Sanitary profiles of selected shellfish water catchments pre- and post-improvements in sewerage infrastructure

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Executive Summary

Quantitative sanitary profiles were produced for six shellfish water catchments [Chichester Harbour (Chichester Channel), Poole Harbour West, Fal/Ruan, Yealm, Taw/Torridge (Estuary Mouth) and Ribble] in which significant improvements in sewerage infrastructure, notably the installation of UV disinfection at sewage treatment works (STWs) and improvements in intermittent discharges (IDs) have been made; and the Conwy catchment, which has not received significant improvements. FIO sources were categorised as follows:

§ Sewerage sources that have been improved: STWs and IDs associated with these; and
§ Other catchment sources: primarily other sewage-related sources (STWs, IDs, septic tanks, etc.) and agricultural sources.

For sewerage sources where improvements have been made, every effort has been made to obtain flow and faecal coliform (FC) and enterococci (EN) concentration data both pre- and post-improvement. Unfortunately, empirical data for quantifying FIO fluxes from sewerage (and the other catchment) sources within the study catchments are totally inadequate. Where data are not available, generic data from previous CREH studies have been used and various assumptions made. For other catchment sources, regression models developed by CREH/Environment Agency, using predictor variables such as density of residences and livestock, have been used to predict the FC and EN concentrations in rivers, and to make provisional source apportionment estimates. Concentration data were combined with river flow data to quantify fluxes.

The sanitary profiles, which must be regarded as estimates since they are based largely on generic data and statistical models, indicated:

§ Reductions in FC and EN fluxes of 39.83–87.98% and 35.64–93.91%, respectively, following sewerage infrastructure improvements, with the smallest improvements in the Yealm catchment and largest in Taw/Torridge.
§ In all six catchments in which improvements have been made to the key STWs, treated effluents from these now make only very minor contributions (≤ 0.61%) to the total fluxes.
§ In the five catchments where IDs have been improved (i.e. excluding Chichester Channel and Conwy), then, on the assumption of a 90% reduction in the estimated volume of ID flow following improvement, the IDs post-improvement contribute only small proportions of the FC (≤ 4.21%) and EN (≤ 6.82%) fluxes. However, under a worst-case scenario in which estimated ID flow volumes are greater pre-improvement and are reduced by only 50% following improvement, ID contributions increase to > 50%.
§ Preliminary source-apportionment estimates suggest that sewage- and agriculture-related sources both contribute significantly to present fluxes from all seven catchments. In none of the catchments does one of the sources account for ≥ 90% of the flux, In fact, only in the case of Chichester Channel does one source (sewerage-related) account for more than about 70% of the FC and EN fluxes, and this almost certainly reflects the lack of ID improvements in this catchment.
§ While these data suggest that investments in both sewerage infrastructure improvements and agricultural best management practices (BMPs) will lead to further reductions in FIO fluxes to shellfish waters, the effectiveness of BMPs in reducing FIO fluxes at the catchment scale has yet to be fully established, and implementation may prove costly in large catchments such as Taw/Torridge (2094 km^2). In contrast, investment in further improvements to STWs and IDs, such as those proposed in the EA's Pollution Reduction Plans (PRPs), is more easily targeted and the benefits more readily evaluated.

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1 Introduction

Over recent decades, UK water companies have made substantial investments to improve point-source discharges from sewerage plant and infrastructure [e.g. installation of UV disinfection at sewage treatment works (STWs) and increases in the storage capacity of intermittent discharges (IDs), notably combined sewer overflows (CSOs) and storm tank overflows (STOs)]. In particular, the National Environment Programme included in the Asset Management Plan (AMP) 3, which covered the period 2000–2005, was the first water company investment period in which the microbial quality of designated shellfish waters was a specific driver for sewerage infrastructure improvement. Although the number of shellfish production areas achieving class B under Regulation (EC) No 854/2004 has increased significantly in England and Wales over the past decade, the number of those achieving class A under the same regulation is at the time of writing this report less than 1% of the total number of classified production areas. Indeed, an investigation of temporal trends in the microbial quality of shellfish production areas, as indicated by the levels of *Escherichia coli* monitored in shellfish flesh, undertaken for the purposes of this project has identified a number of production areas where there has been deterioration in the microbial quality of shellfish (Technical Report 1). Furthermore, many designated shellfish waters have failed compliance with the Guideline faecal coliform standard specified in the Shellfish Waters Directive (79/923/EEC).

The aim of the present study was to assess the effectiveness of recent water company investment in reducing faecal indicator organism (FIO) fluxes (i.e. numbers of organisms discharged per unit time) to coastal shellfish waters at selected sites by undertaking quantitative sanitary profile (or 'sanitary survey') investigations of their catchments. It is expected that the resultant evidence-base should help inform the following policy outputs:

- an assessment of what improvements to shellfish waters are achievable and will result in real improvement to shellfish flesh quality in the short to medium term;
- information as to the effectiveness of previous water company investment to inform future investment decisions; and
- specific recommendations as to the most cost-effective remedial measures to improve targeting of investment which, in the past, has not consistently delivered the expected improvement.

Quantitative sanitary profiling primarily should involve the creation of an inventory of the key sources of pollutants, in this case FIOs, and quantification of fluxes associated with these (Lee *et al.*, 2010). In most UK catchments, three principal FIO sources can be identified: 'natural' (wildlife), farm livestock and human. Of these, wildlife sources are generally of minor significance and can be regarded as generating only relatively low, background concentrations and fluxes of FIOs in surface waters draining to the coastal zone. In contrast, livestock and human populations represent potentially significant sources and sanitary profiling is therefore focused on these.

The present study focuses on two key FIOs: faecal coliform (FC) bacteria (the regulatory microbial parameter for shellfish waters) and enterococci (EN). FC organisms constitute a sub-group of total coliforms that possess a more direct relationship with homeothermic faecal pollution. EN organisms have been widely accepted indicators of faecal pollution and show a close relationship with gastrointestinal disease, particularly in bathing waters. Environment Agency (EA) Disinfection Policy requires that water companies monitor both FC and EN concentrations in UV-disinfected sewage discharges impacting on shellfish and bathing waters. The present study does not report fluxes of *E.coli*, the regulatory microbial parameter for shellfish intended for human consumption. The justification for this is the fact that there is no requirement for water companies to monitor *E. coli* in continuous and/or disinfected discharges. Consequently, insufficient data are available to quantify fluxes of this organism. However, recent reviews of Bathing Water monitoring programme data have suggested that FC and *E. coli* numbers are broadly equivalent (Wither, 2009). Furthermore, research undertaken in the UK has shown higher correlation between *E. coli* and EN than that observed between *E. coli* and alternative indicators in commercially harvested shellfish (Rangdale, 2003).

Seven sites, covering different levels of sewerage infrastructure improvement and including sites showing both an improvement and deterioration in shellfish flesh quality over the period 1999–2008, were selected for investigation (Technical Report 2):

1. Chichester Channel section of Chichester Harbour (here referred to as 'Chichester Channel')
2. Poole Harbour West
3. Yealm
4. Fal/Ruan
5. Taw/Torridge Estuary Mouth (here referred to as 'Taw/Torridge', though it should be noted that there are other shellfish waters within both the Taw and Torridge catchments)
6. Conwy
7. Ribble

Their levels of sewerage infrastructure improvement and trends in shellfish flesh quality are summarised in Table 1 and locations shown in Fig. 1. Six of the sites (the exception being Conwy) have had significant improvements to their sewerage infrastructure over the past decade or so. In the present investigation, sanitary profiling for these six sites was undertaken both pre- and post-improvements to sewerage infrastructure. In the case of Conwy, a more limited analysis was undertaken to establish the present-day sanitary profile.

Figure 1: Shellfish waters investigated.

Table 1: Shellfish waters selected for sanitary profiling: sewerage infrastructure improvements and trends in faecal coliform concentrations in shellfish flesh.

Shellfish water	Significant improvement in sewerage infrastructure (start year)[a]	Change in GM FC concentrations in shellfish flesh: 1999–2008[b]
Chichester Channel	Yes (2008)	No trend
Poole Harbour West	Yes (2003)	No trend
Yealm	Yes (2004)	Increase
Fal/Ruan	Yes (2002)	No trend
Taw/Torridge	Yes (1997)	Decrease
Conwy	No	No trend
Ribble	Yes (1999)	No trend

[a] Year when UV disinfection first introduced at one or more STWs within the catchment.
[b] Results from Technical Report 1.

It should be noted that five of the catchments (catchments 2–6 as listed above) include subcatchments that have been targeted for the investigation of the effectiveness of best management practices (BMPs) in reducing FIO fluxes from agricultural (i.e. livestock-related) sources under the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) and Bathing Waters and Diffuse Pollution (BWDP) project in Wales. In some of the catchments the actions aimed at ensuring reduction of diffuse water pollution from agricultural land under the ECSFDI may not necessarily target microbial pollution (e.g. Poole was considered a priority catchment under the ECSFDI by virtue of diffuse pollution associated with phosphorus and sedimentation). Problems of diffuse pollution associated with direct access of cattle to watercourses leading to increased risk of faecal contamination in the shellfish water have been identified in the Yealm. A preliminary analysis of water quality monitoring data has suggested reductions in FIO levels in watercourses following the implementation of BMPs in this catchment under the ECSFDI (Phil Smith, CSF Monitoring Manager, Environment Agency – pers. comm., 2010). However, so few empirical data are currently available for the catchments that no attempt has been made to undertake a systematic review of the effects of these changes.

Ideally, a quantitative sanitary profile investigation would be able to draw on long-term monitoring data (flow and FIO concentrations) for all key microbial sources within the catchments, thereby enabling accurate characterisation of FC and EN fluxes from each source at different times of year and under base- and high-flow conditions (as defined in the Glossary) – the latter being in response to rainfall events. Unfortunately, many sources are either simply not monitored or, where monitoring is undertaken, the data are often inadequate for accurate characterisation of FC and EN concentrations and fluxes, particularly at times of high flow. Where it has been possible to obtain appropriate FC and EN and/or flow data, then these have been used. For all other sources, FC and EN concentrations and/or flow estimates have been made on the basis of either generic data from previous CREH studies across the UK or predictive models derived from these data (as detailed below). It should be noted that these previous studies were mostly undertaken during the 15 May–30 September summer bathing season (here termed 'summer'), and that estimates presented for the rest of the year ('winter') are necessarily based on much more limited evidence.

The sanitary profiling undertaken provides a basis for evaluating the effectiveness of sewerage infrastructure improvements in reducing inputs of FIOs to the shellfish waters. However, it should be noted that FIO concentrations in the receiving shellfish water depend not only on the magnitude of input fluxes, but also upon the volume of the receiving water and the hydrodynamics of the estuarine/coastal zone – i.e. high fluxes do not necessarily lead to high concentrations in the shellfish water. In the absence of hydrodynamic modelling, the results of the present study therefore need to be interpreted with caution when making inter-site comparisons. Thus, while it is reasonable to assume that a 50% reduction in flux may lead to a similar reduction in FC and EN concentrations in a given shellfish water, the fact that one shellfish water catchment receives much greater FIO inputs than another will not necessarily be reflected in the resulting FC and EN concentrations in the shellfish water.

2 Methods

2.1 Overall approach

Since the principal objective was to investigate the effectiveness of improvements made to the sewerage infrastructure, the various FIO sources within the catchments were categorised as follows:

§ **Sewerage sources that have been improved**: STWs (termed 'key STWs') and IDs associated with these

§ **Other 'catchment' sources**: primarily other sewage-related sources (STWs, IDs, septic tanks, etc. where there has been little or no improvement) and agricultural sources

Typically, improvements to the sewerage infrastructure within catchments have been implemented progressively over several years. For the purposes of the present analysis the time when UV disinfection was first implemented at one or more STWs in a catchment (Table 1) is the date considered as the commencement of the improvements. In order to avoid issues relating to the uncertainty of the timing of improvements within individual years, the 'pre-improvement period' is regarded as extending up to the end of the year before the commencement of improvements and the 'post-improvement period' as starting the year after commencement.

For all sewerage sources where improvements have been implemented, every effort has been made to obtain data on flow volumes and FC and EN concentrations both pre- and post-improvement, during the summer and winter periods. Where such data are not available, then generic data from previous CREH studies have been used (see below). It should be noted that the water companies responsible for the sewerage infrastructure in each of the catchments have each been invited by Defra to comment on the assumptions made, the overall methodology and resulting sanitary profiles, and have not raised any concerns. In the case of other catchment sources, generic models developed by CREH/Environment Agency (EA) have been used to predict the FC and EN concentrations in rivers that are derived from these (see below) during the summer for the pre- and post-improvement periods. River flow data have been used to quantify FC and EN fluxes from these sources, and these have been combined with the flux data from the sewerage sources (i.e. treated effluents and IDs) associated with the key STWs that have been improved to give an overall flux to the shellfish water.

2.2 Existing CREH datasets for the UK

Since 1995, CREH has undertaken many investigations of sewerage- and agriculture-related FIO sources, concentrations and fluxes within UK catchments, mostly during the summer period. In the present study, generic data derived directly or indirectly (via regression modelling of relationships between FIO concentrations and catchment characteristics) from these studies have been used to estimate FC and EN concentrations and/or flow volumes where data are lacking for the shellfish water catchments.

2.2.1 FC concentrations in sewage and treated effluents

A review of FIO data from previous CREH (summer) studies was published by Kay *et al*. (2008a). Summary data for FC and EN concentrations are presented in Table 2. In the present study the base- and high-flow geometric mean (GM) concentrations in effluents from specific treatment types (or treatment level where the specific treatment type is unknown) have been used. It should be noted that GM FC concentrations are typically about a $\log_{10}$ order of magnitude higher than EN concentrations – a finding that is paralleled by GM concentrations in river waters (see below).

Table 2: Summary of faecal coliform and enterococci concentrations (cfu 100 ml^{-1}) for different treatment levels and individual types of sewage-related effluents under different flow conditions: geometric means (GMs), 95% confidence intervals (CIs)[a]; and results of *t*-tests comparing base- and high-flow GMs for each group and type[b]; and (in footnote) results of *t*-tests comparing GMs for the two untreated discharge types and the two tertiary-treated effluent types (from Kay *et al*., 2008a).

Indicator organism	Base flow conditions:				High flow conditions:			
Treatment levels and specific types	*n*[c]	Geometric mean	Lower 95% CI	Upper 95% CI	*n*[c]	Geometric mean	Lower 95% CI	Upper 95% CI
FAECAL COLIFORMS								
Untreated	**252**	**1.7×10^{7} *(+)**	**1.4×10^{7}**	**2.0×10^{7}**	**282**	**2.8×10^{6} *(–)**	**2.3×10^{6}**	**3.2×10^{6}**
Crude sewage discharges[d]	252	1.7×10^{7} *(+)	1.4×10^{7}	2.0×10^{7}	79	3.5×10^{6} *(–)	2.6×10^{6}	4.7×10^{6}
Storm sewage overflows[d]					203	2.5×10^{6}	2.0×10^{6}	2.9×10^{6}
Primary	**127**	**1.0×10^{7} *(+)**	**8.4×10^{6}**	**1.3×10^{7}**	**14**	**4.6×10^{6} *(–)**	**2.1×10^{6}**	**1.0×10^{7}**
Primary settled sewage	60	1.8×10^{7}	1.4×10^{7}	2.1×10^{7}	8	5.7×10^{6}	–	–
Stored settled sewage	25	5.6×10^{6}	3.2×10^{6}	9.7×10^{6}	1	8.0×10^{5}	–	–
Settled septic tank	42	7.2×10^{6}	4.4×10^{6}	1.1×10^{7}	5	4.8×10^{6}	–	–
Secondary	**864**	**3.3×10^{5} *(–)**	**2.9×10^{5}**	**3.7×10^{5}**	**184**	**5.0×10^{5} *(+)**	**3.7×10^{5}**	**6.8×10^{5}**
Trickling filter	477	4.3×10^{5}	3.6×10^{5}	5.0×10^{5}	76	5.5×10^{5}	3.8×10^{5}	8.0×10^{5}
Activated sludge	261	2.8×10^{5} *(–)	2.2×10^{5}	3.5×10^{5}	93	5.1×10^{5} *(+)	3.1×10^{5}	8.5×10^{5}
Oxidation ditch	35	2.0×10^{5}	1.1×10^{5}	3.7×10^{5}	5	5.6×10^{5}	–	–
Trickling/sand filter	11	2.1×10^{5}	9.0×10^{4}	6.0×10^{5}	8	1.3×10^{5}	–	–
Rotating biological contactor	80	1.6×10^{5}	1.1×10^{5}	2.3×10^{5}	2	6.7×10^{5}	–	–
Tertiary	**179**	**1.3×10^{3}**	**7.5×10^{2}**	**2.2×10^{3}**	**8**	**9.1×10^{2}**	**–**	**–**
Reedbed/grass plot[e]	71	1.3×10^{4}	5.4×10^{3}	3.4×10^{4}	2	1.5×10^{4}	–	–
Ultraviolet disinfection[e]	108	2.8×10^{2}	1.7×10^{2}	4.4×10^{2}	6	3.6×10^{2}	–	–

ENTEROCOCCI								
Untreated	**254**	**1.9×10^{6} *(+)**	**1.6×10^{6}**	**2.3×10^{6}**	**280**	**4.9×10^{5} *(–)**	**4.2×10^{5}**	**5.6×10^{5}**
Crude sewage discharges[d]	254	1.9×10^{6} *(+)	1.6×10^{6}	2.3×10^{6}	79	8.9×10^{5} *(–)	6.7×10^{5}	1.2×10^{6}
Storm sewage overflows[d]					201	3.8×10^{5}	3.2×10^{5}	4.5×10^{5}
Primary	**128**	**1.3×10^{6}**	**1.1×10^{6}**	**1.7×10^{6}**	**14**	**9.8×10^{5}**	**4.4×10^{5}**	**2.2×10^{6}**
Primary settled sewage	61	2.4×10^{6}	2.1×10^{6}	2.7×10^{6}	8	1.9×10^{6}	–	–
Stored settled sewage	26	6.2×10^{5}	3.2×10^{5}	1.1×10^{6}	1	2.9×10^{5}	–	–
Settled septic tank	41	9.3×10^{5}	5.3×10^{5}	1.6×10^{6}	5	4.3×10^{5}	–	–
Secondary	**871**	**2.8×10^{4} *(–)**	**2.5×10^{4}**	**3.2×10^{4}**	**182**	**4.7×10^{4} *(+)**	**3.6×10^{4}**	**6.1×10^{4}**
Trickling filter	483	4.1×10^{4}	3.5×10^{4}	4.7×10^{4}	76	5.7×10^{4}	4.2×10^{4}	8.3×10^{4}
Activated sludge	262	2.1×10^{4} *(–)	1.8×10^{4}	2.7×10^{4}	91	4.1×10^{4} *(+)	2.7×10^{4}	6.0×10^{4}
Oxidation ditch	35	2.0×10^{4}	1.0×10^{4}	4.0×10^{4}	5	1.2×10^{5}	–	–
Trickling/sand filter	11	2.1×10^{4}	1.0×10^{4}	5.3×10^{4}	8	1.1×10^{4}	–	–
Rotating biological contactor	80	9.6×10^{3}	6.7×10^{3}	1.4×10^{4}	2	3.7×10^{5}	–	–
Tertiary	**177**	**3.0×10^{2}**	**1.8×10^{2}**	**5.0×10^{2}**	**8**	**2.1×10^{2}**	**–**	**–**
Reedbed/grass plot[e]	73	1.9×10^{3}	7.1×10^{2}	4.3×10^{3}	2	2.3×10^{3}	–	–
Ultraviolet disinfection[e]	104	8.3×10^{1}	4.6×10^{1}	1.1×10^{2}	6	9.7×10^{1}	–	–

[a] CIs only reported where $n \geq 10$.

[b] *t*-tests comparing low- and high-flow GM concentrations only undertaken where $n \geq 10$ for both sets of samples; only statistically significant ($p < 0.05$) differences between base- and high-flow GM concentrations are reported: indicated by *, with the higher GM being identified as *(+) and the lower value by *(–).

[c] *n* indicates number of valid enumerations, which in some cases may be less than the actual number of samples.

[d] *t*-tests comparing the GM concentrations between the two untreated discharge types show high-flow GM concentrations to be significantly higher in crude sewage discharges than storm sewage overflows for EN ($p < 0.001$).

[e] *t*-tests comparing the GM concentrations between the two tertiary-treatment effluent types show GM FC and EN concentrations to be significantly higher ($p < 0.001$) in reedbed/grass plot effluents than effluents from UV disinfection for base-flow conditions (there are too few high-flow samples for these tertiary effluents for meaningful comparisons to be made for high-flow GM concentrations).

2.2.2 *Treated effluent flow volumes at STW*

Treated effluent flow data from 53 STWs are summarised in Table 3. These reveal mean proportions of base and high flow over the summer period of 0.733 and 0.267, respectively.

Table 3: Summary of sewage treatment works summer treated effluent flows from previous CREH studies in the UK

	n[a]	Mean	Minimum	Maximum	Std dev
Proportion base flow	53	0.733	0.415	0.995	0.136
Proportion high flow	53	0.267	0.005	0.585	0.136
Total flow (l pe^{-1} day^{-1})[b]	45	355	61	1,700	257
Derived base flow (l pe^{-1} day^{-1})[c]		260			
Derived high flow (l pe^{-1} day^{-1})[c]		95			

[a] Flow data are available for 53 STWs, but pe data only for 45 of these.
[b] pe = population equivalent.
[c] Base/high flow split of total flow (l pe^{-1} day^{-1}) based on mean proportions reported for all 53 STWs.

For some STWs the human population equivalent (PE) data (i.e. excluding industrial/trade sources) were complicated by tourist numbers, and these have been excluded in calculating flows PE^{-1} day^{-1}. The mean total flow over the remaining STWs is 355 l PE^{-1} day^{-1}. Application of the mean base/high flow proportions to this figure gives mean figures of 260.2 and 94.8 l PE^{-1} day^{-1}, respectively. In the present study these mean flows and proportions have been used where actual flow data are not available. It should be noted that the total mean flow of 355 l PE^{-1} day^{-1} is substantially higher than the estimate of 160–185 l PE^{-1} day^{-1} that is often assumed (Lee *et al*., 2010) – presumably because the latter is based on water consumption per capita and does not take into account inputs of rainwater via combined sewerage systems.

2.2.3 *Flow volumes of IDs (CSOs, STOs, etc.)*

Although overflows of untreated sewage from IDs represent a potentially significant source of FIOs within catchments, and spills are regulated through discharge consents, flow is monitored at very few of these. Indeed, for many there is even a lack of spill frequency data. In one study undertaken by CREH, detailed monitoring and/or modelling of ID flows associated with a large STW was undertaken during the summer bathing season. Of the total sewerage (i.e. treated effluent + ID) flow recorded, 4.12% was from IDs, giving a ratio of ID:STW treated effluent flow of 0.0429. Estimates made in four other studies have revealed extremely wide variability, depending upon the characteristics of the sewerage network and the amount of rainfall during the monitoring period, with ID flow accounting for between 3.05 and 46.6% of the total sewerage flow. These figures equate to ratios of ID:STW treated effluent flow of between 0.0315 and 0.873.

In the present study, a ratio of 0.0429 has been used to estimate the total volumes of ID flow associated with the STWs at which improvements have been made. In addition, a sensitivity analysis has been undertaken to evaluate the effects of varying this ratio (see below). It should be noted that FIO concentrations and fluxes from IDs associated other STWs within the catchments are included within the other catchment sources.

2.2.4 FC and EN concentrations and fluxes in rivers and models of their relationship with catchment characteristics

Over the period 1995-2005, CREH undertook 15 catchment-based investigations across mainland UK during the summer bathing season in which FIO monitoring was undertaken at the outlet of a total of 205 ‘subcatchments’ and detailed land use data obtained (as detailed in Table 4).

A synthesis of the results of these studies has been published (Kay *et al*., 2008b), and summaries of the FC and EN concentration and export coefficient data are presented in Tables 5 and 6).

Table 4: Catchments investigated and land use data used in studies undertaken by CREH in the period 1995-2005.

	Catchment	Year sampled	Number of subcatchments (and degree of urbanisation)[a]	Land use data[b]
England				
1	Holland Brook	1998	14 (1/10/3)	Field mapping/OS
2	River Ribble	2002	40 (18/12/10)	ITE1990/OS
3	Staithes Beck	1995	4 (1/3/0)	Field mapping/OS
4	Lake Windermere inputs	1999	25 (22/2/1)	CEH 2000/OS
5	River Leven/Crake	2005	30 (25/4/1)	CEH2000/OS
Scotland				
6	Sandyhills	2004	4 (4/0/0)[4]	SE
7	Brighouse Bay inputs	2004	2 (1/1/0)[2]	Estimated
8	Troon coastal inputs	2000	6 (1/3/2)	Estimated
9	Killoch Burn[c]	2004	4 (2/2/0) [3]	SE
10	River Irvine/Garnock	1998	30 (19/9/2)	Field mapping + MLCMS
11	Ettrick Bay inputs	2004	3 (3/0/0)[2]	SE
12	River Nairn	2004	1 (1/0/0)	SE
Wales				
13	Afon[d] Ogwr	1997	18 (5/13/0)	Field mapping/OS
14	Afon[d] Nyfer	1996	2 (2/0/0)	Field mapping/OS
15	Afon[d] Rheidol/Ystwyth	1999	22 (20/1/1)	Field mapping/OS

[a] Figures in round parentheses indicate number of subcatchments classified according to degree of urbanisation, as specified in the text: (rural/semi-urban/urban). Numbers of subcatchments used in summer/winter comparisons are shown in square parentheses.
[b] Land use data sources:
Estimated = estimates for the two key land use types: built-up land (from OS 1:50000 maps) and improved pasture (from field reconnaissance);
Field mapping/MLCMS = land use mapping during study period of part of the catchment, supplemented by the 1988 Macaulay Land Cover Map of Scotland, calibrated through field mapping;
Field mapping/OS = land use mapping during study period, supplemented by Ordnance Survey 1:50000 digital map information for built-up land and woodland;
ITE1990/OS = Institute of Terrestrial Ecology Land Cover for 1990, calibrated using ground truth data from the five study areas in England Wales where field mapping was undertaken, and supplemented by Ordnance Survey 1:50000 digital map information for built-up land and woodland; CEH2000/OS = Centre for Ecology and Hydrology Land Cover Map for 2000, supplemented by Ordnance Survey 1:50000 digital map information for built-up land and woodland; and SE = Land use data generated by Scottish Executive.
[c] Killoch Burn is located within the headwaters of the River Irvine/Garnock catchment. [d] 'Afon' (Welsh) = 'River'.

Table 5: Summary of faecal coliform and enterococci concentrations under base- and high-flow conditions: GMs and 95% confidence intervals (CIs) of the GM faecal indicator organism (FIO) concentrations (cfu 100 ml^{-1}) at the 205 sampling points and for various subsets, and results of paired, *t*-tests to establish whether there are significant elevations at high flow compared with base flow.

FIO Subcatchment land use	*n*	Base flow: Geometric mean	Lower 95% CI	Upper 95% CI	High flow: Geometric mean[a]	Lower 95% CI	Upper 95% CI
FAECAL COLIFORMS							
All subcatchments	205	1.8x10^{3}	1.4x10^{3}	2.3x10^{3}	2.8x10^{4}**	2.2x10^{4}	3.4x10^{4}
Degree of urbanisation[b]							
Urban	20	9.7x10^{3}	4.6x10^{3}	2.0x10^{4}	1.0x10^{5}**	5.3x10^{4}	2.0x10^{5}
Semi-urban	60	4.4x10^{3}	3.2x10^{3}	6.1x10^{3}	4.5x10^{4}**	3.2x10^{4}	6.3x10^{4}
Rural	125	8.7x10^{2}	6.3x10^{2}	1.2x10^{3}	1.8x10^{4}**	1.3x10^{4}	2.3x10^{4}
Rural subcatchments with different dominant land uses							
≥ 75% Improved pasture	15	1.9x10^{3}	1.1x10^{3}	3.2x10^{3}	5.7x10^{4}**	4.1x10^{4}	7.9x10^{4}
≥ 75% Rough grazing	13	3.6x10^{2}	1.6x10^{2}	7.8x10^{2}	8.6x10^{3}**	5.0x10^{3}	1.5x10^{4}
≥ 75% Woodland	6	3.7x10	1.2x10	1.2x10^{2}	1.5x10^{3}**	6.3x10^{2}	3.4x10^{3}
ENTEROCOCCI							
All subcatchments	205	2.7x10^{2}	2.2x10^{2}	3.3x10^{2}	5.5x10^{3}**	4.4x10^{3}	6.8x10^{3}
Degree of urbanisation[b]							
Urban	20	1.4x10^{3}	9.1x10^{2}	2.1x10^{3}	2.1x10^{4}**	1.3x10^{4}	3.3x10^{4}
Semi-urban	60	5.5x10^{2}	4.1x10^{2}	7.3x10^{2}	1.0x10^{4}**	7.6x10^{3}	1.4x10^{4}
Rural	125	1.5x10^{2}	1.1x10^{2}	1.9x10^{2}	3.3x10^{3}**	2.4x10^{3}	4.3x103
Rural subcatchments with different dominant land uses							
≥ 75% Improved pasture	15	2.2x10^{2}	1.4x10^{2}	3.5x10^{2}	1.0x10^{4}**	7.9x10^{3}	1.4x10^{4}
≥ 75% Rough grazing	13	4.7x10	1.7x10	1.3x10^{2}	1.2x10^{3}**	5.8x10^{2}	2.7x10^{3}
≥ 75% Woodland	6	1.6x10	7.4	3.5x10	1.7x10^{2}**	5.5x10	5.2x10^{2}

[a] Significant elevations in concentrations at high flow are indicated: ** $p < 0.001$, * $p < 0.05$.

[b] Degree of urbanisation, categorised according to percentage built-up land: ‘Urban’ ≥ 10.0%), ‘Semi -urban’ (2.5-9.9%) and ‘Rural’ (<2.5%).

Table 6: Summary of geometric mean faecal coliform and enterococci export coefficients (cfu km^{-2} hr^{-1}) under base- and high-flow conditions at the 205 sampling points and for various subsets, and results of paired, 1-tailed *t*-tests to establish whether there are significant elevations at high flow compared with base flow.

FIO Subcatchment land use	*n*	Base flow: Geometric mean	Lower 95% CI	Upper 95% CI	High flow: Geometric mean[a]	Lower 95% CI	Upper 95% CI
FAECAL COLIFORMS							
All subcatchments	205	5.5×10^{8}	4.1×10^{8}	7.2×10^{8}	3.6×10^{10}**	2.7×10^{10}	4.8×10^{10}
Degree of urbanisation[b]							
Urban	20	2.8×10^{9}	1.1×10^{9}	7.2×10^{9}	1.3×10^{11}**	4.8×10^{10}	3.6×10^{11}
Semi-urban	60	1.2×10^{9}	7.4×10^{8}	1.9×10^{9}	4.6×10^{10}**	2.5×10^{10}	8.6×10^{10}
Rural	125	2.9×10^{8}	2.1×10^{8}	4.0×10^{8}	2.6×10^{10}**	1.9×10^{10}	3.5×10^{10}
Rural subcatchments with different dominant land uses							
≥ 75% Improved pasture	15	8.3×10^{8}	4.3×10^{8}	1.6×10^{9}	1.2×10^{11}**	6.5×10^{10}	2.2×10^{11}
≥ 75% Rough grazing	13	2.5×10^{8}	1.1×10^{8}	5.7×10^{8}	2.5×10^{10}**	1.1×10^{10}	5.5×10^{10}
≥ 75% Woodland	6	2.0×10^{7}	4.7×10^{6}	8.2×10^{7}	3.3×10^{9}**	1.3×10^{9}	8.8×10^{9}
ENTEROCOCCI							
All subcatchments	205	8.3×10^{7}	6.6×10^{7}	1.1×10^{8}	7.1×10^{9}**	5.5×10^{9}	9.3×10^{9}
Degree of urbanisation[b]							
Urban	20	4.0×10^{8}	2.1×10^{8}	7.6×10^{8}	2.7×10^{10}**	1.1×10^{10}	6.2×10^{10}
Semi-urban	60	1.5×10^{8}	9.8×10^{7}	2.2×10^{8}	1.1×10^{10}**	6.1×10^{9}	1.9×10^{10}
Rural	125	4.9×10^{7}	3.7×10^{7}	6.5×10^{7}	4.7×10^{9}**	3.5×10^{9}	6.3×10^{9}
Rural subcatchments with different dominant land uses							
≥ 75% Improved pasture	15	9.6×10^{7}	5.2×10^{7}	1.8×10^{8}	2.2×10^{10}**	1.3×10^{10}	3.8×10^{10}
≥ 75% Rough grazing	13	3.3×10^{7}	1.2×10^{7}	9.0×10^{7}	3.6×10^{9}**	1.3×10^{9}	9.7×10^{9}
≥ 75% Woodland	6	8.5×10^{6}	3.8×10^{6}	1.9×10^{7}	3.8×10^{8}**	1.3×10^{8}	1.1×10^{9}

[a] Significant elevations in export coefficients at high flow are indicated: ** $p < 0.001$

[b] Degree of urbanisation, categorised according to percentage built-up land: 'Urban' (≥ 10.0%), 'Semi -urban' (2.5-9.9%) and 'Rural' (<2.5%).

Three key findings are evident form these results. Firstly, high-flow conditions are critical in terms of the mobilisation/transport of FIOs within catchments, e.g. the GM FC concentration for all 205 sites increases approximately 10-fold (from 1.4 x 103 to 2.8 x 104 cfu 100 ml-1) and the export coefficient approximately 100-fold (from 5.5 x 108 to 3.6 x 1010 cfu km-2 hr-1) compared with base-flow conditions. Secondly, there are marked differences according to land use within catchments, with the highest FIO concentrations and fluxes being associated with areas of urbanisation (sewerage-related sources) and improved pasture (livestock sources, especially dairy cattle). For example, the GM FC concentrations in urban catchments and rural catchments dominated by improved pasture are 3.2 x 105 and 1.3 x 105 cfu 100 ml-1, respectively, compared with 6.3 x 103 cfu 100 ml-1 for rural catchments dominated by woodland/forestry. Using this subcatchment dataset, successful linear regression models have been developed of the relationships between GM FIO concentrations in rivers and catchment characteristics (soil hydrology, land use, human population densities, stocking levels, etc.) – e.g. an adjusted r2 value of 0.622 was achieved for FC under high-flow conditions using livestock and human population data (Crowther et al., 2011).

While this dataset illustrates well the nature and strength of the relationship between land use and FIO concentrations, the under-representation of catchments in southern England and lack of data for areas of chalk downland limit the wider applicability of the models. This has been addressed in recent modelling work, undertaken in collaboration with the EA, in which data from the eight CREH catchments in England and Wales (165 subcatchments; Table 4) have been combined with data from five catchments (a total of 39 subcatchments) monitored by the EA in the ECSFDI study: Hampshire Avon and Stour, Deben, Yealm and Wyre – which, apart from the Wyre (Lancashire), are all in the south of England, and the Avon and Stour catchments both include extensive areas of chalk. Two points should be noted with regard to the ECSFDI catchment data. Firstly, since the proportions of the catchments affected by the BMPs are relatively small and the data used mostly cover the period prior to and during the early phases of implementation, it has been assumed that these data are representative of conditions in which there has been relatively little BMP implementation. It was felt far preferable to include these catchments in the present modelling so as to increase the overall representativeness of the data (particularly since 5 of the 7 shellfish water catchments are in southern England and two include chalk), than omit them because of the possibility that limited BMP implementation may have affected the GM FIO concentrations recorded. Studies in the Brighouse Bay catchment, Scotland, have suggested that the effects of stream bank fencing upon GM FIO concentrations are detectable only when ≥ 30% of stream banks have been fenced (Kay et al., 2007) – and the levels of BMP implementation within the ECSFDI catchments were less than this. Secondly, the data for the Ribble (CREH) and Yealm (EA) do not coincide with the shellfish water catchments investigated in the present study – i.e. the data cannot be used to quantify FC and EN fluxes, either from the catchment as a whole or from the 'other catchment' sources component. Details of the statistical methods adopted in the regression modelling and the way in which the die-off and sedimentation of FIOs within reservoirs has been accounted for are presented in Crowther *et al*. (2011). The catchment variables used are detailed in Table 7 and the resulting models, which are used in the present study to estimate FC and EN concentrations derived from other catchment sources, both pre- and post-improvements, are summarised in Table 8. As is generally the case, the levels of explained variance are greater under high-flow than base-flow conditions, the adjusted r^2 values for FC, for example, being 0.627 and 0.458, respectively.

Table 7: Catchment (predictor) variables used in multiple regression modelling.

Variable type	Variable[a]
Catchment size	Subcatchment area (km^2)
Catchment hydrology	Base flow index (BFI)[b]
Land cover[c]	Urban (OS Meridian) (%) Urban (%) Improved grassland (%) Rough grazing (%) Arable/set-aside (%) Woodland (%)
Human population	Residences (km^{-2})[d]
Stocking densities[e]	Dairy cattle (km^{-2}) Beef cattle (km^{-2}) Total cattle (km^{-2}) Sheep (km^{-2}) Pigs (km^{-2}) Poultry (km^{-2})

[a] Log_{10} transformations were applied in cases where skewness ≥ 1.00. Except for BFI, 1.00 was added to data values prior to transformation in order to eliminate zero values.

[b] The mean BFI has been derived from the HOST database.

[c] The land cover data have mostly been synthesised from the Centre for Ecology and Hydrology (CEH) Land Cover Map (LCM) 2000, with the various classes amalgamated. In addition, Ordnance Survey (OS) Meridian 2 digital 'developed land use' (DLU) boundary data have been used to provide an additional, independent urban data set. The land cover variables were all expressed as a percentage of the land area.

[d] The National Property Database for 2005 was used to determine the density of residences within each subcatchment, expressed as no km^{-2}.

[e] Agricultural census data were used to determine stocking levels (dairy cattle, beef cattle, sheep, pigs, poultry and other), expressed as number/km^2. These data were not available for the Conwy catchment and in this case EDINA (parish level) statistics have been used – any inconsistencies arising from this are likely to be small (C. Burgess, EA – pers. comm.).

One further point that should be noted is that as flow length increases in larger catchments, the opportunity for die-off and sedimentation along the watercourse increases. This is especially the case at base flow, when the velocity of flow is slow (i.e. a long residence time within the channel), and the water is relatively shallow and of low turbidity (i.e. enabling penetration of UV light through the water column); cf. high-flow conditions, when residence time will be much shorter and the penetration of UV light through the deeper water will be impeded by higher levels of turbidity. The subcatchments used in the present modelling have areas in the range 5 to 1013 km^2, and since catchment area is not entered as an independent variable in any of the regression models, it is reasonable to assume that variations is catchment size up to *c.* 1000 km^2, do not have a major influence over GM FIO concentrations. The models can therefore be applied with some confidence to all of the shellfish water catchments, since the five of them have total areas considerably <1000 km^2, and in the two larger ones (Taw/Torridge and Ribble) the areas of the individual subcatchments that drain to the shellfish water are no larger than *c.* 1000 km^2.

Table 8: CSF and CREH subcatchments: summary of stepwise multiple regression models of relationship between SUMMER bathing season mean $\log_{10}$ total faecal coliform and enterococci concentrations at base and high flow and the catchment variables listed in Table 7.

Step	Variable	Sign of *b*	Adjusted r^2	Sig level (p)
Base-flow models (n = 151)				
Faecal coliforms				
1	Residences ($\log_{10}$, km^{-2})	+	0.321	
2	BFI ($\log_{10}$)	-	0.407	
3	Dairy cattle (km^{-2})	+	0.458	< 0.001
Enterococci				
1	Residences ($\log_{10}$, km^{-2})	+	0.204	
2	BFI ($\log_{10}$)	-	0.305	
3	Area ($\log_{10}$, km^2)	-	0.347	
4	Rough grazing (%)	-	0.360	< 0.001
High-flow models (n = 133)				
Faecal coliforms				
1	Residences ($\log_{10}$, km^{-2})	+	0.182	
2	Sheep (km^{-2})	+	0.448	
3	BFI ($\log_{10}$)	-	0.573	
4	Dairy cattle (km^{-2})	+	0.627	< 0.001
Enterococci				
1	Residences ($\log_{10}$, km^{-2})	+	0.199	
2	Sheep (km^{-2})	+	0.461	
3	BFI ($\log_{10}$)	-	0.576	
4	Total cattle (km^{-2})	+	0.613	
5	Area ($\log_{10}$, km^2)	-	0.637	
6	Pigs ($\log_{10}$, km^{-2})	+	0.648	< 0.001

2.2.5 Summer/winter comparisons of FC and EN concentrations and fluxes in catchments

For 11 (mostly rural, livestock-dominated) of the 205 subcatchments identified in Table 4, comparative FC and EN concentration and export coefficient data were also obtained for the winter period (actually during autumn months). These are summarised in Tables 9 and 10. These results show GM concentrations to be significantly higher in summer than winter under both base- and high-flow conditions. This can be attributed to greater FIO inputs to pastoral land, and possibly directly to streams, in the summer (cf. autumn) from grazing livestock and manure/slurry applications. It is unlikely that these differences will be so great during the spring months, when more livestock will be in the fields and manure/slurry applications are often at their peak. Equally, these results may poorly reflect seasonal patterns in more urbanised UK catchments. Export coefficients, expressed here as cfu km^{-2} hr^{-1}, are also significantly higher under high-flow conditions in summer. This latter finding must, however, also be interpreted with caution since the duration of high flow conditions will inevitably be longer over the winter months – i.e. overall winter fluxes are likely to be similar to, or exceed, summer fluxes.

2.3 Definition of shellfish water catchments

The individual catchments have been defined as comprising all land draining to the designated shellfish water. The catchments exclude inputs from the adjacent coast which may also impact upon the shellfish water as a result of marine and/or estuarine processes. The catchments were defined using digital terrain mapping (DTM) data.

2.4 Data on effluent flows and FIO concentrations for STWs that have been improved

For all STWs where improvements have been made, requests were made to the water companies for data on FIO concentrations in the final treated effluent pre- and post-improvement (ideally data for several years) and 15-minute flow records for four 4-month periods (i.e. a total of 16 months records for each STW):

§ Summer (Jun-Sep) pre-improvement
§ Winter (Dec-Mar) pre-improvement
§ Summer (Jun-Sep) post-improvement
§ Winter (Dec-Mar) post-improvement

Where such data have been supplied, then these have been used. Otherwise, mean figures from previous CREH studies (see above) have been used. Details of the actual data used are presented in Appendices 3 and 4.

2.5 Data on IDs that have been improved

Similarly, requests were made for the following data (for summer/winter and pre-/post-improvement) for all IDs that have been improved – ideally, based on average data for several years:

- § Volume of flow
- § Frequency of spills
- § Geometric mean FIO concentrations

Unfortunately, data on flow volumes both pre- and post-improvement are available for very few of the 41 IDs identified as being improved. Assessment of the contribution of intermittent discharges is further complicated by the fact many of those associated with the key STWs have not been improved, and the availability of monitoring data from these is just as problematic.

In view of the total inadequacy of the ID flux data for the shellfish water catchments, the following approach has been adopted for profiling the IDs: ID flow volumes associated with the key STWs pre-improvement have been estimated to be 0.0429 x total STW final effluent flow (based on CREH data – see above). Improvements have been assumed to have reduced the flow volumes across all IDs (i.e. improved and non-improved) by 90%, which seems reasonable since the more active IDs will generally be the ones targeted for improvement. In addition, the sensitivity of using these figures has been assessed by calculating likely 'best- and worst-case scenarios':

- § **Best-case scenario** assumes a lower ID flow volume of 0.01 x STW effluent flow (i.e. IDs account for 0.99% of total sewerage flow) and a greater reduction in flow (99%) following improvement; and
- § **Worst-case scenario** assumes a much greater ID flow volume of 0.873 x STW effluent flow (i.e. IDs account for 46.6% of total sewerage flow), which is the highest estimated figure from previous CREH studies, and a smaller reduction in flow (50%) following improvement.

2.6 Data on IDs that have been improved

For each shellfish water catchment, long-term flow records (ideally 5 or more years) from the lowermost gauging station on the largest river have been used to derive estimates of the average volumes of base- and high-flow during the summer and winter periods for the entire catchment using the following methods developed by the EA.

Continuous river flow gauging stations within the selected catchments were identified and 15-minute interval gauged flow data were extracted from the EA's WISKI telemetry system. Data were grouped by year and season. Seasons were defined as either bathing water season or winter (all other days). Seasons without a complete set of 15-minute interval data were discarded. The total volume of flow was then distributed between base- and high-flow periods using BFI data derived from the CEH Low Flows 2000 system. The mean and standard deviation total flow (m^3) during high- and base-flow conditions were calculated per gauged point and for all points per catchment where multiple points were used. These data were extrapolated to the full catchment using an hydrologically effective rainfall (HER)-weighted extrapolation, which used the long-term average runoff data per km from the CERF regionalised rainfall-runoff model (developed by CEH and EA) to extrapolate from the gauged area flow to the total catchment flow.

2.7 Estimation of winter and annual fluxes of FC and EN

As noted above (Section 2.2.5), the extensive CREH datasets are mostly based on monitoring undertaken during the summer bathing season, with only very limited comparative (autumn) data for the winter period – as reported in Tables 9 and 10. These datasets do not provide a sound basis for calculating winter FC and EN fluxes, or estimating these from summer data, and the authors are not aware of any other UK datasets that can be used for this purpose.

Table 9: Geometric mean (GM) and 95% confidence intervals (CIs) of the GM faecal coliform and enterococci concentrations (cfu 100 ml^{-1}) under base- and high-flow conditions at the 11 sampling points (mostly rural subcatchments) for which both summer (i.e. bathing season) and autumn/winter data are available; results of paired, 1-tailed *t*-tests to establish whether there are significant elevations at high flow compared with base flow[a]; and results of paired, 2-tailed *t*-tests to compare summer and winter concentrations.

Season FIO	Base flow: Geometric mean[b]	Lower 95% CI	Upper 95% CI	High flow: Geometric mean[b]	Lower 95% CI	Upper 95% CI
Summer						
Faecal coliforms	$1.4\text{x}10^3$*(+)	$4.6\text{x}10^2$	$4.1\text{x}10^3$	$1.7\text{x}10^4$**(+)	$5.1\text{x}10^3$	$5.9\text{x}10^4$
Enterococci	$1.6\text{x}10^2$	9.6x10	$2.5\text{x}10^2$	$4.4\text{x}10^3$**(+)	$1.4\text{x}10^3$	$1.3\text{x}10^4$
Winter						
Faecal coliforms	$3.1\text{x}10^2$*(-)	$1.1\text{x}10^2$	$8.4\text{x}10^2$	$2.1\text{x}10^3$**(-)	$5.8\text{x}10^2$	$7.6\text{x}10^3$
Enterococci	$1.1\text{x}10^2$	4.5x10	$2.8\text{x}10^2$	$7.8\text{x}10^2$**(-)	$2.2\text{x}10^2$	$2.8\text{x}10^3$

[a] In each case significant elevations ($p < 0.05$) were recorded at high flow, and in all cases except enterococci in winter $p < 0.001$.
[b] Significant differences in concentrations between summer and winter are indicated as follows: ** $p < 0.001$, * $p < 0.05$, with (+) identifying the higher concentration and (-) the lower.

Table 10: Summary of export coefficients (cfu km^{-2} hr^{-1}) for faecal coliform and enterococci under base- and high-flow conditions at the 11 sampling points (mostly rural subcatchments) for which both summer (i.e. bathing season) and autumn/winter data are available results of paired, 1-tailed *t*-tests to establish whether there are significant elevations at high flow compared with base flow[a]; and results of paired, 2-tailed *t*-tests to compare summer and winter coefficients.

Season FIO	Base flow: Geometric mean[b]	Lower 95% CI	Upper 95% CI	High flow: Geometric mean[c]	Lower 95% CI	Upper 95% CI
Summer						
Faecal coliforms	$6.6\text{x}10^8$	$2.6\text{x}10^8$	$1.7\text{x}10^9$	$7.1\text{x}10^{10}$*(+)	$2.2\text{x}10^{10}$	$2.3\text{x}10^{11}$
Enterococci	$7.4\text{x}10^7$	$3.7\text{x}10^7$	$1.5\text{x}10^8$	$1.8\text{x}10^{10}$**(+)	$6.0\text{x}10^9$	$5.2\text{x}10^{10}$
Winter						
Faecal coliforms	$2.5\text{x}10^8$	$1.1\text{x}10^8$	$5.7\text{x}10^8$	$7.3\text{x}10^9$*(-)	$2.1\text{x}10^9$	$2.5\text{x}10^{10}$
Enterococci	$9.1\text{x}10^7$	$4.1\text{x}10^7$	$2.0\text{x}10^8$	$2.7\text{x}10^9$**(-)	$8.8\text{x}10^8$	$8.3\text{x}10^9$

[a] In each case significant GM elevations ($p < 0.001$) were recorded at high flow.
[b] At base flow there are no significant differences in GM export coefficients between summer and winter at base flow.
[c] Significant differences in GM export coefficients between summer and winter at high flow are indicated as follows: ** $p < 0.001$, * $p < 0.05$, with (+) identifying the higher value and (-) the lower.

Daily inputs of FIOs to land from livestock sources over winter, when averaged over the full winter period (i.e. with increased inputs from a combination of grazing and slurry/manure application in the spring months compensating for low inputs in the earlier parts of the winter), are likely to be of similar magnitude to those in the summer. Also, mean daily fluxes from sewerage-related sources over winter are likely to be similar to those in the summer, since total inputs of FIOs to the sewerage system are unlikely to differ very much between winter and summer, and the greater flow volumes (due to rainfall) and frequency of ID flows will tend to be compensated by lower FIO concentrations (due to dilution) in the sewage flow. In order to gain some insight into the likely magnitude of winter (and hence, annual) FC and EN fluxes it has simply been assumed, therefore, that the average daily fluxes over the winter and summer periods are the same. Clearly, this assumption will need to be reviewed in due course as additional monitoring data for the winter period become available.

2.8 Source apportionment of FC and EN fluxes from 'other catchment' sources post-improvement

Knowledge of the contribution of different FIO sources (especially sewage *vs* agriculture) to the pollution loadings of rivers/streams is clearly critical to the development of future investment strategies for the remediation of catchment-derived FIOs. Ideally, such source apportionment would be derived using process-based catchment models (e.g. SIMCAT, SWAT and HSFP), but their application to FIOs is prevented by the absence of empirical data with which to parameterise and evaluate these models (Crowther *et al*., 2011). In an attempt to address this issue, Kay *et al*. (2010) explored the use of regression models such as those reported here (Table 8) as a screening tool to estimate the proportions of FC and EN derived from sewage- and livestock-related sources – though it must be emphasised that these models do not provide a rigorous basis for source apportionment, and the results must be regarded as highly provisional. The approach adopted was to run each regression models twice, first using the existing urban land use and/or human population within a catchment, and then with a zero value entered for the urban/human component (i.e. to estimate the residual agricultural component). Subsequent evaluation by CREH has suggested that this procedure will tend to overestimate the urban (sewage-related) component because the contribution made by the constant in the regression equation is effectively all being apportioned to the urban component. To address this problem, a different approach has been used in the present study.

Here, the sewage-related component has been assumed to be represented by the 'residences' term in the regression equation, which is entered first in each of the models (Table 8), and the agriculture-related component by the sum of the various livestock and BFI terms. It should be noted that BFI has been included in this procedure, since it is a key factor affecting the survival and transport of FIOs derived from diffuse livestock inputs to land through direct voiding of faeces, manure applications, etc. On the other hand, the predictor variable 'area' which is entered at step 5 in the high-flow EN model has not been included, since catchment size is a factor affecting the opportunity for die-off along watercourses and therefore equally affects FIOS derived from both sewage- and livestock-related sources. Unfortunately, the base-flow model for EN, which is much weaker than the other models, could not be used in this way since none of the livestock variables is entered as a predictor variable.

2.9 Source apportionment of FC and EN fluxes from 'other catchment' sources post-improvement

It should be noted that the water companies responsible for the sewerage infrastructure in each of the catchments were each been invited by Defra to comment on these assumptions, the overall methodology and resulting sanitary profiles, and have not raised any concerns.

3 Overview of sanitary profile data

3.1 Catchment maps

Three sets of maps for each shellfish water catchment are presented, showing:

§ catchment boundaries and the key STWs at which improvements have been made
§ land use, and
§ locations of the key STWs and IDs at which improvements have been made.

3.2 Details of significant improvements to STWs within the shellfish water catchments

UV disinfection has been installed at all the STWs included in the present study. Table 11 presents details of treatment pre-improvement, the date of UV installation, population equivalent (PE) data for human effluent sources (i.e. excluding trade/industrial effluents) both pre- and post-improvement. It should be noted that no data on flows or FIO concentrations were obtained for the pre-improvement period.

3.3 *Details of significant improvements to IDs within the shellfish water catchments*

The IDs to which significant improvements have been made are listed in Table 12, with details of the nature and date of improvement.

Table 11: Details of improvements to key STWs within the shellfish water catchments.

Shellfish water	STW	E-coord	N-coord	Treatment pre-improvement	PE pre-imp[a]	Year UV installed	PE post-imp[a]
Chichester Channel	Bosham	480800	102380	Percolating filter	3568	2008	3860
	Chichester	483910	103760	PF(90%)/AS(10%)	29196	2008	29196
Poole Harbour West	Wareham	393640	88630	Percolating filter	9411	2003	8673
	Lytchett Minster	396820	92280	Oxidation ditch	7126	2003	7029
Yealm	Brixton	255400	51400	Unspecified secondary	1439	2004	1439
Fal/Ruan	Ladock	187090	47040	Unspecified secondary	3858	2002	3858
	Truro (Newham)	183410	43290	Unspecified: Secondary assumed	24917	2003	28200
Taw/Torridge	Ashford (Barnstaple)	253200	134400	Activated sludge	37620	1997	37620
	Cornborough[b]	240700	128170	Not applicable	n/a	2002	38121
	Yelland[b]	247550	132200	Primary	11500	2002	n/a
	Bideford[b]	245660	127370	Unspecified: Primary assumed	17425	2002	n/a
	Westleigh[b]	246880	128940	Unspecified: Primary assumed	4598	2002	n/a
	Northam[b]			Unspecified: Primary assumed	4598	2002	n/a
Ribble	Hesketh Bank	345430	423940	Activated sludge	5054	1999	5279
	Wigan	348170	412020	Percolating filter	318047	2003	336814
	Skelmersdale	348170	412020	Percolating filter	71818	2004	65796
	Preston	345540	427870	Percolating filter	258290	1999/2005	236855
	Southport	337080	420820	Activated sludge	89126	2001	91914

[a] Where the PE values reported pre- and post-improvement are the same, only one value has been received and this has been applied pre- and post-improvement. These figures will be revised as further information is received.

[b] Cornborough STW is a new plant (with UV disinfection) which discharges treated effluent to the sea. Discharges from Yelland, Bideford, Westleigh and Northam STWs were transferred to Cornborough in 2002.

[c] No data received for Westleigh and Northam STWs. Here it has been assumed that the sum of the PEs for Yelland, Bideford, Westleigh and Northam equate to the PE for Cornborough and that the residual PEs are equally divided between Westleigh and Northam.

Table 12: Details of improvements to intermittent discharges (IDs) within the shellfish water catchments.

Shellfish water	Intermittent discharge	Nature of improvement	Date completed
Poole Harbour West	Wareham CSO	CSO storage increased to meet SFW WQ standard. 6mm screens, overflow monitoring and EO standby systems (permanent standby generator) installed	31/03/2003
	Upton Moorlands Way CSO	Increase in pass forward flow and increased CSO storage. 6mm screens, overflow monitoring and EO standby systems	31/03/2003
	Lytchett Minster Settled SO	CSO storage increased. 6mm screens, overflow monitoring and EO standby systems	31/03/2003
Yealm	Courtwood Road PS	Overflow monitoring. Additional storage to meet EO standby systems	24/06/1905
	Elburton PS CSO/EO	6mm screens and overflow monitoring. Additional storage added to meet EO standby systems	28/06/1905
Fal/Ruan	Malpas outfall	Transferred to Truro (Newham) STW for secondary treatment and UV disinfection	31/03/2003
	Boatyard crude	Transferred to Truro (Newham) STW for secondary treatment and UV disinfection	31/03/2003
	Victoria Lodge crude	Transferred to Truro (Newham) STW for secondary treatment and UV disinfection	31/03/2003
	Campfield Hill CSO	CSO storage to meet SW quality standard. 6mm screens. Overflow monitoring	20/09/2002
	Newham PS CSO	Increased pass forward flow and additional storage downstream STW. 6mm screening. Overflow monitoring	18/07/2006
	Pendeen Road CSO	Overflow sealed	31/03/2006
Taw/Torridge	Fremington Bridge North CSO	Sealed	31/03/2005
	Fremington Bridge South CSO	Sealed	31/03/2005
	Fremington Pill CSO	CSO storage increased. 6mm screens and overflow monitoring installed together with EO standby systems (includes inhibit of upstream PS)	31/03/2003
	Muddlebridge CSO	CSO storage increased and overflow monitoring	31/03/2005
	Bridgeland Street CSO	Sealed	31/12/2003
	Rock Park CSO	Storage increased. 6mm screens and overflow monitoring	31/03/2003
	Abbotsham Road CSO	Sealed	31/12/2003
	Yelland CSO	Storage increased. 6mm screens, overflow monitoring and EO standby systems	31/12/2003
	Pottington CSO	Storage increased. 6mm screens, overflow monitoring and EO standby system	01/01/2006
	Pottington CSO	CSO storage to meet SFW standard. 6mm screens and overflow monitoring installed together with	27/06/1905

		Eo standby systems	
	Appledore CSO	Storage increased. 6mm screens, overflow monitoring and EO standby systems	31/12/2003
	Bideford FSIPS	Storage increased. 6mm screens, overflow monitoring and EO standby systems	31/03/2005
Conwy	Llanrwst STW storm overflow	Additional storm storage provided and 6mm screens on storm flows	31/03/2003
Ribble	Preston STW storm tank	Storage increased	18/03/2005
	Southport STW storm tank	Storage increased	01/05/2001
	Wigan STW storm tank	Storage increased	01/05/2001
	Cattle Market, Preston CSO (PRE0065 also known as PRE0116)	Storage increased	13/01/2005
	56 Ramsay Ave, Preston (PRE0069 also known as PRE0071)	Storage increased	23/03/2005
	Haslam Park North & South, Preston CSO (PRE0090)	Storage increased	23/03/2005
	Haslam Park North & South, Preston CSO (PRE0100 also known as PRE0115)	Storage increased	23/03/2005
	Factory Lane, Walton-le-Dale CSO (SRI0023)	Storage increased and screen	23/03/2005
	Field West of Gasworks, Walton-le-Dale CSO (SRI0030)	Storage increased and screen	29/03/2005
	Weld Road, Southport CSO (SEF0064)	Storage increased and screen	26/03/2003

3.4 'Catchment' versus 'modelled' catchment

It should be noted that in presenting the remaining data a distinction is made between the shellfish water 'catchment', which comprises the whole of the land area that contributes runoff directly to the shellfish water, and those parts of the catchment (termed 'modelled catchment') that are not located upstream of lakes/reservoirs – i.e. the parts that are used in modelling FC and EN concentrations (Table 13). The catchments range in area from 91.44–2114.81 km^2 (Yealm–Ribble). Only two (Yealm and Conwy) have a modelled:total catchment area ratio of <0.900; i.e. the majority of catchments include relatively small proportions of land from which FIOs in runoff are affected by die-off and sedimentation in lakes/reservoirs.

Table 13: Area of shellfish water 'catchments' and 'modelled catchments' (i.e. land which is not upstream of lakes/reservoirs).

Shellfish water	Total catchment area (km^2)	Modelled catchment area (km^2)	Ratio of modelled:total catchment area
Chichester Channel	155.25	151.98	0.979
Poole Harbour West	705.98	682.02	0.966
Yealm	91.44	63.04	0.689
Fal/Ruan	294.94	280.12	0.950
Taw/Torridge	2094.06	2010.10	0.960
Conwy	603.62	525.12	0.870
Ribble	2114.81	1938.77	0.917

3.5 Base flow index (BFI) and land cover of the modelled catchments

The BFI broadly reflects the proportion of catchment runoff that is derived from base flow. Higher values are associated with well-drained soils and substrates (e.g. areas of chalk downland, Tertiary sandstones, etc.) where there is a substantial groundwater component, whereas lower values are associated with less-permeable catchments in which there more surface runoff and a correspondingly greater high-flow component. The modelled catchments display marked variability in mean BFI (Table 14), with values ranging from 0.407 (Ribble) to 0.858 (Chichester Channel).

In general, the survival, mobilisation and transport of FIOs within catchments is favoured by surface runoff and a high connectivity between FIO sources and the stream network – both of which are greater in less-permeable catchments. In contrast, slow soil seepage and groundwater flow will filter out FIOs and provide greater opportunities for die-off/predation, thereby reducing FIO fluxes. The importance of drainage characteristics is reflected in the prominence BFI (with a –ve *b* coefficient) in each of the regression models used in the present study (Table 10).

Table 14: Base flow index (BFI) and land cover[a] of the modelled catchments.

Shellfish water	Mean BFI	Land cover (%): Urban	Improved grassland	Rough grazing	Arable	Woodland	Miscellaneous/ unclassified
Chichester Channel	0.858	6.41	18.17	7.32	42.04	20.82	5.24
Poole Harbour							
West	0.730	4.07	30.64	8.72	42.56	12.32	1.69
Yealm	0.598	8.97	37.97	11.90	24.47	14.17	2.53
Fal/Ruan	0.574	5.43	34.36	8.47	32.75	14.51	4.48
Taw/Torridge	0.537	3.47	50.74	7.73	24.97	12.43	0.66
Conwy	0.431	2.08	19.05	57.20	1.87	18.31	1.48
Ribble	0.407	15.06	32.37	29.21	12.58	7.98	2.80

[a] The land cover data are derived from the Centre for Ecology and Hydrology (CEH) Land Cover Map (LCM) 2000, with the various classes amalgamated.

Of the various land cover classes, urban and improved grassland are critical are surrogates for the two key FIO sources: humans and livestock. The areas of occupied by these varies greatly, with urban ranging from 2.08 (Conwy) to 15.06% (Ribble), and improved grassland from 18.17 (Chichester Channel) to 50.74% (Taw/Torridge). It should be noted that human residence and stocking density data are actually entered in the regression models, rather than either of these two land cover variables. Indeed, the only land cover variable included in the models is rough grazing, in each case with a negative *b* coefficient. Rough grazing varies from 7.32 (Chichester Channel) to 57.20% (Conwy).

3.6 Residences data (for 2005) for modelled catchments and adjustments for residences served by key STWs pre- and post-improvements

Residential properties data for 2005 from the National Property Database are presented in Table 15, expressed both as the number and density of residences within the modelled catchments. As would be anticipated, the densities closely match the proportions of urban land, with values ranging from 28.87 km^{-2} (Conwy) to 253.00 km^{-2} (Ribble). Data are also presented on the number of residences that are served by the STWs at which significant improvements have been made, based on human PE data for the STWs and an assumed 2.36 people/residence (2001 Census for England and Wales) for the pre- and post-improvement periods.

Table 15: Residences data (for 2005) for modelled catchments and adjustments for residences served by key STWs pre- and post- improvement.

Shellfish water	Residences (*n*)	Residences (km^{-2})	PRE-IMPROVEMENT: Residences[a] served by key STWs (*n*)	PRE-IMPROVEMENT: Residences not served by key STWs (km^{-2})[b]	POST-IMPROVEMENT: Residences[a] served by key STWs (*n*)	POST-IMPROVEMENT: Residences not served by key STWs (km^{-2})[b]
Chichester Channel	18120[c]	119.23	13883	27.88	14007	27.06
Poole Harbour West	30467	44.67	7007	34.40	6653	34.92
Yealm	4714	74.78	610	65.11	610	65.11
Fal/Ruan	18491	66.01	12193	22.48	13584	17.52
Taw/Torridge	61701	30.70	32094	14.73	32094	14.73
Conwy[d]	15161	28.87				
Ribble	490510	253.00	314549	90.76	312143	92.00

[a] Derived from human population equivalent data for STWs, assuming 2.36 people per residence.
[b] These data are used in applying regression models to estimate FIO concentrations pre and post improvement.
[c] Includes 2500 from Chichester outside topographic catchment and excludes 148 for which sewage goes outside catchment.
[d] Excludes an estimated 4427 (Conwy and Llandudno Junction) for which sewage goes outside catchment.

These data are then used to calculate the densities of residences not served by these STWs pre- and post-improvement – which are used in the application of the FIO models to the modelled catchments. In the case of the Ribble, for example, a high proportion (312,143 of 490,510) of residences in the modelled catchment are served by the five key STWs at which UV disinfection has been installed, leaving an average density of residences of 92 km^{-2} that are not served by these.

3.7 Stocking density data for the modelled catchments pre- and post-improvement

The stocking density data are presented in Table 16. These reveal marked contrasts between the catchments.

For example, in the post-improvement period, densities of dairy cattle range from 4.21–50.28 km^{-2} (Conwy–Fal/Ruan) and sheep from 35.28–530.47 km^{-2} (Chichester Channel–Conwy). Some of the differences recorded pre- and post-improvement are somewhat greater than might have been anticipated and are difficult explain, but may to some extent reflect inconsistencies in data collection in different years (Chris Burgess, EA, pers. comm.). In the case of the Conwy catchment, only EDINA data (at parish level) were available, rather than Agricultural Census data. Any inconsistencies arising from this are likely to be small (Chris Burgess, EA, pers. comm.).

Table 16: Stocking density data (no km^{-2}) pre- and post-improvement for the modelled catchments.

Shellfish water	Dairy	Other cattle	Total cattle	Sheep	Pigs
Pre-improvement					
Chichester Channel	7.66	5.19	12.85	31.89	24.66
Poole Harbour West	29.14	26.92	56.06	72.13	61.18
Yealm	8.42	49.59	58.01	174.80	1.06
Fal/Ruan	41.66	61.03	102.69	100.31	14.12
Taw/Torridge	41.33	61.66	102.99	385.80	25.89
Conwy	n/a	n/a	n/a	n/a	n/a
Ribble	32.91	35.02	67.93	267.94	28.23
Post-improvement					
Chichester Channel	7.31	5.45	12.76	35.28	24.64
Poole Harbour West	30.68	28.80	59.48	74.82	62.58
Yealm	5.51	40.97	46.48	117.37	0.69
Fal/Ruan	50.28	45.96	96.24	65.87	39.96
Taw/Torridge	43.19	55.51	98.69	270.01	8.46
Conwy[a]	4.21	24.59	28.80	530.47	0.00
Ribble	29.38	24.70	54.08	215.83	11.79

[a] In the case of Conwy, EDINA data (based on parish level statistics) have been used.

3.8 Long-term mean flow data for the shellfish water catchments during the 'summer' (15 May–30 September) periods

Mean base, high and total flow data, derived in most cases from records for the period 2005-10, are presented in Table 17. These reveal marked variability across the seven catchments, primarily as a result of geographical variations in rainfall and differences in catchment hydrology.

Total summer flows, for example, range from 62 m^3 km^{-2} day^{-1} in the Chichester Channel catchment (a relatively dry area with a high BFI) to 1787 m^3 km^{-2} day^{-1} in the Conwy catchment. These data are used as a basis for calculating FIO fluxes from other catchment sources (i.e. other than those from the key STWs and IDs associated with these).

Table 17: Long-term mean daily flow data for the shellfish water catchments during the summer bathing season (15 May–30 September) and winter (1 October–14 May) periods.

Shellfish water	Summer: Years	Total flow (m^3 km^{-2} day^{-1})	Proportion base flow	Proportion high flow	Winter: Years	Total flow (m^3 km^{-2} day^{-1})	Proportion base flow	Proportion high flow
Chichester Channel	2008	62	0.911	0.089	2008	204	0.915	0.085
Poole Harbour West	2005-10	749	0.688	0.312	2005-10	1590	0.705	0.295
Yealm	2005-8	1379	0.450	0.550	2005-8	2799	0.449	0.551
Fal/Ruan	2005-10	748	0.407	0.593	2005-10	1773	0.422	0.578
Taw/Torridge	2005-10	831	0.379	0.621	2005-9	2124	0.368	0.632
Conwy	2005-10	2564	0.303	0.697	2005-10	5116	0.297	0.703
Ribble	2006-10	1330	0.308	0.692	2005-10	2512	0.292	0.708

[a] Rivers and gauging stations used (and percentage of total shellfish water catchment covered) – Chichester Channel (55%): R. Lavant at Graylingwell; Poole Harbour West (85%): R. Priddle at Baggs Mill and R. Frome at East Stoke; Yealm (62%): R. Yealm at Puslinch; Fal/Ruan (55%): R. Fal at Tregony and R. Kenwyn at Truro; Taw/Torridge (75%): Taw at Umberleigh, Torridge at Torrington amd Yeo at Collard Bridge; Conwy (56%): R. Conwy at Cym Lanerch; and Ribble (55%): R. Ribble at Salmesbury.

3.9 Predicted geometric mean Long-term mean flow data for the shellfish water catchments during the 'summer' (15 May–30 September) periods

Predicted GM FC and EN concentrations (derived using the regression models summarised in Table 8) in waters draining the shellfish water catchments during summer period for the pre- and post-improvement periods are presented in Table 18. These figures include adjustments for areas upstream of lakes and reservoirs, but exclude FIOs derived from the key STWs and their associated IDs – FIOs derived from these latter sources are treated separately.

Table 18: Predicted geometric mean FC and EN concentrations (cfu 100 ml-1) in waters draining the shellfish water catchments during summer period for the pre- and post-improvements periods, including adjustments for areas upstream of lakes and reservoirs, but excluding FIOs derived from the key STWs and their associated CSOs, STOs, etc.

Shellfish water	FC Base flow	High flow	EN Base flow	High flow
Pre-improvement				
Chichester Channel	7.9E+02	1.6E+03	1.2E+02	3.2E+02
Poole Harbour West	1.5E+03	4.6E+03	1.2E+02	5.9E+02
Yealm	1.5E+03	6.7E+03	2.4E+02	1.3E+03
Fal/Ruan	2.0E+03	8.1E+03	1.7E+02	9.6E+02
Taw/Torridge	1.8E+03	1.9E+04	1.1E+02	1.6E+03
Conwy				
Ribble	6.0E+03	5.4E+04	2.8E+02	4.3E+03
Post-improvement				
Chichester Channel	7.7E+02	1.6E+03	1.2E+02	3.2E+02
Poole Harbour West	1.6E+03	4.9E+03	1.2E+02	6.2E+02
Yealm	1.4E+03	5.1E+03	2.4E+02	9.7E+02
Fal/Ruan	2.0E+03	7.4E+03	1.5E+02	8.2E+02
Taw/Torridge	1.8E+03	1.3E+04	1.1E+02	8.6E+02
Conwy[a]	1.8E+03	2.9E+04	1.6E+02	2.8E+03
Ribble	5.7E+03	4.2E+04	2.8E+02	2.8E+03

The results reveal high-flow concentrations to be about an order of magnitude higher than those at base flow, and quite marked variability between the various catchments. For example, GM FC concentrations at high flow pre-improvement range from 1.6 x 10^3 (Chichester Channel) to 5.5 x 10^4 cfu 100 ml^{-1} (Ribble) – which largely reflects differences in BFI and residence and stocking densities between these two catchments. Differences in concentrations pre- and post-improvement are on the whole quite small, and are attributable to changes in stocking densities and in the PE of the key STWs.

3.10 Predicted fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources, except from key STWs and their associated IDs, pre- and post-improvement

The predicted summer fluxes, derived from the GM FC and EN concentrations reported in Table 18 and the long-term average flow data reported in Table 16, are presented in Table 19.

Table 19: Predicted fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources, except from key STWs and their associated IDs, pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	9.6E+12	2.0E+12	1.2E+13	1.5E+12	3.8E+11	1.9E+12
Poole Harbour West	7.7E+14	1.1E+15	1.8E+15	6.1E+13	1.4E+14	2.0E+14
Yealm	1.2E+14	6.4E+14	7.6E+14	1.9E+13	1.3E+14	1.5E+14
Fal/Ruan	2.5E+14	1.5E+15	1.7E+15	2.1E+13	1.7E+14	2.0E+14
Taw/Torridge	1.6E+15	2.8E+16	3.0E+16	9.8E+13	2.4E+15	2.5E+15
Conwy						
Ribble	7.3E+15	1.5E+17	1.5E+17	3.4E+14	1.2E+16	1.2E+16
Post-improvement						
Chichester Channel	9.4E+12	1.9E+12	1.1E+13	1.5E+12	3.8E+11	1.8E+12
Poole Harbour West	8.0E+14	1.1E+15	1.9E+15	6.1E+13	1.4E+14	2.0E+14
Yealm	1.1E+14	5.0E+14	6.1E+14	1.9E+13	9.4E+13	1.1E+14
Fal/Ruan	2.5E+14	1.3E+15	1.6E+15	1.9E+13	1.5E+14	1.7E+14
Taw/Torridge	1.7E+15	2.0E+16	2.2E+16	9.8E+13	1.3E+15	1.4E+15
Conwy	1.1E+15	4.4E+16	4.5E+16	1.0E+14	4.1E+15	4.2E+15
Ribble	6.9E+15	1.1E+17	1.2E+17	3.4E+14	7.6E+15	8.0E+15
Change (%)						
Chichester Channel	-2.18	-1.45	-2.06	-1.24	-0.76	-1.14
Poole Harbour West	3.32	5.35	4.50	0.64	4.71	3.45
Yealm	-4.47	-22.87	-20.02	0.00	-27.59	-24.06
Fal/Ruan	-0.09	-8.17	-6.98	-9.84	-15.03	-14.47
Taw/Torridge	2.98	-30.06	-28.27	0.00	-47.21	-45.40
Conwy						
Ribble	-4.69	-21.91	-21.09	0.59	-34.09	-33.11

These figures reveal very marked differences in fluxes from these sources, e.g. pre-improvement total FC fluxes range from 1.3 x 10^{13} cfu (Chichester Channel) to 1.6 x 10^{17} cfu (Ribble).

3.11 Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from key STWs, pre- and post-improvement

Fluxes pre- and post-improvement in the six catchments in which UV disinfection has been installed reveal a very marked reduction in FC and EN fluxes in treated effluent discharges (Table 20).

Table 20: Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from the final effluents of key STWs, pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	4.9E+15	2.4E+15	7.3E+15	4.6E+14	2.4E+14	7.0E+14
Poole Harbour West	1.3E+15	7.8E+14	2.1E+15	1.2E+14	1.2E+14	2.4E+14
Yealm	1.3E+14	7.1E+13	2.0E+14	1.1E+13	6.6E+12	1.7E+13
Fal/Ruan	1.3E+15	7.0E+14	2.0E+15	1.1E+14	6.6E+13	1.7E+14
Taw/Torridge	1.3E+17	2.3E+16	1.5E+17	1.6E+16	4.5E+15	2.1E+16
Conwy						
Ribble	4.7E+16	2.4E+16	7.2E+16	4.3E+15	2.3E+15	6.6E+15
Post-improvement						
Chichester Channel	1.1E+12	4.1E+11	1.5E+12	1.5E+12	5.6E+11	2.1E+12
Poole Harbour West	7.5E+11	2.7E+11	1.0E+12	3.9E+11	1.4E+11	5.3E+11
Yealm	3.5E+11	1.3E+11	4.7E+11	5.0E+10	1.8E+10	6.8E+10
Fal/Ruan	3.5E+12	1.3E+12	4.8E+12	5.5E+11	2.0E+11	7.6E+11
Taw/Torridge	5.8E+11	2.1E+11	8.0E+11	3.7E+11	1.3E+11	5.0E+11
Conwy						
Ribble	1.2E+14	4.5E+13	1.7E+14	2.1E+13	7.7E+12	2.9E+13
Change (%)						
Chichester Channel	-99.98	-99.98	-99.98	-99.67	-99.77	-99.70
Poole Harbour West	-99.94	-99.96	-99.95	-99.69	-99.88	-99.78
Yealm	-99.73	-99.82	-99.76	-99.54	-99.73	-99.61
Fal/Ruan	-99.72	-99.82	-99.76	-99.49	-99.69	-99.57
Taw/Torridge	-100.00	-100.00	-100.00	-100.00	-100.00	-100.00
Conwy						
Ribble	-99.74	-99.81	-99.76	-99.51	-99.67	-99.56

In all cases the reductions exceed 99% (i.e. a 100-fold reduction), with the majority of the reductions in FC exceeding 99.9% (i.e. 1000-fold reduction). Overall, the greatest reductions are recorded for the Taw/Torridge, which are the result of several previously primary-treated effluents being transferred to the new STW at Cornborough, which has UV disinfection.

3.12 Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from IDs associated with key STWs

It should be emphasised that these results are based on a very limited evidence base, and must therefore be interpreted with extreme caution. Estimates of FC and EN fluxes from the IDs associated with the key STWs pre- and post-improvement, assuming a flow equivalent to 0.0429 x

STW final effluent flow pre-improvement and a 90% reduction in flow post-improvement, are presented in Table 21.

Table 21: Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from IDs associated with key STWs, assuming a flow equivalent to 0.0429 x total STW final effluent flow pre-improvement and a 90% reduction in flow post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	0	1.9E+15	1.9E+15	0	3.4E+14	3.4E+14
Poole Harbour West	0	6.4E+14	6.4E+14	0	1.1E+14	1.1E+14
Yealm	0	6.3E+13	6.3E+13	0	1.1E+13	1.1E+13
Fal/Ruan	0	6.3E+14	6.3E+14	0	1.1E+14	1.1E+14
Taw/Torridge	0	4.4E+15	4.4E+15	0	7.7E+14	7.7E+14
Conwy						
Ribble	0	2.0E+16	2.0E+16	0	3.6E+15	3.6E+15
Post-improvement						
Chichester Channel	0	2.0E+15	2.0E+15	0	3.4E+14	3.4E+14
Poole Harbour West	0	6.0E+13	6.0E+13	0	1.1E+13	1.1E+13
Yealm	0	6.3E+12	6.3E+12	0	1.1E+12	1.1E+12
Fal/Ruan	0	7.0E+13	7.0E+13	0	1.2E+13	1.2E+13
Taw/Torridge	0	3.7E+14	3.7E+14	0	6.5E+13	6.5E+13
Conwy						
Ribble	0	2.0E+15	2.0E+15	0	3.5E+14	3.5E+14
Change (%)						
Chichester Channel	0.00	0.80	0.80	0.00	0.80	0.80
Poole Harbour West	0.00	-90.51	-90.51	0.00	-90.51	-90.51
Yealm	0.00	-90.00	-90.00	0.00	-90.00	-90.00
Fal/Ruan	0.00	-88.89	-88.89	0.00	-88.89	-88.89
Taw/Torridge	0.00	-91.51	-91.51	0.00	-91.51	-91.51
Conwy						
Ribble	0.00	-90.11	-90.11	0.00	-90.11	-90.11

Inevitably, in cases where there is no change in the PE of the STWs, the resulting reductions in flux are 90.00%. The effects of varying the flow ratio and reduction in flow post-improvement (as detailed in Section 2.5) are presented as best- and worst-case scenarios in Tables 22 and 23, respectively.

Table 22: Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from IDs associated with key STWs assuming a flow equivalent to 0.01 x total STW final effluent flow pre-improvement and a 99% reduction in flow post-improvement (i.e. BEST-CASE SCENARIO).

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	0	4.5E+14	4.5E+14	0	7.9E+13	7.9E+13
Poole Harbour West	0	1.5E+14	1.5E+14	0	2.6E+13	2.6E+13
Yealm	0	1.5E+13	1.5E+13	0	2.6E+12	2.6E+12
Fal/Ruan	0	1.5E+14	1.5E+14	0	2.6E+13	2.6E+13
Taw/Torridge	0	1.0E+15	1.0E+15	0	1.8E+14	1.8E+14
Conwy						
Ribble	0	4.7E+15	4.7E+15	0	8.3E+14	8.3E+14
Post-improvement						
Chichester Channel	0	4.6E+12	4.6E+12	0	8.0E+11	8.0E+11
Poole Harbour West	0	1.4E+12	1.4E+12	0	2.5E+11	2.5E+11
Yealm	0	1.5E+11	1.5E+11	0	2.6E+10	2.6E+10
Fal/Ruan	0	1.6E+12	1.6E+12	0	2.9E+11	2.9E+11
Taw/Torridge	0	8.7E+12	8.7E+12	0	1.5E+12	1.5E+12
Conwy						
Ribble	0	4.7E+13	4.7E+13	0	8.2E+12	8.2E+12
Change (%)						
Chichester Channel	0.00	-98.99	-98.99	0.00	-98.99	-98.99
Poole Harbour West	0.00	-99.05	-99.05	0.00	-99.05	-99.05
Yealm	0.00	-99.00	-99.00	0.00	-99.00	-99.00
Fal/Ruan	0.00	-98.89	-98.89	0.00	-98.89	-98.89
Taw/Torridge	0.00	-99.15	-99.15	0.00	-99.15	-99.15
Conwy						
Ribble	0.00	-99.01	-99.01	0.00	-99.01	-99.01

Table 23: Estimated fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from IDs associated with key STWs assuming a flow equivalent to 0.873 x total STW final effluent flow pre-improvement and a 50% reduction in flow post-improvement (i.e. WORST-CASE SCENARIO).

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	0	4.0E+16	4.0E+16	0	6.9E+15	6.9E+15
Poole Harbour West	0	1.3E+16	1.3E+16	0	2.3E+15	2.3E+15
Yealm	0	1.3E+15	1.3E+15	0	2.3E+14	2.3E+14
Fal/Ruan	0	1.3E+16	1.3E+16	0	2.3E+15	2.3E+15
Taw/Torridge	0	9.0E+16	9.0E+16	0	1.6E+16	1.6E+16
Conwy						
Ribble	0	4.1E+17	4.1E+17	0	7.2E+16	7.2E+16
Post-improvement						
Chichester Channel	0	2.0E+16	2.0E+16	0.0E+00	3.5E+15	3.5E+15
Poole Harbour West	0	6.1E+15	6.1E+15	0.0E+00	1.1E+15	1.1E+15
Yealm	0	6.5E+14	6.5E+14	0.0E+00	1.1E+14	1.1E+14
Fal/Ruan	0	7.2E+15	7.2E+15	0.0E+00	1.3E+15	1.3E+15
Taw/Torridge	0	3.8E+16	3.8E+16	0.0E+00	6.7E+15	6.7E+15
Conwy						
Ribble	0	2.0E+17	2.0E+17	0.0E+00	3.6E+16	3.6E+16
Change (%)						
Chichester Channel	0.00	-49.60	-49.60	0.00	-49.60	-49.60
Poole Harbour West	0.00	-52.53	-52.53	0.00	-52.53	-52.53
Yealm	0.00	-50.00	-50.00	0.00	-50.00	-50.00
Fal/Ruan	0.00	-44.43	-44.43	0.00	-44.43	-44.43
Taw/Torridge	0.00	-57.53	-57.53	0.00	-57.53	-57.53
Conwy						
Ribble	0.00	-50.55	-50.55	0.00	-50.55	-50.55

3.13 Estimated total fluxes and sources pre-improvement during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources

The total fluxes of FC and EN reported in Table 24 represent the magnitude of the pollution load delivered to each of the shellfish waters over the summer period pre-improvement. In all the catchments, apart from the Yealm and the Ribble, more than 59% of the FC and EN fluxes are derived from the key STWs and their associated IDs.

Table 24: Estimated total fluxes and their sources during the summer bathing season pre-improvement of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources (as reported in Tables 18-20).

Shellfish water	FC Base flow	High flow	Total flow	EN Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	4.9E+15	4.3E+15	9.2E+15	4.7E+14	5.8E+14	1.0E+15
Poole Harbour West	2.1E+15	2.5E+15	4.5E+15	1.8E+14	3.7E+14	5.5E+14
Yealm	2.5E+14	7.8E+14	1.0E+15	3.0E+13	1.5E+14	1.8E+14
Fal/Ruan	1.5E+15	2.8E+15	4.3E+15	1.3E+14	3.5E+14	4.8E+14
Taw/Torridge	1.3E+17	5.6E+16	1.8E+17	1.6E+16	7.7E+15	2.4E+16
Conwy						
Ribble	5.5E+16	1.9E+17	2.5E+17	4.6E+15	1.7E+16	2.2E+16
Key STWs (%)						
Chichester Channel	99.81	54.82	78.88	99.68	41.35	67.34
Poole Harbour West	62.38	31.48	45.48	67.09	32.41	44.05
Yealm	52.00	9.08	19.40	36.28	4.50	9.86
Fal/Ruan	83.47	25.12	45.71	83.61	18.81	36.24
Taw/Torridge	98.72	41.06	81.12	99.39	58.47	86.12
Conwy						
Ribble	86.73	12.73	29.22	92.73	13.43	30.06
IDs associated with key STWs (%)						
Chichester Channel	0.00	45.13	21.00	0.00	58.58	32.48
Poole Harbour West	0.00	25.55	13.97	0.00	30.38	20.18
Yealm	0.00	8.17	6.21	0.00	7.54	6.27
Fal/Ruan	0.00	22.60	14.63	0.00	31.50	23.03
Taw/Torridge	0.00	7.91	2.41	0.00	9.93	3.22
Conwy						
Ribble	0.00	10.66	8.28	0.00	20.36	16.09
Other catchment sources (%)						
Chichester Channel	0.19	0.05	0.12	0.32	0.07	0.18
Poole Harbour West	37.62	42.96	40.54	32.91	37.21	35.76
Yealm	48.00	82.74	74.39	63.72	87.96	83.88
Fal/Ruan	16.53	52.28	39.66	16.39	49.69	40.73
Taw/Torridge	1.28	51.04	16.47	0.61	31.59	10.66
Conwy						
Ribble	13.27	76.62	62.50	7.27	66.22	53.86

3.14 Estimated total fluxes and sources post-improvement during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources

The total fluxes of FC and EN reported in Table 25 represent the magnitude of the present (i.e. post-improvement) pollution load delivered to each of the shellfish waters over the summer period.

Table 25: Estimated total fluxes and their sources during the summer bathing season post-improvement of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources (as reported in Tables 18-20).

Shellfish water	FC Base flow	FC High flow	FC Total flow	EN Base flow	EN High flow	EN Total flow
Post-improvement						
Chichester Channel	1.1E+13	2.0E+15	2.0E+15	3.0E+12	3.4E+14	3.5E+14
Poole Harbour West	8.0E+14	1.2E+15	2.0E+15	6.2E+13	1.5E+14	2.1E+14
Yealm	1.1E+14	5.0E+14	6.2E+14	1.9E+13	9.5E+13	1.1E+14
Fal/Ruan	2.6E+14	1.4E+15	1.7E+15	2.0E+13	1.6E+14	1.8E+14
Taw/Torridge	1.7E+15	2.0E+16	2.2E+16	9.8E+13	1.4E+15	1.5E+15
Conwy	1.1E+15	4.4E+16	4.5E+16	1.0E+14	4.1E+15	4.2E+15
Ribble	7.0E+15	1.2E+17	1.2E+17	3.6E+14	8.0E+15	8.3E+15
Key STWs (%)						
Chichester Channel	10.77	0.02	0.08	51.39	0.16	0.61
Poole Harbour West	0.09	0.02	0.05	0.63	0.09	0.25
Yealm	0.31	0.03	0.08	0.26	0.02	0.06
Fal/Ruan	1.38	0.09	0.29	2.82	0.13	0.42
Taw/Torridge	0.03	0.00	0.00	0.38	0.01	0.03
Conwy	0.00	0.00	0.00	0.00	0.00	0.00
Ribble	1.76	0.04	0.14	5.91	0.10	0.35
IDs associated with key STWs (%)						
Chichester Channel	0.00	99.88	99.35	0.00	99.73	98.86
Poole Harbour West	0.00	5.09	3.03	0.00	6.89	4.91
Yealm	0.00	1.26	1.03	0.00	1.17	0.97
Fal/Ruan	0.00	4.97	4.21	0.00	7.65	6.82
Taw/Torridge	0.00	1.85	1.71	0.00	4.81	4.49
Conwy	0.00	0.00	0.00	0.00	0.00	0.00
Ribble	0.00	1.73	1.63	0.00	4.41	4.22
Other catchment sources (%)						
Chichester Channel	89.23	0.10	0.57	48.61	0.11	0.53
Poole Harbour West	99.91	94.89	96.91	99.37	93.02	94.84
Yealm	99.69	98.71	98.89	99.74	98.81	98.97
Fal/Ruan	98.62	94.94	95.50	97.18	92.23	92.77
Taw/Torridge	99.97	98.15	98.29	99.62	95.18	95.48
Conwy	100.00	100.00	100.00	100.00	100.00	100.00
Ribble	98.24	98.23	98.23	94.09	95.50	95.44

Following installation of UV disinfection at the key STWs, contributions from these are now negligible (maximum, 0.61% for EN in Chichester Harbour catchment). Based on an assumed reduction of 90% in ID flow as a result of improvements in storage, etc., then the IDs are now also relatively minor contributors to the overall fluxes, and other catchment sources are overwhelmingly dominant, mostly 95% of the total fluxes. The notable exception is Chichester Channel, where no improvements have been made to the IDs.

3.15 *Estimated total fluxes pre- and post-improvement during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources*

Comparison of the total fluxes of FC and EN pre- and post-improvement reveals reductions over the six sites of 39.83–87.98% and 35.64–93.91%, respectively (Table 26).

Table 26: Estimated total fluxes during the summer bathing season of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources (as reported in Tables 18-20).

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	4.9E+15	4.3E+15	9.2E+15	4.7E+14	5.8E+14	1.0E+15
Poole Harbour West	2.1E+15	2.5E+15	4.5E+15	1.8E+14	3.7E+14	5.5E+14
Yealm	2.5E+14	7.8E+14	1.0E+15	3.0E+13	1.5E+14	1.8E+14
Fal/Ruan	1.5E+15	2.8E+15	4.3E+15	1.3E+14	3.5E+14	4.8E+14
Taw/Torridge	1.3E+17	5.6E+16	1.8E+17	1.6E+16	7.7E+15	2.4E+16
Conwy						
Ribble	5.5E+16	1.9E+17	2.5E+17	4.6E+15	1.7E+16	2.2E+16
Post-improvement						
Chichester Channel	1.1E+13	2.0E+15	2.0E+15	3.0E+12	3.4E+14	3.5E+14
Poole Harbour West	8.0E+14	1.2E+15	2.0E+15	6.2E+13	1.5E+14	2.1E+14
Yealm	1.1E+14	5.0E+14	6.2E+14	1.9E+13	9.5E+13	1.1E+14
Fal/Ruan	2.6E+14	1.4E+15	1.7E+15	2.0E+13	1.6E+14	1.8E+14
Taw/Torridge	1.7E+15	2.0E+16	2.2E+16	9.8E+13	1.4E+15	1.5E+15
Conwy	1.1E+15	4.4E+16	4.5E+16	1.0E+14	4.1E+15	4.2E+15
Ribble	7.0E+15	1.2E+17	1.2E+17	3.6E+14	8.0E+15	8.3E+15
Change (%)						
Chichester Channel	-99.79	-54.45	-78.70	-99.36	-40.79	-66.88
Poole Harbour West	-61.10	-52.30	-56.29	-66.68	-58.12	-60.99
Yealm	-54.00	-35.35	-39.83	-36.11	-35.54	-35.64
Fal/Ruan	-83.25	-49.44	-61.37	-84.80	-54.22	-62.44
Taw/Torridge	-98.68	-63.63	-87.98	-99.39	-82.48	-93.91
Conwy						
Ribble	-87.12	-39.09	-49.79	-92.23	-54.30	-62.25

The smallest percentage improvements are in the Yealm catchment and the largest in the Taw/Torridge (Fig. 23).

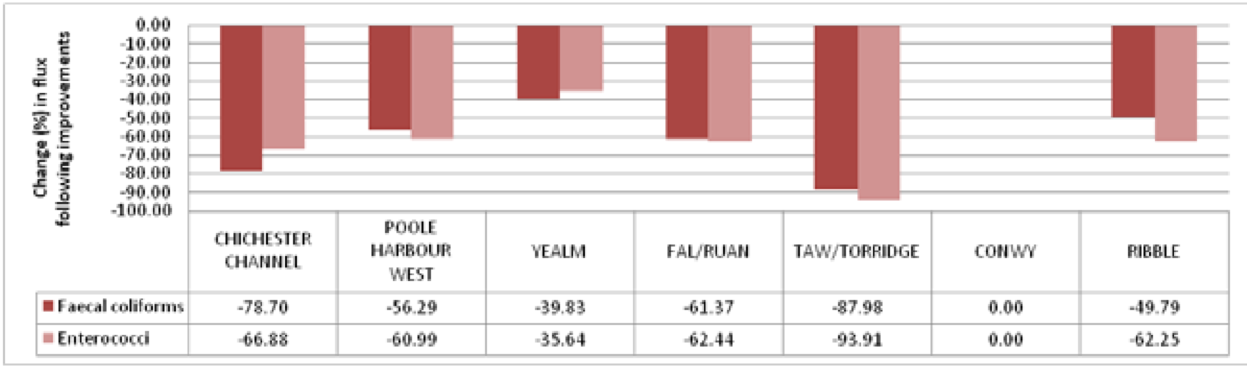

Fig. 23: Change (%) in total flux of faecal coliforms and enterococci during summer following improvements to STWs and IDs to the various shellfish waters (no significant improvements were made in the Conwy catchment).

3.16 Estimated total fluxes of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources pre- and post-improvement during winter

As explained in Section 2.7, in order to gain some insight into the likely magnitude of winter (and hence, annual) FC and EN fluxes it has been assumed that the average daily fluxes over the winter and summer periods are the same. The resulting winter and annual fluxes are presented in Tables 27 and 28.

Table 27: Estimated winter total fluxes of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	8.0E+15	7.0E+15	1.5E+16	7.6E+14	9.4E+14	1.7E+15
Poole Harbour West	3.3E+15	4.0E+15	7.4E+15	3.0E+14	5.9E+14	9.0E+14
Yealm	4.0E+14	1.3E+15	1.7E+15	4.9E+13	2.4E+14	2.9E+14
Fal/Ruan	2.5E+15	4.6E+15	7.0E+15	2.1E+14	5.7E+14	7.8E+14
Taw/Torridge	2.1E+17	9.0E+16	3.0E+17	2.6E+16	1.3E+16	3.9E+16
Conwy	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ribble	8.9E+16	3.1E+17	4.0E+17	7.5E+15	2.8E+16	3.6E+16
Post-improvement						
Chichester Channel	1.7E+13	3.2E+15	3.2E+15	4.9E+12	5.6E+14	5.6E+14
Poole Harbour West	1.3E+15	1.9E+15	3.2E+15	1.0E+14	2.5E+14	3.5E+14
Yealm	1.8E+14	8.2E+14	1.0E+15	3.1E+13	1.5E+14	1.9E+14
Fal/Ruan	4.2E+14	2.3E+15	2.7E+15	3.2E+13	2.6E+14	2.9E+14
Taw/Torridge	2.7E+15	3.3E+16	3.6E+16	1.6E+14	2.2E+15	2.4E+15
Conwy	1.9E+15	7.1E+16	7.3E+16	1.6E+14	6.7E+15	6.9E+15
Ribble	1.1E+16	1.9E+17	2.0E+17	5.9E+14	1.3E+16	1.4E+16

Table 28: Estimated annual total fluxes of faecal coliforms and enterococci (cfu) to the shellfish waters from all catchment sources pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Chichester Channel	1.3E+16	1.1E+16	2.4E+16	1.2E+15	1.5E+15	2.7E+15
Poole Harbour West	5.4E+15	6.5E+15	1.2E+16	4.9E+14	9.6E+14	1.4E+15
Yealm	6.5E+14	2.0E+15	2.7E+15	7.8E+13	3.9E+14	4.7E+14
Fal/Ruan	4.0E+15	7.4E+15	1.1E+16	3.4E+14	9.2E+14	1.3E+15
Taw/Torridge	3.3E+17	1.5E+17	4.8E+17	4.2E+16	2.0E+16	6.3E+16
Conwy	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ribble	1.4E+17	5.0E+17	6.4E+17	1.2E+16	4.6E+16	5.8E+16
Post-improvement						
Chichester Channel	2.8E+13	5.1E+15	5.2E+15	7.9E+12	9.0E+14	9.1E+14
Poole Harbour West	2.1E+15	3.1E+15	5.2E+15	1.6E+14	4.0E+14	5.6E+14
Yealm	3.0E+14	1.3E+15	1.6E+15	5.0E+13	2.5E+14	3.0E+14
Fal/Ruan	6.7E+14	3.7E+15	4.4E+15	5.2E+13	4.2E+14	4.7E+14
Taw/Torridge	4.4E+15	5.3E+16	5.8E+16	2.6E+14	3.6E+15	3.8E+15
Conwy	3.0E+15	1.1E+17	1.2E+17	2.7E+14	1.1E+16	1.1E+16
Ribble	1.8E+16	3.1E+17	3.2E+17	9.5E+14	2.1E+16	2.2E+16

3.17 Provisional estimates of percentage of fluxes of faecal coliforms and enterococci to the shellfish waters post-improvement from all catchment sources, except from key STWs and their associated IDs, that are derived from sewage- and agriculture-related sources

As noted in Section 2.8, the source apportionment estimates made in the present study (Table 29) must be regarded as highly provisional. These suggest that sewage- and agriculture-related sources both contribute significantly to present fluxes from all seven catchments. In none of the catchments does one source account for≥ 90% of the flux, In fact, only in the case of Chichester Channel does one source (sewerage-related) account for more than about 70% of the FC and EN fluxes, and this almost certainly reflects the lack of ID improvements in this catchment. In presenting data for the individual shellfish waters (Tables 30–36 and Figs 24–30), these source-apportionment estimates have been applied to the percentage of the post-improvement FIO fluxes derived from other catchment sources (Table 25) in order to estimate the proportions of FC and EN derived from sewage- and agriculture-related sources.

Table 29: Provisional estimates of percentage of fluxes of faecal coliforms and enterococci to the shellfish waters post-improvement from all catchment sources, except from key STWs and their associated IDs, that are derived from sewage- and agriculture-related sources.

Shellfish water	FC		EN	
	Base flow	High flow	Base flow[a]	High flow
Sewage-related sources				
Chichester Channel	85.4	79.0	-	69.1
Poole Harbour West	69.1	60.3	-	56.4
Yealm	75.1	64.3	-	63.1
Fal/Ruan	51.8	44.2	-	45.2
Taw/Torridge	50.7	36.9	-	38.1
Conwy	61.3	38.4	-	39.5
Ribble	60.5	48.7	-	50.3
Agriculture-related sources				
Chichester Channel	14.6	21.0	-	30.9
Poole Harbour West	30.9	39.7	-	43.6
Yealm	24.9	35.7	-	36.9
Fal/Ruan	48.2	55.8	-	54.8
Taw/Torridge	49.3	63.1	-	61.9
Conwy	38.7	61.6	-	60.5
Ribble	39.5	51.3	-	49.7

Fig. 24: Chichester Channel: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

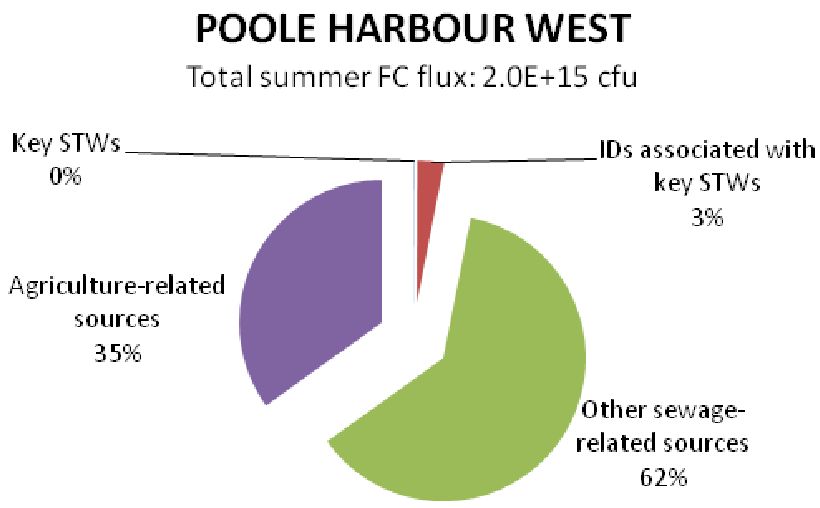

Fig. 25: Poole Harbour West: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

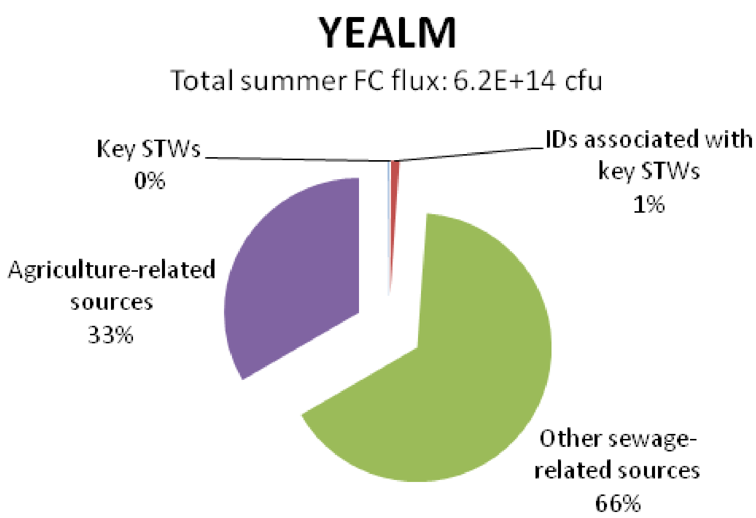

Fig. 26: Yealm: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

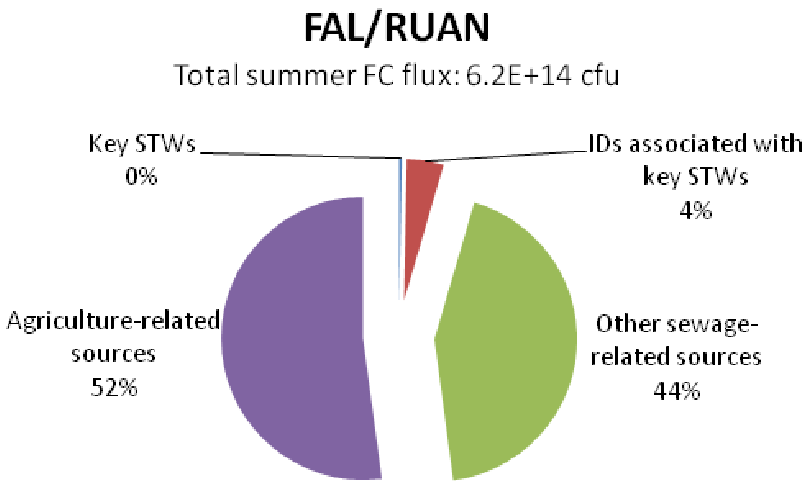

Fig. 27: Fal/Ruan: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

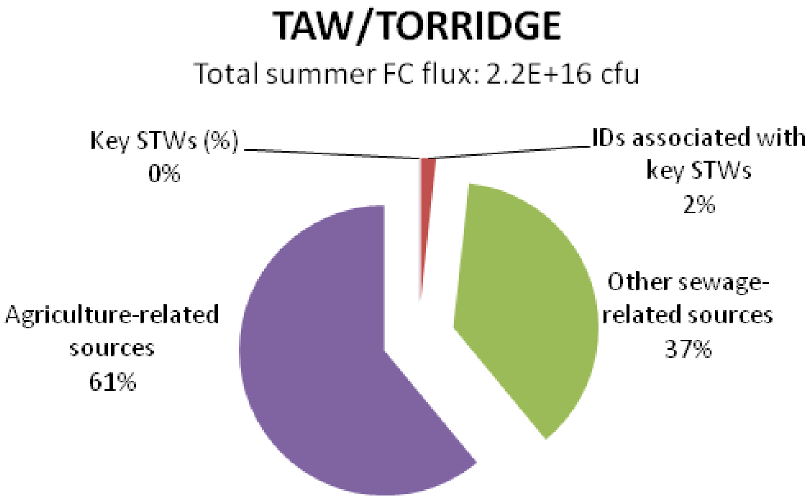

Fig. 28: Taw/Torridge: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

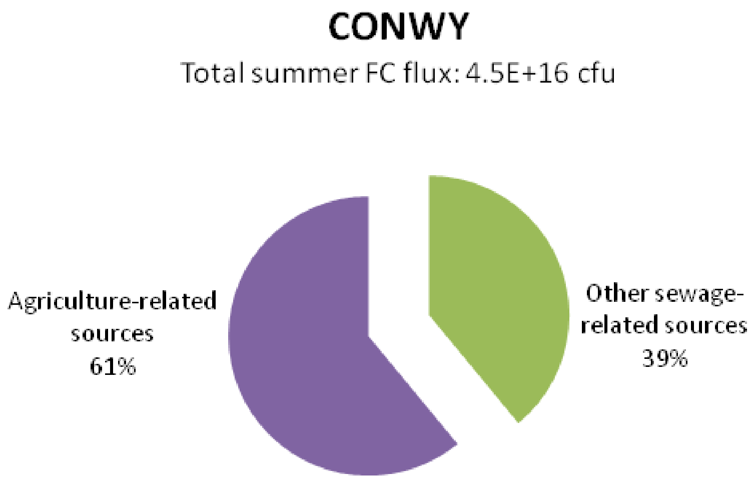

Fig. 29: Conwy: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

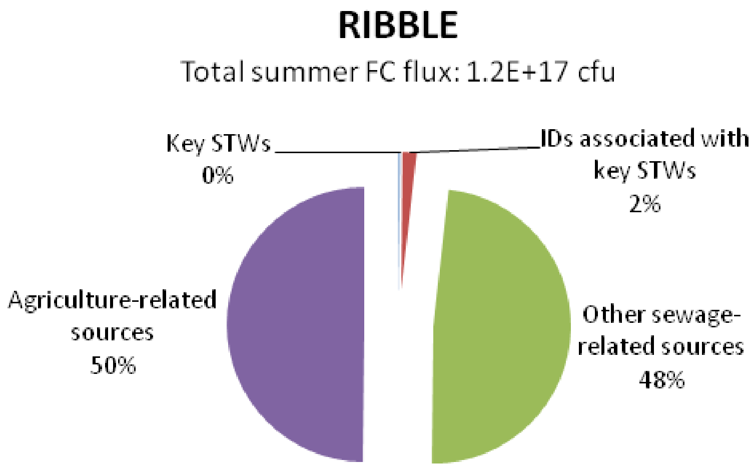

Fig. 30: Ribble: Estimated source apportionment of present total (i.e. base + high flow) faecal coliform flux to the shellfish water in summer.

Although these latter figures must be regarded as highly provisional, and do not include base-flow estimates for EN, it is hoped that they may help inform the prioritisation of future investment as proposed in the EA's Pollution Reduction Programme (PRP) for each of these shellfish waters.

4 Sanitary profiles of individual shellfish water catchments

4.1 Chichester Channel

4.1.1 Overview of designated shellfish water

Chichester Harbour is a macrotidal bar built estuary with an intertidal area of approximately 23.4 km^2. The harbour supports important populations of cockles (*Cerastoderma edule*, *C. glaucum*), clams (*Mya arenaria, Scrobicularia plana, Tapes decussatus*) and native oysters (*Ostrea edulis*).

Chichester Harbour (Chichester Channel) designated shellfish water (Plate 1) is one of three shellfish waters in the wider harbour and covers an area of approximately 5.3 km^2. It was first designated in 1999. This area of the harbour is predominantly muddy.

Plate 1: Chichester Channel - River Lavant mouth.

The harbour supports an important traditional oyster fishery. One or two oyster dredges with a fixed flat bar and a bag behind the bar are towed from the stern of vessels (typically < 10 m) during the winter season. The oyster fishery is closed from 1 May–31 September. No trend in GM FC concentrations in shellfish flesh was recorded over the period 1999–2008 (Table 1).

4.1.2 Catchment characterisation

The extent of the catchment is shown in Fig. 2. It covers an area of 155.25 km^2, with very little runoff to the shellfish water being affected by lakes/reservoirs (modelled:total catchment ratio, 0.979).

The northern half of catchment is dominated by Chalk and Clay-with-flints of the South Downs, with soils predominantly shallow well-drained calcareous silty soils over chalk (Andover 2 association; Soil Map of England and Wales (SMEW), Sheet 6 (Soil Survey of England and Wales (SSEW), 1983). The southern half is dominated by Tertiary sands and clays, a high proportion of which are overlain by aeolian silty drift. The resulting soils are typically deep silty soils, variably affected by groundwater (Park Gate association). Because of the extensive areas of well-drained soils on the Chalk a high proportion of the rainfall is absorbed by the soils and bedrock, and there is relatively little surface runoff – hence the very high BFI of 0.858 (Table 14), which is much higher than any of the other study catchments. This, combined with the relatively low rainfall, leads to very low volumes of runoff (62 and 204 m^3 km^{-2} day^{-1}, respectively, in summer and winter) and also very low proportions of high-flow runoff (0.089 and 0.085, respectively; Table 17).

Land use within the catchment is shown in Fig. 3. Urban land occupies 6.41% of the modelled catchment (Table 14) and the estimated density of residences is 119.23 km^{-2} (see footnote to Table 15 for details of how this latter figure has been derived).

The principal settlement is Chichester, which is located very close to the shellfish water. The agricultural land is predominantly arable (42.04%), with relatively small proportions of improved grassland (18.17%) and rough grazing (7.32%). Stocking levels are correspondingly low, with total cattle and sheep densities post-improvement of 12.6 and 35.28 km^{-2}, respectively. The catchment also includes quite a high proportion of woodland (20.28%), which is mostly broadleaf woodland.

Fig. 2: Chichester Channel: boundary of shellfish water catchment.

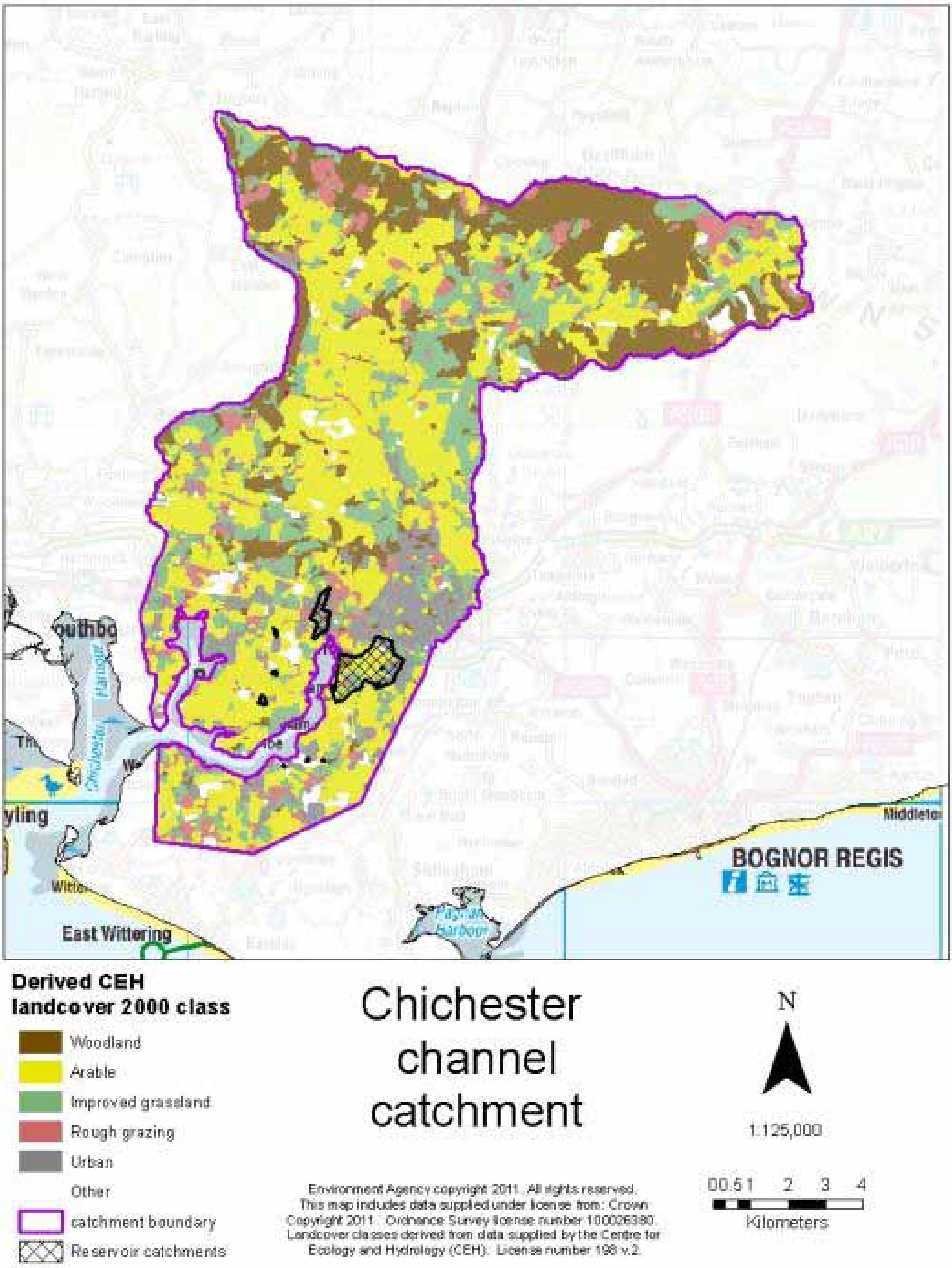

Fig. 3: Chichester Channel: land use within shellfish water catchment.

4.1.3 Sewerage sources and improvements to key STWs and IDs

The locations of the two key STWs are shown in Fig. 4: Bosham STW (post-improvement PE: 3860) and the much larger Chichester STW (PE: 29196) (Table 11).

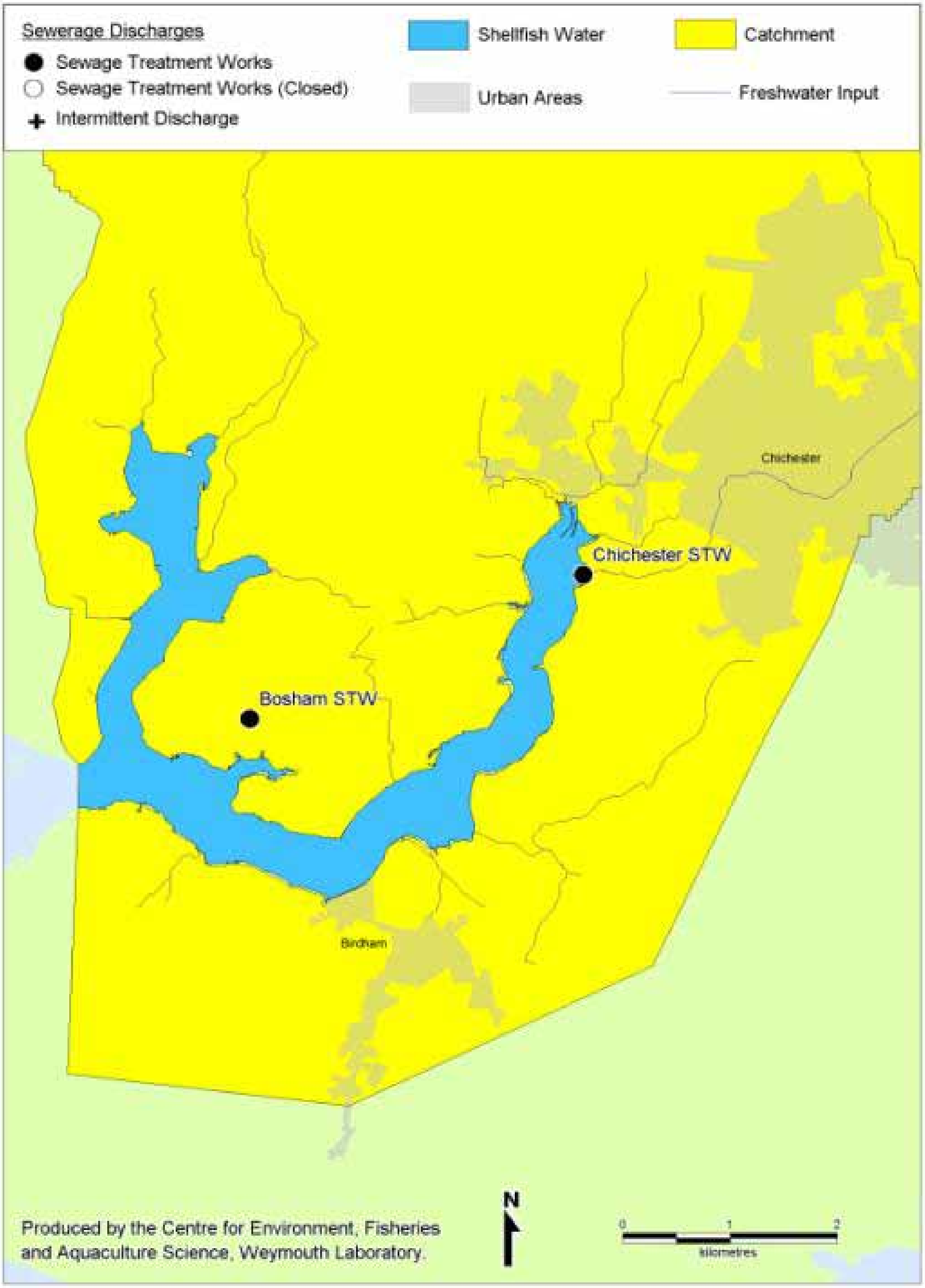

Fig. 4: Chichester Channel: locations of the key STWs/IDs at which improvements have been made.

UV disinfection was installed at both in 2008. No significant improvements have been made to IDs within the catchment. It is estimated that post-improvement there are an average of 27.06 residences km^{-2} in the modelled catchment that are not served by either of the two key STWs (Table 15), and these represent a further significant sewerage-related source.

4.1.4 Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement

The predicted GM FC and EN concentrations are lower than any of the other catchments (Table 18), e.g. high-flow concentrations post-improvement are 1.6×10^3 and 3.2×10^2 cfu 100 ml^{-1}, respectively. These figures reflect the relatively low density of residences; predominance of arable farming and woodland – which together occupy more than 60% of the catchment; and the well-drained soils with a very high BFI – i.e. most rainfall is absorbed by the soil, thereby allowing greater opportunities for any entrained FIOs to be filtered out by the soil matrix. These low concentrations, combined with the very low volumes of flow (from what is one of the smaller catchments), lead to very small fluxes of FC and EN over the summer period, e.g. total fluxes of FC and EN post-improvement are 1.1×10^{13} and 1.8×10^{12} cfu, respectively (Table 19).

4.1.5 Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement

The estimated fluxes reveal very marked reductions in FC and EN fluxes post-improvement under both base- and high-flow conditions (Table 20). The total fluxes of FC and EN change by -99.96 and -99.70%, respectively.

4.1.6 Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 1.9×10^{15} and 3.4×10^{14} cfu, respectively. In the Chichester Channel catchment there are no recorded improvements to IDs.

4.1.7 *Assessment of impact of improvements to STWs (no improvements to IDs)*

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Chichester Channel catchment and of the resulting changes is presented in Table 30.

Table 30: CHICHESTER CHANNEL: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Total flux	4.9E+15	4.3E+15	9.2E+15	4.7E+14	5.8E+14	1.0E+15
Key STWs (%)	99.81	54.82	78.88	99.68	41.35	67.34
IDs associated with key STWs (%)	0.00	45.13	21.00	0.00	58.58	32.48
Other catchment sources (%)	0.19	0.05	0.12	0.32	0.07	0.18
Post-improvement						
Total flux	1.1E+13	2.0E+15	2.0E+15	3.0E+12	3.4E+14	3.5E+14
Key STWs (%)	10.77	0.02	0.08	51.39	0.16	0.61
IDs associated with key STWs (%)	0.00	99.88	99.35	0.00	99.73	98.86
Other catchment sources (%)	89.23	0.10	0.57	48.61	0.11	0.53
Sewage-related sources (%)	76.22	0.08	0.48		0.08	
Agriculture-related sources (%)	13.01	0.02	0.09		0.03	
Post-improvement change						
Total flux	-4.9E+15	-2.3E+15	-7.3E+15	-4.6E+14	-2.4E+14	-7.0E+14
Total flux (%)	-99.79	-54.45	-78.70	-99.36	-40.79	-66.88
Key STWs (%)	-99.78	-54.81	-78.86	-99.35	-41.26	-67.14
IDs associated with key STWs (%)	0.00	0.36	0.17	0.00	0.47	0.26
Other catchment sources (%)	0.00	0.00	0.00	0.00	0.00	0.00
Best case ID scenario post-improvement						
Total flux	1.1E+13	6.9E+12	1.7E+13	3.0E+12	1.7E+12	4.7E+12
Flux from IDs associated with key STWs (%)	0.00	66.13	26.21	0.00	45.86	16.85
Worst case ID scenario						
Total flux	1.1E+13	2.0E+16	2.0E+16	3.0E+12	3.5E+15	3.5E+15
Flux from IDs associated with key STWs (%)	0.00	99.99	99.94	0.00	99.97	99.89

In the pre-improvement period, the key STWs and their associated IDs accounted for virtually the entire FC and EN fluxes under both base- and high- flow conditions, with ≤ 0.18% of the total fluxes being derived from other catchment sources. At base flow, the treated effluents from key STWs account for 99.81 and 99.68% of the FC and EN fluxes, whereas under high-flow conditions the IDs assume considerable significance, accounting for 45.13 and 58.58% of the fluxes, respectively.

Following STW improvement the total fluxes of FC and EN changed by -78.69 and -66.88%, respectively. While the STWs continue to contribute significantly to the FC (10.77%) and, especially

EN (51.39%) fluxes at base flow, fluxes at high flow and the total fluxes are almost entirely derived from IDs (≥ 98.86% of the total fluxes) on the basis of an assumed flow volume of 0.0429 x STW effluent flow. Under the worst-case ID flow volume scenario (i.e. 0.846 x STW effluent flow) the proportions of ID flow increase to ≥ 99.89%. These results suggest that the improvements to the STWs have resulted in modest reductions in FC and EN fluxes to the Chichester Channel, and that further reductions are most likely to be achieved by reducing fluxes from the larger IDs located in close proximity to the shellfish water.

4.1.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 30 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), indicate that the IDs associated with the key STWs, none of which have been improved, represent the major source (*c.* 99%) of FIOs within this catchment following the installation of UV disinfection at Bosham and Chichester (Fig. 24). Other catchment sources, from a combination of sewage- and agriculture-related sources, are estimated to account for less than 1% of the total FC and EN fluxes, though they account for 89.23% and 48.61%, respectively, of the base-flow fluxes. Of the base-flow FC flux, 76.22% is estimated to be derived from sewage-related sources other than those associated with the key STWs (no source-apportionment estimates could be made for EN, but these are likely to be of a similar magnitude to FC). These results strongly support the assessment of the latest PRP (November 2009, p. 9), which targets point sources of pollution (small continuous discharges from several small SWTs and IDs) for improvement and states that “Diffuse sources are not thought to be a significant source of pollution to the Shellfish Water”. In cases where flow and FIO monitoring data are available, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose.

4.2 Poole Harbour West

4.2.1 Overview of designated shellfish water

Poole is a microtidal bar-built estuary with an intertidal area of approximately 20.5 km^2. Poole Harbour West (total area, 6.5 km^2; Plate 2) was first designated in 1981 and is one of three designated shellfish waters in the wider harbour area. Poole Harbour supports an important shellfishery. A variety of shellfish species are either wild harvested or farmed in the wider harbour area, including mussels, Pacific oysters, native clams (*Tapes decussatus*) and manila clams (*T. philippinarum*) which are harvested from beds across intertidal and subtidal areas to the west of Brownsea Island. Beds of the common cockle (*Cerastoderma edule*) are sparsely distributed across intertidal areas of the harbour. Other species of bivalves occur in the upper reaches of the harbour, such as cockles (*Cerastoderma glaucum*), clams (*Mya arenaria, Scrobicularia plana*) and native oyster (*Ostrea edulis*).

Plate 2: Poole Harbour West - Russell Quay, Arne.

Pacific oysters, native oysters, clams and mussels have been classified in the harbour under Food Hygiene Regulations since 1992. Currently, only Manila clams, mussels and cockles are commercially harvested in Poole Harbour West shellfish water. The Manila clam fishery is open from late October–early January. Clams are harvested from the seabed at high tide by means of a pump scoop dredge towed behind a small boat. Seed mussels are laid on the beds and harvested on a year-round basis using a conveyor harvester. Cockles are harvested using a pump-dredge trailed behind a small boat or hand-raked in littoral sand flats from 1 May–31 January. No trend in GM FC concentrations in shellfish flesh was recorded over the period 1999–2008 (Table 1).

4.2.2 *Catchment characterisation*

The extent of the catchment is shown in Fig. 5. It covers an area of 705.98 km^2, with very little of the runoff to the shellfish water being affected by lakes/reservoirs (modelled:total catchment ratio, 0.966). The catchment is largely drained by the R. Frome and R. Piddle.

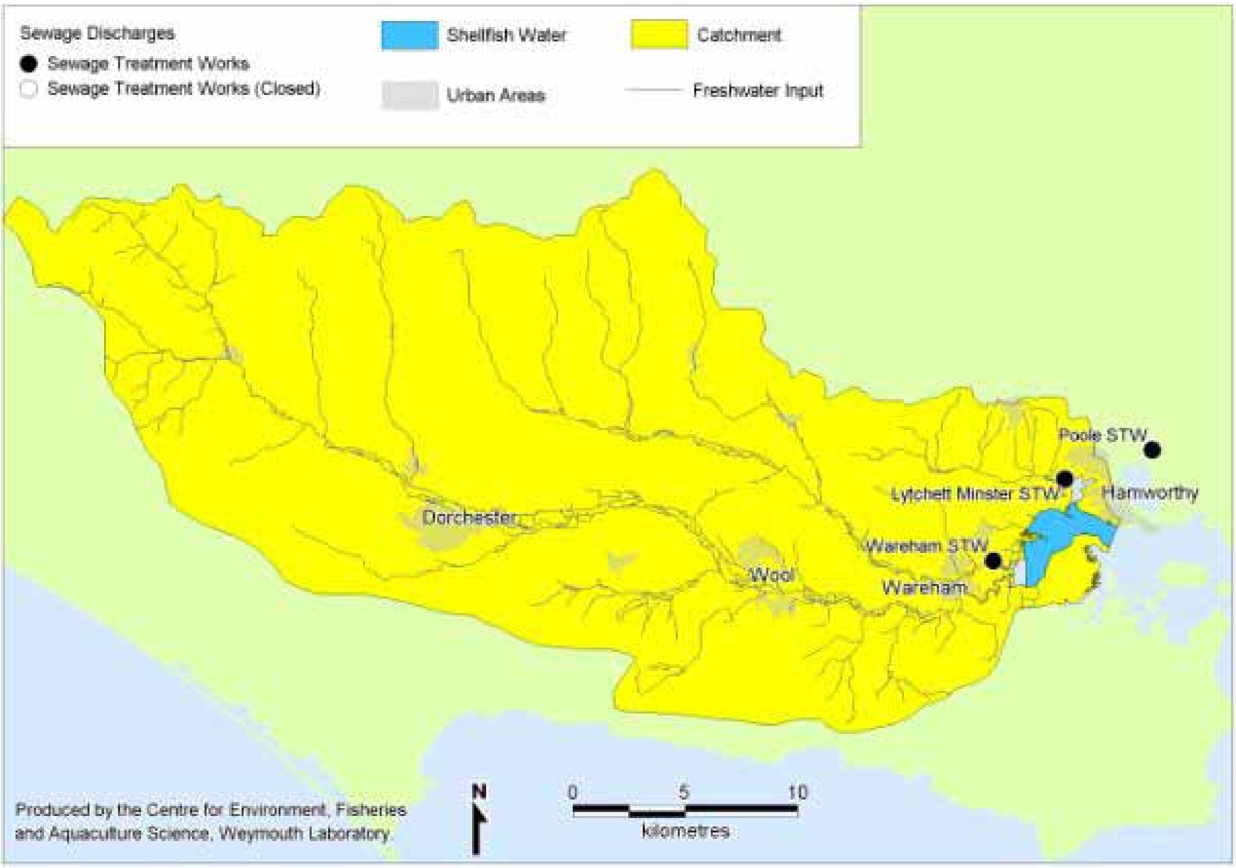

Fig. 5: Poole Harbour West: boundary of shellfish water catchment.

The geology, which is quite complex, includes quite extensive areas of Chalk, Clay-with-flints and Tertiary sands. While the soils on the Chalk are typically well-drained calcareous silty soils (Andover 1 and 2 associations), the soils on the Clay-with-flints (e.g. Batcombe association) have slowly permeable subsoils and those on the Tertiary sands (Sollom 2 association) are affected by groundwater (SMEW, Sheet 5, SSEW, 1983). Because of the high permeability of some of the soils and underlying substrates, the overall BFI (0.730) is relatively high. This, combined with a low annual rainfall, leads to quite low volumes of runoff: 749 and 1590 m^3 km^{-2} day^{-1} in summer and winter, respectively.

Land use within the catchment is shown in Fig. 6. Urban land occupies 4.07% of the modelled catchment (Table 14) and the estimated density of residences is 44.67 km^{-2}.

The principal settlements within the catchment are Wareham, which is located close to the shellfish water, and Dorchester, which lies upstream within the Frome valley. The agricultural land is predominantly arable (42.56%), but also includes quite a high proportion of improved grassland (30.64%). Moderate numbers of dairy and total cattle are present, with densities in the post-improvement period of 30.68 and 59.48 km^{-2} (Table 16), respectively. The catchment also includes quite a high density of pigs (62.58 km^{-2}).

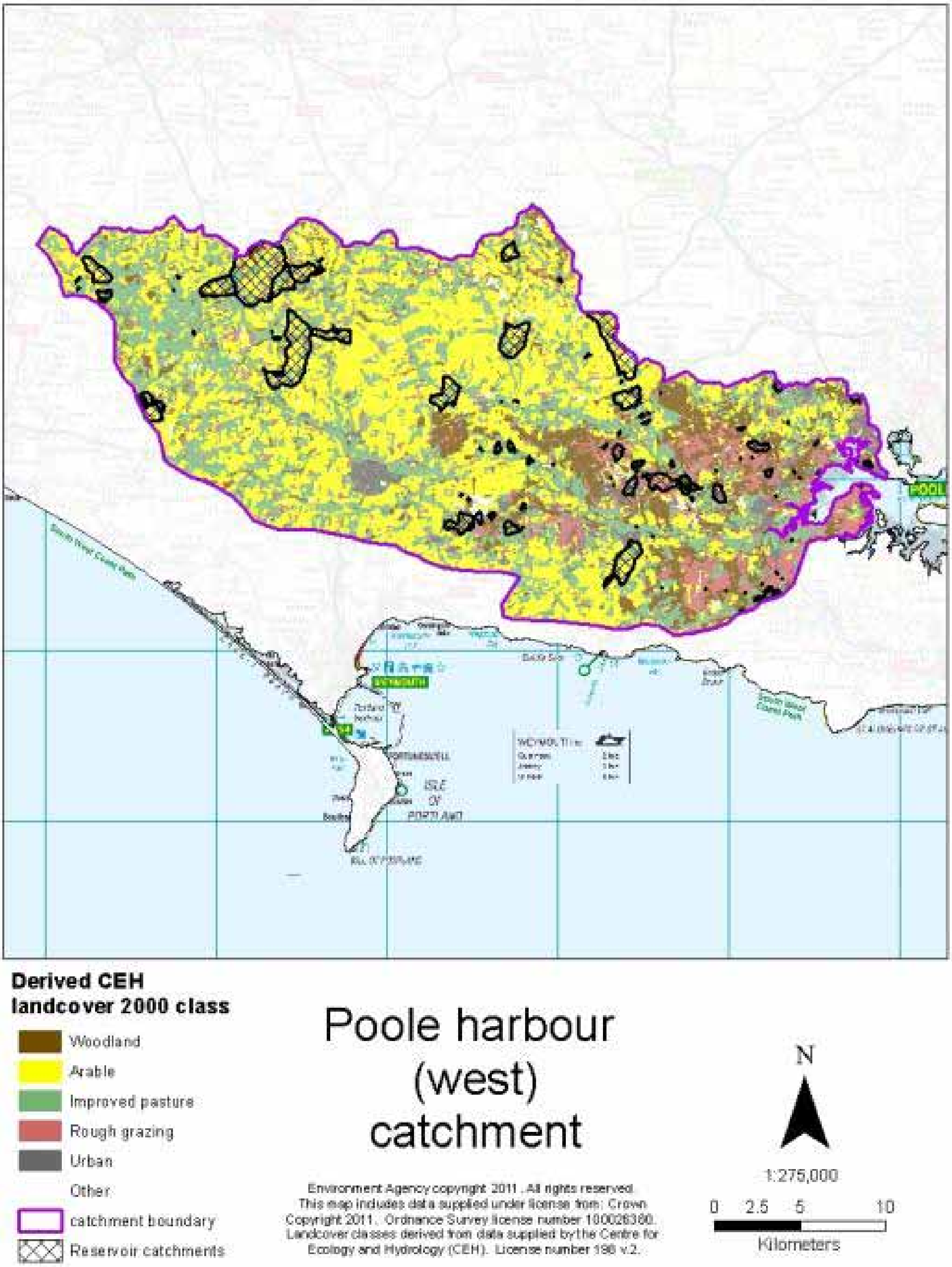

Fig. 6: Poole Harbour West: land use within shellfish water catchment.

4.2.3 *Sewerage sources and improvements to key STWs and IDs*

The locations of the key STWs and IDs that have been improved are shown in Fig. 7. There are two key STWs within the catchment (Table 11): Wareham STW (post-improvement PE: 8673) and Lytchett Minster STW (PE: 7029).

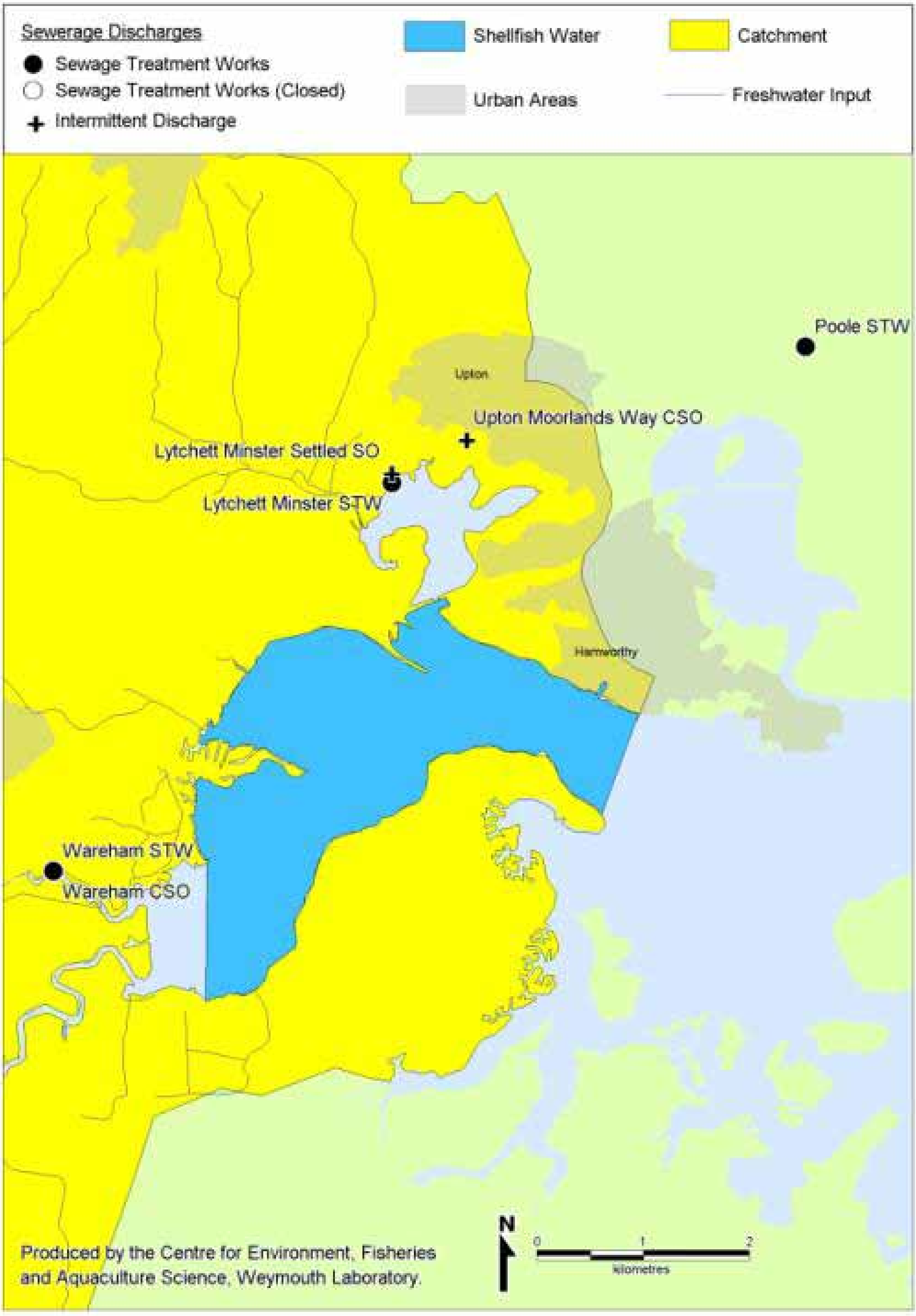

Fig. 7: Poole Harbour West: locations of the key STWs/IDs at which improvements have been made.

UV disinfection was installed at both in 2003. In addition, improvements were also completed to three IDs in 2003 (Table 12). It is estimated that post-improvement there are an average of 34.92 residences km^{-2} in the modelled catchment that are not served by either of the two key STWs (Table 15), and these represent a further significant sewerage-related source. It should be noted that Poole STW, which is located outside the topographic catchment studied, is a large works (post-improvement PE: 130,880) that discharges treated effluent into Poole Harbour at a distance of only *c.* 3 km from the seaward limit of the shellfish water (Fig. 7). UV disinfection was installed here in 2003. It is likely therefore that discharges from Poole STW and its associated IDs will contribute to the overall FIO loading of the Poole Harbour West shellfish water. Sanitary profiling of the catchment of the inlet to which Poole STW discharges, combined with hydrodynamic modelling of flows in the upper reaches of Poole Harbour, would be required to assess the impact of this geographical source area upon Poole Harbour West shellfish water.

4.2.4 Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement

The predicted GM FC and EN concentrations are quite low (Table 18), e.g. high-flow concentrations post-improvement are 4.9×10^3 and 6.2×10^2 cfu 100 ml^{-1}, respectively. These figures are a reflection of the moderate density of residences; predominance of arable farming; and the well-drained soils with a high BFI – i.e. most rainfall is absorbed by the soil, thereby allowing greater opportunities for any entrained FIOs to be filtered out by the soil matrix. The resulting total fluxes of FC and EN over the summer period post-improvement are: 1.9×10^{15} and 2.0×10^{14} cfu, respectively (Table 19).

4.2.5 Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement

The results reveal very marked reductions in FC and EN fluxes following improvement under both base- and high-flow conditions (Table 20). The total fluxes of FC and EN change by -99.95 and -99.78%, respectively.

4.2.6 *Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement*

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 6.4 x 10^{14} and 1.1 x 10^{14} cfu, respectively. Best- and worst-case scenarios are presented in Tables 22 and 23.

4.2.7 *Assessment of impact of improvements to STWs and IDs*

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Poole Harbour West catchment and of the resulting changes is presented in Table 31.

In the pre-improvement period, the key STWs and other catchment sources are dominant, with each accounting for >35.00% of the FC and EN fluxes. At base flow, the key STWs are more prominent sources of FC (62.38%) and EN (67.09%) fluxes.

Following improvements to the key STWs and their associated IDs the total fluxes of FC and EN changed by -56.29 and -60.99%, respectively. Other catchment sources are now very dominant, accounting for 96.91% (FC) and 94.48% (EN) of the total fluxes; the IDs contribute only 3.03% (FC) and 4.91% (EN); and the key STWs are of minor significance (≤0.25%). These results suggest that installation of UV disinfection at the key STWs has effectively eliminated these as sources of FIOs, and the overall reductions achieved in FC and EN fluxes to the Poole Harbour West shellfish water are about 60%. While other catchment sources (both sewerage- and livestock-related) would appear to offer by far the greatest potential for achieving further reductions on the basis of the standard assumptions made with regard to ID flows pre- and post-improvement, it should be noted that under the worst-case scenario, the IDs become dominant, contributing 76.10 and 84.01%, respectively of the FC and EN fluxes.

Table 31: POOLE HARBOUR WEST: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC Base flow	FC High flow	FC Total flow	EN Base flow	EN High flow	EN Total flow
Pre-improvement						
Total flux	2.1E+15	2.5E+15	4.5E+15	1.8E+14	3.7E+14	5.5E+14
Key STWs (%)	62.38	31.48	45.48	67.09	32.41	44.05
IDs associated with key STWs (%)	0.00	25.55	13.97	0.00	30.38	20.18
Other catchment sources (%)	37.62	42.96	40.54	32.91	37.21	35.76
Post-improvement						
Total flux	8.0E+14	1.2E+15	2.0E+15	6.2E+13	1.5E+14	2.1E+14
Key STWs (%)	0.09	0.02	0.05	0.63	0.09	0.25
IDs associated with key STWs (%)	0.00	5.09	3.03	0.00	6.89	4.91
Other catchment sources (%)	99.91	94.89	96.91	99.37	93.02	94.84
Sewage-related sources (%)	69.08	57.24	62.02		52.44	
Agriculture-related sources (%)	30.82	37.65	34.90		40.58	
Post-improvement change						
Total flux	-1.3E+15	-1.3E+15	-2.6E+15	-1.2E+14	-2.1E+14	-3.4E+14
Total flux (%)	-61.10	-52.30	-56.29	-66.68	-58.12	-60.99
Key STWs (%)	-62.34	-31.47	-45.46	-66.89	-32.37	-43.96
IDs associated with key STWs (%)	0.00	-23.13	-12.65	0.00	-27.50	-18.27
Other catchment sources (%)	1.25	2.30	1.82	0.21	1.75	1.23
Best case ID scenario						
Pre-: total flux	2.1E+15	2.0E+15	4.1E+15	1.8E+14	2.8E+14	4.7E+14
Post-: total flux	8.0E+14	1.1E+15	1.9E+15	6.2E+13	1.4E+14	2.0E+14
Post-: flux from IDs associated with key STWs (%)	0.00	0.12	0.07	0.00	0.17	0.12
Change: total flux	-1.3E+15	-8.7E+14	-2.1E+15	-1.2E+14	-1.4E+14	-2.6E+14
Change: total flux (%)	-61.10	-43.62	-52.49	-66.68	-49.07	-56.06
Key STWs (%)	-62.34	-39.14	-50.92	-66.89	-42.20	-52.01
IDs associated with key STWs (%)	0.00	-7.34	-3.61	0.00	-9.15	-5.51
Other catchment sources (%)	1.25	2.86	2.04	0.21	2.28	1.46
Worst case ID scenario						
Pre-: total flux	2.1E+15	1.5E+16	1.7E+16	1.8E+14	2.5E+15	2.7E+15
Post-: total flux	8.0E+14	7.3E+15	8.1E+15	6.2E+13	1.2E+15	1.3E+15
Post-: flux from IDs associated with key STWs (%)	0.00	84.50	76.10	0.00	88.27	84.01
Change: total flux	-1.3E+15	-7.5E+15	-8.8E+15	-1.2E+14	-1.3E+15	-1.4E+15
Change: total flux (%)	-61.10	-50.86	-52.11	-66.68	-51.67	-52.69
Key STWs (%)	-62.34	-5.29	-12.27	-66.89	-4.71	-8.96
IDs associated with key STWs (%)	0.00	-45.95	-40.33	0.00	-47.22	-43.99
Other catchment sources (%)	1.25	0.39	0.49	0.21	0.25	0.25

4.2.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 31 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that Wareham and Lytchett Minster STWs and their associated IDs now contribute only a relatively small proportion (≤ 6%) of the total FIO fluxes to the shellfish water. Provisional source-apportionment estimates suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 25). This assessment therefore supports the PRP proposal to install UV disinfection at Holton Heath STW and reduce spill frequency from the associated storm tank (due for completion in 2013), since both are likely to lead to significant reductions in FIO fluxes. If flow and FIO monitoring data are available, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in these individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose. The proposed investigations of other IDs that are considered to impact on this shellfish water, and of the impacts of the CSF initiative within the catchment, are both also supported by this assessment.

4.3 Yealm

4.3.1 Overview of designated shellfish water

The Yealm is a macrotidal ria with an intertidal area of approximately 1.54 km^2. The shellfish water (Plate 3) was first designated in 1999 and includes an area of 0.53 km^2 across the estuary, from Broad Ooze to Clitters Wood/Court Wood at Newton Ferrers. The estuary contains populations of cockles *Cerastoderma edule*, clams (*Mya arenaria, Scrobicularia plana, Venerupis senegalensis*) and mussels (*Mytilus edulis*). The substrate in this area is intertidal sand and mudflats interspersed by rocky outcrops.

Plate 3: Yealm Estuary.

Pacific oysters and mussels have been classified in this estuary under Food Hygiene Regulations since 1992 and 1999, respectively. Currently, shellfish farming operations are established in two main areas (Fox Cove and Thorn) within the shellfish water. These consist of on-growing stock brought from other areas and grown in bags suspended above the riverbed on trestles. Wild stock is also harvested, although this is considerably less significant. Natural spatfall of Pacific oysters has been recorded with episodes of settlement being associated with warmer years. Commercially sized stock is harvested by hand during periods of low water on a year-round basis.

In the past, the native oyster *Ostrea edulis* was also cultivated in this estuary but commercial operations for this species were severely affected by the parasite *Bonamia*. Populations of the common cockle (*Cerastoderma edule*) have been found in the upper to middle reaches of the estuary. However, at the moment there is no commercial interest for this species. An increase in GM FC concentrations in shellfish flesh was recorded over the period 1999-2008 (Table 1).

4.3.2 *Catchment characterisation*

The extent of the catchment is shown in Fig. 8. It covers an area of 91.44 km^2, of which quite a high proportion is located upstream of lakes/reservoirs, notably Silverbridge Lake, located immediately upstream of Brixton STW (modelled:total catchment area ratio, 0.689).

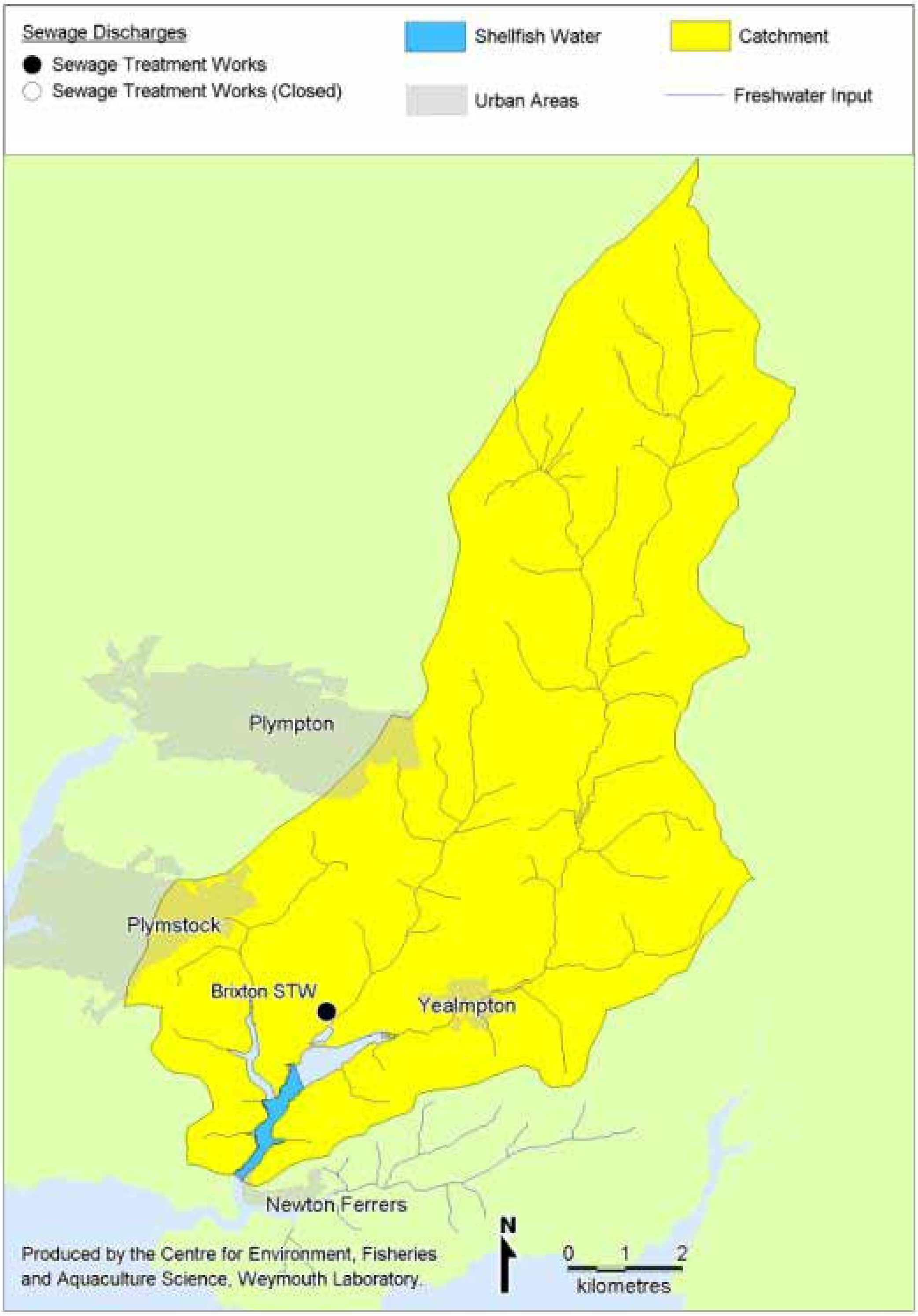

Fig. 8: Yealm: boundary of shellfish water catchment.

In this case, therefore, the predicted FC and EN fluxes from the catchment are markedly reduced by the effects of die-off and sedimentation within water bodies. Apart from the uppermost headwaters of the R. Yealm, which rise on the granites of Dartmoor, and have a soil cover of peats (Crowdy 2 association) and podzols (Moor Gate association), the catchment is dominated by typical brown earths (Denbigh 1 and 2 and Trusham associations). These are well-drained loamy and silty soils over Palaeozoic slaty mudstones, siltstones and, more locally, basic igneous and metamorphic rocks (SMEW, Sheet 5, SSEW, 1983). Although the BFI is quite high (0.598), the upper part of the catchment on the flanks of Dartmoor is quite wet and the resulting volumes of flow are quite high (e.g. 1379 m^3 km^{-2} day^{-1} in summer).

Land use within the catchment is shown in Fig. 9. Urban land occupies 8.97% of the modelled catchment (Table 14) and the estimated density of residences is 74.78 km^{-2}.

While Yealmpton is the principal settlement within the catchment, some urban land on the outskirts of Plymouth is also included. The agricultural land is very mixed, with 37.79% improved grassland, 11.90% rough grazing (mostly on Dartmoor) and 24.47% arable. Moderate numbers of total cattle and sheep are present, with densities in the post-improvement period of 46.48 and 117.37 km^{-2}, respectively, but only small numbers of dairy cattle (density, 5.51 km^{-2}).

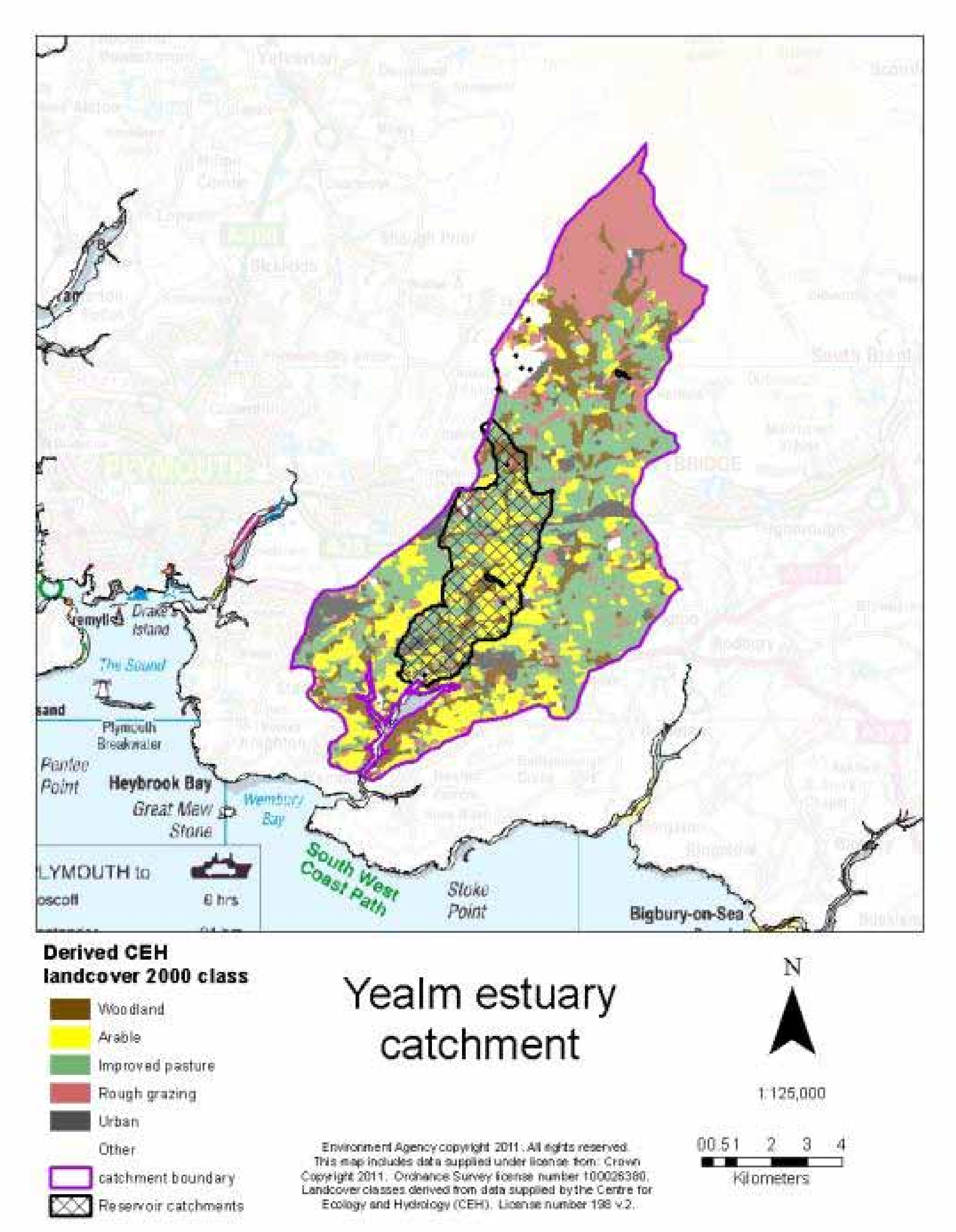

Fig. 9: Yealm: land use within shellfish water catchment.

4.3.3 *Sewerage sources and improvements to key STWs and IDs*

The locations of the key STW (Brixton) and IDs that have been improved are shown in Fig. 10. UV disinfection was installed at Brixton STW (PE post-improvement: 1439) in 2003 (Table 11). In addition, improvements were also completed to two IDs in 2005 (Table 12). It is estimated that post-improvement there are an average of 65.11 residences km^{-2} in the modelled catchment that are not served by Brixton STW (Table 15), and these represent a further significant sewerage-related source.

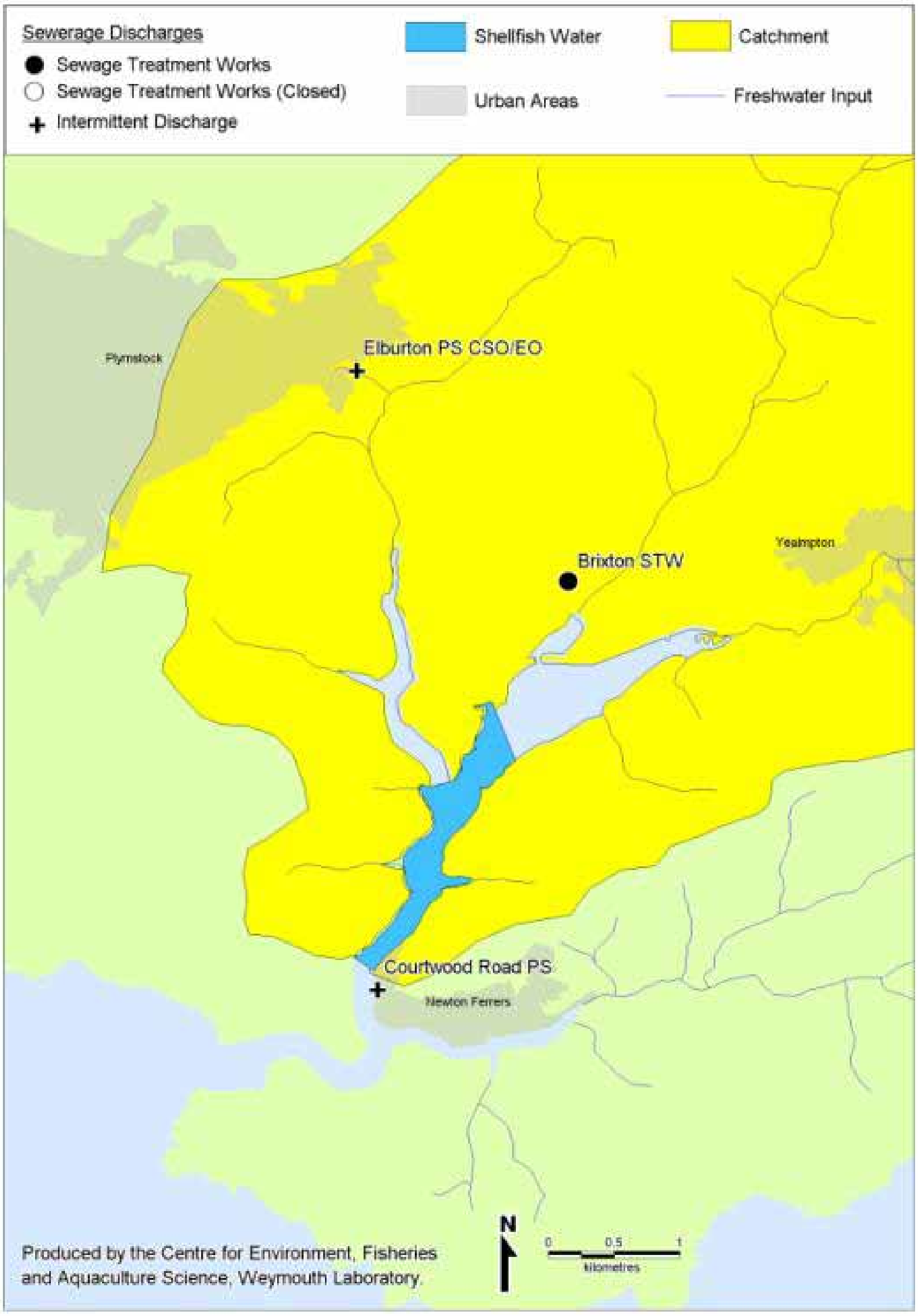

Fig. 10: Yealm: locations of the key STWs/IDs at which improvements have been made.

4.3.4 Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement

The predicted GM FC and EN concentrations are quite low (Table 18), e.g. high-flow concentrations post-improvement are 5.1×10^{3} and 9.7×10^{2} cfu 100 ml^{-1}, respectively. These figures are a reflection of the moderate density of residences; moderate stocking densities, but with especially low numbers of dairy cattle; and the reasonably well-drained soils with quite a high BFI. The resulting total fluxes of FC and EN over the summer period post-improvement are 6.1×10^{14} and 1.1×10^{14} cfu, respectively (Table 19).

4.3.5 Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement

The results reveal very marked reductions in FC and EN fluxes following improvement under both base- and high-flow conditions (Table 20). The total fluxes of FC and EN change by -99.76 and -99.61%, respectively.

4.3.6 Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 6.3×10^{13} and 1.1×10^{13} cfu, respectively. Best- and worst-case scenarios are presented in Tables 22 and 23.

4.3.7 Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Yealm catchment and of the resulting changes is presented in Table 32.

In the pre-improvement period, high proportions of the total fluxes of FC (74.39%) and EN (83.88%) were derived from other catchment sources, and the key STW accounted for most of the remaining fluxes. Indeed, at base flow the key STW contributes 52.00 and 36.28%, respectively, of the FC and EN fluxes.

Table 32: YEALM: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Total flux	2.5E+14	7.8E+14	1.0E+15	3.0E+13	1.5E+14	1.8E+14
Key STWs (%)	52.00	9.08	19.40	36.28	4.50	9.86
IDs associated with key STWs (%)	0.00	8.17	6.21	0.00	7.54	6.27
Other catchment sources (%)	48.00	82.74	74.39	63.72	87.96	83.88
Post-improvement						
Total flux	1.1E+14	5.0E+14	6.2E+14	1.9E+13	9.5E+13	1.1E+14
Key STWs (%)	0.31	0.03	0.08	0.26	0.02	0.06
IDs associated with key STWs (%)	0.00	1.26	1.03	0.00	1.17	0.97
Other catchment sources (%)	99.69	98.71	98.89	99.74	98.81	98.97
Sewage-related sources (%)	74.88	63.44	65.54		62.34	
Agriculture-related sources (%)	24.81	35.27	33.35		36.47	
Post-improvement change						
Total flux	-1.3E+14	-2.7E+14	-4.1E+14	-1.1E+13	-5.2E+13	-6.3E+13
Total flux (%)	-54.00	-35.35	-39.83	-36.11	-35.54	-35.64
Key STWs (%)	-51.86	-9.07	-19.35	-36.11	-4.49	-9.82
IDs associated with key STWs (%)	0.00	-7.36	-5.59	0.00	-6.78	-5.64
Other catchment sources (%)	-2.15	-18.93	-14.89	0.00	-24.27	-20.18
Best case ID scenario						
Pre-: total flux	2.5E+14	7.3E+14	9.7E+14	3.0E+13	1.4E+14	1.7E+14
Post-: total flux	1.1E+14	5.0E+14	6.1E+14	1.9E+13	9.4E+13	1.1E+14
Post-: flux from IDs associated with key STWs (%)	0.00	0.03	0.02	0.00	0.03	0.02
Change: total flux	-1.3E+14	-2.3E+14	-3.6E+14	-1.1E+13	-4.5E+13	-5.6E+13
Change: total flux (%)	-54.00	-31.88	-37.46	-36.11	-32.37	-33.03
Key STWs (%)	-51.86	-9.67	-20.32	-36.11	-4.76	-10.32
IDs associated with key STWs (%)	0.00	-2.01	-1.50	0.00	-1.85	-1.52
Other catchment sources (%)	-2.15	-20.19	-15.64	0.00	-25.76	-21.19
Worst case ID scenario						
Pre-: total flux	2.5E+14	2.0E+15	2.3E+15	3.0E+13	3.6E+14	3.9E+14
Post-: total flux	1.1E+14	1.1E+15	1.3E+15	1.9E+13	2.1E+14	2.3E+14
Post-: flux from IDs associated with key STWs (%)	0.00	56.57	51.47	0.00	54.62	50.01
Change: total flux	-1.3E+14	-8.6E+14	-1.0E+15	-1.1E+13	-1.6E+14	-1.7E+14
Change: total flux (%)	-54.00	-43.06	-44.25	-36.11	-42.89	-42.37
Key STWs (%)	-51.86	-3.51	-8.79	-36.11	-1.83	-4.44
IDs associated with key STWs (%)	0.00	-32.21	-28.69	0.00	-31.19	-28.82
Other catchment sources (%)	-2.15	-7.33	-6.77	0.00	-9.87	-9.12

Following improvements to the key STW and its associated IDs the total fluxes of FC and EN changed by -39.83 and -35.64%, respectively. Other catchment sources are now very dominant, accounting for 98.89% (FC) and 98.97% (EN) of the total fluxes, and treated effluent from the key STW is a very minor contributor (≦ 0.08%). These results suggest that while installation of UV disinfection at the key STW has effectively eliminated this source of FIOs, the overall reductions in FC and EN fluxes to the Yealm shellfish water are only just over 35%. While other catchment sources (both sewerage- and livestock-related) would appear to offer by far the greatest potential for achieving further reductions on the basis of the standard assumptions made with regard to ID flows pre- and post-improvement, it should be noted that under the worst-case scenario, the IDs become dominant, contributing 51.47 and 50.01%, respectively, of the FC and EN fluxes.

4.3.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 32 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that Brixton STW and the IDs associated with these now contribute only a relatively small proportion (≦ 2%) of the total FIO fluxes to the shellfish water. Provisional source-apportionment estimates suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 26). This finding is broadly consistent with preliminary source-tracking work reported in the PRP, which indicates that "approximately 70% of faecal pollution in samples taken during and after rainfall in the vicinity of the shellfish beds, came from agricultural sources"; and it seems clear that significant reductions in FIO fluxes to the shellfish water will be achieved by addressing both sources. These findings support the PRP proposals to reduce spills and event duration for storm discharge at Brixton STW and complete an investigation into 11 other sewage discharges, while at the same time awaiting the outcome of the on-going monitoring work currently being undertaken in the catchment as part of the CSF project. In cases where flow and FIO monitoring data are available, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose. In view of the potential reductions in FIO fluxes that are achievable through UV disinfection at STWs, consideration should also be given to installing UV at Yealmpton STW (PE, 1523), which discharges to the R. Yealm only 3.4 km upstream of the shellfish water.

4.4 Fal/Ruan

4.4.1 Overview of designated shellfish water

The Fal is a macrotidal ria with an intertidal area of approximately 7.46 km^2. Fal (total area, 3 km^2) shellfish water (Plate 4) is one of six shellfish waters designated in the wider Fal Estuary in 1999, and is situated in the upper reaches of the estuary. This area of the estuary contains populations of cockles (*Cerastoderma edule*), mussels (*Mytilus edulis*), oysters (*Ostrea edulis*) and clams (*Scrobicularia plana*; *Venerupis senegalensis*). The substrate in this area is intertidal mud interspersed by rocky outcrops.

Plate 4: Fal/Ruan - King Harry.

The estuary supports a traditional oyster and mussel fishery. Native oysters and mussels have been classified in this estuary under Food Hygiene Regulations since 1992 and 1993, respectively. Cockles were also classified at Ruan Creek in the past; at the moment, there is no commercial interest for this species in the estuary. The Truro Oyster Fishery is the second largest native oyster fishery in the

UK and it is famous for only permitting dredging under sail or traditional “haul-tow” boats, with dredging under power being prohibited. Despite the decline seen in the native oyster fishery in the past (to which Bonamiosis, pests, competition from limpets, chemical contaminants certainly contributed), this traditional fishery has recovered in recent years. The season runs from 1 November–31 March. Native oyster halfware is supplied from the Fal Estuary to other locations for growing on, including the nearby Helford Estuary. Wild mussels are harvested on a year-round basis in various areas of the estuary: Truro River, lower Tresillian River, stretches of the River Fal and lower Mylor Creek. There is also a mussel farming operation using lines suspended from buoys or rafts at King Harry Ferry. There are currently lines for the collection of seed hanging from Ruan Pontoon; these are not grown to harvestable size at this location but transferred to South Wood for growing on. No trend in GM FC concentrations in shellfish flesh was recorded over the period 1999–2008 (Table 1).

4.4.2 Catchment characterisation

The extent of the catchment is shown in Fig. 11. It covers an area of 294.94 km^2, with very little of the runoff to the shellfish water being affected by lakes/reservoirs (modelled:total catchment area ratio, 0.950).

Geologically, the catchment largely comprises Palaeozoic slates, mudstones and siltstones, the only notable exception being a small area of granite on Hensbarrow Downs, which is heavily disturbed by China Clay quarrying. The lower and mid sections of the catchment are dominated well-drained fine loamy brown earth soils (Denbigh 2 association), whereas on the higher ground in the northern part of the catchment these give way to brown podzols (Manod association) (SMEW, Sheet 5, SSEW, 1983). The well-drained soils lead to a moderate BFI (0.574) which, combined with quite a low rainfall, generates only a moderate volume of flow (e.g. 748 m^3 km^{-2} day^{-1} in summer).

Fig. 11: Fal/Ruan: boundary of shellfish water catchment.

Land use within the catchment is shown in Fig. 12. Urban land occupies 5.43% of the modelled catchment (Table 14) and the estimated density of residences is 17.52 km^{-2}. Truro, which is the principal settlement within the catchment, is located close to the shellfish water.

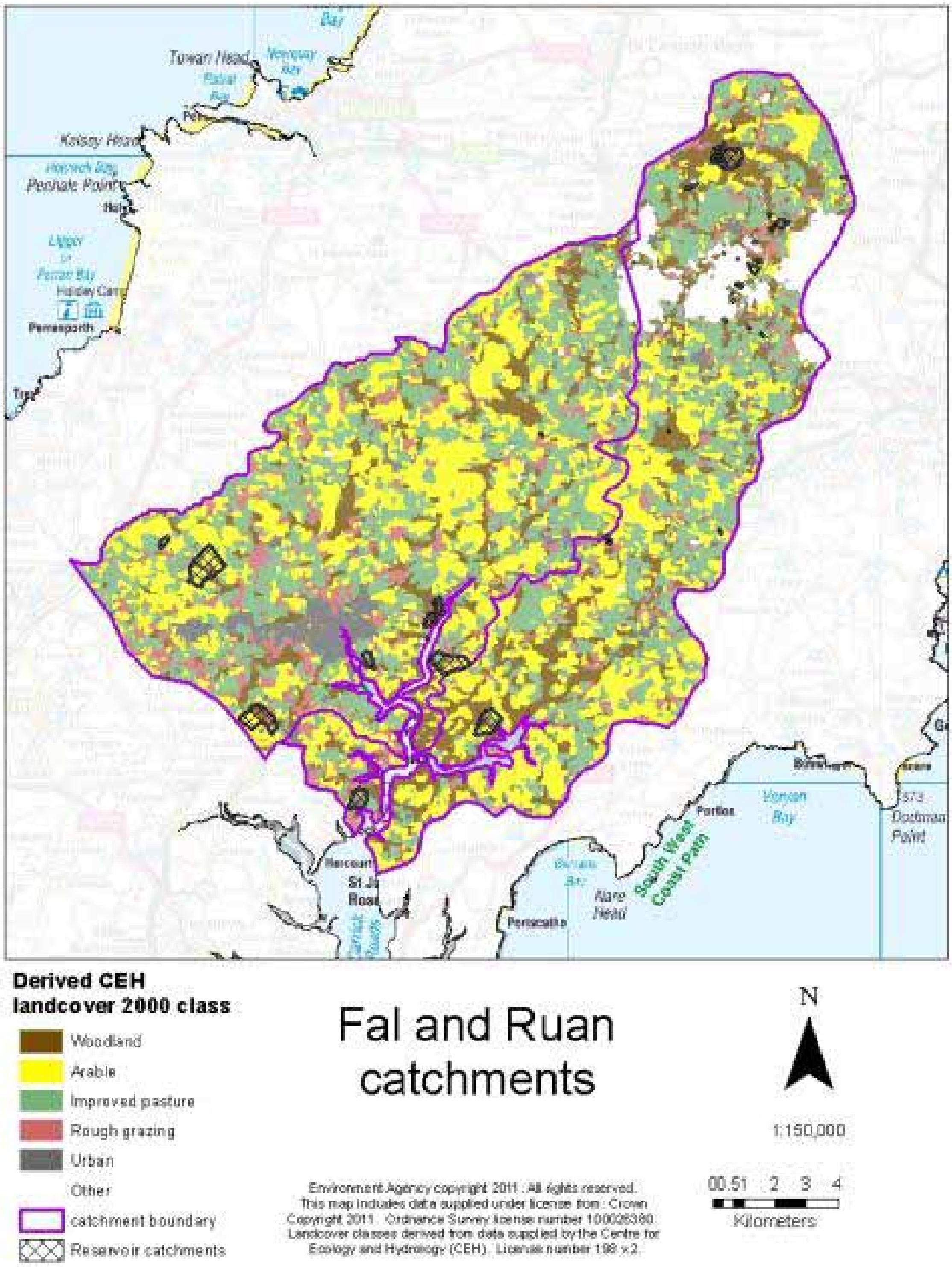

Fig. 12: Fal/Ruan: land use within shellfish water catchment.

The agricultural land is very mixed, with 34.36% improved grassland and 32.75% arable. Quite high numbers of dairy cattle and total cattle are present, with densities in the post-improvement period of 50.28 and 96.24 km^{-2}, respectively, but only moderate numbers of sheep (density, 65.87 km^{-2}).

4.4.3 Sewerage sources and improvements to key STWs and IDs

The locations of the key STWs and IDs that have been improved are shown in Fig. 13. There are two key STWs within the catchment (Table 11): Ladock STW (post-improvement PE: 3858) and the much larger Truro (Newham) STW (PE: 28200). UV disinfection was installed at both in 2003. In addition, improvements were also completed to six IDs over the period 2002–2006, three of which were transferred to Truro for treatment (Table 12).

It is estimated that post-improvement there are an average of 17.52 residences km^{-2} in the modelled catchments that are not served by either of the two key STWs (Table 15), and these represent a further sewerage-related source.

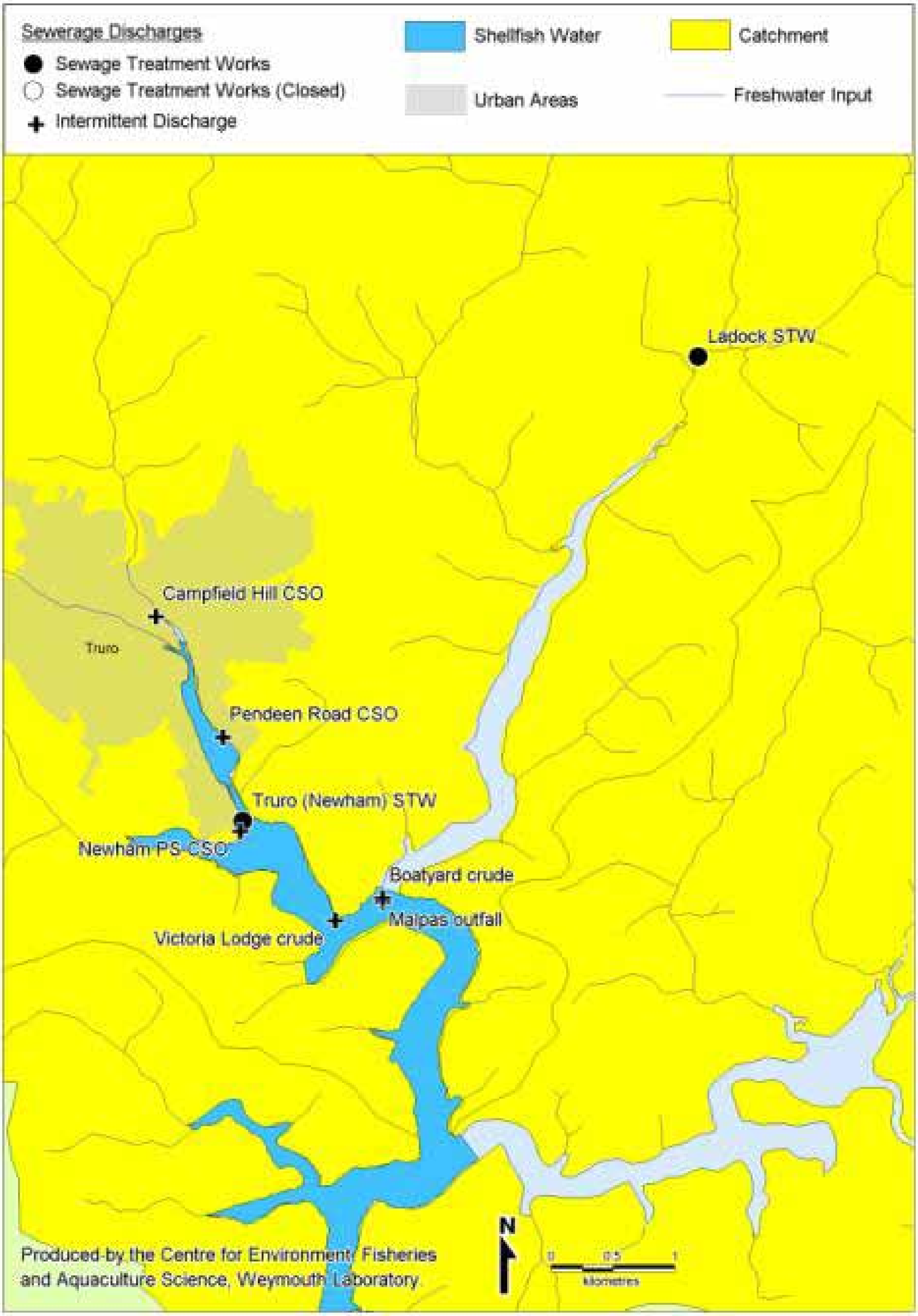

Fig. 13: Fal/Ruan: locations of the key STWs/IDs at which improvements have been made.

4.4.4 *Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement*

The predicted GM FC and EN concentrations are quite low (Table 18), e.g. high-flow concentrations post-improvement are 7.4 x 10^3 and 8.2 x 10^2 cfu 100 ml^{-1}, respectively. These figures are a reflection of the low density of residences; a roughly even mix of arable and pastoral farming; and the reasonably well-drained soils with a moderate BFI. The resulting total fluxes of FC and EN over the summer period post-improvement are 1.6 x 10^{15} and 1.7 x 10^{14} cfu, respectively (Table 19).

4.4.5 *Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement*

The estimated fluxes reveal very marked reductions in FC and EN fluxes following improvement under both base- and high-flow conditions (Table 20). The total fluxes of FC and EN change by -99.76 and -99.57%, respectively, following improvement.

4.4.6 *Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement*

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 6.3 x 10^{14} and 1.1 x 10^{14} cfu, respectively. Best- and worst-case scenarios are presented in Tables 22 and 23.

4.4.7 *Assessment of impact of improvements to STWs and IDs*

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Fal/Ruan catchment and of the resulting changes is presented in Table 33.

Table 33: FAL/RUAN: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Total flux	1.5E+15	2.8E+15	4.3E+15	1.3E+14	3.5E+14	4.8E+14
Key STWs (%)	83.47	25.12	45.71	83.61	18.81	36.24
IDs associated with key STWs (%)	0.00	22.60	14.63	0.00	31.50	23.03
Other catchment sources (%)	16.53	52.28	39.66	16.39	49.69	40.73
Post-improvement						
Total flux	2.6E+14	1.4E+15	1.7E+15	2.0E+13	1.6E+14	1.8E+14
Key STWs (%)	1.38	0.09	0.29	2.82	0.13	0.42
IDs associated with key STWs (%)	0.00	4.97	4.21	0.00	7.65	6.82
Other catchment sources (%)	98.62	94.94	95.50	97.18	92.23	92.77
Sewage-related sources (%)	51.10	42.01	43.40		41.67	
Agriculture-related sources (%)	47.51	52.93	52.10		50.55	
Post-improvement change						
Total flux	-1.3E+15	-1.4E+15	-2.7E+15	-1.1E+14	-1.9E+14	-3.0E+14
Total flux (%)	-83.25	-49.44	-61.37	-84.80	-54.22	-62.44
Key STWs (%)	-83.24	-25.07	-45.60	-83.18	-18.75	-36.08
IDs associated with key STWs (%)	0.00	-20.09	-13.00	0.00	-28.00	-20.47
Other catchment sources (%)	-0.01	-4.27	-2.77	-1.61	-7.47	-5.89
Best case ID scenario						
Pre-: total flux	1.5E+15	2.3E+15	3.8E+15	1.3E+14	2.7E+14	4.0E+14
Post-: total flux	2.6E+14	1.3E+15	1.6E+15	2.0E+13	1.5E+14	1.7E+14
Post-: flux from IDs associated with key STWs (%)	0.00	0.12	0.10	0.00	0.19	0.17
Change: total flux	-1.3E+15	-9.7E+14	-2.2E+15	-1.1E+14	-1.2E+14	-2.3E+14
Change: total flux (%)	-83.25	-41.80	-58.28	-84.80	-44.14	-57.42
Key STWs (%)	-83.24	-30.33	-51.36	-83.18	-24.72	-43.82
IDs associated with key STWs (%)	0.00	-6.30	-3.80	0.00	-9.58	-6.45
Other catchment sources (%)	-0.01	-5.17	-3.12	-1.61	-9.85	-7.16
Worst case ID scenario						
Pre-: total flux	1.5E+15	1.5E+16	1.7E+16	1.3E+14	2.5E+15	2.6E+15
Post-: total flux	2.6E+14	8.5E+15	8.8E+15	2.0E+13	1.4E+15	1.4E+15
Post-: flux from IDs associated with key STWs (%)	0.00	84.17	81.72	0.00	89.39	88.15
Change: total flux	-1.3E+15	-6.5E+15	-7.8E+15	-1.1E+14	-1.1E+15	-1.2E+15
Change: total flux (%)	-83.25	-43.49	-47.16	-84.80	-43.84	-45.86
Key STWs (%)	-83.24	-4.67	-11.90	-83.18	-2.64	-6.61
IDs associated with key STWs (%)	0.00	-38.03	-34.53	0.00	-40.14	-38.16
Other catchment sources (%)	-0.01	-0.79	-0.72	-1.61	-1.05	-1.08

In the pre-improvement period, the key STWs and other catchment sources are the dominant sources of FC and EN fluxes, with the IDs associated with the key STWs accounting for only 14.63 and 23.03%, respectively.

Following improvements to the key STWs and their associated IDs the total fluxes of FC and EN changed by -61.37 and -62.44%, respectively. The treated effluents from the key STWs are now very minor contributors (≤ 0.42%), and their associated IDs contribute only 4.21% and 6.82%, respectively of the total FC and EN fluxes. These results suggest that installation of UV disinfection at the key STWs has effectively eliminated the treated effluents as sources of FIOs, and overall reductions in FC and EN fluxes to the Fal/Ruan shellfish water of about 60% have been achieved. While other catchment sources (both sewerage- and livestock-related) would appear to offer by far the greatest potential for achieving further reductions on the basis of the standard assumptions made with regard to ID flows pre- and post-improvement, it should be noted that under the worst-case scenario, the IDs become dominant, contributing 81.72 and 88.15%, respectively, of the FC and EN fluxes.

4.4.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 33 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that Ladock and Truro STWs and their associated IDs now contribute only a relatively small proportion (≤ 8%) of the total FIO fluxes to the shellfish water. Provisional source-apportionment estimates suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 27). These findings support the PRP's dual focus on addressing sewage-related point-source pollution, such as the proposed investigation of the Calenick PS discharge and upgrading of sewage treatment on various individual properties within the catchment; and diffuse agricultural sources, through the CSF initiative. In cases where flow and FIO monitoring data are available for the sewage-related sources, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose.

4.5 Taw/Torridge

4.5.1 Overview of designated shellfish water

The Taw-Torridge is a bar-built macrotidal estuary with an intertidal area of approximately 20.2 km^2. The estuary mouth supports important populations of cockles (*Cerastoderma edule*) and other less abundant bivalves such as various species of clams (*Chamelea gallina*; *Scrobicularia plana*; *Spisula solida; Tapes decussatus; Ensis* spp.) and mussels (*Mytilus edulis*) in intertidal and sub-tidal sandflats. Mussels also occur on rocky outcrops.

The designated shellfish water (Plate 5) covers an area of approximately 4.2 km^2. The Taw-Torridge Estuary Mouth shellfish water was first designated in 1999.

Plate 5: Taw/Torridge Estuary.

Mussels are the only species currently classified (since 1992) within this shellfish water under Food Hygiene Regulations. Commercially harvested mussel beds are situated at Pulley Ridge, Neck Gut, Spratt Ridge and off the Lifeboat Slipway. These mussels are harvested by hand during periods of low water. A decrease in GM FC concentrations in shellfish flesh was recorded over the period 1999–2008 (Table 1).

4.5.2 Catchment characterisation

The extent of the catchment is shown in Fig. 14. It covers an area of 2094.06 km^2, with very little of the runoff to the shellfish water being affected by lakes/reservoirs (modelled:total catchment area ratio, 0.960).

Fig. 14: Taw/Torridge: boundary of shellfish water catchment.

In view of the large size of the catchment, it is possible that the catchment fluxes reported will be overestimates, especially under base-flow conditions, because of the likelihood of some die-off of FIOs along the watercourse. Geologically, the catchment largely comprises Carboniferous sandstones and shales. The soils vary in terms of their drainage characteristics, with the majority of soils being either well-drained fine loamy brown earths (Neath association) or slowly permeable, seasonally waterlogged clayey pelo-stagnogleys (Hallsworth 1 and 2 associations) (SMEW, Sheet 5, SSEW, 1983). The catchment has a BFI of 0.537, and mean summer and winter flows of 831 and 2124 m^3 km^{-2} day^{-1}, respectively.

Land use within the catchment is shown in Fig. 15. Urban land occupies only 3.47% of the modelled catchment (Table 14) and the estimated density of residences is 30.70 km^{-2}.

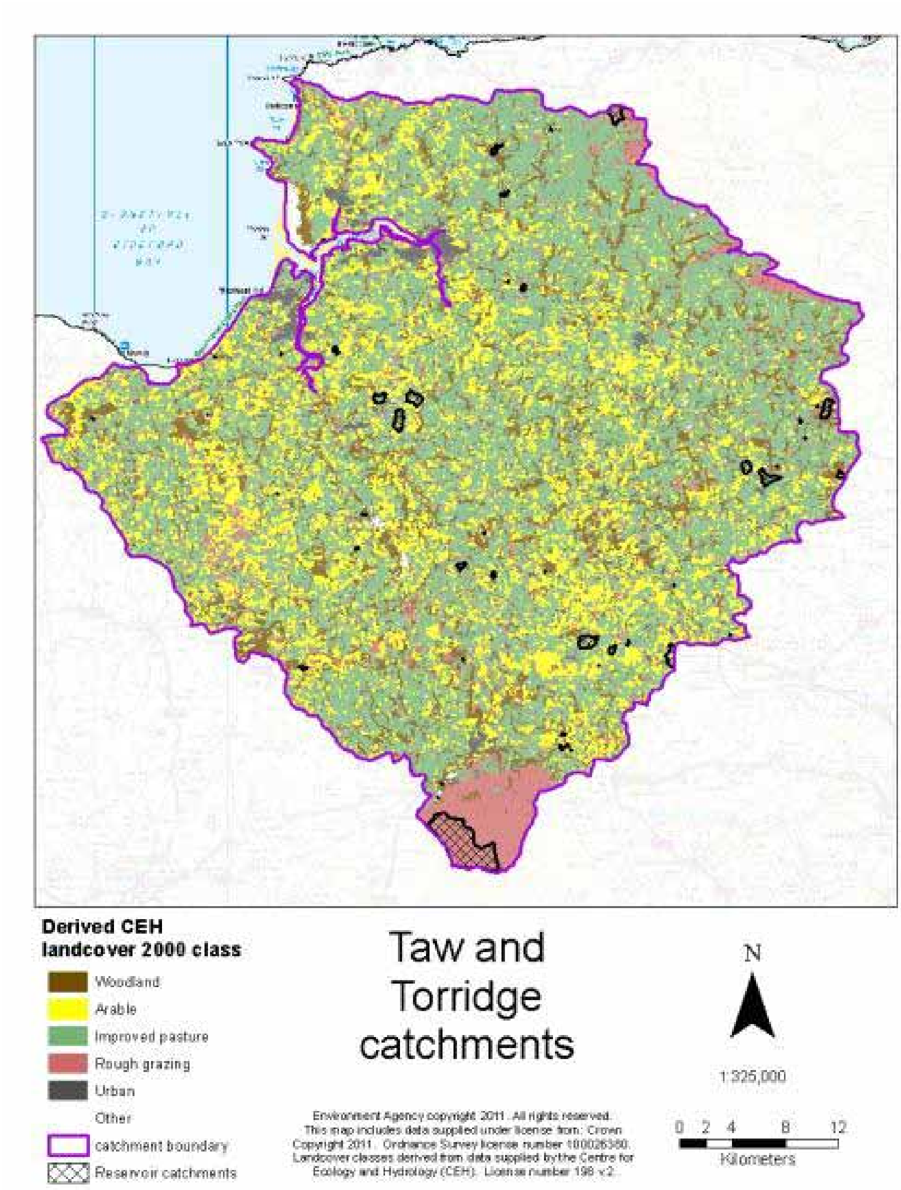

Fig. 15: Taw/Torridge: land use within shellfish water catchment.

The principal settlements are Barnstaple and South Molton on the R. Taw, and Bideford and Great Torrington on the R. Torridge – with Barnstaple and Bideford being located close to the shellfish water. The agricultural land is dominated by improved grassland (50.47%) and arable (24.97%). Quite high numbers of dairy cattle, total cattle and especially sheep are present, with densities in the post-improvement period of 43.19, 98.69 and 270.01 km^{-2}, respectively.

4.5.3 Catchment characterisation

The locations of the key STWs and IDs that have been improved are shown in Fig. 16. There are two key STWs within the catchment (Table 11): Ashford (Barnstaple) STW (post-improvement PE: 37620) and Cornborough STW (PE: 38121).

Fig. 16: Taw/Torridge: locations of the key STWs/IDs at which improvements have been made.

UV disinfection was installed at Ashford STW in 1997, whereas Cornborough STW, which was completed in 2002, is a new plant with UV, treating effluents from four other STWs/fine screen installation (FSI), some of which were previously only subject to primary treatment. In addition, improvements were also completed to 12 IDs over the period 2003–6 (Table 12).

It should be noted that of the four other (now closed) STWs, Northam FSI discharged directly to the coast outside the shellfish water catchment, and effluent from this site has therefore been excluded in calculating FC and EN fluxes to the shellfish water. In the absence of suitable ID monitoring data, it has been assumed that two-thirds of the ID flow associated with Northam FSI was discharged within the catchment.

With regard to the post-improvement period it should be noted that Cornborough STW also discharges direct to the sea outside the topographic catchment of the shellfish water, and treated effluent from this source has therefore been excluded from the flux calculations. As with Northam FSI (see above), it has been assumed that two-thirds of the ID flows associated with Cornborough STW discharge within the catchment. It is estimated that post-improvement there are an average of 14.73 residences km^{-2} in the modelled catchment that are not served by either of the two key STWs (Table 15), and these represent a further potential sewerage-related source.

4.5.4 Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement

Moderate GM FC and EN concentrations are predicted (Table 18), e.g. high-flow concentrations post-improvement are 1.3×10^4 and 8.6×10^2 cfu 100 ml^{-1}, respectively. These figures are a reflection of the low density of residences (i.e. human sources) being compensated by the relatively high numbers of livestock present and the presence of some less well-drained soils (BFI, 0.537). The resulting total fluxes of FC and EN over the summer period post-improvement from this large (2094.06 km^2) catchment are: 2.2×10^{16} and 1.4×10^{15} cfu, respectively (Table 19).

4.5.5 *Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement*

The estimated fluxes reveal very marked reductions in FC and EN fluxes following improvement under both base- and high-flow conditions (Table 20) – the figures for the changes in FC and EN both being recoded (to 2 d.p.) as -100.00% . This is a reflection of both the installation of UV at Ashford STW and the fact the new UV plant Cornborough, which treats effluents that were previously treated within the catchment, actually discharges to the coast outside the catchment.

4.5.6 *Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement*

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 4.4 x 10^{15} and 7.7 x 10^{14} cfu, respectively. Best- and worst-case scenarios are presented in Tables 22 and 23.

4.5.7 *Assessment of impact of improvements to STWs and IDs*

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Taw/Torridge catchment and of the resulting changes is presented in Table 34.

In the pre-improvement period, more than 80% of the total fluxes of FC (81.12%) and EN (86.12%) were derived from treated effluents from the key STWs – which is, in part, a reflection of the fact that some of the sewerage was subject only to primary treatment. Other catchment sources accounted for the majority of the remaining fluxes of FC (16.47%) and EN (10.66%).

Following improvements to the key STWs and their associated IDs the total fluxes of FC and EN changed by -87.98 and -93.91%, respectively. The treated effluents from the key STWs are now very minor contributors to the total fluxes of FC (< 0.00%) and EN (0.03%). With the IDs associated with the key STWs contributing only 1.71 and 4.49%, respectively, other catchment sources now completely dominate the fluxes of FC (98.29%) and EN (95.48%). These results suggest that other catchment sources (sewerage- and livestock-related) appear to offer considerable potential for achieving further reductions.

Table 34: TAW/TORRIDGE: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Total flux	1.3E+17	5.6E+16	1.8E+17	1.6E+16	7.7E+15	2.4E+16
Key STWs (%)	98.72	41.06	81.12	99.39	58.47	86.12
IDs associated with key STWs (%)	0.00	7.91	2.41	0.00	9.93	3.22
Other catchment sources (%)	1.28	51.04	16.47	0.61	31.59	10.66
Post-improvement						
Total flux	1.7E+15	2.0E+16	2.2E+16	9.8E+13	1.4E+15	1.5E+15
Key STWs (%)	0.03	0.00	0.00	0.38	0.01	0.03
IDs associated with key STWs (%)	0.00	1.85	1.71	0.00	4.81	4.49
Other catchment sources (%)	99.97	98.15	98.29	99.62	95.18	95.48
Sewage-related sources (%)	50.68	36.20	37.31		36.26	
Agriculture-related sources (%)	49.29	61.95	60.99		58.91	
Post-improvement change						
Total flux	-1.3E+17	-3.5E+16	-1.6E+17	-1.6E+16	-6.4E+15	-2.2E+16
Total flux (%)	-98.68	-63.63	-87.98	-99.39	-82.48	-93.91
Key STWs (%)	-98.72	-41.06	-81.12	-99.39	-58.47	-86.12
IDs associated with key STWs (%)	0.00	-7.23	-2.21	0.00	-9.09	-2.95
Other catchment sources (%)	0.04	-15.34	-4.66	0.00	-14.91	-4.84
Best case ID scenario						
Pre-: total flux	1.3E+17	5.2E+16	1.8E+17	1.6E+16	7.2E+15	2.3E+16
Post-: total flux	1.7E+15	2.0E+16	2.2E+16	9.8E+13	1.3E+15	1.4E+15
Post-: flux from IDs associated with key STWs (%)	0.00	0.04	0.04	0.00	0.12	0.11
Change: total flux	-1.3E+17	-3.2E+16	-1.6E+17	-1.6E+16	-5.9E+15	-2.2E+16
Change: total flux (%)	-98.68	-61.98	-87.96	-99.39	-81.92	-94.03
Key STWs (%)	-98.72	-43.70	-82.65	-99.39	-63.29	-88.30
IDs associated with key STWs (%)	0.00	-1.94	-0.57	0.00	-2.48	-0.76
Other catchment sources (%)	0.04	-16.33	-4.74	0.00	-16.14	-4.96
Worst case ID scenario						
Pre-: total flux	1.3E+17	1.4E+17	2.7E+17	1.6E+16	2.3E+16	3.9E+16
Post-: total flux	1.7E+15	5.8E+16	6.0E+16	9.8E+13	7.9E+15	8.0E+15
Post-: flux from IDs associated with key STWs (%)	0.00	65.68	63.84	0.00	83.73	82.71
Change: total flux	-1.3E+17	-8.3E+16	-2.1E+17	-1.6E+16	-1.5E+16	-3.1E+16
Change: total flux (%)	-98.68	-58.88	-77.73	-99.39	-64.91	-79.26
Key STWs (%)	-98.72	-16.23	-55.30	-99.39	-20.01	-53.05
IDs associated with key STWs (%)	0.00	-36.58	-19.25	0.00	-39.79	-23.23
Other catchment sources (%)	0.04	-6.06	-3.17	0.00	-5.10	-2.98

4.5.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 34 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that Ashford and Cornborough STWs and their associated IDs associated now contribute only a relatively small proportion ≤(5%) of the total FIO fluxes to the shellfish water. Provisional source - apportionment estimates suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 28). These findings support the dual focus on sewage- (mostly IDs) and agriculture-related sources in the separate PRPs for the Taw and Torridge Estuaries. In cases where flow and FIO monitoring data are available for the sewage-related sources, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose. Unfortunately, the CSF Associate Projects in the Taw and Torridge catchments are primarily concerned with nutrient pollution and sediment loss, and it is unclear how much insight they will provide into the control of diffuse- and point-sources of FIOs from agricultural land.

4.6 Conwy

4.6.1 Overview of designated shellfish water

The Conwy is a spit enclosed macrotidal estuary with an intertidal area of approximately 10.8 km^2. It contains areas of sandflats and mudflats, of which extensive areas are exposed during low tide. The estuary contains populations of mussel (*Mytilus edulis*) in intertidal and subtidal sand and muddy flats.

The designated shellfish water (Plate 6) covers an area of 8.3 km^2 in the lower estuary from Gyffin–Llandudno Junction to Penmaenmawr–Llandudno. It was first designated in 1999. The estuary supports a traditional mussel fishery.

Plate 6: Conwy - estuary mouth.

Mussels in this estuary have been classified under Food Hygiene Regulations since 1992. Mussel beds occur at Cae Conwy, Gamlwys, Morfa, Green Island, Benarth and Conwy Bridge. The cultivation method is by means of intertidal and subtidal ground laying of mussels, with mussels being moved and relayed to improve quality. Mussel beds are harvested using long handled rakes from small boats. No trend in GM FC concentrations in shellfish flesh was recorded over the period 1999–2008 (Table 1).

4.6.2 Catchment characterisation

The extent of the catchment is shown in Fig. 17. It covers an area of 603.62 km^2, with 13.0% of the runoff to the shellfish water being affected by lakes/reservoirs (modelled:total catchment area ratio, 0.870).

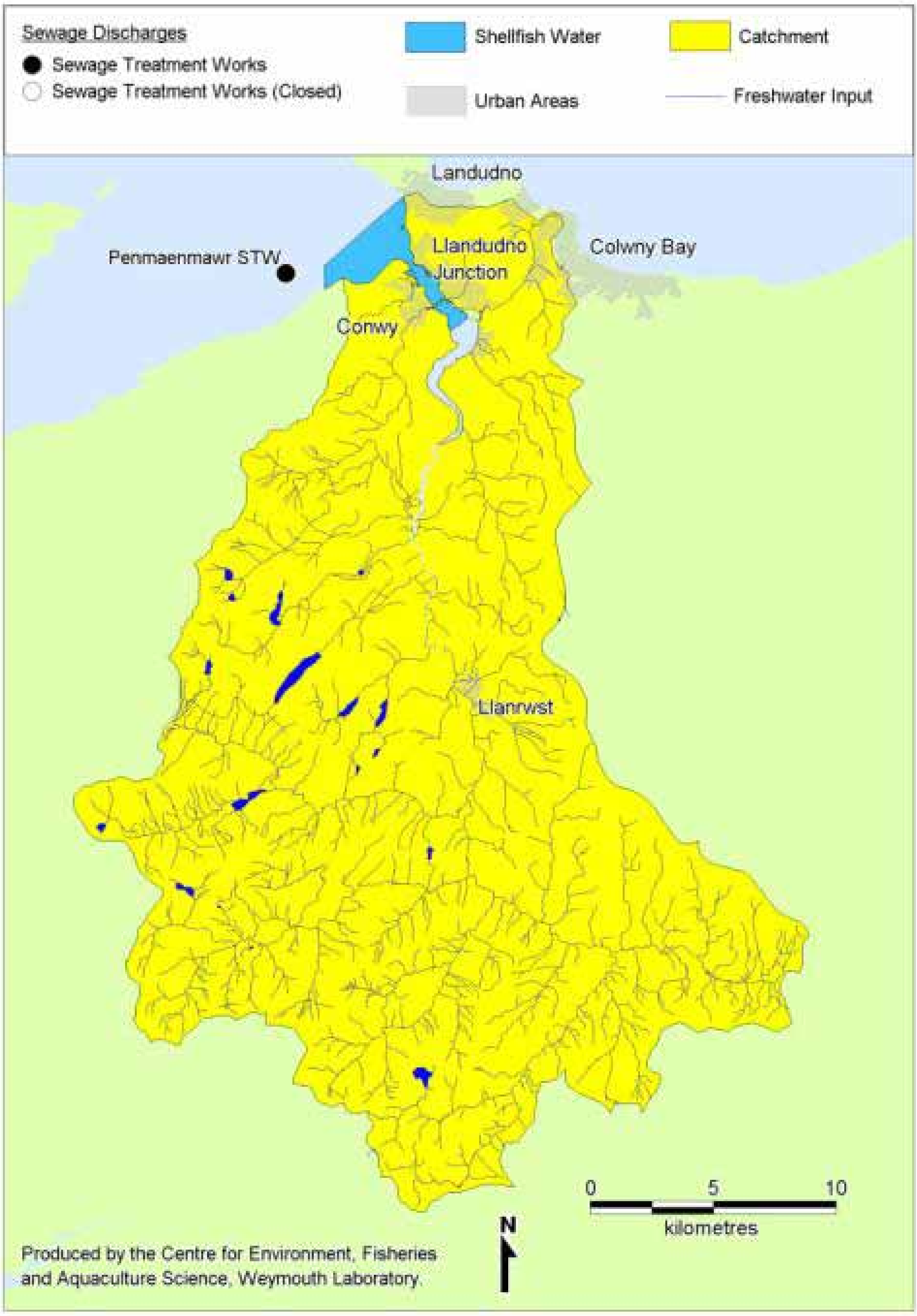

Fig. 17: Conwy: boundary of shellfish water catchment.

Geologically, the catchment is dominated by Palaeozoic shales, mudstones and sandstones, but includes a significant area of acid igneous rock along the western flank in the northern half. The soils are on the whole well drained, typically ranging from brown earths (Denbigh 1 association) on the lower ground, through brown podzols (Manod association) and ferric stagnopodzols (Hafren association) at increased elevations, to peats (Crowdy 2 association) on the highest ground in the southern headwaters (SMEW, Sheet 2, SSEW, 1983). Despite this, the mean BFI is low (0.431) and this, combined with the generally quite steep relief and high rainfall, particularly in the headwaters, leads to high volumes of flow (2564 and 5116 m^3 km^{-2} day^{-1}, respectively, in summer and winter), of which high proportions (0.697 and 0.703, respectively) occur under high-flow conditions.

Land use within the catchment is shown in Fig. 18. Urban land occupies only 2.08% of the modelled catchment (Table 14) and the estimated density of residences is 28.81 km^{-2}.

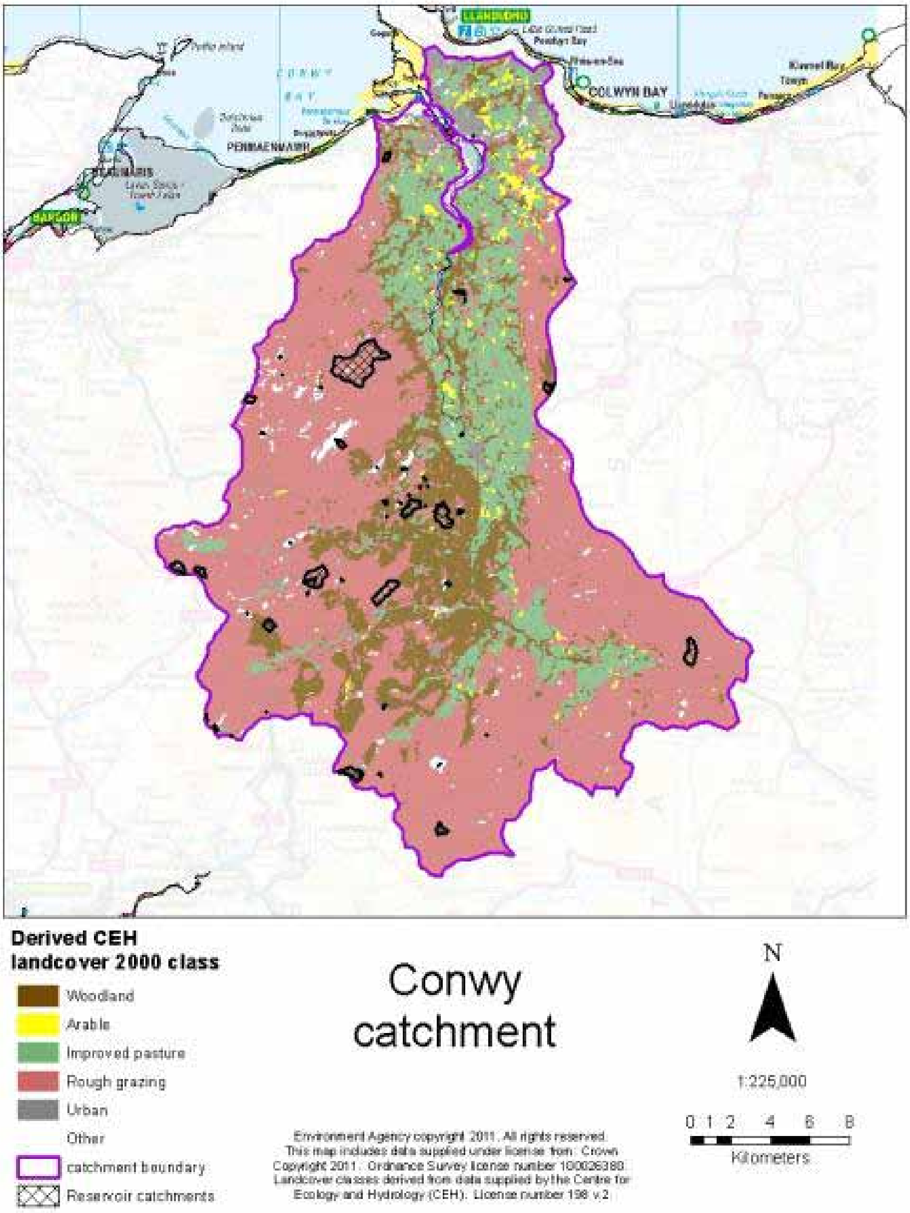

Fig. 18: Conwy: land use within shellfish water catchment.

The principal settlements are all located close to the shellfish water: Conwy, Llandudno Junction and parts of Llandudno, much of the sewerage of which is exported out of the catchment for treatment. The agricultural land is almost entirely associated with sheep farming (stocking density, 530.47 km^{-2}), with 57.20% rough grazing and 19.05% improved grassland. There are also significant areas of woodland (18.31%), more than half of which comprises conifer plantations.

4.6.3 Sewerage sources and improvements to key STWs and IDs

No significant improvements were made to any of the STWs within the catchment, and only one ID was improved: Llanrwst STW overflow, which is located in the mid reaches of the catchment (Fig. 19; Table 12).

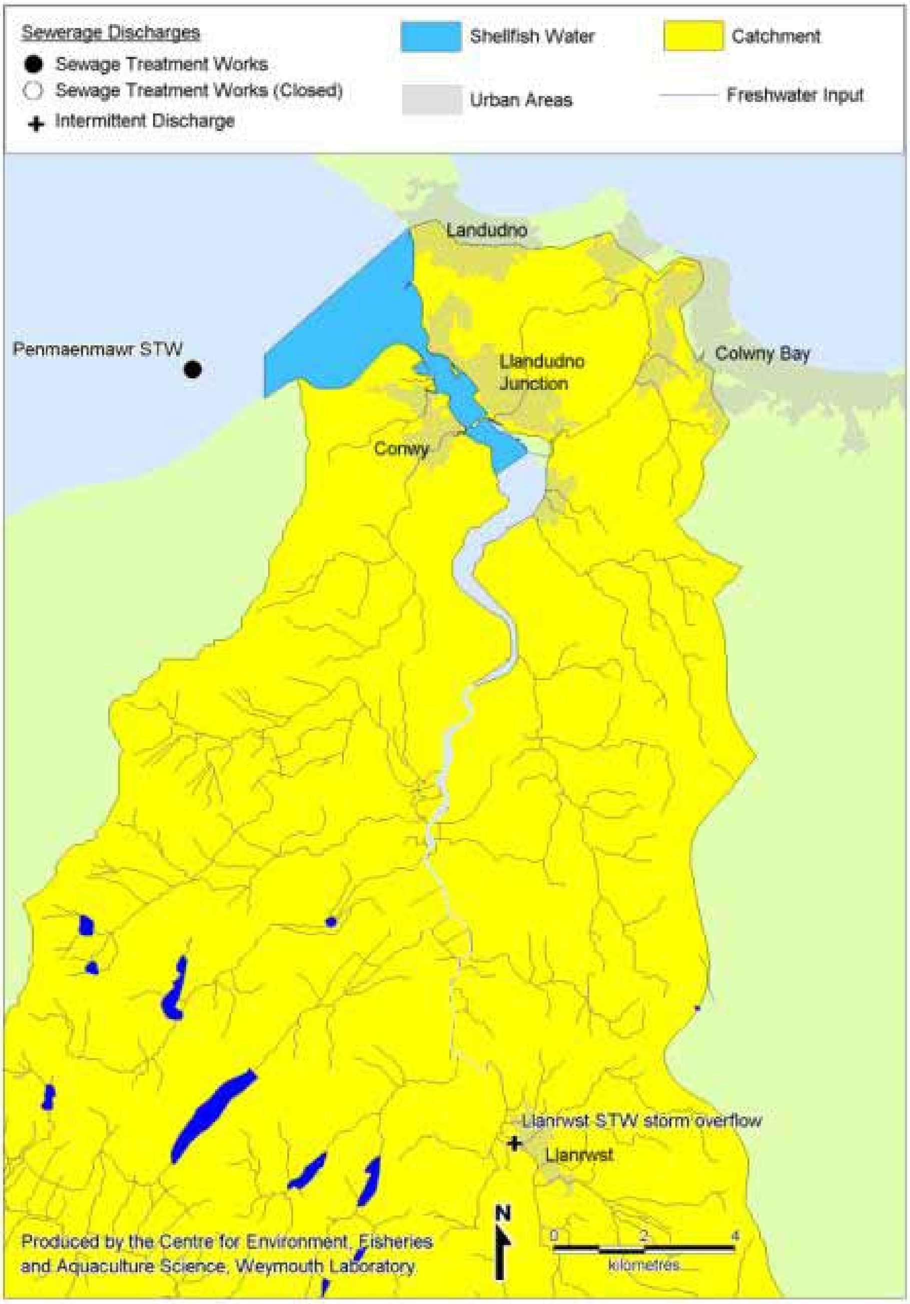

Fig. 19: Conwy: locations of the key STWs/IDs at which improvements have been made.

In these circumstances, the catchment has been regarded has having had no significant sewerage infrastructure improvements over the past decade or so. Sanitary profiling of this shellfish water catchment is complicated by the fact that much of the sewage from Conwy and Llandudno Junction (together with that from Llandudno) is UV-treated at Ganol SWT, which is located to the east of Llandudno, well outside the topographic catchment. Since the treated effluent from this plant discharges to the sea > 10 km to the east of the designated shellfish water, it is unlikely to affect shellfish water quality. In addition, however, some sewage from the north-western part of the catchment is treated at Penmaenmawr STW (Fig. 19), which has secondary treatment and discharges via a long-sea outfall < 2 km from the western edge shellfish water. Clearly, effluent from Penmaenmawr STW may impact upon the shellfish water.

In total, there are 19,588 properties within the catchment. In the absence of data on the number of residences for which sewage is exported outside the topographic catchment, it has been assumed that the all the sewage from Conwy and Llandudno Junction is exported. According to the 2001 Census, the combined population of Conwy and Llandudno Junction was 10,448, which equates to 4427 residences (at the standard occupancy rate of 2.36 people/residence). After eliminating these residences, the number of residences served by STWs within the catchment is 15,161. This equates to an average of 28.81 residences km^{-2} in the modelled catchment.

4.6.4 Predicted summer FC and EN concentrations and fluxes in waters derived from all catchment sources

Quite high GM FC and EN concentrations are predicted (Table 18), e.g. present day high-flow concentrations are 2.9×10^4 and 2.8×10^3 cfu 100 ml^{-1}, respectively. These figures are a reflection of the low density of residences (i.e. human sources) being compensated by the very large numbers of sheep (530.47 km^{-2}) and quite low BFI. The resulting total fluxes of FC and EN over the summer period are: 4.5×10^{16} and 4.2×10^{15} cfu, respectively (Tables 19 and 35).

Table 35: CONWY: Summary of present fluxes to the shellfish waters during the summer bathing season.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Total flux	1.1E+15	4.4E+16	4.5E+16	1.0E+14	4.1E+15	4.2E+15
Key STWs (%)	0.00	0.00	0.00	0.00	0.00	0.00
IDs associated with key STWs (%)	0.00	0.00	0.00	0.00	0.00	0.00
Other catchment sources (%)	100.00	100.00	100.00	100.00	100.00	100.00
Sewage-related sources (%)	61.33	38.45	39.03		39.51	
Agriculture-related sources (%)	38.67	61.55	60.97		60.49	

4.6.5 Observations on Pollution Reduction Programme proposals

The results presented in Table 35 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 29). These findings support the dual focus on sewage- and agriculture-related sources in the PRP. In the PRP 13 STWs are identified has having a significant or potentially significant impact on the shellfish water: Penmaenmawr. Llanrwst, Dolgarrog/Talybont, Trefriw, Eglwysbach, Rowen, Tyn-y-Groes, Henrhyd, Melin-y-Coed, Prentrfelin, Graig, Dolwyd and Fron Dawel/Cartrefle Marine Drive. In cases where flow and FIO monitoring data are available for the sewage-related sources, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose. Hopefully, the outcomes of the on-going Welsh BWDP project in the Conwy catchment will provide useful insight into the control of diffuse- and point-sources of FIOs from agricultural land.

4.7 Ribble

4.7.1 Overview of designated shellfish water

The Ribble is a funnel shaped macrotidal estuary with an intertidal area of approximately 106km^2. The estuary supports important populations of mussels (*Mytilus edulis*) on littoral mixed substrata, cockles (*Cerastoderma edule*) and other less abundant bivalves such as razor clams (*Ensis* spp.) in intertidal sandy flats and peppery-furrow clams (*Scrobicularia plana*) in littoral sandy mud shores.

The designated shellfish water (Plate 7) covers a total area of approximately 41 km^2. It was first designated in 1999.

Plate 7: Upper Ribble.

Cockles and mussels were firstly classified under Food Hygiene Regulations in 1992 and 1995, respectively. Currently, mussel beds occur along the edges of the main river channel at Long Bank. Commercially sized cockles occur in various discrete areas at Sanks Sands, Marshside Sands and Salter's Bank. Shellfish are harvested by hand over periods of low water. The cockle fishery is usually closed during the period 1 May–31 August on conservation grounds. Large cockle beds with harvestable stocks are intensively fished during the first weeks of September. No trend in GM FC concentrations in shellfish flesh was observed over the period 1999–2008 (Table 1).

4.7.2 *Catchment characterisation*

The extent of the catchment is shown in Fig. 20. It covers an area of 2114.81 km^2, with *c.* 8% of the runoff to the shellfish water being affected by lakes/reservoirs, mostly in the higher land of the Pennines and Forest of Bowland (modelled:total catchment area ratio, 0.917).

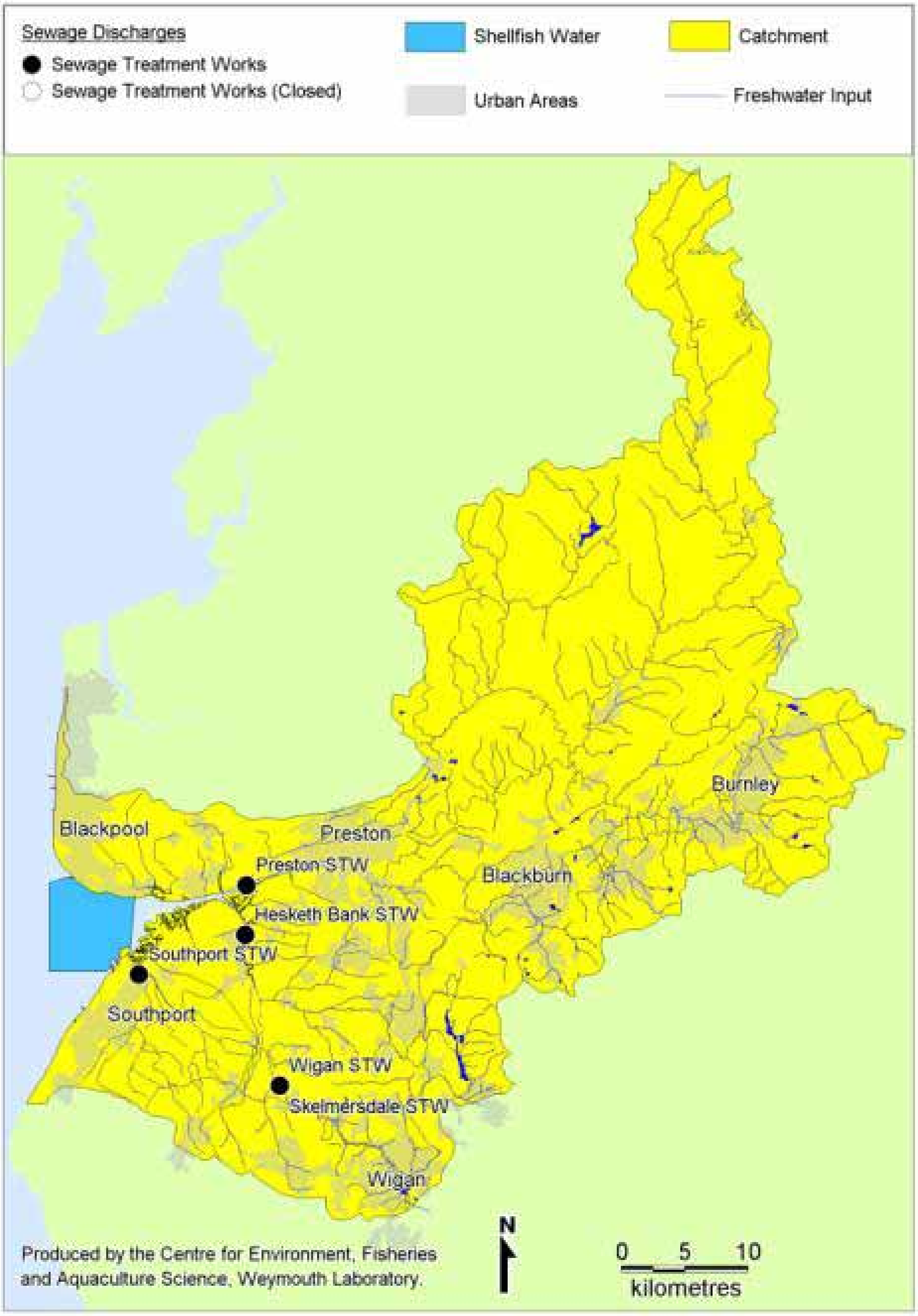

Fig. 20: Ribble: boundary of shellfish water catchment.

In view of the large size of the catchment, it is possible that the catchment fluxes reported will be overestimates, especially under base-flow conditions, because of the likelihood of some die-off of FIOs along the watercourse. The geology largely comprises Permo-Triassic sandstones with a cover of glacial till, mostly in the lower reaches, and a mixture of Carboniferous sandstones, shales and limestones. On the whole, the soils are poorly drained, with the majority being surface-water gleys: notably typical stagnogleys with clay-enriched subsoils (Salop association) in the lower sections and cambic stagnogleys (Brickfield 3 association), which lack clay-enriched subsoils, in the mid sections. Ironpan stagnopodzols (Belmont association), with a wet peaty surface horizon, and blanket peats (Winter Hill association) occur on the higher ground (SMEW, Sheet 1, SSEW, 1983). Because of the generally poorly drained soils and the areas of steeper terrain in the Pennine and Forest of Bowland headwaters, the mean BFI is low (0.407) – the lowest of the seven shellfish water catchments. As a consequence, while the total volumes of flow are not especially high (1330 and 2512 m^3 km^{-2} day^{-1}, respectively, in summer and winter), high proportions (0.692 and 0.708, respectively) occur under high flow conditions.

Land use within the catchment is shown in Fig. 21. Urban land occupies 15.06% of the modelled catchment (Table 14) and the estimated density of residences is 253.00 km^{-2}.

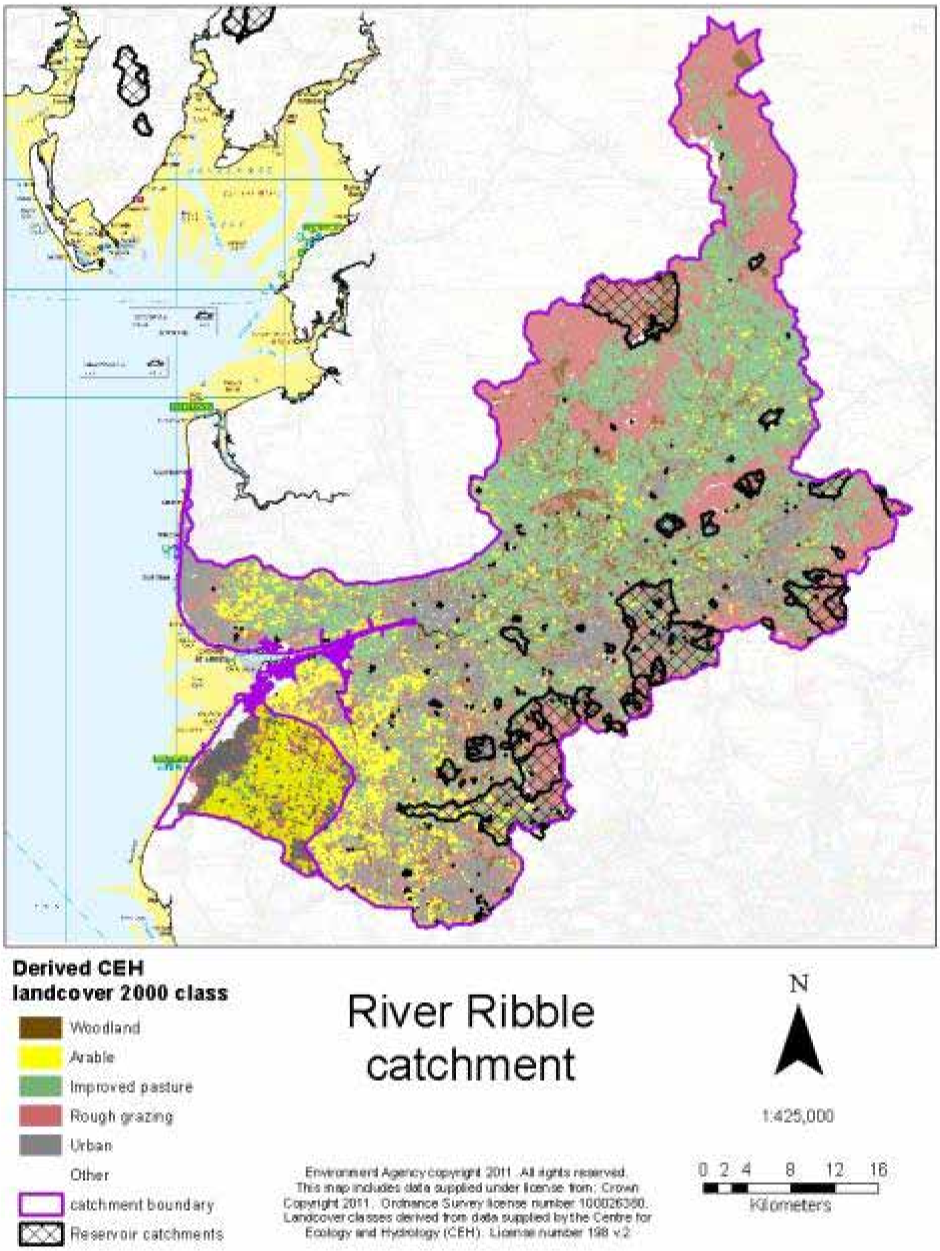

Fig. 21: Ribble: land use within shellfish water catchment.

The catchment includes several major urban settlements, including Preston, Blackburn, Accrington, Leyland, Chorley, Wigan and Skelmersdale – all of which are located in the lower reaches of the catchment. The agricultural land is predominantly used for pastoral farming, with 32.37% improved grassland and 29.21% rough grazing (cf. 12.58% arable). Total cattle and sheep stocking densities in the post-improvement period average 54.08 and 215.83 km^{-2}, respectively.

4.7.3 Sewerage sources and improvements to key STWs and IDs

The locations of the key STWs and IDs that have been improved are shown in Fig. 22.

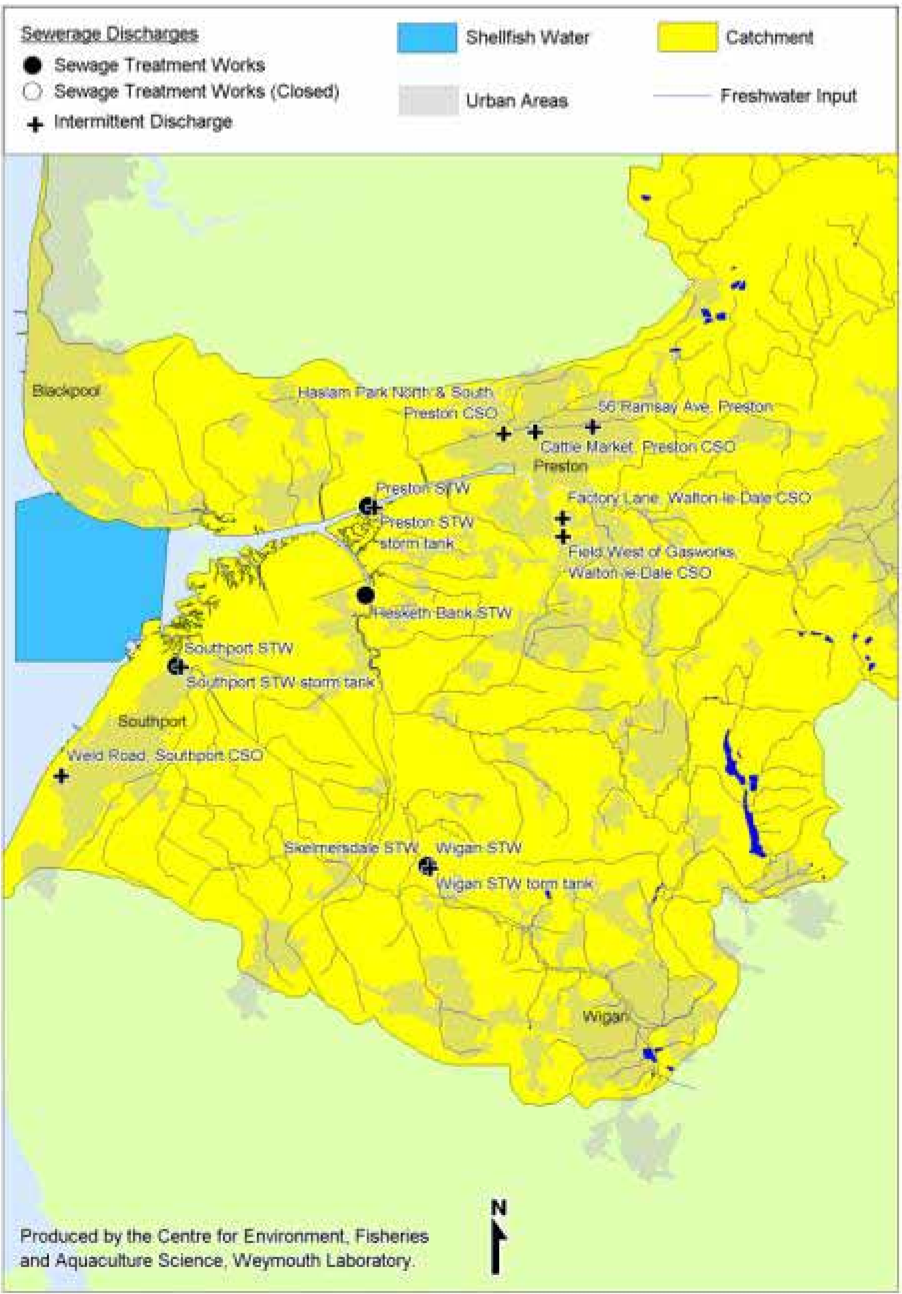

Fig. 22: Ribble: locations of the key STWs/IDs at which improvements have been made.

There are five key STWs within the catchment (Table 11): Hesketh Bank (post-improvement PE: 5279), combined Wigan/Skelmersdale (PEs: 336814/65796), Preston (PE: 236855) and Southport (PE: 91914) – all of which are located in the lower reaches of the catchment, and hence in quite close proximity to the shellfish water.

UV disinfection was installed at each at some time between 1999 and 2005 (as detailed in Table 11). In the case of Wigan/Skelmersdale, FC and EN concentrations in the UV-treated effluent were initially quite high, which was thought to be attributable to the effectiveness of the UV disinfection being reduced by the presence of coloured trade effluent from a food processing plant (Philip Wittred, Environment Planning Officer, EA – pers. comm.). A scheme commissioned in March 2010 to improve final effluent quality for BOD and ammonia at Wigan/Skelmersdale has also led to marked reductions in FC and EN concentrations. Consequently, GM FC and EN concentrations recorded since March 2010 have been used for the post-improvement period at Wigan/Skelmersdale STW.

In addition, improvements were also completed to 10 IDs in the period 2001–5 (Table 12). It is estimated that post-improvement there are an average of 92.00 residences km^{-2} in the modelled catchment that are not served by the five key STWs (Table 15), and these represent a further significant sewerage-related source.

4.7.4 Predicted summer FC and EN concentrations and fluxes in waters derived from catchment sources other than those associated with key STWs pre- and post-improvement

Quite high GM FC and EN concentrations are predicted (Table 18), e.g. high-flow concentrations post-improvement are 4.2 x 10^{4} and 2.8 x 10^{3} cfu 100 ml^{-1}, respectively. These figures are a reflection of the high density of residences (134.24 km^{-2}), quite high numbers of livestock, and predominantly poorly-drained soils (BFI, 0.407). The resulting total fluxes of FC and EN from this large catchment (2114.81 km^{2}) over the summer period post-improvement are 1.2 x 10^{17} and 8.0 x 10^{15} cfu, respectively (Table 19).

4.7.5 Estimated summer FC and EN fluxes derived from the final effluents of the key STWs pre- and post-improvement

The estimated fluxes reveal very marked reductions in FC and EN fluxes following improvement under both base- and high-flow conditions (Table 20). The total fluxes of FC and EN change by -99.76 and -99.56%, respectively.

4.7.6 Estimated summer FC and EN fluxes derived from key IDs pre- and post-improvement

The estimated fluxes (all at high flow) based on the standard assumptions detailed in Section 2.5 are presented in Table 21. FC and EN fluxes prior to improvement are 2.0 x 10^{16} and 3.6 x 10^{15} cfu, respectively. Best- and worst-case scenarios are presented in Tables 22 and 23.

4.7.7 Assessment of impact of improvements to STWs and IDs

A summary of the estimated FC and EN fluxes pre- and post-improvement to the Ribble catchment and of the resulting changes is presented in Table 36.

In the pre-improvement period, just under one-third of the total fluxes of FC (29.22%) and EN (30.06%) were derived from the key STWs, whereas their associated IDs account for a further 8.28 and 16.09%, respectively. Other catchment sources therefore contribute significantly to the overall fluxes of FC (62.50%) and EN (53.86%) – which is, in part, attributable to the large size of the catchment and high density of residences that are not served by the key STWs.

Following improvements to the five key STWs and their associated IDs the total fluxes of FC and EN changed by -49.79 and -62.25%, respectively. The treated effluents from the key STWs are now very minor contributors to the total fluxes of FC (0.14%) and EN (0.35%), and their associated IDs only contribute a further 1.63 and 4.22%, respectively. The majority of the fluxes of FC (98.23%) and EN (95.44%) are therefore derived from other catchment (sewerage- and livestock-related) sources, and it is these that would appear to offer the greatest potential for achieving further reductions.

Table 36: RIBBLE: Summary of estimated fluxes to the shellfish waters during the summer bathing season pre- and post-improvement.

Shellfish water	FC			EN		
	Base flow	High flow	Total flow	Base flow	High flow	Total flow
Pre-improvement						
Total flux	5.5E+16	1.9E+17	2.5E+17	4.6E+15	1.7E+16	2.2E+16
Key STWs (%)	86.73	12.73	29.22	92.73	13.43	30.06
IDs associated with key STWs (%)	0.00	10.66	8.28	0.00	20.36	16.09
Other catchment sources (%)	13.27	76.62	62.50	7.27	66.22	53.86
Post-improvement						
Total flux	7.0E+15	1.2E+17	1.2E+17	3.6E+14	8.0E+15	8.3E+15
Key STWs (%)	1.76	0.04	0.14	5.91	0.10	0.35
IDs associated with key STWs (%)	0.00	1.73	1.63	0.00	4.41	4.22
Other catchment sources (%)	98.24	98.23	98.23	94.09	95.50	95.44
Sewage-related sources (%)	59.36	47.76	48.42		47.96	
Agriculture-related sources (%)	38.88	50.48	49.81		47.54	
Post-improvement change						
Total flux	-4.8E+16	-7.5E+16	-1.2E+17	-4.3E+15	-9.5E+15	-1.4E+16
Total flux (%)	-87.12	-39.09	-49.79	-92.23	-54.30	-62.25
Key STWs (%)	-86.50	-12.70	-29.15	-92.27	-13.38	-29.92
IDs associated with key STWs (%)	0.00	-9.60	-7.46	0.00	-18.34	-14.50
Other catchment sources (%)	-0.62	-16.78	-13.18	0.04	-22.57	-17.83
Best case ID scenario						
Pre-: total flux	5.5E+16	1.8E+17	2.3E+17	4.6E+15	1.5E+16	1.9E+16
Post-: total flux	7.0E+15	1.1E+17	1.2E+17	3.6E+14	7.6E+15	8.0E+15
Post-: flux from IDs associated with key STWs (%)	0.00	0.04	0.04	0.00	0.11	0.10
Change: total flux	-4.8E+16	-6.1E+16	-1.1E+17	-4.3E+15	-7.1E+15	-1.1E+16
Change: total flux (%)	-87.12	-34.79	-47.24	-92.23	-48.17	-58.71
Key STWs (%)	-86.50	-13.83	-31.13	-92.27	-15.86	-34.14
IDs associated with key STWs (%)	0.00	-2.68	-2.04	0.00	-5.57	-4.24
Other catchment sources (%)	-0.62	-18.28	-14.08	0.04	-26.75	-20.34
Worst case ID scenario						
Pre-: total flux	5.5E+16	5.8E+17	6.4E+17	4.6E+15	8.6E+16	9.1E+16
Post-: total flux	7.0E+15	3.2E+17	3.3E+17	3.6E+14	4.3E+16	4.4E+16
Post-: flux from IDs associated with key STWs (%)	0.00	64.18	62.79	0.00	82.42	81.74
Change: total flux	-4.8E+16	-2.7E+17	-3.1E+17	-4.3E+15	-4.3E+16	-4.7E+16
Change: total flux (%)	-87.12	-45.43	-49.00	-92.23	-49.68	-51.85
Key STWs (%)	-86.50	-4.15	-11.20	-92.27	-2.71	-7.28
IDs associated with key STWs (%)	0.00	-35.80	-32.73	0.00	-42.40	-40.23
Other catchment sources (%)	-0.62	-5.48	-5.07	0.04	-4.57	-4.34

4.7.8 Observations on Pollution Reduction Programme proposals

The results presented in Table 36 (which are based on generic assumptions made with regard to the contributions of IDs to FIO fluxes and must therefore be interpreted with caution), suggest that the five key STWs and their associated IDs now contribute only a relatively small proportion (≤5%) of the total FIO fluxes to the shellfish water. Provisional source-apportionment estimates suggest that both sewage- and agriculture-related sources contribute significantly to the present fluxes (Fig. 30). These findings support the PRP's dual focus on addressing sewage-related point-source pollution (e.g. UV installation at Blackburn, Croston and Walton-le-Dale STWs (all due to be completed in 2013) and improvements to targeted IDs) and diffuse agricultural sources, through the CSF initiative (the Ribble is identified as a Priority Catchment for Phase 2 of the ECSFDI project). In cases where flow and FIO monitoring data are available for the sewage-related sources, then estimates can be made of the reductions in fluxes that are likely to be achieved as a result of investment in individual programmes of work. In the absence of such data, then the generic figures reported in the present investigation could be used for this purpose. Hopefully, the outcomes of the CSF project will provide useful insight into the control of diffuse- and point-sources of FIOs from agricultural land within the Ribble catchment.

5 Conclusions/recommendations

5.1 Data limitations

Quantitative sanitary profiling involves the creation of an inventory of the key sources of pollutants, in this case FIOs, and quantifying the fluxes associated with these. Ideally, such an investigation would be able to draw on long-term monitoring data (flow and FIO concentrations) for all key microbial sources within the catchments, thereby enabling accurate characterisation of FC and EN fluxes from each source at different times of year and under base- and high-flow conditions. Unfortunately, however, many sources are simply not monitored and where monitoring is undertaken the data generated are often inadequate for accurate characterisation of FC and EN concentrations and fluxes, particularly at times of high flow associated with rainfall events.

The present study catchments clearly highlight the inadequacy of existing data:

- **Catchment-derived fluxes:** none of the shellfish water catchments have suitable monitoring data available for calculating seasonal or annual, base- and high-flow FC and EN fluxes pre- and post-improvement, either from the entire catchment or for those areas upstream of the key STWs.
- **STW treated effluent fluxes:** for none of the key STWs are data available for effluent fluxes prior to installation of UV disinfection, and even for the post-improvement period the data available are often very limited, with no base-/high-flow separation being made.
- **ID fluxes:** the existing flow/FIO database is totally inadequate for each of the shellfish water catchments, thereby precluding the calculation of the reductions in fluxes at most of the IDs where improvements in storage capacity have been made, and providing no basis for calculating the overall fluxes derived from all the IDs within the sewerage network of each of the key STWs.

As a consequence it has been necessary to estimate fluxes using the following generic data (mostly from previous CREH studies):

- **Catchment-derived fluxes:** based on regression models of the relationship between GM FC and EN concentrations in rivers draining 204 (CREH and CSF) subcatchments across England and Wales (the CREH data published in Kay *et al*., 2008b) and catchment characteristics; and flow volume estimates supplied by the EA. It should be noted that most of the CREH studies were specifically undertaken to investigate FIO sources and fluxes during the summer bathing season, and that insufficient data are available for modelling FC and EN concentrations during the winter period.
- **STW effluent fluxes:** for key STWs where monitoring data are lacking, GM concentration data for raw sewage flows (associated with IDs) and for effluents produced by different levels/types of treatment have been used. These data are mostly based on quite large numbers of samples (Table 2; Kay et al., 2008a). In the absence of flow data a mean total flow of 355 l PE^{-1} day^{-1} has been used, with base and high flows of 260.2 and 94.8 l PE^{-1} day^{-1}, respectively (CREH data derived from 53 STWs; Table 3).
- **ID fluxes:** the existing empirical flow/FIO database is inadequate in each of the shellfish water catchments, thereby precluding the calculation of the reductions in fluxes at most of the IDs where improvements in storage capacity have been made, and providing no basis for calculating the overall fluxes derived from all the IDs within the sewerage network of each of the key STWs. In this regard the ratio of ID flow:total STW effluent flow (0.0429) recorded in one detailed

monitoring/modelling investigation undertaken by CREH of the ID flows associated with a large STW in the UK has been used to estimate the total flow from IDs within the area served by the key STWs. Since estimates made in four other CREH studies have revealed extremely wide variability in this ratio (0.031–0.873), the value used in the present study needs to be regarded with extreme caution. Unfortunately, these previous CREH studies provide no basis for estimating the reductions in flow volumes resulting from improvements to the IDs (mostly increases in storage capacity, but also transfers of flow for treatment). For present purposes it has been assumed that improvements have reduced flow volumes at the IDs by 90%. Generic GM FC and EN concentration data for untreated sewage flows from previous CREH studies have been used in estimating the ID fluxes. The effects of varying the ID flow:total STW effluent flow ratio and the percentage reductions in ID flows following improvements are reflected in the best- and worst-case scenarios reported.

The sanitary profiles presented for the seven shellfish water catchments for the summer period must therefore be regarded as best estimates based on the assumptions specified. In the absence of adequate winter data, it has been argued that mean daily fluxes in winter are likely to be very similar to those in summer. On this basis, the winter and annual figures have been estimated *pro rata* from the summer fluxes.

Clearly, the empirical evidence base currently available for underpinning policy is limited with regard to the sources and fluxes of FIOs. In order to undertake an accurate quantitative assessment of the effectiveness of measures introduced to reduce FIO fluxes to shellfish waters, detailed programmes of monitoring need to be undertaken to determine the fluxes of the individual sources, both before and after intervention, to allow accurate characterisation of both seasonal variations and, in particular, base- and high-flow conditions. This applies to interventions with respect both to point sources (primarily sewerage-related) of FIO pollution and to diffuse sources (e.g. agricultural BMPs) – hitherto, monitoring data from the ECSFDI and BWDP projects provide an inadequate basis for assessing the impacts of BMPs.

5.2 Assessment of impact of improvements to key STWs and IDs upon FC and EN fluxes to the shellfish waters studied

Comparison of the total fluxes of FC and EN pre- and post-improvement reveals reductions over the six sites of 39.83–87.98% and 35.64–93.91%, respectively (Table 26). Clearly, these figures are the result of the interaction between the reductions in fluxes achieved through improvements to the STWs and IDs and the levels of background fluxes from other catchment sources. The latter are dependent upon factors such as density of residences not served by the key STWs, stocking densities, hydrological characteristics of the soils (BFI), proportion of catchment located upstream of lakes/reservoirs, and catchment size (which affects overall volumes of flow). The smallest percentage improvements are in the Yealm catchment, which is largely attributable to the relatively small contribution that key STW and its associated IDs were making to overall FC and EN fluxes (25.61 and 16.12%, respectively) in the pre-improvement period. The largest percentage improvements were recorded for the Taw/Torridge catchment. In this case the treated effluents from the key STWs pre-improvement (some of which effected only primary treatment) accounted for higher proportions of the FC (81.12%) and EN (86.12%) fluxes than in the other catchments (Table 24), and therefore the potential for improvement through the introduction of UV disinfection was greater. In fact, with the establishment of Cornborough STW, a much higher proportion of treated effluent from within the catchment is now discharged to sea outside the shellfish water catchment.

On the basis of the assumptions used in the present investigation, the estimated percentages of FC and EN presently (i.e. post-improvement) derived from the treated effluents of key SWTs, IDs associated with the key STWs and other catchment sources (which include both sewerage- and agriculture-related sources) are presented in Table 25. These results are critical from the point of view future interventions to reduce FIO fluxes to the shellfish waters in that they identify the sources that might best be targeted. In all six catchments in which improvements have been made to the key STWs, treated effluents from these now make only very minor contributions (≤ 0.61%) to the total fluxes. On the basis of the assumptions used, in the five catchments (i.e. excluding Chichester and Conwy) where some IDs have been improved, then the IDs post-improvement contribute only relatively small proportions of the total FC (≤ 4.21%) and EN (≤ 6.82%) fluxes. It should be emphasised, however, that these figures are very strongly dependent upon the assumptions made. Thus, under the worst-case scenarios reported for the IDs, the contributions of IDs following improvement in these same five catchments are all > 50%, with figures ranging from 51.47–81.72% for FC and 50.01–88.15% for FC (as reported in Tables 31–34 and 36). Clearly, in the absence of accurate flux data for the IDs pre- and post-improvement, the outcomes of the present quantitative sanitary profiling must be regarded with extreme caution, both in terms of the fluxes reported pre- and post-improvement, and of their apportionment to the three sources identified, namely: treated effluent from key STWs, IDs associated with the key STWs and other catchment sources.

5.3 *Recommendations regarding strategies for reducing further the FIO fluxes to the shellfish waters studied*

On the basis of the various assumptions used in the present investigation, estimates have been made of the annual FC and EN fluxes to the shellfish waters (Table 28) both pre- and post-improvements. The post-improvement figures provide a measure of the present situation, and it is against these that the likely impact of any further improvements in the sewerage infrastructure, such as those proposed in the various PRPs, and/or the implementation of BMPs to reduce FIO fluxes from agricultural sources would need to be assessed. Very preliminary source-apportionment estimates suggest that both sewage- and agriculture- related sources contribute significantly to the present fluxes from all seven catchments investigated (Table 29) – a finding which supports the dual focus of PRPs on both sources.

5.3.1 *Assessment of likely impacts of further improvements to sewerage infrastructure*

In the case of STWs, then the most likely area of future investment would be the extension of UV disinfection to other STWs within the catchments. The likely reductions in FC and EN fluxes resulting from any new UV installations would largely depend upon the type of treatment presently employed and the volume of flow through the plant. On the basis of the generic data on GM FC and EN concentrations in sewage effluents reported in Table 2, and assuming an average flow of 355 l PE^{-1} day^{-1}, with a base- and high-flow components of 260.2 and 94.8 l PE^{-1} day^{-1}, respectively (Section 2.2.2), then estimates can be made of the likely reductions that would be achieved for a given STW. For example, in the case of a STW with secondary treatment (using generic secondary figures in Table 2), then the effect of installing UV disinfection would be an estimated reduction in FC and EN fluxes of 4.9×10^{11} and 4.3×10^{10} cfu PE^{-1} yr^{-1}, respectively.

In order to evaluate the specific impact of improvements to a particular ID within a catchment, then water company data would be needed on the present volumes of flow and GM FC and EN concentrations (ideally, on a seasonal basis), and on the estimated reductions in flow volume that would be achieved as a result of improvement. In the absence of FIO data, then the generic figures for untreated sewage (Table 2) could be used.

5.3.2 *Assessment of likely impacts of future implementation of BMPs to reduce FIO fluxes from agricultural sources*

There is a reasonably good understanding of the effectiveness of individual BMPS in reducing FIO fluxes to watercourses from steading and field sources (see review by Kay et al. (in press), based on CREH (2010) – commissioned by Defra as part of the Demonstration Test Catchments Initiative (project WQ0203)). By comparison, relatively few empirical data are available on their overall effectiveness in reducing FIO fluxes at the catchment scale, and investigations that have been undertaken have produced somewhat equivocal and inconsistent results. For example, studies in Scotland provide evidence of FIO flux reductions resulting from streambank fencing in the Brighouse Bay, Sandyhills and Nairn catchments, especially where fencing exceeds 30% of streambank length, though there is no consistent relationship between the reductions observed and extent of fencing (Kay et al., 2005; Kay et al., 2007). Similarly, the effects of improvements in steadings were evident in results from the Ettrick Bay catchment, but not from the Killoch catchment (Kay et al., 2005). The need for further catchment-scale investigation is presently being addressed by Defra- and SEPA-funded projects on the effectiveness of farm ponds and streambank fencing in reducing catchment fluxes; the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) and the Bathing Waters and Diffuse Pollution (BWDP) project in Wales. Indeed, small subcatchments with five of the shellfish water catchments have been targeted by ECSFDI, though the impacts of these improvements are still being investigated. At present, therefore, even for these five catchments, there is no basis for evaluating the impacts that BMPs are likely to have at the wider catchment scale.

On present evidence, BMP implementation (e.g. fencing of ≥ 30% of stream banks on livestock farms) sufficient to make a significant impact in large SW catchments such as the Taw/Torridge (2094 km^2) could therefore prove extremely costly. Compared with investment in further improvements to STWs and IDs, BMP implementation is therefore less easily targeted and the resulting benefits less easily evaluated.

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8 Appendices

Appendix 1: Acronyms

Acronym	Description
BFI	Base flow index
BMP	Best management practice
BWDP	Bathing Waters and Diffuse Pollution project (in Wales)
cfu	Colony forming units
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CEH	Centre for Ecology and Hydrology
CERF	Regionalised rainfall-runoff model developed by CEH and EA
CREH	Centre for Research into Environment and Health
CSO	Combined sewer overflow
DTM	Digital terrain mapping
ID	Intermittent discharge (storm tank overflow, combined sewer overflow, etc.)
EA	Environment Agency
ECSFDI	England Catchment Sensitive Farm Delivery Initiative
EA	Environment Agency
EN	Enterococci
FC	Faecal coliform
FIO	Faecal indicator organism
FSI	Fine screen installation (at STW)
GM	Geometric mean
HER	Hydrologically effective rainfall
PE	Population equivalent (in present study only human population data are included, i.e. excludes industrial/trade effluent)
PRP	EA Pollution Reduction Programme
PS	Pumping station
SMEW	Soil Map of England and Wales
SSEW	Soil Survey of England and Wales
STO	Storage tank overflow
STW	Sewage treatment works
UV	Ultra-violet (disinfection)

Appendix 2: Glossary

Term	Definition
Adjusted r^2	Proportion of the variance in the dependent variable explained by the predictor variables in a regression model after adjusting for degrees of freedom
Base flow	Periods of relatively low river/stream flow occurring between periods of episodic high flows resulting from rainfall events – conventionally applied in the separation of river hydrographs, but here also applied to STW effluent flow.
Base flow index (BFI)	Index of the proportion of base flow compared with total runoff generated within a catchment
Best management practice (BMP)	Agricultural management practice designed to reduce pollution risk, e.g. streambank fencing to prevent direct voiding of faeces watercourses by livestock
Shellfish water catchment	The land area within the topographic boundary (i.e. located 'upstream') of the seaward ends of shellfish water – as defined by digital terrain models
Export coefficient	Pollution load generated per unit area per unit time – here, for FIOs, expressed as cfu km^{-2} hr^{-1}
Flux	Pollution load discharged from a particular source (sewage treatment works effluent, an entire catchment, etc.) per unit time – here expressed on basis of the 'summer', 'winter' or annual period
Geometric mean (GM)	Antilog of the mean of $\log_{10}$ concentrations of FIOs
High flow	Periods of increased river/stream flow resulting from rainfall events (cf. base flow) – conventionally applied in the separation of river hydrographs, but here also applied to STW effluent flow.
Intermittent discharge (ID)	A discharge point (CSO, STO, etc.) on the sewerage network that has intermittent flow, usually triggered by rainfall
Key sewage treatment works (STWs)	STWs within a shellfish water catchment that have been improved (in all cases by installation of UV disinfection plant) to reduce FIO fluxes in treated sewage effluent
Modelled catchment area	Area of a catchment that is not located upstream of lakes/reservoirs – because of high rates of die-off and sedimentation of FIOs within such waterbodies, FIO concentrations in waters issuing from lakes/reservoirs are evaluated separately (as discussed in text)
Pre-improvement period	Period extending up to the end of the year before the year in which UV disinfection was first installed at one (or more) of the STWs within the catchment
Post-improvement period	Period starting the at the beginning of the year after the year in which UV disinfection was first installed at one (or more) of the STWs within the catchment
Population equivalent (PE)	Number of people served by a STW (based on BOD data) – the data used in the present study exclude industrial/trade effluents
Subcatchment	Topographically defined area upstream of a monitoring point on the river network – often many subcatchments are nested within a single large study catchment
'Summer'	Summer bathing season in England and Wales: 15 May–30 September
'Winter'	Winter here refers to the period outside the summer bathing season – i.e. 1 October–14 May

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