	FS
1	6-Sep-99	9:35 am	L	12967	2333	90
2	8-Sep-99	9:50 am	L	10250	2100	500
3	27-Jan-00	12:00 pm	L	2850	1267	273
4	28-Jan-00	12:50 pm	L	12050	1267	1573
5	24-Mar-00	12:44 pm	L	6150	2700	243
6	31-May-00	10:10 am	L	4150	1473	100
7	31-May-00	2:15 pm	L	9550	3500	450
8	31-May-00	5:30 pm	L	980	167	43
9	1-Sep-00	12:40 pm	L	1115	267	100
10	10-Sep-00	10:00 pm	(L)*	59000	7333	833
11	5-Aug-99	9:55 am	H	270000	10000	10000
12	21-Sep-00	3:07 pm	H	149000	47667	8133
13	21-Sep-00	5:06 pm	H	133000	30667	12233
14	24-Sep-00	11:10 am	H	129500	7500	4233
15	24-Sep-00	3:50 pm	H	56000	6133	1900
16	24-Sep-00	5:20 pm	H	29500	3000	500
17	27-Sep-00	5:58 pm	H	75000	4967	2900

	n	Geometric mean		
Low-flow events =>	9	4743	1192	213
High-flow events =>	8	91849	9622	3149

* These results are included in the geometric means as high-flow results, on the basis that a high-flow event with storm pumping occurred on the previous day.

Microbial water quality at Bray Harbour was poor even during dry weather conditions and it deteriorated greatly during rainfall events when the geometric means for TC, FC and FS all increased by about one order of magnitude. The highest concentrations were evident on August 5th 1999, when the sewerage system malfunction referred to above occurred. Concentrations were high also on the 10th September 2000, the day following upon storm overflow discharge. Again, these results seem to implicate storm pumping as a factor in the deterioration of microbial water quality in Bray Harbour.

3.6.2.3 Kilruddery stream

The Kilruddery stream discharges onto Bray south beach, above sea level during about half of each tidal cycle. The stream drains a small subcatchment of 186 ha, bounded by Little Sugar Loaf and Bray Head and passes through the south-eastern part of Bray town. The CREH land use is: LU1 (Grade 1 Pasture) - 16%, LU4 (Moorland) - 10%, LU5 (Arable) - 15%, LU6 (Woodlands) - 8%, LU7 (Built up) - 39% and LU8 (Other: recreation, rocks, quarries etc.) - 12%. The water quality of the stream was monitored at a suitably accessible site (Putland Road) as close as possible to the beach. The results obtained during the study period are shown in Table 3.33. The results were sorted according to whether the samples were taken during low-flow (no rainfall) or high-flow (rainfall) conditions, and the geometric means calculated.

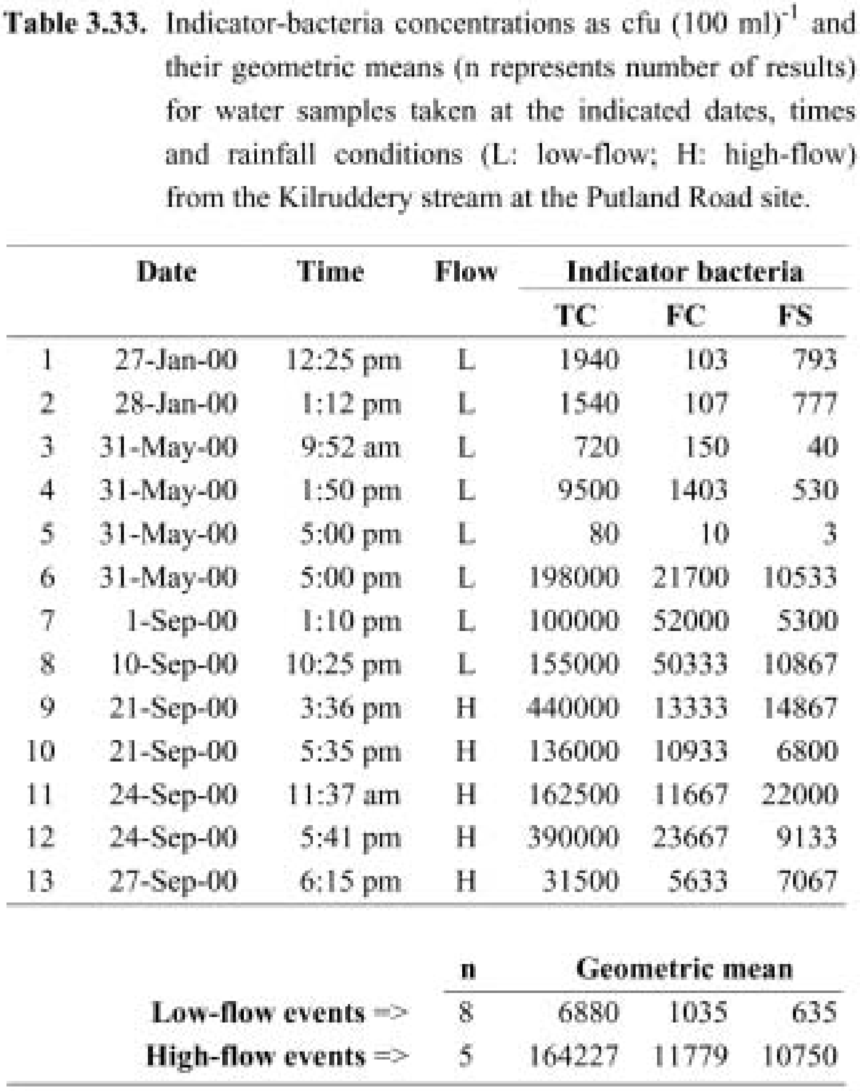


Table 3.33. Indicator-bacteria concentrations as cfu (100 ml)$^{-1}$ and their geometric means (n represents number of results) for water samples taken at the indicated dates, times and rainfall conditions (L: low-flow; H: high-flow) from the Kilruddery stream at the Putland Road site.

	Date	Time	Flow	Indicator bacteria		
				TC	FC	FS
1	27-Jan-00	12:25 pm	L	1940	103	793
2	28-Jan-00	1:12 pm	L	1540	107	777
3	31-May-00	9:52 am	L	720	150	40
4	31-May-00	1:50 pm	L	9500	1403	530
5	31-May-00	5:00 pm	L	80	10	3
6	31-May-00	5:00 pm	L	198000	21700	10533
7	1-Sep-00	1:10 pm	L	100000	52000	5300
8	10-Sep-00	10:25 pm	L	155000	50333	10867
9	21-Sep-00	3:36 pm	H	440000	13333	14867
10	21-Sep-00	5:35 pm	H	136000	10933	6800
11	24-Sep-00	11:37 am	H	162500	11667	22000
12	24-Sep-00	5:41 pm	H	390000	23667	9133
13	27-Sep-00	6:15 pm	H	31500	5633	7067

	n	Geometric mean		
Low-flow events =>	8	6880	1035	635
High-flow events =>	5	164227	11779	10750

While the microbial water quality was poor in dry weather conditions, grave deterioration was evident in response to rainfall, with a 24-fold, an 11-fold and a 17-fold increase in the geometric mean result for TC, FC and FS respectively.

Flow volumes were not measured for this stream, but during the bathing season they were generally of the order of a litre or so per minute in dry weather conditions and did not increase substantially in rainfall conditions. Flows were observed to be much higher at other times of year. These observations were of a preliminary nature, but they warrant concern about the impact of the stream on bathing water quality at Bray south beach.

Summary

1. Recent research has demonstrated that catchment derived sources of faecal pollution may affect compliance of bathing waters against EC Directive 76/160/EEC standards. The delivery of faecal indicator organisms from river and stream catchments with differing mixtures of land use is of particular interest. This study in north Ceredigion, Wales and north Co. Wicklow, Ireland builds on previous catchment studies in the UK. The project was part funded by the INTERREG-II programme of the European Union and administered through the National Assembly for Wales and the Marine Institute of Ireland.

Study aims and execution

2. The main aims of the study were to: (i) examine relationships between water quality and antecedent environmental conditions at the Welsh and Irish beaches using compliance data, (ii) quantify faecal indicator budgets to coastal waters adjacent to the confluence of the Afon Rheidol and Afon Ystwyth catchments at Aberystwyth harbour, Ceredigion, and to the beach adjacent to the Dargle catchment at Bray, Co. Wicklow, (iii) investigate the impacts of land use on stream water quality within the catchments, and (iv) examine potential impacts on marine water quality.

3. Environmental microbiological surveys were undertaken in the Irish and Welsh study catchments and involved the analysis of sewage effluent, stream and marine water quality for total coliforms, faecal coliforms and faecal streptococci (enterococci) during base flow and high-flow conditions. The Welsh survey took place during the summer of 1999, and the Irish survey during the summer/early autumn seasons of 1999 and 2000.

4. Detailed land-use surveys of both study catchments were made in 1999. The survey of the Dargle catchment was updated in 2000.

Results (Wales)

5. Statistical analysis of bathing water-quality compliance data and antecedent environmental conditions showed significant improvements in water quality since upgrade of the local sewerage infrastructure. This has resulted in higher numbers of samples achieving compliance with EC Directive 76/160/EEC criteria for faecal indicator organisms. However, the beaches still fail to achieve overall compliance with the *Guide* criteria necessary for “blue flag” status, despite the investment in the infrastructure improvements.

6. Prior to completion of sewerage improvements the significant predictors of faecal indicator concentrations were dominated by wind direction (Aberystwyth beaches) and river discharge (Clarach and Borth) variables. After completion of the schemes variables predicting water quality at the Aberystwyth beaches and Borth relate to tidal conditions, wind speed and sunshine. River discharge variables remain the dominant predictor at Clarach.

7. Faecal indicator budgets estimates for the Afon Rheidol/Afon Ystwyth catchment revealed the Afon Ystwyth during high-flow events to be the largest single source of faecal indicator organisms (total coliforms 33%, faecal coliforms 56% and enterococci 47%). The next largest source was from Tan-y-cae CSO (>25%) which delivered less than 1% of the total discharge. Treated sewage effluent provided a minimal input (<0.1%) due to the high effluent quality achieved by ultraviolet disinfection.

8. Local stream inputs to Aberystwyth North beach were dominated by Nant Penglais during high-flow conditions which provided over 90% of the faecal indicator load estimates.

9. Comparison of current faecal indicator budgets with those for a crude sewage discharge and activated sludge treatment suggest that recent improvements at Aberystwyth have virtually eliminated faecal indicators associated with treated sewage, reducing the overall loads by more than 95%. The Afon Ystwyth during high flow and Tan-y-cae CSO are the dominant components of the remaining faecal indicator load to nearshore waters.

10. Regression modelling showed the proportion of improved pasture in subcatchments to be the dominant predictor of geometric mean high-flow $\log_{10}$ faecal indicator concentrations in the rivers and streams of the Afon Rheidol and Afon Ystwyth catchments. At base flow the most significant predictor is the proportion of built up land.

11. A series of highly significant ($p<0.001$) multivariate regression models predicting water quality from land use were produced for the study catchment under base and high-flow conditions. The models, based on lumped subcatchment land-use data, land use in buffer strips around the stream network and land use in various zones upstream of each stream sampling point, typically explained over 70% of the variance in faecal indicator concentrations.

12. Marine water quality at the two Aberystwyth beaches deteriorated during and after hydrograph events when the faecal indicator loading from the catchment is greatest. This pattern was particularly pronounced at Aberystwyth South beach, which is closest to the river outlet at Aberystwyth harbour. Here, concentrations under such conditions exceeded the *Imperative* criteria of EC Directive 76/160/EEC. At Aberystwyth North beach the faecal coliforms concentration exceeded the *Imperative* level on one occasion. Thus, despite the dramatic reduction in faecal indicator load achieved by the disinfected effluent at Aberystwyth, the remaining organism load from the Afon Ystwyth and Tan-y-cae CSO is enough to produce *Guide*, if not *Imperative*, “fail” conditions at the Aberystwyth beaches.

13. **Implications and remediation potential:** Reduction in the spill from the Tan-y-cae CSO would provide a significant reduction in the remaining faecal indicator load. However, the impact on compliance would be difficult to ascertain without detailed hydrodynamic and tracer studies. Such studies could also be used to examine the impact of local stream inputs to Aberystwyth North beach.

(A more detailed account of the Welsh studies is found in Wyer *et al*., 2000)

Results (Ireland)

14. A retrospective study of bathing water-quality compliance data for Bray beaches and antecedent environmental conditions demonstrated a *prima facie* association between high-rainfall events and failure in hygiene standards at Bray Beach.

15. Water quality in the Dargle catchment streams was highly variable. The geometric mean concentrations during storms were, for the majority of sites, an order of magnitude or more greater than during non-storm periods. However, the Kilmacanogue stream was an exception to this for total coliforms, for which the non-storm mean concentration was greater than during storm conditions.

16. At some other sites sites, the range of indicator concentrations during non-storm and storm conditions overlapped, yet another indicator of the high variability of these concentrations.

17. None of the waters, even in the upper reaches of the catchment, was free of indicator bacteria.

18. The catchments formed three groups, “relatively clean” (upper reaches of the Dargle and Glencree rivers downstream as far as Tinnehinch bridge, Onagh and Powerscourt stream), “relatively dirty” (Dargle, from N11 bridge downstream, Swan river, Kilmacanogue, County Brook), with two “intermediate” ones (Dargle at Dublin Road Bridge and Cookstown River (Glencullen)).

19. There was a strong and consistent positive correlation between percentage settlement in a catchment and bacterial concentration. This was slightly stronger for non-storm periods than for storm periods.

20. There was some positive correlation between percentage pasture and bacterial concentrations, but only during storm periods. The correlation was generally strongest for faecal streptococci.

21. When land use was examined in detail, a strong negative correlation emerged between bacterial concentrations and percentage forest and a positive correlation with percentage lake and bare rock, i.e. the more forest, lake or bare rock land-cover there was in the subcatchment the less the bacterial concentrations associated with the subcatchment were.

22. Correlations with land use within a 100 metre wide corridor (buffer strip) each side of the channel did not produce any better correlations than with land use over theentire catchment. An implication of this is that eliminating bacterial contributing activities within such buffer strips would not reduce significantly the impact of such activities elsewhere in subcatchments.

23. Regression equations relating percentage land use with the logarithm of bacterial concentrations can explain approximately 50% of the variance in the concentration measurements. Factors other than land use must be considered if the remaining variance is to be explained. Interestingly the equations explain more of the variation in faecal streptococci in storm events and of total and faecal coliforms in non-storm events.

24. No consistent simple relationship between concentrations and flows at a single site could be identified. However, it is likely that considerably more data would be needed to reliably detect such a relationship.

25. During a ten-day storm period of intensive analysis, Bray contributed slightly more bacteria to the Dargle during a total of 7.13 hours pumping than the rest of the catchment contributed over the entire ten-day period and is the major source of bacteria.

26. Considering other sources of indicator bacteria, Enniskerry contributed significantly (34% each of total and faecal coliforms and 28% of streptococci during non-storm events and larger percentages, 43% total coliforms, 61% faecal coliforms and 34% faecal streptococci during storms), and generally contributed more bacteria than the entire Dargle catchment upstream of its outfall.

27. Considering their size, the Swan and Kilmacanogue rivers contributed significantly, generally with the Swan (from 15% to 21%) being worse during storm periods and the Kilmacanogue (from 15% to 29%) during non-storm periods.

28. As well as having higher mean bacterial concentrations during non-storm events than for storms events, the Kilmacanogue maintains a relatively higher base flow throughout the year, the source of which should be investigated.

29. Although there is considerable natural and experimental variability in the data collected and analysed, both concentrations and flows, the above conclusions emerged strongly and consistently from the large number of analyses performed.

30. A further search for correlations of bacterial concentrations with land use revealed definite curvilinear relationships with respect to the land-use category “percentage settlement”. Of particular interest was the finding of a distinct gradual fall-off in the rate of increase of the concentrations of the indicator bacteria with increasing percentage settlement. This was interpreted as perhaps reflecting an improvement in the control of leakage of sewage from higher settlement densities. No convincing curvilinear correlations were obtained for the land-use category “percentage pasture”.

31. Bray south beach showed deterioration in water quality coincident with rainfall events, the geometric means for total coliforms and faecal coliforms increasing by about one order of magnitude, and there was about a three-fold increase for faecal streptococci. There was a strong indication that the discharge of storm overflow from Bray was associated with this.

32. If the compliance of Bray south beach with the EC Bathing Water Directive was to be judged on the results obtained during this study, it would have failed to comply with the *Guideline* and *Imperative* criteria in 1999, probably because of a sewerage system malfunction. It would have failed to comply with the *Guideline* criteria also in 2000.

33. Microbial water quality at Bray Harbour was poor even during dry weather conditions and it deteriorated greatly during rainfall events when the geometric means for the three indicator bacteria all increased by about one order of magnitude. Storm overflow, although it is discharged to the outside of the harbour wall, appears to contribute to this deterioration.

34. The Kilruddery stream, which discharges directly onto Bray south beach, showed poor microbial water quality in dry weather conditions, and grave deterioration in rainfall conditions. While these observations were of a preliminary nature, they warrant concern about the impact of the stream on bathing water quality at Bray south beach.

35. **Implications and remediation potential:** cessation of storm overflow from Bray would reduce the impact of storm events on the microbial pollution of Bray beach and the harbour. The remaining faecal indicator load would still be substantial, especially the loading from urban streams and from the Enniskerry outfall, and also the loading from the Kilruddery stream. Detailed hydrological and pollution dispersal studies would be required to establish in a scientifically satisfactory way the potential for remediation of this pollution which is unrelated to storm pumping.

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APPENDIX A: Acknowledgements

The authors wish to thank the following people for their contribution to the work reported herein:

Wales

Pre Carbo, Alice Craven, Maggie Gorringe, Mark Johnson and Huw Thomas, assisted with sample collection, routine analysis and laboratory preparation; Paula Hopkins (CREH) undertook data preparation and field logistics organization; Trevor Harris, (University of Wales, Lampeter) and Dave Pinniger (Dr Cymru/WelshWater) provided GIS/cartographic support.. For logistical support and advice we are grateful to the staff of the Environment Agency, including Simon Gardner, Jon Knight, Colin Strange and Hanna Wilkinson, the staff of Dr Cymru/Welsh Water including Aled Daniel, Evan Davies, Dave Jones, Paul Jones, Hilary Ford, Norman Lowe, Margaret Wadley, the staff of the Institute of Grassland and Environmental Research including Roger Cook and Steve Cuttle, and the staff at the Power Gen Cwm Rheidol power station including Paul Miller and Henry Drake. We further thank Dr Gareth Evans of Ceredigion County Council Environmental Health Department for local information and advice.

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Ireland

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Cover image

Abrystwyth image: M.D. Wyer.
Bray image: *www.doorbell.com/bryant/images/ire99-017.jpg*.

APPENDIX B: Reports, presentations/publicity and project meetings

Reports

National Assembly for Wales	Report March 1999.
Marine Institute of Ireland	First Quarterly Report March 1999.
National Assembly for Wales	Second Quarterly Report (Welsh/Irish) June 1999.
Marine Institute of Ireland	Impact Statement June 1999.
Marine Institute of Ireland	Update: Project/Network Summaries July 1999 p. 21.
National Assembly for Wales	Report September 1999.
Marine Institute of Ireland	Joint Interim Report. December 1999.
Marine Institute of Ireland	Update: Directory of Projects August 2000 p. 26.
Anon. (Special Report)	Directory of INTERREG II Projects October 2000 p. 41
National Assembly for Wales	Final Report (Wales) October 2000.

Presentations/publicity

Welsh team.	University of Wales Staff Colloquium 8th April 1999.
Welsh team.	Royal Welsh Show Conference. 21st July 1999.
Masterson, B.	Radio presentation. West Dublin Local Radio 21st August 1999.
Anon.	Hyder News Aug./Sept. 1999 pp. 16. Research: Euro-funding for Wales-Ireland study into causes of pollution. Probe will look at threats in drive for clean beaches.
Bruen, M.	Centre for Water Resources Research. The Irish Scientist Yearbook November 1999, Samton Ltd., Dublin. p. 177.
Chawla, R.	Poster presentation (microbiological work). University College Dublin, Postgraduate Day Seminar. 25th November 1999.
Anon.	Inland, Coastal, and Estuarine Waters (2) February 2000, 15. Achieving EU Standards in Recreational Waters.
Anon.	Achieving EU Standards in Recreational Waters. FLOW Information Awareness, (issue no. 2, Autumn 2000), p. 3.
Project team.	Achieving EU Standards in Recreational Waters. Joint poster presentation. Irish Sea Forum meeting. Isle of Man, 18th-20th October 2000.
Masterson, B.	Inland, Coastal, and Estuarine Waters (7) December 2000/January 2001, 18-20. The EU Water Framework Directive: Ireland.

M. Bruen, R. Chawla, B. Masterson, A. Nasr, P. O’Connor, B. Parmentier, J. Stokes, and M. Thorp. Factors influencing riverine inputs of bacteria into the Irish coastal zone. Oral presentation (M. Bruen) at European Geophysical Society General Assembly, Nice, France, 2001.

(Joint Wales/Ireland WWW site — to be launched after its content has been agreed with the funding/participating agencies and following submission of this Report.)

Project meetings

Meetings with Irish EPA staff (Johnstown Castle Estate, Co. Wexford) 21st December 1998, 27th July 2000.
INTERREG-II meeting Marine Institute of Ireland 3rd March 1999.
Meetings with WCC staff (County Buildings, Wicklow) 5th March 1999, 12th March 1999; (Pumping Station , Bray) 12th May 1999.
Co-ordinators meeting (Dublin) 13th March 1999.
Partnership co-ordination meeting (Aberystwyth) 9-10th April 1999.
Co-ordinators meeting (Dublin) 4th May 1999.
Co-ordinators meeting (Lampeter) 27th May 1999.
Project management meeting (Aberystwyth) 2nd Sept. 1999.
Investigators meeting (Liverpool) 6th July 2000.
Co-ordinators meeting (Lampeter). 24th-25th July 2000.
Investigators meeting (Dublin) 24th November 2000.
Co-ordinators meeting (Lampeter) 14th February 2001.

APPENDIX C: Inter-regional benefits achieved

1. Promoted the transfer of information between the inter-regional partners, involving sharing of expertise on coastal pollution and for diffuse-source modelling. Extended microbial enumeration techniques. Shared the benefit of eight other CREH (Wales) studies funded by the UK Environment Agency and water companies.

2. Facilitated development and enhancement of a regional marine and coastal environmental co-operative network and database. A compliance database has been constructed to be used as a tool in 'vulnerability' assessment (i.e. of the susceptibility of a beach to pollution taking into account its characteristics and use). It underpins the empirical fieldwork and diffuse sources modelling study being conducted in both regions of the INTERREG area. Already the project has enhanced co-operation between Dr Cymru, the Irish and the Welsh Environmental Agency, Wicklow (Ireland) and Credigion (Wales) County Council, the National Health Service (Wales) and, NUI-Dublin and the University of Wales.

3. Provided enhanced information for the management of inter-regional recreational amenity and for promotion of their sustainable development in respect of environmentally acceptable waste management.

4. Contributed to the development of coastal zone planning and management systems in the region by which the border areas may be treated as integrated geographical areas for management and planning purposes.

5. Assisted investigation of environmental change and quality in the Irish Sea linked to the Third Report of the Irish Sea Co-ordinator.

6. Produced novel scientific insights that will be the subjects of future co-operative projects.

7. Contributed substantially to the training of postgraduate students, thereby enhancing inter-regional expertise.

APPENDIX D MARITIME INTERREG PROJECTS

The following co-operative projects and networks are supported under Measure 1.3 “Protection of the Marine and Coastal Environment and Marine Emergency Planning”, of the Maritime (Ireland/Wales) INTERREG Programme (1994 – 1999):

Co-operative Projects

1. **Roseate Terns - The Natural Connection - A Conservation and Research Project linking Wales and Ireland**
   Irish Wildbird Conservancy / North Wales Wildlife Trust.
2. **Marine Mammal Strandings - A Collaborative Study for the Irish Sea.**
   National University of Ireland, Cork / Countryside Council for Wales.
3. **South West Irish Sea Survey (SWISS).**
   Trinity College Dublin / National Museum of Wales, Cardiff.
4. **The Fate of Nutrients in Estuarine Plumes.**
   National University of Ireland, Galway / University of Wales, Bangor.
5. **Water Quality and Circulation in the Southern Irish Sea**
   National University of Ireland, Galway / University of Wales, Bangor.
6. **Grey Seals: Status and Monitoring in the Irish and Celtic Seas.**
   National University of Ireland, Cork / Dyfed Wildlife Trust.
7. **Sensitivity and Mapping of inshore marine biotopes in the Southern Irish Sea (SensMap).**
   Ecological Consultancy Services (Dublin), Dúchas / Countryside Council for Wales.
8. **Marine Information System: Scoping Study (Phase I).**
   Marine Institute, National Marine Data Centre/ Countryside Council for Wales.
9. **Achieving EU Standards in Recreational Waters.**
   National University of Ireland, Dublin / University of Wales, Aberystwyth.
10. **Irish Sea Southern Boundary Study**
    Marine Informatics Ltd (Dublin) / University of Wales, Bangor.
11. **Marine Information System: Demonstration (Phase II).**
    Marine Institute, National Marine Data Centre / Countryside Council for Wales.
12. **Emergency Response Information System (ERIS)**
    Enterprise Ireland, Compass Informatics, IMES / University of Wales, Bangor.
13. **Risk Assessment and Collaborative Emergency Response in the Irish Sea (RACER)**
    Nautical Enterprise Centre (Cork), National University of Ireland, Cork, University of Wales, Cardiff.
14. **Critical assessment of human activity for the sustainable management of the coastal zone.**
    National University of Ireland, Cork / University of Wales, Aberystwyth.
15. **SeaScapes – Developing a method of seascape evaluation**
    Brady Shipman Martin, National University of Ireland, Dublin / University of Wales, Aberystwyth.
16. **Ardfodir Glan – Clean Coasts/Clean Seas**
    CoastWatch Ireland / Keep Wales Tidy Campaign.

Co-operative Networks

17. **Irish Sea Hydrodynamic Modelling Network**
Trinity College Dublin / University of Wales, Bangor.
18. **CoAST - Co-operative Action - Sustainability Network**
Dublin Regional Authority / Isle of Anglesey County Council.
19. **ECONET - Erosion Control Network**
Enterprise Ireland / Conwyn County Council.
20. **Navigate with Nature**
Irish Sailing Association / Centre for Economic and Environmental Development (UK).
21. **"Land Dividing - Sea Uniting" Irish Seas Exhibition**
Irish Seal Sanctuary, ENFO / National Assembly for Wales.
22. **From Seawaves to Airwaves**
West Dublin Community Radio / Radio Ceredigion CYF.
23. **BENSIS – Benthic Ecology Network**
Trinity College Dublin / National Museum of Wales, Cardiff.
24. **Remote Sensing of Suspended Sediment Load in the Coastal Zone**
National University of Ireland, Galway / University of Wales, Bangor.
25. **Paving the Information Highway**
Ecological Consultancy Services (Dublin) / Irish Sea Forum, University of Wales, Bangor.
26. **Inland, Coastal and Estuarine (ICE) Journal**
National University of Ireland, Dublin / Centre for Economic and Environmental Development (UK).

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For further information on the Maritime Ireland/Wales INTERREG-II Programme see http://www.marine.ie/intcoop/interreg/

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