Dŵr Cymru Welsh Water

intertek
Total Quality. Assured.

Evolution of outcome focussed modelling techniques

Authors and Presenters: Paul Taylor and Nick Barcock

Paul Taylor, Principal Consultant, Intertek. mob: 07943 812738. e-mail: paul.taylor@intertek.com
Nick Barcock, Coastal Waters Manager, Dŵr Cymru Welsh Water, mob: 07867 326654. e-mail: nick.barcock@dwrcymru.com

Abstract

Numerical models have been used in support of the planning and design of asset investment schemes for many years and since Asset Management Plan 1 (AMP2, 1990-1995) coastal models have been used to help water utilities deliver the regulatory outputs required of them.

AMP6 saw a change in thinking, and the industry is now outcomes-focussed, with a need to deliver the required evidence-based *outcomes* to address the issues of a catchment or waterbody as a whole, rather than producing a series of individual *outputs* agreed with the regulator, as in previous AMP periods.

Many outcomes identified in the National Environment Programme (NEP) are to address the requirements of the Water Framework Directive (WFD), including helping to achieve compliance with the regulations at designated Bathing Waters and Shellfish Waters. In order to enable the appropriate WFD outcomes to be delivered, a holistic understanding of the whole environment, and the influence of all potential sources on compliance with the relevant directives is required.

Environmental compliance assessments that integrate sewer network models, river catchment models and coastal models, combined with the acquisition and analysis of field data, have been used to provide this understanding, with increasing detail and success as technology and experience have improved tools and methods. The modelling is now entirely outcome-based, using data and other models to represent actual impacts in the environment. This allows the proportional contribution to the problem from each source to be assessed, and enables the modeller to test the environmental benefit that could be achieved through different management approaches. A particular benefit of the evolution of modelling techniques has been the improvement in the representation of diffuse sources and other sources separate to the water company. Furthermore, the risk to future compliance resulting from changes in the sewerage and/or river catchments, or to changes in climate, can also be readily assessed.

This paper provides a history of the application of coastal modelling and improvements in modelling assessment techniques that have evolved over the last three decades through the AMP process. It outlines the current environmental legislation relating to bathing and shellfish waters in particular, and the increasing difficulty in achieving the ever-tightening requirements through asset investment alone, as well as introducing some challenges and potential opportunities for the future. The paper showcases the Coastal Investigations Programme, an £8 million nationwide integrated modelling assessment commissioned by Dŵr Cymru Welsh Water (DCWW) that has helped DCWW and Natural Resources Wales (NRW) to have a better, holistic understanding of all the issues and to develop a targeted, evidence-based investment strategy.

Background

Asset Management Planning

Coastal numerical models have been used for many years but saw increased use in the early 1990s to support investment planning post-privatisation (AMP1), when a large number of crude discharges needed to be replaced with new WwTWs and long sea outfalls to meet the new bathing water standards. The cost of outfall construction was significant and numerical models provided a means of optimising outfall length and minimising cost.

In these early days models and supporting surveys were expensive to commission, restricting the use of models to a few key sites. Model development was limited to a few specialist consultants who developed and ran the software, typically on UNIX platforms as PC's of the time were simply not powerful enough. The process was labour-intensive with data typed in using very prescriptive formats and the programmes run using command lines. Considerable effort was required to extract and plot results using scripts and primitive graphics programmes. Model domains were relatively small, grids optimised, and simulation periods kept to a minimum to keep computation times to acceptable lengths. Runs typically only considered a single outfall for limited (best case / worst case) scenarios. Results often needed to be interpreted by the user to fill in the blanks, with potential risks of over or under-design.

Modelling CSOs presented particular challenges and was generally limited to a few key discharges using worst case scenarios and probability analysis to estimate impacts (or absence of impact) at bathing waters. In most cases CSO investment was based on prescriptive 'three-spill solutions' that could not always take account of local environmental conditions, e.g. dispersion, dilution and decay.

By AMP3 investment in large coastal WwTWs was largely complete and the regulatory focus was moving toward investment in CSOs (unsatisfactory intermittent discharges or UIDs) to further improve bathing water quality. The need for catchment based solutions to secure the necessary water quality improvements was also being recognised, especially where sensitive waters were close to large population centres or at the mouths of rivers with large upstream populations. Improvements in the performance of PCs, advances in numerical modelling software and data processing techniques made coastal modelling more accessible, coast effective and efficient. Improvements in network modelling also meant that large continuous time series describing waste water inputs could be produced. The combination of these factors and innovation in post processing techniques meant that the impacts of CSOs could be accurately modelled and considered as part of catchment based solutions – i.e. focusing investment on those catchments or key assets that made the greatest contribution to non-compliance at sensitive waters. Investment could now be driven by environmental need rather than by applying prescriptive end-of pipe solutions that might not always deliver good value. Modelling now allowed a demonstration of the limited additional benefit that might be gained from a three-spill solution over a less prescriptive (e.g. ten spill) solution, a no-build option where assets did not present a significant risk to water quality, or the use of innovative technologies such as treatment of storm discharges.

By AMP5 concerns over compliance with the Urban Wastewater Treatment Directive (UWWTD) [1] saw a return to more prescriptive CSO design which largely restricted the use of coastal models to assessing the effects of design solutions on water quality.

However in AMP5 and AMP6 considerable investment has been made by a number of water companies in developing coastal models as part of large scale investigation programmes to support current and future investment planning. Output from these models is used to identify the relative contribution of sewage discharges to impacts at bathing waters and determine whether further asset investment could achieved desired regulatory outcomes, e.g. Excellent bathing waters or Guideline quality shellfish waters. In Wales the AMP6 Coastal Investigation Programme has demonstrated that, at most locations around the Welsh coast, further investment would not deliver the necessary improvements in water quality and that these standards cannot be achieved without significant reductions in other pollutant sources, e.g. diffuse pollution and misconnections. The investigations also highlight the potential risk of climate change to maintaining existing standards.

Environmental Legislation

There are a range of environmental requirements, driven by a number of EU Directives, which are applicable to the water industry. These include: the Urban Wastewater Treatment Directive (UWWTD); the Habitats Directive[2]; and the Water Framework Directive (WFD)[3], which incorporates both the Bathing Water Directive (BWD)[4] and the Shellfish Water Directive (SWD)[5]. In terms of water quality in coastal and estuarine waters, the key requirements relate to concentrations of bacteria in the water

---

[1] EU, 1991. Directive 91/271/EEC of the European Parliament and of the Council of 21 May 1991 concerning urban waste-water treatment

[2] EU, 1992. Directive 92/43/EEC of 21 May 1992 of the European Parliament and of the Council on the conservation of natural habitats and of wild fauna and flora

[3] EU, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327, 22/12/2000 P. 0001 – 0073

[4] EU, 2006. Directive 2006/7/EC of the European Parliament and of the Council of 15 February 2006 concerning the management of bathing water quality and repealing Directive 76/160/EEC. Official Journal of the European Union L 64 pp. 37-51. 4 March 2006

[5] EC (2006), Directive 2006/113/EC of the European Parliament and of the Council of 12 December 2006 on the quality required of shellfish waters.

column, and relevant statistical measures are assessed against the requirements for bathing and shellfish waters.

The fundamental objective of the BWD and the SWD is to protect human health (bathers and consumers of shellfish) by promoting better water quality and better management of the designated (protected) areas. The purpose of these directives is not to protect the environment itself.

Bathing Water Directive (daughter directive of the Water Framework Directive)

The 2006 BWD is a daughter Directive of the WFD which came into legislation on 24 March 2006 and came into force in UK waters from the start of the bathing season in 2015. The standards of the 2006 BWD are significantly tighter than those of the previous 1976 BWD[6]. The UK requires all BWs to achieve at least the Sufficient standard by the end of the 2015 bathing season.

The BWD uses bacterial determinands to assess performance, namely *Escherichia coli* (E. coli or EC) and intestinal enterococci (IE). The BWD has four levels of performance; Excellent, Good, Sufficient and Poor. The standards are assessed statistically using data collected during the current bathing season and the three preceding bathing seasons (where possible), making a four-year rolling assessment period providing approximately 80 samples (4 x 20 samples per year). The BWD classifications are assessed by calculating the 90^{th} and 95^{th} percentile value of a log-normal distribution. The distribution is generated from the (usually) 80 samples collected at the bathing water from the preceding four years.

Shellfish Water Directive (now repealed by the Water Framework Directive)

Standards for shellfish flesh quality for human consumption are described under the EU Regulation No. 854/2004 for Products of Animal Origin. The Regulations provide a four tier classification of shellfish flesh quality, based on the concentration of EC present in shellfish flesh, from Class A (highest) to Class D (prohibition as unfit for human consumption). The SWD was implemented to protect or improve shellfish waters in order to support shellfish life and growth and thus to contribute to the high quality of shellfish products directly edible by man. The SWD was repealed in 2013, when its provisions were formally moved under the WFD (March 2016), and sets out physical, chemical and microbiological requirements that designated shellfish waters must either comply with (Mandatory Standard) or endeavour to meet (Guideline Standards).

Shellfish bacterial standards relate to shellfish flesh and cannot be compared directly to water quality due to the complex nature of take up of bacteria by shellfish from the water column. In AMP 4 the Environment Agency (EA) produced a Shellfish Policy for the Class B flesh standard, which states a water quality standard of maximum (97%ile) 1500 EC/100ml and 112 EC/100ml as a maximum geomean. Under WFD member states should endeavour to achieve a Guideline flesh standard of 300 EC/100ml, close to the Class A standard (230 EC/100ml). For the purpose of Price Review 2019 (PR19), the EA have proposed a water quality criteria of 5 EC/100 ml as a geomean to deliver the Guideline flesh standard, although this has not yet been introduced as a formal water quality policy. This represents a

[6] EEC, 1976. Council Directive 76/160/EEC of 8 December 1975 concerning the quality of bathing water. Official Journal of the European Communities L 31 pp. 1-7. 5 February 1976

significantly tighter standard than the existing Class B policy, and will be extremely difficult, if not impossible, to achieve in many shellfish waters.

Disproportionate Costs

In terms of shellfish standards, the WFD requires member states to endeavour to achieve the Guideline flesh standard, and the latest regulations for England and Wales (2017)[7], which came into force on 10th April 2017, have explicitly introduced the concept of undertaking a cost-benefit analysis when assessing the investment requirements needed to achieve the Guideline standard. Specifically the deadline by which environmental objectives should be achieved can be extended, or a less stringent standard can be set, where achievement of the environmental objectives set would be infeasible or disproportionately expensive.

The Shellfish Industry

The value of the UK shellfish industry in 2015 was approximately £264 million (based on shellfish landings into the UK by UK vessels[8]), and for Wales the value was approximately £10 million.

The majority of the shellfish landed is Class B, with only a very small percentage (<5%) being Class A. The increase in value of the industry if all shellfish were Class A is likely to be less than 10% which over a 25 year period equates to approximately £660 million in additional revenue to the UK (based on the 2015 value of the industry).

There has been a steady increase in the quantity and value of shellfish landed in the UK from 1994 to 2011, but there has been a recent decline in shellfish stock levels in recent years, with the quantity of shellfish landings decreasing between 2011 and 2015, from 147,000 tonnes to 141,000 tonnes[8]. Many beds have been closed, or opened for limited periods, due to lack of stock and many more are no longer harvested (active) and have been declassified. The WFD requires the whole designated shellfish water to be compliant with the standards, irrespective of the classification of individual harvested beds. The same standard is applied throughout the shellfish water, which are often large waterbodies, even though only a relatively small proportion is occupied by harvested beds that require protection. This situation could lead to over-investment in assets that may impact the shellfish water locally, but have little or no impact on the more sensitive harvested areas.

Historic water company investment

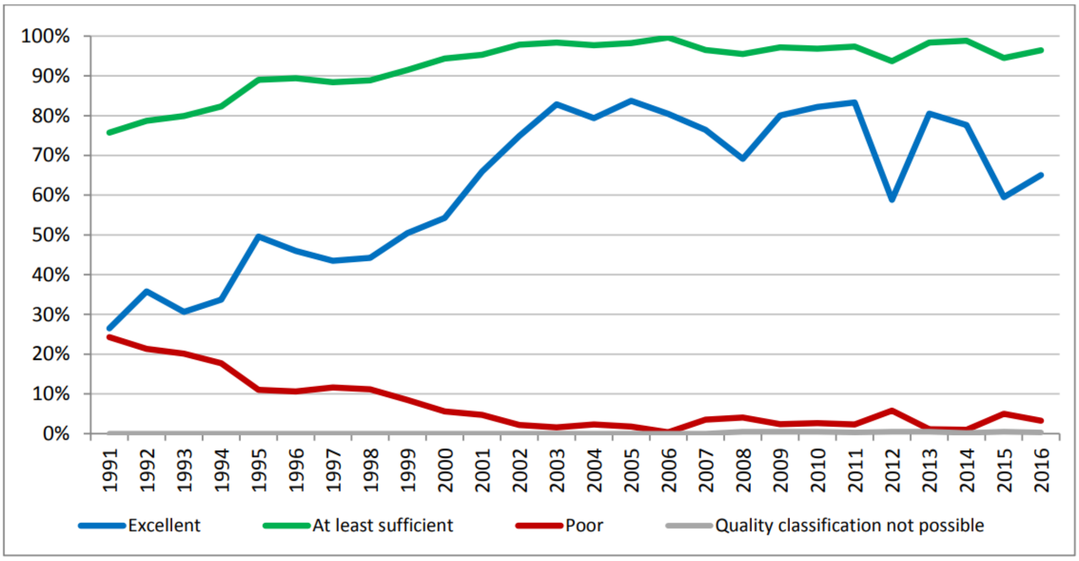
Since privatisation there has been a significant investment by the water industry to improve the performance of assets. This has led to a reduced risk of sewer flooding and a significant improvement in water quality in our rivers, estuaries and coastal waters. Over the last three decades there has been a

[7] Water Environment (Water Framework Directive) (England and Wales) Regulations, 2017
[8] Marine Management Organisation, 2015. UK Sea Fisheries Statistics 2015. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/598208/UK_Sea_Fisheries_Statistics_2015_full_report.pdf

steady improvement in water quality at bathing waters and, to a lesser extent in shellfish waters, significantly reducing risks to human health.

Figure 1 shows the trend in bathing water quality in the UK from 1991 to 2016, which clearly demonstrates a steady reduction in the number of bathing waters of Poor quality (from 25% to < 5%) and a marked increase in the number of bathing waters achieving Excellent classification. In Wales, 84 out of 103 bathing waters achieved the Excellent class in 2016, and only one beach failed to achieve at least the Sufficient classification (Figure 2).

Figure 1. Coastal bathing water quality trend in the UK.



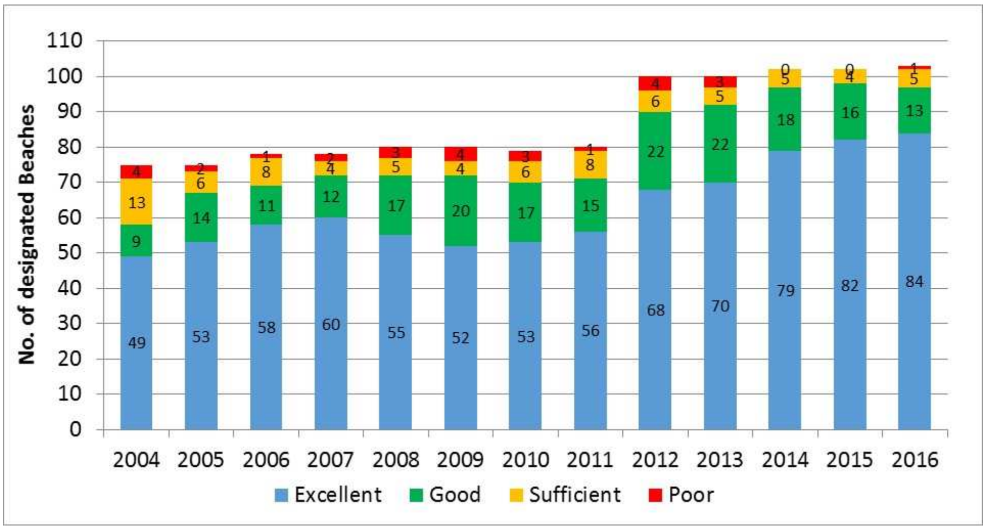
Notes:

1. the "At least sufficient" class also includes bathing waters of "Excellent" quality, so the sum of shares is not 100%

2. Although the current BWD classifications only came into force in 2015, the sample data has been used to determine what the classifications would have been.

Source: BWD report for the bathing season 2016. (https://www.eea.europa.eu/themes/water/status-and-monitoring/state-of-bathing-water/country-reports-2016-bathing-season/united-kingdom-2016-bathing-water-report)

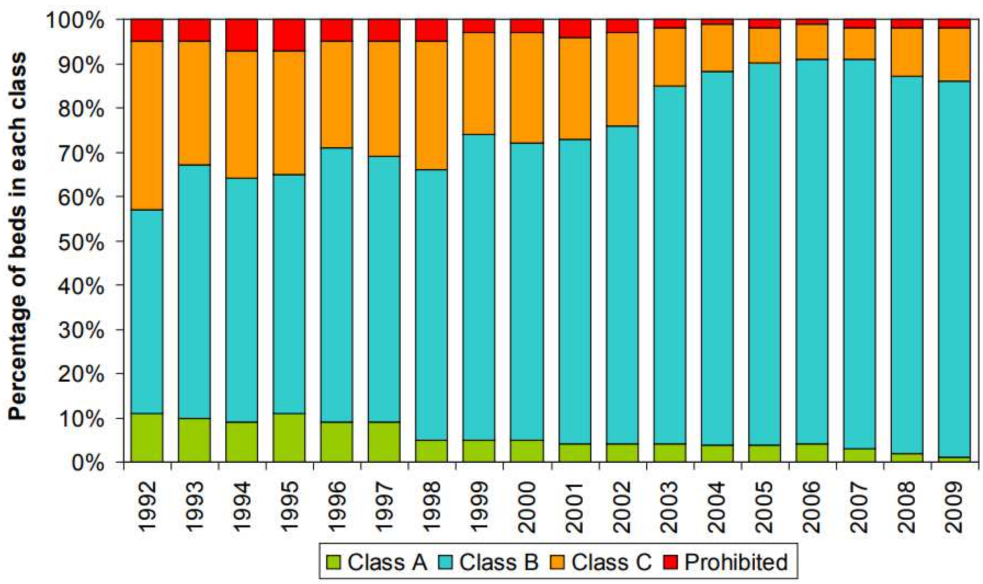
Figure 2. Classification of Bathing Waters in Wales from 2004 to 2016



Source: Natural Resources Wales

Figure 3 shows the classification of shellfish beds in England and Wales for the period 1992 to 2009 (no more recent summary data is available). This again shows a steady increase in the percentage of beds that are Class B or better (from about 55% to 88%), although it is noted that the percentage of Class A beds has fallen (from about 10% to about 1%). In Scotland and Northern Ireland the percentage of Class A or B beds is higher (98% and 100% respectively in 2009), with a higher proportion of Class A beds (40% and 9% respectively in 2009).

Figure 3. Classification of Shellfish beds in England and Wales, 1992 to 2009



Source: Cefas

Current and future compliance

The significant investment in assets by the water industry over the last thirty years, together with more stringent environmental regulations introduced by the WFD, means that the relative importance of non-water company sources of bacteria to water quality has been increasing. Whereas in the past compliance with the relevant standards was largely dominated by water company discharges, current and future compliance with the regulations is increasingly influenced by diffuse loads from agriculture. The necessary improvements in water quality which will be required for all bathing waters to achieve at least the Good classification and for shellfish beds to achieve the Guideline flesh standard, will be increasingly difficult, if not impossible, to achieve through asset investment alone. Furthermore, with efficiency improvements required by OfWAT it is unreasonable for water companies and their customers to continue to invest disproportionately more than their fair share, especially if continued asset improvements deliver ever-diminishing environmental benefits.

In order to develop the most targeted, efficient and effective investment strategies which will deliver the required environmental outcomes, a much better understanding of all potential sources, and the fate and behaviour of their discharges once in the environment is required. Integrated modelling and analysis techniques are now available to enable holistic assessments to be undertaken which deliver an evidence-based understanding of the proportional contribution of each source, so that sound decisions that can realistically address the actual problems can be made collectively by the water company, the regulator and other interested parties.

Evolution of modelling and assessment

Advances in numerical modelling

Over the last thirty years there have been enormous advances in modelling techniques that have led to a huge improvement in the capability and capacity of modelling since AMP1. A range of improvements have developed, including:

- Better computers: The processing power of computers has dramatically improved, combined with a significant reduction in the costs of hardware. This has meant that numerical modelling is now much faster, bigger domain models with much higher resolution can be developed, and an increased number of model scenarios and sensitivity testing is possible.
- Better software: Industry-standard modelling software has continually improved, with more accurate numerical schemes available and a greater range of options, providing a much more flexible and accurate range of tools.
- Better inputs: We now have much better information enabling more accurate inputs. For instance, modelling continuous hydrographs from ten years or more of measured rainfall rather than discrete events based on stochastic rainfall is now possible.
- Better integration: fully integrated modelling is now possible whereby sewer network models, river catchment models, and coastal models can be combined to assess flows and water quality.

- Better compliance assessments: More robust compliance assessments are now possible since better computing and better inputs has enabled limitations due to unknowns and uncertainties to be significantly reduced through sensitivity testing.

Advances in analytical techniques

In addition to the advances in numerical modelling, there have been significant advances over the last thirty years in the acquisition, collection and analysis of the data and information required as inputs for compliance assessments which have also helped the evolution of modelling assessments. These include the following:

- Better data acquisition: There have been vast improvements in data acquisition equipment and techniques, such as LiDAR and multi-beam bathymetry, which has resulted in a far greater quantity of information with a far greater quality. Without this improvement in the accuracy and precision in the data which underpins the models, the improvement in the refinement of the models themselves would have delivered little benefit.
- Better data analysis: Increases in the capacity of laboratories has enabled greater numbers of samples to be collected, and improved data processing tools, such as MATLAB, have meant that we can now analyse, visualise and combine huge volumes of data very rapidly.
- More data: More and more data is being collected and made available, often freely, from different sources. For example, this includes all LiDAR collected by the EA which is now freely available, and long duration rain gauge measurements.
- Better understanding: There has been ongoing and continually improving research into key areas of interest, which has provided a greater understanding of the often complex relationship between different factors influencing an assessment.

Case study – DCWW's Coastal Investigation Programme

Background

DCWW began using coastal numerical models in the early 1990s to support investment planning post-privatisation. The early DCWW models were built by WL Delft on the Delft 3D software suite and the validated models provided to DCWW’s in-house consultancy (Wallace Evans) to operate on SUN (UNIX) workstations. Model domains were relatively small and limited to a few key schemes in the largest coastal catchments: Swansea Bay (Swansea and Afan); Menai Strait (Treborth); and Colwyn Bay (Ganol).

Models developed in AMP1 and 2 were supplemented by further models in AMP3 and 4, notably the Bristol Channel model to support the Barry bathing waters improvements. A number of shellfish water models were also constructed over this period. This period saw the introduction of catchment based solutions in Wales using combined network, river and coastal models and the use of advanced post processing techniques for compliance assessment. AMP5 saw continued use of existing models to support investment in the Swansea Catchment and a few areas in North Wales.

AMP6 has seen a major step change with an ambitious programme to replace all the existing models with a complete suite of high resolution models covering the entire Welsh coastline. These models were used in AMP6 for NEP investigations to support PR19 investment, and will be used to support DCWW investment well beyond AMP7.

Overview of Coastal Investigation Programme

DCWW commissioned its Capital Delivery Alliance Team (AT), supported by Intertek Energy and Water Consultancy Services (Intertek) who provided compliance assessment expertise, to undertake a Coastal Investigation Programme. The project was to assess water quality at 49 sensitive receivers: 29 bathing waters and 20 shellfish waters. These sites were identified by Natural Resources Wales (NRW) in 2013 as part of the AMP6 National Environment Programme (NEP), and completion of all 49 assessments formed a key set of DCWW's NEP outputs.

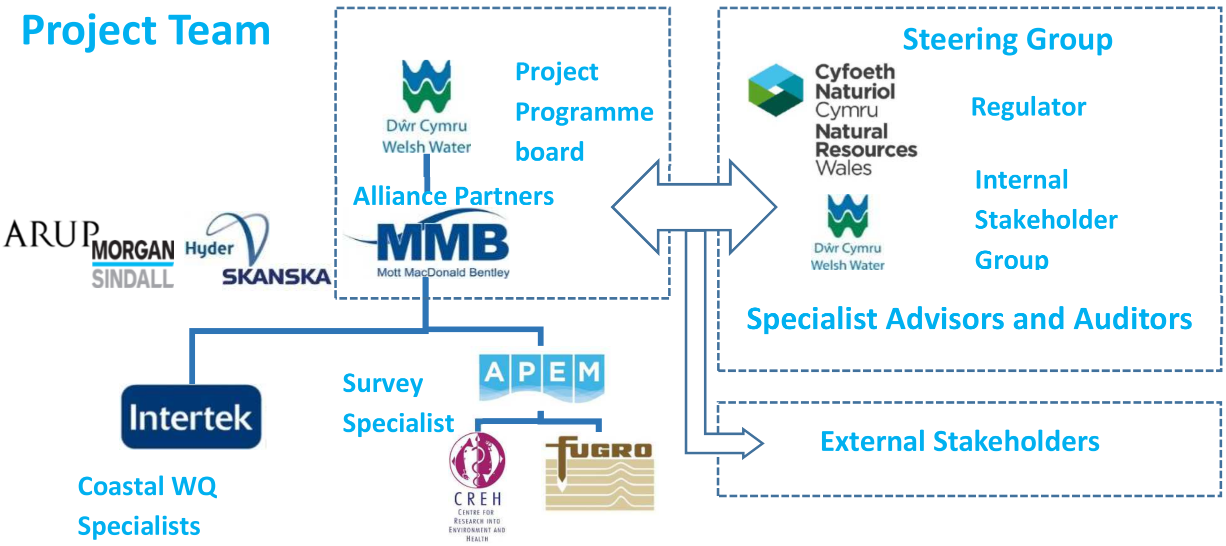
The main objective of this project was to enable DCWW and NRW to identify which sources of bacteria are the most important contributors to water quality issues at the sensitive receivers, and to inform DCWW's PR19. An indication of the level of improvement that might be needed at any identified assets (in order to help improve / maintain bathing and shellfish water performance in the future) was determined to assist with PR19 cost estimates.

The project aimed to answer three key questions:

1. How to achieve and maintain Excellent class bathing waters and gain more Blue Flag beaches in a changing climate?
2. How to improve shellfish quality to meet the WFD Guideline standard and add value to the shellfish industry in Wales?
3. Can water quality be accurately forecast to warn of periods of reduced water quality to help further protect public health?

The £8M project was the largest DCWW has ever undertaken and began in 2015 with final reports issued to NRW summer 2017. Figure 4 shows the project team and relevant stakeholders. Figure 5 indicates the 49 bathing and shellfish waters assessed, and Figure 6 provides an example of the model resolution and field data locations in the north-east area of Wales.

Figure 4. DCWW's Coastal Investigation Programme Project Team



Some of the key features of the Coastal Investigation Programme are as follows:

- NRW agreed approach at the start of the project and fully engaged throughout
- Development of state-of-the-art coastal modelling system for Wales using latest, open-source Flexible Mesh software from Deltares. 2,700 km of coastline modelled using > 500,000 computational nodes.
- External expert audit to review quality of the new coastal models.
- Data collation and gap analysis to ensure all available data was utilised.
- Dedicated survey programme over two years, resulting in 99 vessel surveys and 13 fixed stations generating more than 27,000 hours of data.
- Extensive source sampling and flow gauging exercise to best represent time-varying asset and river loads, delivering more than 8,000 samples in 272 rivers and 72 DCWW assets.
- Utilisation of 700 telemetry datasets and 500 EDM records.
- Flexible sewer modelling approach to best represent the majority of DCWW assets, in 95 sewerage catchments.
- Ongoing stakeholder consultation with local regulators, DCWW operatives, academics and other interested parties.
- Industry-leading compliance assessment approach developed by Intertek and applied throughout the UK which integrates sewer network models, river catchment models and coastal models.
- Successful completion of all NEP deliverables to the satisfaction of NRW.

Figure 5 Geographic overview of the project extent: the 49 sensitive receivers

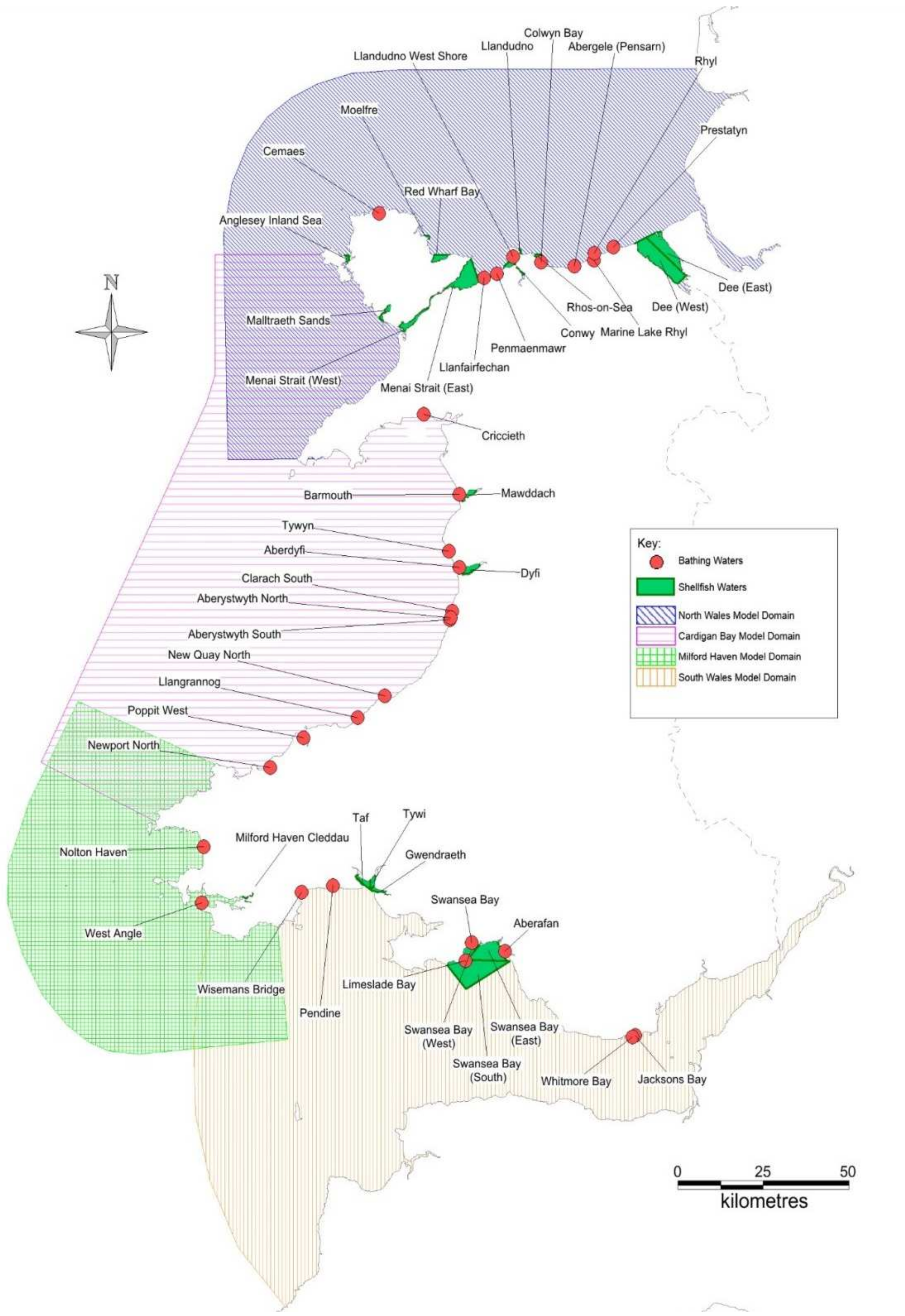
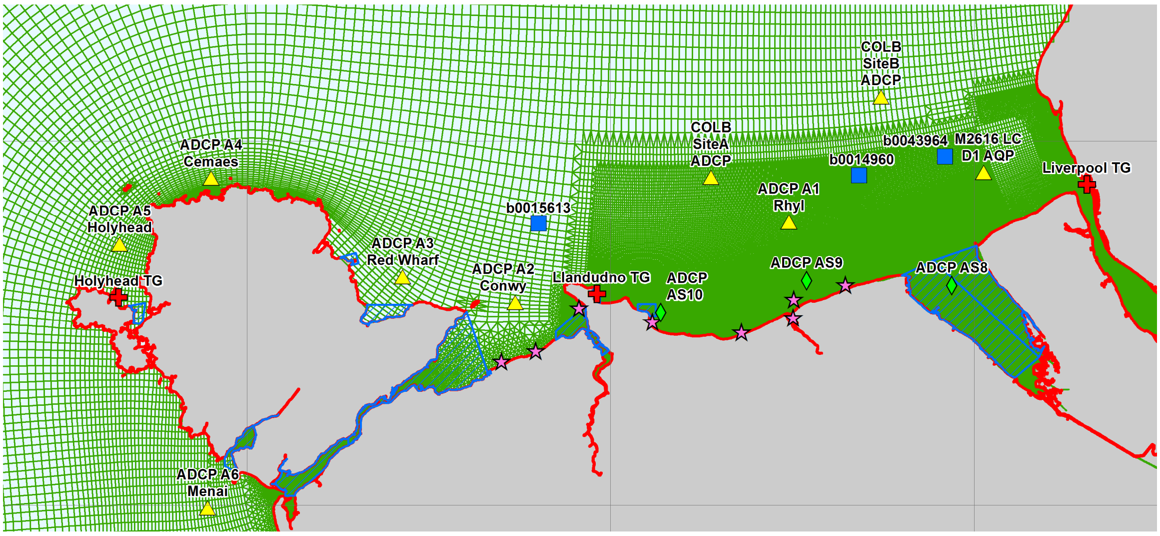


Figure 6. Example coastal model domain and resolution and field data collection locations



Conclusions

The Coastal Investigations Programme is now complete, and the following conclusions can be drawn from the study:

- All NEP outputs were successfully delivered.
- DCWW have an evidence-based investment strategy which has been agreed with the regulator.
- Only a small number of DCWW assets have been identified as requiring investment.
- The majority of water quality compliance issues at the sites investigated are dominated by river loads.
- Most shellfish waters cannot be significantly improved, and achieving the WFD Guideline flesh standard is not possible through asset investment due to the dominance of diffuse pollution. Any asset investment would be disproportionately expensive.
- Some more detailed catchment-wide investigations will be undertaken in AMP7 to provide further detail in key areas.
- Three spills (BWs) and ten spills (SFWs) solutions are not justified in most cases

Future challenges and opportunities

In addition to the current difficulties facing coastal waters, there are a number of future challenges, as well as some potential opportunities, facing us. These include the following:

- The BWD now permits as few as four samples per bathing season from which to determine classification. Reduction in sampling frequency compromises compliance and risks misclassification of bathing waters.

- Improved measurement techniques, such as developments in technology deliver a 'lab on a chip' that could provide real time water quality sampling at sensitive receivers.
- The EU are undertaking research to understand the implications of implementing a Norovirus standard for shellfish waters, other viral standards might also be applied. While this could potentially improve public health outcomes these may be small compared to the impact on the shellfish industry of associated restrictions on harvesting.
- The relationship between ambient water quality and shellfish flesh quality is complex and non-linear. Based on current guidance for water quality to achieve Guideline flesh standard it is likely that the Guideline standard will be very difficult, if not impossible, to achieve in many cases, making asset investment hard to justify on a cost-benefit basis.
- Accurate forecasting of water quality both for bathing waters (under Prediction and Discounting) and shellfish waters (as Active Management) provides an effective means of mitigating public health risk and improving compliance. However, there are currently technological and logistical challenges to implementation, and there is a risk that forecasting might become an alternative to tackling difficult catchment issues.
- Climate change presents a significant risk to future water quality compliance. Wetter summers may lead to increased periods of short term pollution. If legislation, innovation, design and customers' willingness to pay cannot keep pace with climate change, will we simply have to accept deteriorating performance?

Most of these challenges can be addressed through the use of numerical modelling techniques and can therefore be overcome. However, another potential future challenge is the uncertainty around Brexit and what that might mean in terms of legislative requirements.

Summary

In summary, the advances in numerical modelling and in data acquisition, availability and analysis has resulted in a huge improvement, since AMP1, in assessment techniques. Fundamentally assessments have evolved significantly, and compared with the single asset driven assessments typical of AMP1 and 2, are now holistic, catchment-wide studies which can include all necessary inputs, and which can assess a greater range of scenarios with better resolution, improved inputs, fewer assumptions and fewer compromises. This has enabled much more robust assessments, such as DCWW's Coastal Investigations Programme, that can provide evidence-based conclusions with greater confidence, and can support the development of targeted and effective investment strategies.

In order to meet the challenges of the future, pragmatic approaches, developed fairly in partnership with all stakeholders will be necessary. Evidence-based holistic modelling assessments such as DCWW's Coastal Investigation Programme will help to develop appropriate, catchment-wide improvement and management strategies that can effectively deliver actual environmental benefits.