Environmental Science Processes & Impacts

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Environmental Impact Statement

This paper sets out an overview and the rationale for the Demonstration Test Catchments (DTC) as a platform for research on diffuse agricultural water pollution. DTC brings together over 40 institutions to coordinate research activities on sources of pollution, the processes through which pollutants move through the environment, their impacts and potential mitigation strategies. It directly links researchers to policy makers, farmers and other key stakeholders. The paper sets the scene for the platform for other contributions from the DTC programme to this themed issue. More broadly, it sets out the concept of a research platform, which is being adopted for several English and Welsh strategic research programmes on the impacts of land-use on the environment.

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, putting this evidence into a practical, context at large spatial scales to inform policy remains challenging. Understanding the behaviour of pollutants (nutrients, sediment, microbes and pesticides) and the effectiveness of mitigation strategies over whole catchments and long timeframes requires new, interdisciplinary approaches to organise and undertake research. This paper provides an introduction to the Demonstration Test Catchments (DTC) programme, which was established in 2009 to gather empirical evidence on the cost-effectiveness of combinations of diffuse pollution mitigation measures at catchment scales. DTC 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, it has established national and local knowledge exchange networks between researchers and stakeholders through which research has been co-designed. These have provided a vehicle to disseminate emerging findings to inform policy and land management practice. The role of DTC is that of an outdoor laboratory to develop knowledge

and approaches that can be applied in less well studied locations. The *research platform* approach developed through DTC has brought together disparate research groups from different disciplines and institutions through nationally coordinated activities. It offers a model that can be adopted to organise research on other complex, interdisciplinary problems to inform policy and operational decision-making.

Introduction

As global demand for land and food increases, negative trade-offs between farming and the environment are becoming 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[1]. 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 disrupted 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 (WFD) standards[2] 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[3], ~20% of phosphorus[4] and ~75% of sediment[5] that is contributed from agricultural sources. To do so will require changes to the way that land is managed and the implementation of pollution mitigation measures such as those set out by Cuttle *et al.*[6] and Newell-Price *et al.*[7].

Significant policy challenges are set by (1) the diffuse or distributed nature of the sources of agricultural water pollution, (2) uncertainty around the fate and impact of pollutants, and (3) interdependencies with other environmental and food production objectives. 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-based 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.*[8]). 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[9].

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 on approaches to tackle agricultural water pollution. This research is being undertaken to inform the development of effective policies that can reduce the impact of agriculture on water quality and aquatic ecology without undermining the productivity and economic viability of farming. We also discuss the potential application of the research platform approach developed in DTC to undertake multidisciplinary, landscape-scale, policy-focused research on other environmental and land management issues.

Challenges for catchment research

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[10], Schofield and Stone[11], Sharpley[12], Eghball and Gilley[13], Mishra *et al.*[14], Carneiro *et al.*[15], Sugihara *et al*.[16], Dimassi *et al*.[17]). Whilst the mechanisms affecting the source-mobilisation-transport-receptor continuum[18] of diffuse pollution are relatively well understood at small spatial scales and over short timeframes, considerable uncertainties remain over their net effects on water quality and ecology across whole catchments over extended timeframes. Likewise, while plot-scale studies have demonstrated the effectiveness of individual mitigation measures, robust empirical evidence of their effectiveness when deployed in combination at catchment scales is still relatively scant. Catchment-scale studies to predict and measure the long-term effectiveness of diffuse pollution mitigation measures need to take account of a range of confounding factors, several of which are discussed in the following paragraphs.

Firstly, the episodic, event-driven nature of diffuse pollution can make it hard to detect trends against an unstable baseline through monitoring schemes. Pollution spikes associated with heavy rainfall can be missed by weekly or monthly water quality sampling. Time-lags and transformations inherent in the movement of pollutants through catchments add complexity and uncertainty in predicting the cost-effectiveness of actions to mitigate diffuse pollution[19, 20, 21, 22, 23, 24, 25]. Nutrient cycling, sediment deposition, remobilisation, attenuation, losses to the atmosphere, chemical transformations and surface/groundwater interactions can all cause complex lags in the transport of pollutants. Different processes and transfer mechanisms become important when investigating water quality trends over larger spatial and temporal scales. Uncertainty or unreliable information on these processes can make it difficult to predict or measure the outcomes of mitigation interventions (e.g. Lemke *et al.*[26]).

Complexity in the linkages between pollutant pressures and biological impacts is further compounded by synergistic, additive and antagonistic interactions between chemical and physical stressors[27, 28, 29]. 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.

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[30, 42].

Understanding an anthropogenic problem like diffuse pollution requires an understanding of human behaviours and activities alongside these biophysical processes. For example, to understand the success of a policy intervention to mitigate pollution, it is as important to understand the social, economic and cultural barriers that limit or encourage the uptake of measures. Modellers have recognised this, for example through the development of multi-agent system models to account for the varying motives and behaviours of stakeholders, including farmers[31, 32].

The emphasis on stakeholder-led approaches to catchment management in the Water Framework Directive provides challenges and opportunities in this respect. A successful catchment management strategy needs to be based on good science but also has to involve land owners and other key actors in the local community. This is essential firstly because they will need ultimately to implement any recommended changes in land management, secondly because their permission is usually needed to access land to carry out investigations and thirdly because they can contribute information to help understand environmental pressures. 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.

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[9]). This will inform more integrated, inclusive, participatory, adaptive and collaborative approaches to land management policy. One term for this is Integrated Catchment Management, 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"*[33]. Such bottom-up approaches to land management are currently being piloted in England for the delivery of the WFD and to meet wider nature conservation objectives[34, 35, 36].

To address these challenges and to meet the evidence needs of policy makers, 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 pollution sources, pathways and impacts (cf. Collins and Walling[37], Haygarth *et al.*[38], Johnes *et al.*[39], Hewett *et al.*[40], Winter *et al.*[41], Collins *et al.*[42]) alongside the activities and motivations of a wide range of stakeholders.

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[43, 44, 45, 46]. 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.*[41]). Breaking down communication barriers between academic disciplines can be seen as a first step towards tackling the multi-dimensional, complex issues faced by policy makers and other end-users of environmental research.

There also need to be incentives for researchers to collaborate. Funders have a clear role to play in bringing research disciplines together to tackle real-world problems, particularly where they are also the beneficiaries and end-users of the knowledge generated by programmes. 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 the exercises through which university and academic research excellence is judged[47].

The need for researchers to interact with local stakeholder communities can cause additional communication challenges when undertaking land management research at large spatial scales[48]. 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.

Involving the end users of research in its design and execution has two-way benefits. 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 to inform their decisions. 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*[49]. 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[50,51]. 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 that covers groundwater, surface water, flow, ecology and socio-economic aspects of land management.
- **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 and knowledge sharing between researchers and other interested groups. This 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). These projects are funded by a number of different organisations. Co-locating them in the same geographical area helps to link fundamental and applied research ranging from work focusing on the needs of government policymaking, practical environmental management, agricultural issues and water company catchment schemes according to the funders. With increasing pressure on research budgets, this provides opportunities to pool resources between funders to fund larger projects on common issues. The platform 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. This is similar to the idea of *Learning and Action Alliances*, which have been used elsewhere to bring together organisations to share learning, develop innovation and take ideas to implementation[52, 53].

The Demonstration Test Catchments

The Demonstration Test Catchments consist of outdoor, sub-catchment scale laboratories in four English river catchments: the Rivers Eden (Cumbria), Wensum (Norfolk), Avon (Hampshire) and Tamar (Devon/Cornwall) (Figure 2). 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 and Tamar, which are covered by a single consortium. 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.*[54] and Smith[55, 56]) 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.

It is recognised that the complex catchment processes discussed above may mean that it will take tens of years to monitor changes in water quality as a result of mitigation measures. For this reason, an iterative 'weight of evidence' approach is being developed through DTC. This involves using a number of qualitative and quantitative techniques together to build up layers of evidence to continually improve a conceptual model of how the system functions and the effectiveness of interventions. These combined measures form an evolving 'catchment science toolkit', illustrated in Table 2.

This multi-strand approach to field investigation forms the first element of a twin-track approach in DTC. The second element involves the incremental development of conceptual models to interpret emerging experimental and observed data. These are tested against new data as it emerges 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 extrapolate findings to larger spatial scales and other catchments for supporting strategic policy decisions.

Whilst the intensive, high resolution monitoring used in DTC is likely to be too expensive to deploy widely in its entirety, subsets of the emerging catchment science toolkit can be used operationally by catchment managers. Data generated by high resolution monitoring can potentially also be used in sensitivity analyses to inform more targeted and economical approaches to deploy water quality monitoring. The combination of quick and simple qualitative approaches with medium to long term monitoring to iteratively improve conceptual models reflects the way that evidence is used in policy making. Policy makers cannot usually afford to wait five, ten or twenty years for the results of research. At any given time, the best available evidence is needed to inform 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[41]. The involvement of local farmers, landowners, government bodies, non-governmental organisations and other stakeholders (cf. Winter *et al.*[41])

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.

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 Integrated Catchment Management 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 as described above. DTC also offers an opportunity to explore the role of science in engaging stakeholders in tackling environmental issues.

Making research relevant to policy

Whilst research often is long-term in nature, policy decisions need to be made over much shorter timeframes[9]. Whereas research programmes are often measured in years, timescales for policy decisions are more usually measured in days or weeks. This poses significant challenges both in evidence-based policy making but also in designing applied research programmes that remain relevant throughout their existence. To address this, DTC provides three parallel functions.

Firstly, on a multi-annual timeframe, DTC hosts strategic research to address long-term evidence gaps to a timeframe that is aligned to long-term policy cycles, such as the negotiation of EU directives (as set out in McGonigle *et al.* [9]). These long-term research themes are set out in table 1. As discussed above, policy decisions cannot usually wait for research projects to finish, they need to be made on the best available evidence. Therefore the knowledge exchange activities in DTC aim to communicate findings and partial findings as they emerge.

Secondly, on a timeframe ranging from weeks to months, the DTC platform also hosts shorter-term, projects and workshops on a reactive basis to address specific emerging policy questions. Hosting these activities alongside more strategic research has the advantage that it (a) can rapidly consolidate the collective knowledge and experience of a large group of multi-disciplinary researchers, and (b) can make use of emerging, unpublished findings. As well as capitalising on the DTC research community, these short-term projects can also utilise the physical platform, for example by piloting approaches with collaborating farmers.

Finally, the community of researchers working on the DTC platform act as a sounding board for policy teams on a very short-term basis, often responding within a few days. This has the benefit of allowing policy makers rapid access to expert advice, as well as helping researchers to understand continually evolving policy debates and adapting their work accordingly to improve its impact.

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[57]. 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

As discussed above, ecological and other 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[58]. Whereas definitive experimental data on the outcomes of catchment-scale pollution mitigation interventions is likely in some cases to take longer than the initial funding period, improving predictions through better process understanding is possible. Likewise, the research platform also provides opportunities to demonstrate approaches to government, industry and other stakeholders. The aim with DTC is to improve predictive capability and demonstration activities whilst generating more definitive empirical evidence through successive projects on the platform over a number of years. This is 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[57]. 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[59].

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 the 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 also being exploited to support the UK Agricultural Greenhouse Gas Research Platform[60].

This approach also helps to ensure conformance to the EU's INSPIRE (Infrastructure for Spatial Information in the European Community) 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[61].

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 net result of this is that policy-makers have access to more robust evidence, whilst researchers are able to improve the impact of their work.

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[60]. The same 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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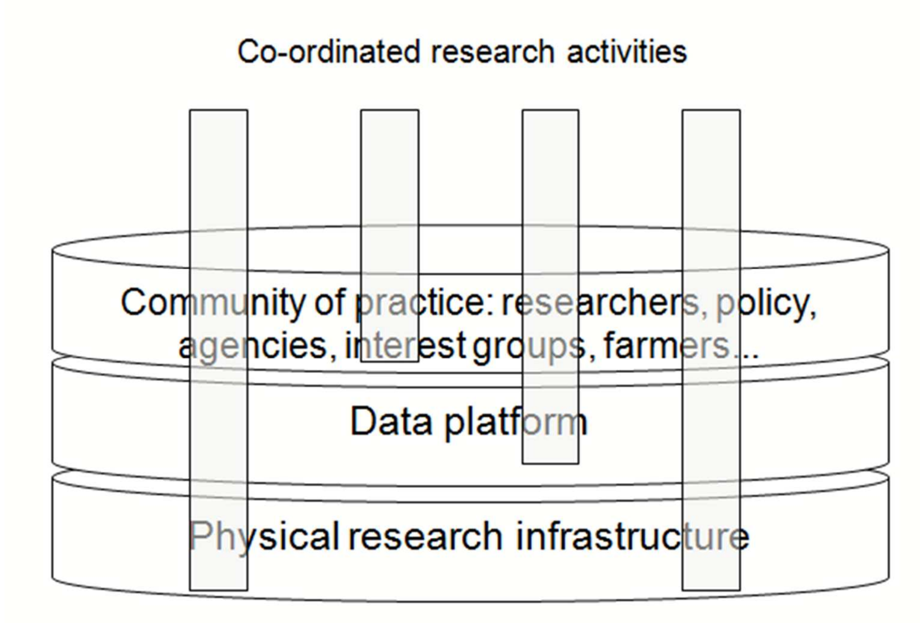

Figure 1: Components of a research platform. The platform consists of a community of researchers with a shared understanding of the issues, shared data and shared research sites and infrastructure. Research activities hosted on the platform, represented by vertical bars, make use of one or more of these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

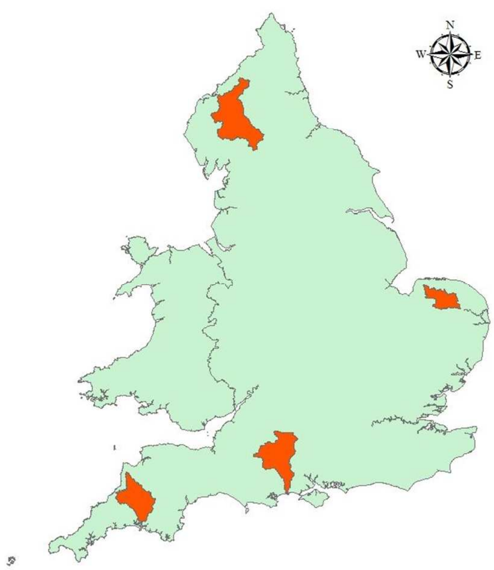

Figure 2: The Demonstration Test Catchments (shown clockwise from the most northerly; Rivers Eden, Wensum, Avon and Tamar).

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

1. Understanding the nature of the problem (catchment function and response)
• Sources of agricultural pollution • Transport and transformations of pollutants • Impact of pollution on ecology and other receptors • Extrapolating findings to the wider catchment and nationally (spatial and temporal variation in risk)
2. Designing and targeting mitigation interventions
• Cost-effectiveness of mitigation measures • Developing approaches to design and target catchment pollution mitigation strategies • Measure cost, design and maintenance • Environmental outcomes of mitigation
3. Working with stakeholders and influencing behaviour change
• Land manager behaviour and practices • Attitudes to pollution and its mitigation • Requirements for financial and technical support • Collaborative, stakeholder-led approaches to catchment management
4. Developing improved monitoring and research techniques to inform, monitor and evaluate policy
• Improving monitoring approaches • Developing approaches to up-scale up and extrapolate the results of research/ investigations • Testing models and decision support tools • Improving research coordination

Table 2: Examples of approaches that can be used in combination to form a 'catchment science toolkit' to monitor changes in water quality following pollution mitigation interventions.

	Approaches:	*Timescale to measure changes*
Source	- Visual assessment and mapping	Short
	- Farm practice surveys	"
	- Farm-gate nutrient balances	"
Mobilisation	- Visual assessment and mapping	Short
	- Soil risk-mapping approaches	"
	- Monitoring soil pore water e.g. using porous pots	Medium
	- Hill-slope run-off studies	"
Pathway	- Visual assessment and mapping	Short
	- Field scale water quality sampling	Medium
	- Monitoring field drains	"
Receptor	- Visual assessment and habitat assessment	Short
	- Tracer studies (e.g. magnetic/ fluorescent/ rare earth/ microbial)	Medium
	- Repeat source apportionment (sediment/ nutrient fingerprinting)	"
	- Microbial source tracking	"
	- Sub-catchment scale water quality monitoring	Long
	- Ecological monitoring (community and functional metrics)	"
	- Groundwater monitoring and modelling	"

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
5 years	**Measuring** • Reductions in pollutant delivery at small spatial scales • The effect of measures on economic and agronomic farm performance • Pollutant fluxes at sub-catchment outlets and their relationship to precipitation • Source apportionment changes linked to targeted mitigation • Land management practice • Ecosystem process rates
	Predicting • Improving conceptual and numerical models of catchment processes • Improving ability to predict mitigation effectiveness • Practicability of measures • Extrapolating information to other parts of the country • Quantifying real and marginal costs and benefits of pollution mitigation measures
	Demonstrating • On-farm measures to policy makers and industry • Improved approaches to monitor catchment systems • Stakeholder-based approaches to catchment management
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 • Continually improving guidance on best practice

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