Developing Demonstration Test Catchments as a platform for transdisciplinary land management research in England and Wales

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Abstract

Whilst a large body of plot and field scale research exists on the sources, behaviour and mitigation of diffuse water pollution from agriculture, significant outstanding evidence gaps remain in putting this evidence into a catchment context to inform policy. Interdisciplinary, catchment-scale research to investigate the behaviour of pollutants (nutrients, sediment, microbes and pesticides) and the effectiveness of mitigation strategies over long timeframes requires new research approaches. The Demonstration Test Catchments (DTC) programme was established in 2009 to bring together researchers from different disciplines and institutions to address the gap in empirical evidence on the cost-effectiveness of combinations of diffuse pollution mitigation measures at catchment scales. It firstly provides a physical platform of instrumented study catchments in which approaches for the mitigation of diffuse agricultural water pollution can be experimentally tested and iteratively improved. Secondly, DTC has established national and local knowledge exchange networks through which (1) research has been co-designed between researchers and stakeholders, and (2) knowledge and emerging findings have been rapidly disseminated to inform policy and land management. The research platform approach developed

through DTC has brought together disparate research groups through nationally coordinated activities. It offers a model that could be adopted to address other complex, interdisciplinary problems through research that feeds directly into policy and operational decision-making.

Introduction

As global demand for land and food increases, potential negative trade-offs between farming and the environment will become harder to avoid. It is becoming increasingly important to find ways of reducing environmental impacts whilst maintaining agricultural production and the economic viability of farms (Foresight, 2011). In densely populated countries like the UK, almost all land is managed, much of it for agriculture. The intensification of farming, particularly over the past 60 years, has perturbed biogeochemical cycles and ecological communities. The polluting effects of nutrients, sediment, microbes and pesticides from agricultural sources are estimated to be the main cause of failure of EU Water Framework Directive standards (WFD, 2000/60/EC; European Parliament, 2000) in 30% of English water bodies. In order to meet the WFD conditions for good status of water bodies in the UK, it will be essential to address the estimated ~55% of nitrate (Hughes *et al.*, 2008), ~20% of phosphorus (White and Hammond, 2009) and ~75% of sediment (Collins and Anthony, 2008) that is contributed from diffuse agricultural sources. To do so will require changes to the way that land is managed and the implementation of diffuse pollution mitigation measures (e.g. those set out in Cuttle *et al.* 2006 and Newell-Price *et al.* 2011).

The diffuse or distributed nature of the sources of agricultural water pollution, uncertainty around the fate and impact of pollutants, and interdependencies with other environmental and food production goals set significant policy challenges. The large number of land managers that contribute to the problem and thus need to be engaged with mitigation strategies, adds an extra level of complexity. Robust evidence of the cost-effectiveness of measures included in regulatory, voluntary or incentive schemes is needed both to ensure that policies are proportionate and effective, and to engender support and uptake from the farmers and other stakeholders who will ultimately need to adopt them (cf. Zhang *et al.*, 2012). Ultimately, an improved understanding of the principal causes and varied impacts of diffuse pollution is needed to inform the development of robust policy. Alongside this, the socio-economic factors that influence the land management decisions that impinge on water and air pollution need to be considered (McGonigle *et al.,* 2012).

Our understanding of the processes underlying nutrient loss from soils has benefited from a large body of plot and field-scale research (e.g. Edwards and Daniel, 1994; Schofield and Stone, 1995; Sharpley, 1997; Eghball and Gilley, 1999; Mishra *et al.*, 2006; Carneiro *et al.*, 2012; Sugihara *et al.*, 2012; Dimassi *et al.*, 2013). Whilst the mechanisms affecting the source-mobilisation-transport-receptor continuum (Lemunyon and Gilbert, 1993) of diffuse pollution are relatively well understood at small spatial scales and short temporal timeframes, considerable uncertainties remain over how these effects accumulate, affecting water quality and ecology at catchment scales. Likewise, while plot-scale studies have demonstrated the effectiveness of individual mitigation measures, robust empirical evidence on their effectiveness when deployed in combination at catchment scales is still relatively scant.

The episodic, event-driven nature of diffuse pollution can make it hard to detect trends against an unstable baseline. Pollution spikes associated with heavy rainfall can be missed by weekly or monthly monitoring. Time-lags and transformations inherent in the movement of pollutants through catchments add complexity and uncertainty in predicting the cost-effectiveness of policy interventions to mitigate diffuse pollution (Boesch *et al.*, 2001; McDowell *et al.*, 2003; Haygarth *et al.*, 2005b, Hughes *et al.*, 2007; Collins and McGonigle, 2008; Meals *et al.*, 2009; Bouraoui and Grizzetti, 2011). This makes it difficult to predict the long-term effectiveness of policy interventions applied over whole catchments and especially those targeting specific contributing sectors such as agriculture (Collins *et al.*, 2009a; McGonigle *et al.,* 2012). From a policy perspective, the level of mitigation effort that is required for a given catchment is hard to quantify and it is still difficult to predict the length of time it may take for water quality to recover.

To address these policy evidence gaps, research is needed to integrate existing strands of knowledge, considering the physical, ecological and human aspects of a catchment system together. This requires a shift from reductionist plot scale experimentation to more holistic, multi-disciplinary sub-catchment to catchment-scale studies. These need to take account of multiple, cross-sector sources, pathways and impacts (cf. Collins and Walling, 2004; Haygarth *et al.,* 2005a, Johnes *et al.*, 2007; Hewett *et al.*, 2009; Winter *et al.*, 2011; Collins *et al.*, 2014). This integrative research also needs to address the human aspects of a catchment system. For example, the development of multi-agent system (MAS) models to account for the motives and behaviours of stakeholders, including farmers, can help inform decision-making for improved environmental management (Matthews *et al.*, 2007; Bakker and van Doorn, 2009).

The emphasis on stakeholder-led approaches to catchment management in the Water Framework Directive provides challenges and opportunities. An investigative catchment science approach, which underpins a management strategy and plan, has to involve land owners and other key actors in the local community, not only ultimately to influence their actions but to access land and understand or influence its management. The citizens' knowledge of those who live, work and interact with the environment, such as farmers and anglers, can help identify key processes and impacts and inform the design of scientific investigations undertaken by researchers.

This paper describes a *research platform* approach that has been developed in England to bring together researchers and stakeholders from a wide range of institutions to undertake multi-disciplinary, catchment-scale research to address the challenges described above. This research aims to inform the development of effective policies and management strategies to reduce the impact of agriculture on water quality and aquatic ecology whilst maintaining the productivity and economic viability of farming. We also discuss the potential further application of research platforms in undertaking multidisciplinary research at landscape scales.

Challenges in catchment science

Untangling the linkages between pollutant losses to watercourses and ecological impacts is complex and poses clear challenges for targeting remedial actions. Catchment scale studies to predict and measure the effectiveness of diffuse pollution mitigation measures through long-term studies need to take account of a range of confounding factors.

Different processes and transfer mechanisms become important when investigating water quality trends over larger spatial and temporal scales. Nutrient cycling, sediment deposition, remobilisation, attenuation, losses to the atmosphere and chemical transformations can all cause complex lags in transport of pollutants through a catchment. Uncertainty or unreliable information on these processes, or on the dominant sources of pollution in a catchment, can make it difficult to predict or measure the outcomes of mitigation interventions (e.g. Lemke *et al.*, 2011).

Different pollution sources can give rise to different pollutant species and fractions. This combined with differences in the timing and mechanism of their delivery can mean that some sources or sectors can be more damaging than others in a given catchment despite contributing similar loads. Mitigation that is limited to a single sector, such as agriculture or road run-off, may not be sufficient to achieve water quality compliance standards and thresholds unless other sectors are also targeted (e.g. Collins *et al.*, 2009a, 2014).

Complexity in the linkages between pollutant pressures and biological impacts is further compounded by synergistic, additive and antagonistic interactions between chemical and physical stressors (Townsend *et al.*, 2008; Collins *et al.*, 2009b; Mattaei *et al.*, 2010). An ecological response to a change in nutrient levels in a water body may, for example, be masked by another limiting factor such as the availability of light. Mitigation strategies need to be able to adapt to changes in stressors as they respond to management.

Organising collaborative approaches to research

The conceptual and methodological challenges of undertaking research on catchment management can make it difficult to bring together researchers from the appropriate academic disciplines (Hodgson and Smith, 2007; Standing *et al.*, 2007; Hatton-Ellis, 2008; Blackstock, 2009). Language and cultural differences can cause barriers to collaboration between different academic disciplines. Such barriers take time to break down and it is only relatively recently that the environmental science research community has started to address the issue by building research programmes that are delivered by multi-disciplinary consortia (e.g. Winter *et al.*, 2011).

There also need to be incentives for researchers to collaborate. Although funders often stipulate the requirement to form multi-disciplinary consortia to fulfil the needs of a research programme, reward systems for academics have not yet developed to fully accept interdisciplinary science outputs. Benefits to society that arise from research or papers published in journals that include a strong interdisciplinary content, do not always score highly in research assessment exercises upon which university and academic research excellence is judged (Holmes and Harris, 2010).

The need for researchers to interact with the local community can cause additional communication challenges when undertaking land management research at large spatial scales (Gooday *et al.*, 2014). The collaboration of land managers is essential to implement monitoring and experimental interventions. This means that it is vital to develop relationships with individual farmers and landowners, involving them in the design and implementation of a pollution mitigation strategy. The behaviour of land managers and the local community is, however, also an important subject of study in its own right. The effective design of diffuse pollution mitigation measures, whether on an experimental or operational basis, requires a thorough understanding of practical and economic considerations including consideration of their compatibility with the farming system within which they are to operate. Effective modes of stakeholder engagement also need to be adopted. Hence, it is essential that social science and natural science activities take place in parallel.

Involving the end users of research in its design and execution has two-way benefits. Stakeholders can contribute important citizen knowledge and help formulate research questions. Farmers often have an excellent understanding of their land which includes the location of high risk areas for run-off, flooding or soil erosion. By developing a conceptual understanding of the key issues and the dominant processes affecting them that is shared between researchers, farmers and operational staff implementing a catchment management system, academic knowledge is given the same weight as the citizen knowledge of the different stakeholders. The different parties thereby become partners in undertaking catchment scale appraisal and management.

The importance of integrative, holistic studies that place findings into a real-world context is particularly pronounced from the perspective of policy makers and land managers. The synthesis of various strands of learning to inform land management policy and practice is often left to decision-makers themselves. At different ends of the spectrum, policy-makers and farmers are required to make sense of a fragmented evidence-base, balancing knowledge of individual elements of a complex system. There is now a desire for this synthesis to be undertaken much earlier by the researchers themselves, or, better still, in concert with users. Whereas interdisciplinary studies bring together knowledge from different strands of the natural and social sciences, the inclusion of citizen knowledge from non-academic stakeholders has been defined as *transdisciplinary* (Tress *et al.* 2005). The demand for such approaches will only increase in future years with the move towards "bottom-up", community-led approaches to catchment management advocated by the WFD (Hirschfield *et al.*, 2005; Volk *et al.*, 2005). In order for sub-catchment or catchment management to work, there has to be a clear understanding of the specific local issues that need to be addressed. Communities engaged in catchment management will need ready access to knowledge which is easily digestible, rather than embedded in a multitude of research papers in learned journals.

The 'research platform' approach

Building partnerships or communities of practice between researchers, policy makers, farmers, environmental managers and other stakeholders to undertake the sub-catchment-to-catchment-scale transdisciplinary research described above represents a significant departure from the way research has traditionally operated. The concept of a *research platform* has been developed, whereby research projects on multiple elements of a system (in this case rural river catchments) are co-located in a single geographical area. This has been implemented in England through the Demonstration Test Catchments programme (DTC). Co-locating researchers and research infrastructure in specific study catchments offers opportunities for researchers from different disciplines and institutions to share resources and co-generate knowledge to inform integrated land management policy. In the case of the DTC, the platform consists of a number of layers as follows:

- **A network of instrumented study sites.** Data are collected at appropriate temporal and spatial resolutions in a consistent manner from monitoring arrays that cover groundwater, surface water, flow and ecology.
- **An integrated data infrastructure allowing others to freely use the data and information to promote collaboration in research and analysis.** Making data freely and easily available is essential to attract new groups onto the platform. It also supports the development of unified data analysis and modelling solutions that describe and forecast relevant processes and transformations across scales, and extrapolate findings to new catchments for strategic policy advice and support.
- **A community of researchers, policy-makers, regulators, land management advisers, farmers and other stakeholders.** The DTC platform has catalysed dialogue between researchers and other interested groups. This knowledge-sharing has helped researchers

to understand the practical implications of their findings, enabling research questions to evolve. It has also played an important role in communicating research findings to stakeholders.

The platform hosts a number of projects, each of which makes use of one or more of these layers (Figure 1). It thus provides a vehicle to link disparate research on the many interactions between agriculture and the environment and a mechanism for the translation of research into policy and practice.

The Demonstration Test Catchments

The Demonstration Test Catchments consist of outdoor, sub-catchment scale laboratories in four English river catchments (Figure 2); the Rivers Eden (Cumbria), Wensum (Norfolk), Avon (Hampshire) and Tamar (Devon/Cornwall). These host a nationally co-ordinated programme of work and provide a focal point for sub-catchment-to-catchment and land management research. The monitoring infrastructure in the DTC catchments was established in late 2009 through three core consortium projects, which are linked by a central strategy, secretariat and governance structure. Each consortium is responsible for one of the DTC catchments, with the exception of the Avon DTC, which also covers the Tamar. An additional project is developing approaches for data archiving. The platform hosts a number of associated research projects, for example to experimentally test mitigation measures. These make use of the DTC monitoring infrastructure, datasets or stakeholder networks.

The overall objective of the DTC programme is to provide underpinning research from farm to catchment scale that informs policy and practical approaches for the reduction of agricultural diffuse pollution and the improvement of ecological status in freshwaters, whilst maintaining economically viable food production. The programme is testing the effects of targeted diffuse pollution mitigation measures and land management changes on environmental outcomes and farm performance indicators. Collectively, the DTC projects aim to address questions across four themes as set out in Table 1.

Developing a 'catchment science toolkit'

The core of the DTC experimental design is a Before-After, Control-Intervention (BACI) approach (cf. Stewart-Oaten *et al.*, 1986; Smith, 1993, 2002) that monitors changes in sub-catchment response following the implementation of pollution mitigation measures over time and against "business as usual" control areas. A semi-automated, web-enabled monitoring network has been established to collect water quality at a high temporal resolution and nested spatial scales. These data are being interpreted alongside aquatic ecological surveys, farm practice and socio-economic information to detect changes in pollutant sources, mobilisation, transport and impact at farm to sub-catchment scales.

An iterative 'weight of evidence' approach is being developed through the DTC. This involves building up layers of evidence, gradually improving a conceptual model of how the system functions and where remedial actions need to be targeted to optimise environmental benefits. Multiple approaches and techniques are used in combination as a 'catchment science toolkit' to build up layers of evidence to detect change (Table 2).

A twin-track approach is being used in the DTC programme to improve our understanding of diffuse agricultural pollution and the effectiveness of on-farm mitigation measures. The first strand of this consists of experimentation and observation through paired sub-catchment studies and monitoring changes in pollutant pressure against a baseline following the establishment of mitigation measures. Water quality data collected at nested spatial scales and farm practice data are being analysed using statistical approaches to assess the effectiveness of pollution mitigation measures at farm to catchment scales. The second strand is an iterative conceptual modelling approach to interpret and extrapolate emerging experimental and observed data. The conceptual models are, in turn, tested against water quality data at a variety of scales and iteratively adapted.

This approach can be used to continually reassess the dominant processes at relevant scales, and to inform an adaptive management approach through which mitigation measures are improved as knowledge improves and system behaviour changes. This improved conceptual understanding of the sub-catchment is essential to interpret and extrapolate findings to larger spatial scales and other catchments for supporting strategic policy decisions.

Working with local stakeholders: governance and social research

Working across real farms that are privately and individually owned and managed necessitates a collaborative approach (Winter *et al.*, 2011). The involvement of local farmers, landowners, government bodies, non-governmental organisations and other stakeholders (cf. Winter *et al.*, 2011) has been central to the DTC approach. These groups have helped to co-design the programme at local and national levels. The contribution of farmers in the study areas has been significant both in terms of allowing access to land and in terms of providing information to help formulate a conceptual understanding of how the sub-catchments function.

Farmers have also helped to co-design the experimental mitigation approaches that are being tested within DTC. This is essential as it is farmers or land managers who will ultimately need to implement and maintain them if they are adopted more widely. This aspect of co-design has meant that an adaptive approach with a certain level of opportunism has had to be used to finalise experimental designs within the DTC BACI framework. Compromise has been needed between what is most effective for controlling pollution and what is practical and affordable. Such opportunistic measure implementation is compatible with the 'twin-track' approach as described above, but it has been essential to ensure that the measures implemented fit into an overall systemic plan for the sub-catchment/ catchment. Their rationale has therefore been retrospectively established and mapped onto a 'Catchment Plan' within which the pollutant transfer continuum is set out and the options for measures aligned.

A major challenge facing the implementation of agricultural and land management policy is to connect top-down, largely government-led processes operating at regional, national and even international scales, with local knowledge and activity operating at smaller scales (McGonigle *et al.* 2012). This will inform more integrated, inclusive, participatory, adaptive and collaborative approaches to land management policy. One term for this is Integrated Catchment Management (ICM), an example definition of which is: *"a process that recognises the catchment as the appropriate organising unit for understanding and managing ecosystem goods and services in a context that includes social, economic and political considerations, and guides communities towards an agreed vision of sustainable land and water resource management for their catchment"* (Landcare Research, 2012). Such bottom-up approaches to land management are currently being piloted in the UK for the delivery of the WFD and to meet wider nature conservation objectives (Defra, 2011a; Defra, 2011b; Defra, 2013).

The involvement of local stakeholders in the co-design and implementation of the DTC programme provides a mechanism to develop and test approaches for bottom-up catchment governance. This includes, for example, exploring the potential role of farmer groups and local community organisations in catchment management. A critical challenge to sustaining ICM involving multiple parties is the difficulty in detecting positive environmental outcomes in response to targeted interventions, especially at landscape scale. This challenge is a key driver for integrating data streams using the 'weight of evidence' toolkit approach described above.

Bringing researchers together through DTC: experiences and challenges

For the researchers involved in implementing the DTC platform, the first three years entailed a substantial learning process. More than 40 organisations are involved in DTC and associated projects, with personnel from a wide variety of disciplinary backgrounds. Developing effective communication strategies within and between consortia has been very important. This has involved the use of regular face-to-face team meetings, teleconferences, workshops, conferences and informal interactions. Whilst each catchment consortium has been responsible for setting up and managing local stakeholder networks, exchanges between the consortia have helped to share ideas and build common understanding.

Collaboration between the consortia, at the level of both team leaders and junior researchers, has been particularly valuable in terms of the challenges of locating, designing and implementing an effective, web-enabled monitoring network. The first few months of the programme were marked by a major field reconnaissance and equipment procurement exercise. Field reconnaissance involved the collection of existing water quality and ecological datasets, assessment of sub-catchment areas under pressure from diffuse pollution sources relative to WFD targets, and catchment walkover surveys to locate sites suitable for hosting bank-side monitoring stations, including the requirement for a mains power supply to run the nutrient (N and P) analysers installed at the primary monitoring kiosks. Farmer engagement at this stage was co-ordinated through farm liaison staff as well as attendance at agricultural demonstration events to raise awareness of the DTC project and establish landowner contacts likely to be interested in hosting instrumented research platforms on their land.

Since the four DTC study catchments are very different in their geological, hydrological and land use characteristics there was inevitably some variation in the monitoring plans developed by the consortia, but all are using similar equipment for their primary monitoring kiosks. This has since proved of major benefit in terms of establishing standard operating procedures and data comparability, as well as developing a network of expertise that can be called upon in the event of equipment failure or other practical problems. The sharing of experiences, discussions with contacts in other countries and joint site visits were instrumental in arriving at a more cost-effective and practical monitoring solution. To date, there is general satisfaction with the equipment purchased, though all of the consortia would probably acknowledge that the staff time required for ongoing maintenance and sampling has proved greater than initially anticipated. A similar situation exists with respect to the volumes of data now being generated and the requirements for quality control prior to wider dissemination. All three of the DTC consortia are now making monitoring data available on their websites and also to the national DTC data archive (DTC Archive, 2013). The effort required to both maintain and regularly update the raw and quality controlled data for these purposes has proved a significant undertaking.

The investment in a web-enabled monitoring network of water level, water quality and weather station sensors has had several identifiable benefits. The hosted telemetry system enables checking by researchers of equipment functioning and helps support decisions concerning routine fieldwork activities. The telemetry system also permits the remote and automatic triggering and programming of water sampling routines. As a raw dataset, the telemetry system helps engage stakeholders, particularly farmers, in factors such as hydrological events and on-farm and in-field operations that directly affect water quality responses at various timescales.

Alongside the technical challenges there have been others associated with building stakeholder networks and a broad 'community of practice'. By starting from existing contacts of consortia members it has been relatively straightforward to engage local agencies and organisations, using means such as an annual conference, site open days and a regularly updated website as tools for awareness building and dissemination. In undertaking such activities it has, however, proved important to be aware of local sensibilities and take care to position the DTC programme as complementary to existing initiatives rather than something that duplicates or could be perceived as a competitor for resources. Often this has been a matter of demonstrating the potential to achieve common objectives through exchange of expertise, data or other resources.

Given the focus and objectives of DTC, engagement with the local agricultural communities has been a particular priority. This has needed to occur at two levels, firstly to gradually raise general awareness of the research being conducted and its implications for farming and secondly, in a smaller number of cases, obtain agreement to host monitoring equipment and/or participate in programmes of land management measures. Both of these have presented challenges, not least because of suspicions regarding external interference and regulation held by many farmers. It has therefore been important to try to build trust, demonstrate credibility and emphasise that the DTC programme represents an opportunity for farmers to both influence policy-relevant research and obtain insights that could improve their land and business. To meet these aims it has proved essential to have representation within the DTC consortia of individuals who can act as a bridge to the local farming community. In some cases this has been staff from an existing Rivers Trust or the local Catchment Sensitive Farming officer, whilst in others involving agronomists or farm advisers in a specific liaison role as knowledge brokers has been very beneficial. All the DTCs have organised specific local events for farmers, but in terms of reach probably more has been achieved by taking part in activities arranged by other organisations (e.g. annual farm open days or training programmes) instead of proliferating separate ones. It is too early to assess whether these efforts have resulted in changes in farming practice, but awareness of the DTC programme has certainly been established and key agreements regarding participation in measures and monitoring have been achieved.

The DTC programme is providing important opportunities for the researchers and stakeholders involved. Alongside the ability to conduct studies using state-of-the-art equipment there is the inherent satisfaction of investigating matters of real practical and policy importance. If interdisciplinary science does not always carry the highest academic kudos then there is no doubt that research 'impact' is gaining increasing prominence and, for instance, will feature in the forthcoming UK 2014 Research Excellence Framework exercise. The platforms provided by the DTC facilities have also helped to develop new research collaborations for consortia participants and are proving particularly attractive as a framework and training opportunity for MSc and PhD students to undertake additional specific studies. Expanding research teams in this way has also been very beneficial in terms of providing extra personnel to help maintain some of the core DTC facilities and services.

Expected outcomes from the DTC platform approach

Ecological and other off-site impacts of diffuse agricultural water pollution are often spatially and temporally distant from the key sources. This means that catchment-scale interventions have often shown limited success, especially over the short-term and in the context of highly variable weather patterns (Bernhardt *et al.* 2005). In establishing the DTC platform, it is recognised that an iterative approach to research is needed. Collection of definitive experimental data to show the effectiveness of combinations of measures is likely in some cases to take longer than the initial funding period. However, using the 'toolkit' and iterative conceptual modelling approaches described above, and by maintaining long-term research activity through successive projects on the DTC platform, a strategic and informative approach can be taken. Some anticipated short, medium and long-term outputs from the DTC programme are illustrated in Table 3.

Data infrastructure and archiving

A key feature of the DTC programme is that data generated in the study catchments is freely available for others to download and use. Datasets generated by the catchments are deposited, preserved, curated and made available for reuse by a diverse set of potential stakeholders via the DTC Archive (DTC Archive, 2013). The archive also provides a research environment and tools allowing data from different sources to be integrated, analysed and visualised as a whole.

The overall architecture of the data infrastructure may be represented schematically in terms of four main components:

1. Data capture facilities, which ensure that datasets are ingested into the archive in standards-compliant form, in conformance with the data model described below.
2. The archive proper, in which the captured datasets are curated, together with their metadata and structural or semantic relationships.
3. An integration framework that enables data within individual datasets to be combined into a common "data soup".
4. An extensible range of tools for querying, browsing, visualising and analysing the data.

The overall data model for the archive is based on the ISO 19100 series of standards, which address standardisation in the representation of digital geographic information, and in particular ISO 19156:2011 (Observations and Measurements), which defines a conceptual model for observations, and a common set of features that may be involved in sampling when a researcher makes an observation (ISO 19156:2011).

The fundamental information unit here is the observation, which typically observes a real-world feature, such as a river or field, and measures certain phenomena, such as concentration of an ion or density of a species, as well as temporal and spatial information (when and where the observation took place), the results (recorded as, for example, numeric or textual data), and information about the process (how was the measurement made, and by whom). Basing the archive's data representations on such a model ensures that the fundamental organisation of the information is independent of any particular implementation; this in turn both ensures the longevity of the archive (as the data can be migrated to future systems without fundamental change) and facilitates the exchange of observational information with other systems, tools and researchers. The common model is already being exploited to support another research platform, the Agricultural Greenhouse Gas Platform (GHG Platform, 2013).

This approach also helps to ensure conformance to the EU's INSPIRE (Infrastructure for Spatial Information in the European Community: INSPIRE, 2007) Directive, which aims to create a European Spatial Data Infrastructure to improve sharing of spatial information between public authorities and to make such information more accessible for the public, as well as developing better environmental policies within the EU member states.

Summary and conclusions

The DTC research platform has established a focal point for catchment research and knowledge sharing activities. As well as helping to develop a more coordinated and strategic approach to research planning, it has provided a vehicle for knowledge exchange. The dialogue and partnerships established have helped researchers, policy makers and other stakeholders to co-design a research agenda, align research activities to policy priorities, and frame knowledge in a real-world context. A principle of adaptive management has been used to allow research questions to evolve and adapt to new knowledge and a changing policy arena. From a policy perspective, the community of researchers and practitioners developed through DTC plays an important role as a sounding board, helping to address immediate policy-focused questions alongside longer-term strategic catchment research.

The partnerships established between research groups and across disciplines through the research platform approach provide opportunities to tackle complex, interdisciplinary research questions that require holistic, systems-based understanding and collaborative approaches. The DTC platform provides a focal point to pool funding, equipment, data and other resources between research groups. The intention has been to establish a self-perpetuating research community focused on a common purpose, shared experimental sites, and funded from multiple sources to help develop robust long-term research activities through successive projects to address these bigger questions.

The research platform approach discussed here is applicable to a wider range of research and policy objectives. By establishing long-term research sites, collaborations with land managers and contextual data, the DTC platform provides an opportunity to host wider research on the trade-offs between food production and environmental protection at farm and landscape scales. It also provides a potential model to build collaborations between researchers, policy makers and other stakeholders to address broader questions. In the UK, a similar research platform approach has been adopted to conduct coordinated research to improve the greenhouse gas emissions inventory from agriculture (GHG Platform, 2013). The DTC approach is also currently being adapted to establish a further research platform on the sustainable intensification of English and Welsh agriculture. These three platforms promote a whole-community, transdisciplinary approach to tackle the complex interactions between land management and environmental outcomes across farmed landscapes.

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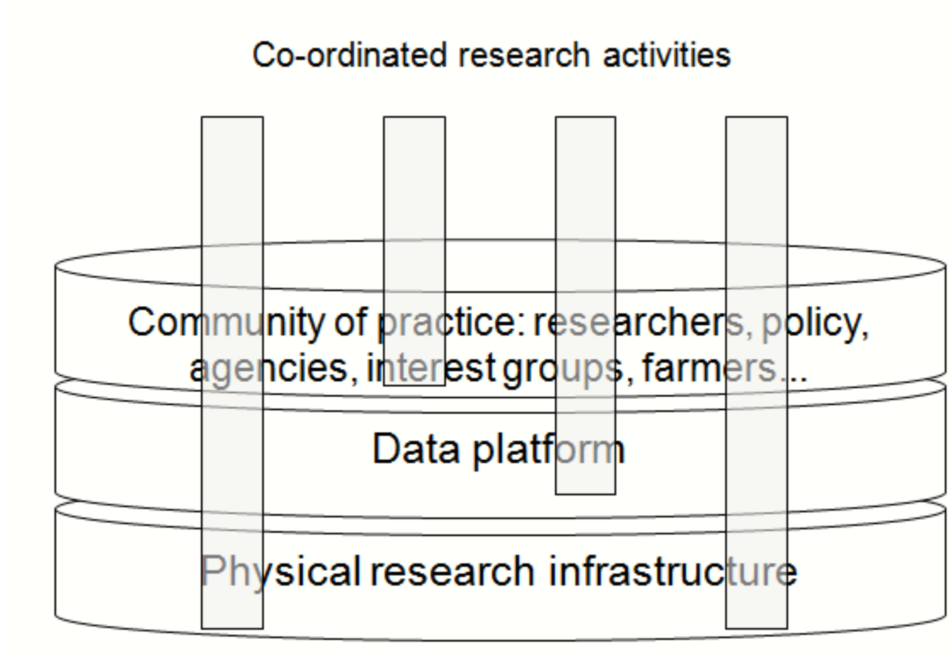

Figure 1: Components of a research platform. The platform consists of a community of researchers with a shared understanding of the issues, shared data and shared research sites and infrastructure. Research activities hosted on the platform, represented by vertical bars, make use of one or more of these layers.

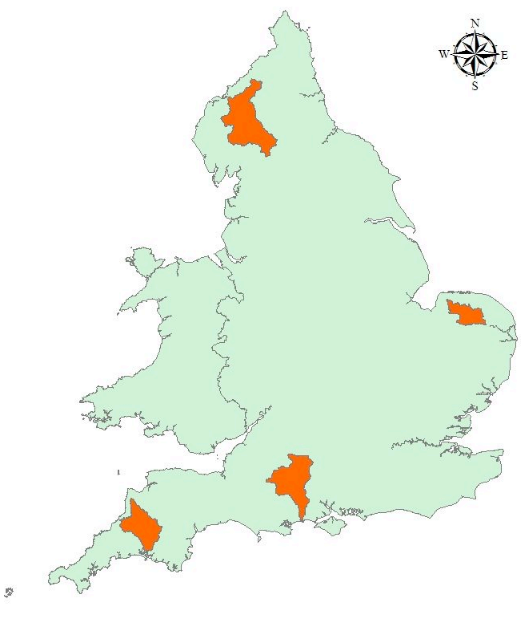

Figure 2: The Demonstration Test Catchments (shown clockwise from the most northerly; Rivers Eden, Wensum, Avon and Tamar).

Table 1: The main research questions being collectively addressed by projects in the Demonstration Test Catchments.

1. Understanding the nature of the problem (catchment function and response)

- **Pollutant transport and transformations:**
  1. How long does it take for pollutants to travel from their source to their point of impact (taking account of nutrient cycling, deposition, remobilisation, attenuation, loss to the atmosphere and transformations)?
  2. How do pollutants interact with each other?
- **Spatial variation in risk:**
  3. What are the main diffuse pollution risk factors and how do they vary spatially in terms of (1) the likelihood of pollutant loss from farming, and (2) the sensitivity of ecology and other receptors? (How does pollution risk vary between catchments and how can pollution hot-spots be identified within a catchment?)
- **Temporal variation in risk:**
  4. What is the significance of storm event-driven pollution spikes and seasonal trends for water quality and ecological response?

2. Designing and targeting mitigation interventions

- **Targeting – implementing measures within a catchment:**
  5. Which combinations of measures are the most cost-effective a given catchment and how do they interact?
  6. How can measures be most cost-effectively targeted within a catchment and what level of coverage is needed to (a) improve water quality and (b) achieve an ecological response?
  7. How can mitigation strategies account for trade-offs and interactions between pollutants?
- **Measure cost, design and maintenance:**
  8. What are the direct and indirect cost of these measures, including implementation, maintenance, impact on productivity/ profitability and savings due to more effective resource management?
  9. What are the practical constraints to implementing measures within the context of a farm business?
  10. What is the lifespan and what are the maintenance requirements for a given mitigation measure?
- **Environmental outcomes of mitigation:**
  11. How do pollutant loads affect concentrations and what is the impact on receptors (ecology, abstracted drinking water quality, quality of bathing and shellfish waters and wider ecosystem services)
  12. How does pollution interact with other factors, such as the morphology of the river channel?
  13. How long will it take for mitigation interventions to (a) meet a set pollutant threshold at a given point in a catchment and (b) achieve an ecological response?
  14. How far downstream will benefits accrue from mitigation measures?

3. Working with stakeholders and influencing behaviour change

- **Behaviour/ practices:**
  15. What is the baseline level of practice in terms of diffuse pollution mitigation?
  16. How far are we likely to get towards water quality targets with existing uptake of measures?
- **Attitudes:**
  17. Which factors motivate farmers to adopt measures and what are the main things likely to put them off?
  18. What level of financial and technical support do land managers require to adopt measures?
  19. Does increased self-monitoring affect farmers' attitudes to diffuse pollution?
  20. How can farmers be encouraged to collaborate to implement measures strategically at a catchment or sub-catchment scale?

4. Developing improved monitoring and research techniques to inform, monitor and evaluate policy

- **Improving monitoring approaches:**
  21. Which are the most cost-effective monitoring technologies and investigative techniques for:
      i. Identifying pressures in a catchment?
      ii. Undertaking source apportionment?
      iii. Detecting the effects of pollution mitigation?
  22. How can monitoring be optimally deployed, and what is the minimum amount of data needed to detect a reduction in diffuse pollution at given spatial and temporal resolutions?
- **Scaling up and down:**
  23. Which techniques can be used to interpret low spatial and temporal resolution water quality monitoring data to understand pressures within individual water bodies?
  24. How can the results of plot-scale research be reliably up-scaled and applied to inform decision making in heterogeneous landscapes?
  25. Can catchments be grouped according to land-use, dominant processes and environmental risk factors

to inform pollution mitigation strategies?

- **Modelling and decision support:**
  26. How can emerging conceptual models be used to inform risk-based approaches to catchment management?
  27. How reliable are existing models and decision-support tools (how well do they perform in well monitored catchments)?
  28. How can monitoring and modelling tools be practically used in combination to build 'weight of evidence' to inform catchment management?
- **Research coordination:**
  29. How can we bring together a fragmented research community to address complex, interdisciplinary questions?
  30. How can we undertake catchment scale research?
  31. How can we improve the sharing of data and other resources between research groups?
  32. How can we link different funding sources to address large, complex, interrelated and long-term research questions?
- **Knowledge exchange:**
  33. How can we put reductionist research into a holistic policy/ practical context?
  34. How can we better communicate policy needs to steer research?
  35. How can we make better use of emerging knowledge to inform decisions by policy makers, catchment managers and farmers?

Table 2: A ‘catchment science toolkit’ consisting of multiple approaches that build evidence to characterise catchment-scale changes in water quality following experimental diffuse pollution mitigation interventions.

	Approaches:	*Timescale to measure changes*
Source	• Visual assessment and mapping. • Sampling manures before application e.g. to test the effectiveness of changing livestock diets. • Collection of farm practice data to monitor uptake of measures - behavioural monitoring of cross compliance/best practice uptake. • Farm-gate nutrient balances.	• Short • Short • Short • Short
Mobilisation	• Visual assessment and mapping • Monitoring soil pore water e.g. using porous pots. • Hill-slope experimentation (unbounded plots). • Soil risk-mapping approaches.	• Short • Short • Medium • Short
Pathway	• Visual assessment and mapping • Field scale monitoring – e.g. upstream and downstream of an ‘in-line’ feature such as a pond or ditch. • Monitoring field drains. • Measurements to understand remobilisation of nutrients.	• Short • Medium • Medium • Medium
Receptor	• Visual assessment and habitat assessment. • Use of tracers (e.g. magnetic/ fluorescent particles, microbial tracers). • Repeat source apportionment of: o Sediment (source fingerprinting approaches) o Nutrients (‘nutrient fingerprinting’ using dissolved organic matter to determine between agricultural and non-agricultural sources) o FIOs (microbial source tracking) • Nested, high temporal resolution water quality monitoring (sediment, faecal indicator organisms nitrogen and phosphorus species). • Ecological monitoring (community and functional metrics). • Groundwater monitoring and modelling.	• Short • Short • Medium • Long • Long • Long
The conceptual understanding of sub-catchment function developed from the data gathered through the above techniques can be used to inform modelling approaches to scale-up and disaggregate the contributions of individual measures at the catchment scale. These models will require appropriate uncertainty frameworks to be developed and implemented.		

Table 3: Example short, medium and long-term outputs from the DTC programme.

Timeframe	Outputs
1 year	**Measuring** • Social science, attitudes and behaviour • Uptake of measures
	Predicting • Initial conceptual modelling to predict effectiveness of measures
	Demonstrating • The development of approaches to integrated catchment research • The efficiencies and effectiveness of working collaboratively through research consortia
5 years	**Measuring** • Reductions in pollutant delivery at small spatial scales (towards the **source/ mobilisation** of the delivery continuum and at field / farm scale) • The effect of measures on economic and agronomic farm performance • Pollutant fluxes, flow-weighted mean concentrations, instantaneous concentrations etc and variations at sub-catchment outlet and how they relate to precipitation events • Source apportionment changes linked to targeted mitigation • Providing catchment attribute, practice and activity data to underpin conceptual and predictive modelling • Changes in ecosystem process rates
	Predicting • Improving conceptual models of key catchment processes (in specific areas of catchments where the investment and learning is high) • Improving certainty in detecting real impacts due to the effectiveness of measures on pathways and receptors • Improved catchment modelling capabilities and a greater understanding of the uncertainty therein • Ability to extrapolate information to other parts of the country • Robust quantification of the real and marginal costs and benefits of on-farm approaches to diffuse pollution mitigation.
	Demonstrating • A range of on-farm measures to bring changes in water quality/ecosystem that policy-makers and industry have confidence in. • Cost and practicability of measures with an improved ability to predict effectiveness • A robust and transferable integrated toolkit for monitoring freshwater systems to determine consequential changes in water quality from changing land management practices. • Successful 'communities of practice'. Communicating the issues to key stakeholders • Clear, evidence-based messages on the relationship between land management and the environment are developed.
10-20 years	**Measuring** • Measuring positive changes in water quality at sub-catchment outlets • Measuring positive ecological changes (understanding **receptors**)
	Predicting • Understanding catchment processes and hysteresis (understanding **pathways**)
	Demonstrating • Clear messages to farmers and advisers on diffuse pollution, its impacts and mitigation • Continually improving guidance on best practice