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Contaminant Movement and Attenuation along Pathways from the Land Surface to Aquatic Receptors: the PATHWAYS Project

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Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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ENVIRONMENTAL PROTECTION AGENCY

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- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiological Protection
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

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EPA Research Report

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DISCLAIMER

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The Pathways Project investigated pathways of contaminant transport in Irish catchments, and developed a national suite of Catchment Management Support Tools (CMSTs). This is a synthesis report of the research undertaken; related final technical reports are available online (http://erc.epa.ie/safer/reports).

These CMSTs were developed to assist with the delineation of critical source areas, that is areas that make disproportionately high contributions to overall pollutant loads, for use by environmental and water managers. This required an improvement in the characterisation of the hydrological pathways that deliver water-borne contaminants to aquatic receptors. A preliminary four-pathway working conceptual model was identified that included overland flow, interflow, shallow groundwater flow and deep groundwater flow; the main contaminants of interest were phosphorus (P), nitrogen (N) and sediment. A literature review identified a number of knowledge gaps (Archbold *et al*., 2010) and guided the research. Field and modelling studies were conducted in four study catchments in order to improve the understanding of contaminant transport along the different hydrological pathways, and their associated impacts on water quality and river ecology. The catchments included three poorly drained catchments underlain by poorly productive aquifers, namely the Mattock catchment in Co. Louth/Meath, the Glen Burn catchment in Co. Down and the Gortinlieve catchment in Co. Donegal, along with the well-drained Nuenna catchment, which is underlain by a regionally important aquifer, in Co. Kilkenny.

Findings from field studies supported the use of the initial four-pathway conceptual model, although the research also showed that artificial drainage and the transition zone (the broken-up weathered zone at the top of the bedrock) were also important nutrient transfer pathways in areas underlain by poorly productive aquifers.

In terms of contaminant transport, nitrate (NO_3) from diffuse sources was found to be typically delivered via the subsurface pathways. By contrast, P was primarily transported via overland flow, in both particulate and soluble forms, and delivered on a more intermittent basis. Arable land was identified as the most significant

land type for the delivery of sediment, although channel bank and in-stream sources proved more important in the Glen Burn catchment. Overland flow was the predominant sediment transport pathway in the poorly drained catchments. This field-based research, which built on existing literature, informed the development of the CMST.

The CMST is a geographical information system (GIS)-based application and provides a user-friendly interface for a series of hydrological and water-quality models. Components of the CMST have been further developed since the Pathways Project was completed; this report reflects the development undertaken only in the Pathways Project. The CMST consists of three components, namely base maps in GIS, a Catchment Characterisation Tool (CCT) and a Catchment Modelling Tool (CMT). The tools aim to assist environmental managers with the prediction of flows of water and contaminant loads along various flow paths so that critical source areas (i.e. the highest risk areas) can be targeted by effective programmes of measures.

The base maps in GIS draw on existing environmental GIS-based data to generate catchment summary statistics, while the CCT provides estimates of long-term annual average nutrient fluxes by linking data on loadings with transport factors, using the source–pathway–receptor methodology and the datasets stored in GIS. The pollution impact potential maps generated by the CCT show the relative risk of contaminants to surface water and groundwater receptors. Scenario analysis undertaken using the CCT assists with the assessment of potential mitigation measures by changing datasets on loadings or land use. Comparisons of CCT model outputs with field data demonstrate that the model outputs broadly match the levels observed in study catchments, in both magnitude and trend, thus giving confidence in this methodology.

The CMT is a numerical modelling tool that simulates temporal variations in fluxes of water and contaminants. This tool incorporates the four hydrological pathways and in-stream water quality dynamics to model the transport of contaminants from their sources to downstream receiving waters. The CMT can be used to model diffuse-source N, P and sediment export from

networks of subcatchments. The hydrological model underpinning the CMT has demonstrated its capacity to simulate field conditions, reproducing dynamic storm response behaviour in the study catchments. The water quality component of the CMT remains a work in progress and is being further developed under a separate research fellowship with the Environmental Protection Agency (EPA).

The flexible platform structure of the CMST means that, in the future, it could potentially be adapted by investigators for land-use planning and for predicting or assessing the anticipated impacts of climate change. The CMST will need to be continually refined and updated to realise its full potential.

1   Introduction

1.1   Context and Background for the Pathways Project

An integrated view of the water cycle and its components is required in order to protect, preserve and improve the aquatic environment while encouraging the sustainable use of water. Such an integrated approach requires a greater emphasis on developing scientifically justifiable criteria to support decisions aimed at achieving integrated catchment management (Archbold *et al.*, 2010). The physical and chemical characterisation of water bodies forms a critical element of the work required to understand catchment processes and to determine appropriate management strategies at a catchment scale. This process includes establishing the relationship between catchment pressures caused by human activities and their impacts on aquatic ecosystems, and determining whether or not a water body is at risk of not meeting its Water Framework Directive (WFD, Directive 2000/60/EC) objectives, thus requiring responsive action.

The identification of nutrient and sediment critical source areas (CSAs), in catchments in which such pollutants have an impact, is essential for the development of appropriate targeted management strategies. To successfully understand catchment processes that inform CSA delineation, a detailed understanding of hydrological and contaminant transport is required in order to develop conceptual models for hydrological and contaminant transport in the Irish context. Delineation occurs at different scales, ranging from those identified at the catchment level, which correspond to subcatchments in the Catchment Management Support Tools (CMSTs), to smaller field-scale areas which occur within subcatchments. The development of hydrological process characterisation protocols and contaminant transport models for Irish catchments is challenging given the highly heterogeneous geological conditions across the country, with substantial variations occurring over short distances. Many catchments contain a range of highly heterogeneous subsoil and bedrock types that are often overlain by subsoils and associated soils bearing little relation to the underlying rock. As a consequence, approaches that are used for integrated catchment management in other countries, with more homogeneous conditions, are often difficult to apply in Irish settings. Similarly, many of the processes reported from elsewhere deal with different climatic conditions, where geological processes have resulted in soil and subsoil types that differ significantly from those in the Irish context. The integration of datasets from multiple disciplines is necessary to support an evidence-based approach to delineate diffuse CSAs. In Ireland, in recent years, numerous datasets derived from a diverse range of environmental and geo-scientific disciplines have been made available. These datasets reflect the variability of environmental conditions across the country. However, some gaps in these data were evident at the outset of the project, highlighting the need for targeted field investigations and modelling at the catchment scale. It was also recognised that it would be desirable to integrate all relevant aspects of these datasets with findings from field investigations and modelling into a CMST, suitable for delineating catchment-level diffuse source CSAs.

1.2   Overall Project Aims and Objectives

The overall aim of the Pathways Project was to develop an improved conceptual understanding of water-borne contaminant transport dynamics in Irish catchments, in order to inform the development of an appropriate CMST. This, in turn, was intended to inform the assessment of CSAs and contaminant pressures on water bodies to assist with the identification of management strategies and measures at a catchment scale, in order to ensure that "good" WFD status is reached and maintained. The main objectives of the project were:

1 to identify significant hydrological pathways within Irish catchments;

2 to quantify flows along the identified hydrological pathways;

3 to identify significant pathways for delivering diffuse contaminants to surface water receptors with emphasis on the attenuation of nitrogen (N), phosphorus (P) and also sediments;

4 to assess the impact of physico-chemical conditions on aquatic ecological receptors in Irish catchments;

5 to develop a CMST, suited to Irish conditions, in order to identify CSAs for diffuse contaminants in Irish catchments.

1.3 Project Reporting Structure

To meet the aims and objectives of the Pathways Project, field investigations and flow and contaminant modelling were undertaken in order to inform the development of a three-tiered CMST. An integrated overview of the project findings are provided in this Pathways Project Synthesis Report. More detailed information on the specific research components, along with project datasets, can be found in the reports listed below (available from http://erc.epa.ie/safer/reports).

- Pathways Project Final Report Volume 1: *Field Investigation and Catchment Conceptual Models*;
- Pathways Project Final Report Volume 2: *Physical Hydrograph Separation and Flow Pathway Modelling*;

- Pathways Project Final Report Volume 3: *Catchment Characterisation Tool*;
- Pathways Project Final Report Volume 4: *Catchment Modelling Tool*.

In addition, design specifications for the CMST and guidance on using and installing the tool are provided in the following additional documents but are not available for public dissemination:

- Pathways Project Final Report Volume 5: *Catchment Management Support Tools User Manual*;
- Pathways Project Final Report Volume 6: *Installation Instructions for Catchment Management Support Tools Final Version 0.5*;
- Pathways Project Final Report Volume 7: *Design Specification for the Pathways Catchment Management Support Tools*.

Please contact project partners directly regarding access to the CMST, as further development is ongoing.

2 Synthesis of the Pathways Project

2.1 Introduction

This chapter summarises the research undertaken and highlights some of the main findings from the literature review (Section 2.2), field investigations (Section 2.3) and modelling (Section 2.4). These findings informed the development of the CMST. An overview of the tool and, in particular, its benefits for environmental and water managers, is provided in Section 2.5.

2.2 Literature Review and Catchment Selection

An extensive literature review, focusing on contaminant transport along different hydrological pathways, and their associated impacts on water quality and river ecology in Irish catchments, was undertaken. This review identified knowledge gaps relating to Irish catchments and highlighted research areas that should be considered during the Pathways Project. Archbold *et al*. (2010) provide details of gaps in the knowledge

and data encountered at the outset of the project, which informed the direction of subsequent research. In addition, the review informed the selection and weighting of a multi-criteria decision support protocol used for the selection of four study catchments (Pathways Project Final Reports Volume 1).

2.3 Field Investigations

2.3.1 Overview

Building on the findings of the literature review, the field-based investigations of the Pathways Project were targeted at addressing the identified knowledge gaps. This understanding was developed in the context of the source–pathway–receptor conceptual model, with particular emphasis on hydrological pathways that deliver contaminants from sources to receptors. An existing pathways conceptual model (Figure 2.1), including overland flow, interflow, shallow groundwater and deep groundwater (RPS, 2008; Archbold *et al*., 2010), was
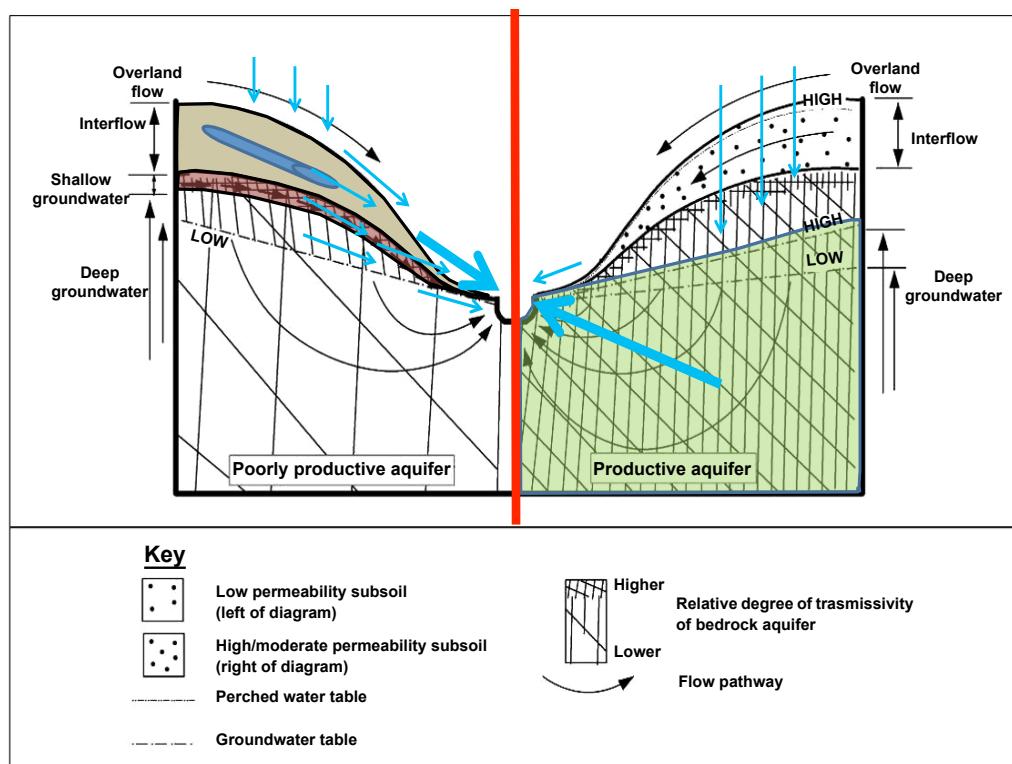
Figure 2.1. Pathways present in poorly productive aquifers (left) and productive aquifers (right) (adapted from RPS, 2008).

initially adopted for testing and refinement in four study catchments. In addition, the transport and attenuation of P, N and sediment along each of these pathways was investigated, as outlined in Pathways Project Final Reports Volumes 1 and 2.

Multi-criteria decision analysis informed the selection of field sites for further study from a range of potentially suitable areas. The selection of catchments for further study aimed to cover the range of geological, climatic and land use conditions encountered across Ireland. The analysis considered catchment size, climate, geology, land use and pressures, accessibility, availability of data, existing instrumentation and any ongoing research in the catchments. The final catchments selected were the Mattock catchment, Co. Louth/Meath; the Gortinlieve catchment, Co. Donegal; the Nuenna catchment, Co. Kilkenny; and the Glen Burn catchment, Co. Down (Figure 2.2). The Nuenna catchment is a well-drained catchment underlain by a regionally important karstified

limestone aquifer covered by permeable limestone tills and gravels. By contrast, the other three catchments are underlain by poorly productive aquifers covered by low permeability, poorly draining clayey tills, and therefore their rivers' discharge show a more rapid 'flashy' response to rainfall than the groundwater-dominated Nuenna. The study catchment settings selected reflect the dominance of poorly drained catchment conditions, overlying poorly productive aquifers, that directly underlie a significant proportion of the country.

Instruments were installed at all of the study catchments to allow the continuous monitoring of flow, temperature and electrical conductivity. Water quality was sampled during low-flow conditions in groundwater, surface water and drains/ditches. The condition of the aquatic ecology in the streams was assessed across all catchments over a 2-year period. A key component of the project was to carry out high temporal resolution water sampling during a summer and winter rainfall event
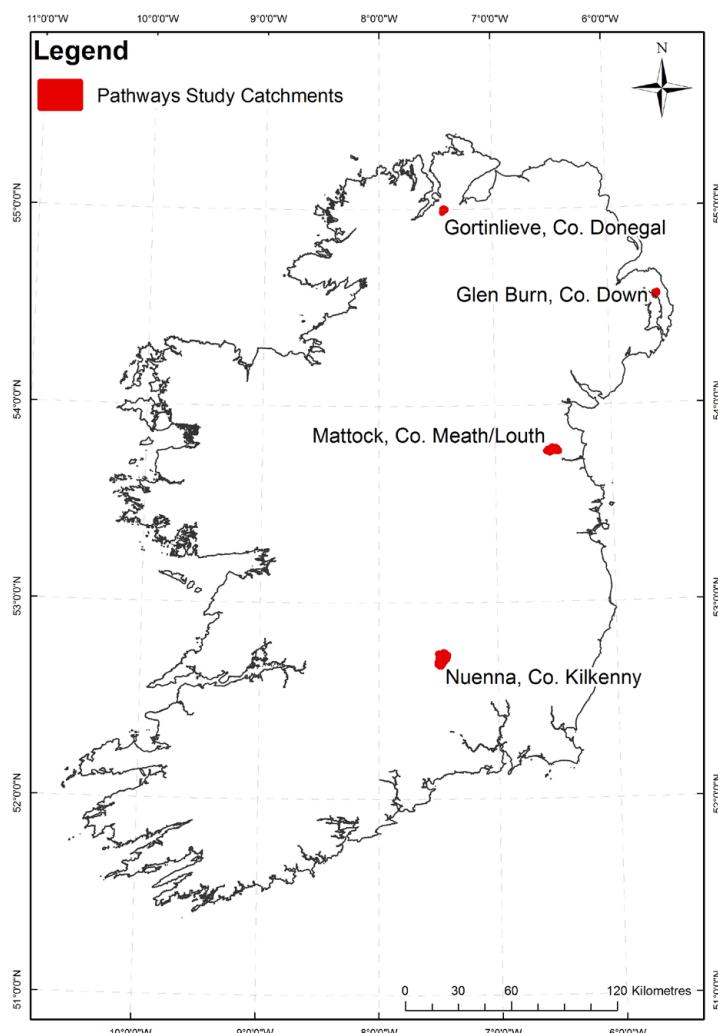
Figure 2.2. Study catchment locations.

in each of the study catchments to further investigate the dynamics of nutrient and sediment transport along individual pathways. Table 2.1 provides a more detailed breakdown of the work undertaken in each study catchment, while Figure 2.3 shows flow and chemistry monitoring locations in the Mattock and Nuenna study catchments.

2.3.2   Findings

The fieldwork findings were broadly consistent with the four-pathway conceptual model of water-borne contaminant transport by overland flow, interflow, shallow groundwater and deep groundwater. However, the field research also found that in the catchments overlying poorly productive aquifers, artificial drainage networks (field drains and ditches) and the transition zone at the top of bedrock are key transport pathways for nutrients during low flows and during peak flows in wet antecedent conditions. Both artificial drainage and the transition zone are considered as subcomponents of the four-pathway model. ('Interflow' in the initial conceptual model includes both subsoil interflow and flow in the transition zone at the top of bedrock.) Based on the field investigations, the transition zone was observed to occur and operate in two different hydrogeological

Table 2.1. Detailed breakdown of fieldwork undertaken in the study catchments

Fieldwork activity	Study catchment
Land use surveys	MK, GO, GB, NU
Macroinvertebrate analysis	MK, GO, GB, NU
Monthly spatial catchment sampling of baseflow/low-flow conditions	MK, GO, GB, NU
Quarterly groundwater sampling (including EPA/Northern Ireland Environment Agency GW sampling)	MK, GO, GB, NU
River longitudinal profiles (flows and chemistry)	MK, GO, GB, NU
Large rainfall events – multiple pathways and rainfall sampled. Two events were targeted in each catchment	MK, GO, GB, NU
Continuous turbidity measurement and suspended solids calibration	MK, GO, GB, MS
Hydrometric rating curves	MK, GO, GB, NU
Soil analyses	MK, GO, GB
Packer testing	GO, NU, GB
FIO sampling and analysis	MK, GB, NU
Nitrogen isotope speciation in groundwater	NU, GB
Interflow instrumentation and sampling	MK
Hydrograph separation into different pathways splits to inform the CMST and CSA delineation (also involving flow modelling undertaken as described in Pathways Project Final Report Volume 2).	MK, GO, GB, NU

FIO, faecal indicator organism; GB, Glen Burn, Co. Down; GO, Gortinlieve, Co. Donegal; GW, groundwater; MK, Mattock, Co. Louth; NU, Nuenna, Co. Kilkenny.

Figure 2.3. Flow and chemistry monitoring locations in (a) Mattock and (b) Nuenna River catchments.

scenarios in these catchments. The first scenario occurs in groundwater discharge zones in which the transition zone is considered to operate together with the shallow groundwater pathway. The second scenario occurs in groundwater recharge zones in which flow in the transition zone is more closely associated with interflow and flow in drains and ditches.

The field studies found that NO_3 was typically delivered via the subsurface pathways, especially via the transition zone and land drains/ditches in the poorly productive aquifer catchments, and through bedrock groundwater pathways in the karst limestone catchment (the Nuenna catchment). Consequently, the field-scale CSAs for NO_3 in the study sites were likely to be locations in which intensive agricultural land use coincides with areas that have thin soils and subsoils overlying bedrock; elsewhere, a thick sequence of high permeability soils and subsoils can inhibit/prevent denitrification and, therefore, also give rise to elevated NO_3 levels in groundwater.

Excess P (particulate and/or soluble) was predominantly delivered to the surface water receptor via overland flow. However, where there were preferential (highly permeable) flow paths present in the soil and subsoil, soluble P and, to a lesser extent, particulate P were also transported through the transition zone and in drains and ditches. With this in mind, the field-scale CSAs for P are likely to be those land areas in which there has been an over-application of P (high excess P), and in which physical settings can give rise to overland flow; these may include areas with low permeability soils, (locally) elevated water tables or steep slopes that connect the source area(s) with surface water receptors. Drains and ditches were also found to be important pathways for P delivery, particularly if they are also linked to point sources.

Point sources of nutrients from farmyards, livestock access points, domestic waste water treatment systems and municipal waste water treatment facilities were encountered in all the catchments and affected main river channels as well as the drainage networks. Arable land was found to be the most significant land type to influence the generation of sediment, although channel bank and in-stream sources were the most significant in the Glen Burn catchment (Thompson *et al*., 2012, 2013, 2014; Thompson, 2013).

The lack of contrast in water quality or ecological metrics along surface water courses limited the possibilities to conclusively link changes in either set of metrics to differences in land use. Despite this, the results tentatively suggest that chronic levels of nutrient pollution, including NO_3 pollution, may be responsible for reducing the biological water quality in the study catchments. From an assessment of the relationship between physico-chemical and biological conditions, it is suggested that in the Nuenna, Glen Burn and Gortinlieve catchments, a relationship may exist between biological water quality and N and P concentrations. Specific findings of some of the innovative research undertaken within the Pathways Project are discussed in more detail in the next section.

Critical source areas for sediment and total phosphorus

One component of the Pathways Project focused on defining the utility of field-scale CSAs with regard to sediment and total P (TP). Thompson *et al*. (2012) studied interactions between overland flow connectivity and nutrient transfers at the field scale using a Sensitive Catchment Integrated Modelling Analysis Platform approach. The results showed that the dynamics of sediment and P concentrations throughout storm hydrographs are complex and storm dependent. Export coefficients for TP, calculated using hectare-scale plots, were found to underestimate annual losses by a factor of 17, compared with those calculated using the contributing area. This component of research suggests that current CSA definitions for implementing mitigation measures may overlook the importance of storm characteristics in determining nutrient transfers. Further research is required in this area to better constrain catchment-scale risk and the complexities associated with upscaling (Thompson *et al*., 2012).

In addition, research was undertaken on field-scale sediment CSAs in two of the Pathways Project study catchments. To date, the approaches that have been used to predict high-risk areas, with regard to sediment loss, have relied predominantly on connectivity and risk, with little consideration being given to process-driven water quality responses. The geochemical tracing of sediment sources related to land use was conducted in three headwater agricultural subcatchments, two in the Mattock catchment and one in the Glen Burn catchment, to investigate the applicability of structural metrics, such as wetness indices, for the prediction of CSAs. Arable land generated the highest risk of sediment

loss associated with land use across all catchments and sampling times. These findings constitute some of the first data on sediment provenance in Ireland, and highlight the need for cautious consideration of land use with regard to informing the identification of CSAs at the headwater scale. Furthermore, this research highlighted that not all of the study catchments were dominated by loss of agricultural top soils, and that channel bank sediment can contribute significantly to stream sediment sources. These results demonstrate the importance of considering and managing eroding channel banks for the mitigation of diffuse sediment delivery (Thompson, 2013; Thompson *et al*., 2013).

To assess the dynamics of suspended sediment, 15-minute turbidity measurements were validated against suspended sediment from stream samples taken over a variety of flow and sediment conditions (Thompson *et al*., 2014). This almost continuously obtained dataset allowed the estimation of the annual load, which was calculated to be 43.9 tonnes in the Glen Burn catchment, resulting in a suspended sediment yield (SSY) of 0.067 t/ha per year. This is significantly smaller than the annual load for the Mattock catchment, which was estimated to be 921.8 t, resulting in a SSY of 0.44 t/ha per year. The Mattock figures are at the upper end of the estimates for other Irish catchments compiled in a review by Regan *et al*. (2012), which range from 0.08 t/ha per year to 0.41 t/ha per year, and far exceed the estimated yield values reported in a recent study of two large catchments in southern Ireland of 0.17 t/ha per year and 0.19 t/ha per year (Harrington and Harrington, 2013). However, estimated erosion rates for Ireland (0.5 t/ha per year) and the UK (0.9 t/ha per year) are below the European estimated erosion rate of 1.2 t/ha per year (Cerdan *et al*., 2010).

The annual load provides an estimate of the total net erosion of a catchment, yet this does not provide an indication of the potential threat to aquatic organisms. Consequently, in light of other research (Bilotta *et al*., 2010), the frequency of exceedance of the Freshwater Fish Directive (Directive 2006/44/EC) guideline value of 25 mg/L was used as an indication of the ecological significance of the concentration dynamics; this was found to account for 17.8% of the monitoring period in the Mattock catchment. Analysis of exceedance events, above 25 mg/l, in the Mattock catchment revealed a total of 409 events, 78% of which lasted less than 2.5 hours. To understand the potential implications of

these dynamics for organisms that may be sensitive to lower concentrations, thresholds of 10 mg/L, 15 mg/L, and 20 mg/L were also examined. Data show that as suspended sediment concentration (SSC) thresholds increase, the frequency of exposure episodes decreases and, importantly, that short duration exposures tend to dominate for all the thresholds assessed in this study. This indicates that prolonged high SSC events are not characteristic of these sites, as shown for the Mattock catchment in Figure 2.4. Results were similar for the Glen Burn catchment (Thompson *et al*., 2014).

Overall, these findings highlight the importance of understanding and considering the hydrological regime that connects field-scale CSAs and surface water receptors, and the contribution of various land use types to the receptors. It also highlights the need to consider whether chronic or acute levels of sediment impact sediment-sensitive aquatic ecology, as this may determine the types of management strategies required in these catchments.

The role of artificial drainage

As mentioned previously, the Pathways Project considered the role of drain flow in flow and contaminant transport. A significant component of the field investigations in the Mattock catchment in particular focused on nutrient transport pathways in artificial drains (Deakin, 2014).

The findings showed that land drain flows varied over five orders of magnitude and continued to flow under unsaturated conditions, corroborating the evidence from a detailed study of soil dynamics, which indicated that flow through macropores was important. The chemistry of both the land drains and the ditches highlighted that the hydrogeological drainage regime influences the nature of the drainage waters which, in turn, influences nutrient transport. Drains and ditches collected NO_3 from stores that were perched above lower permeability layers in the landscape, especially the transition zone in the groundwater recharge areas, in which conditions were unfavourable for denitrification. NO_3 was otherwise generally low in the soils, subsoils and groundwater because of low infiltration and/or attenuation.

Soluble P was high in all land drains and ditches on occasions, although the mechanisms of its delivery differed to those of NO_3. P was washed through the soils and subsoils from the surface into the drainage system
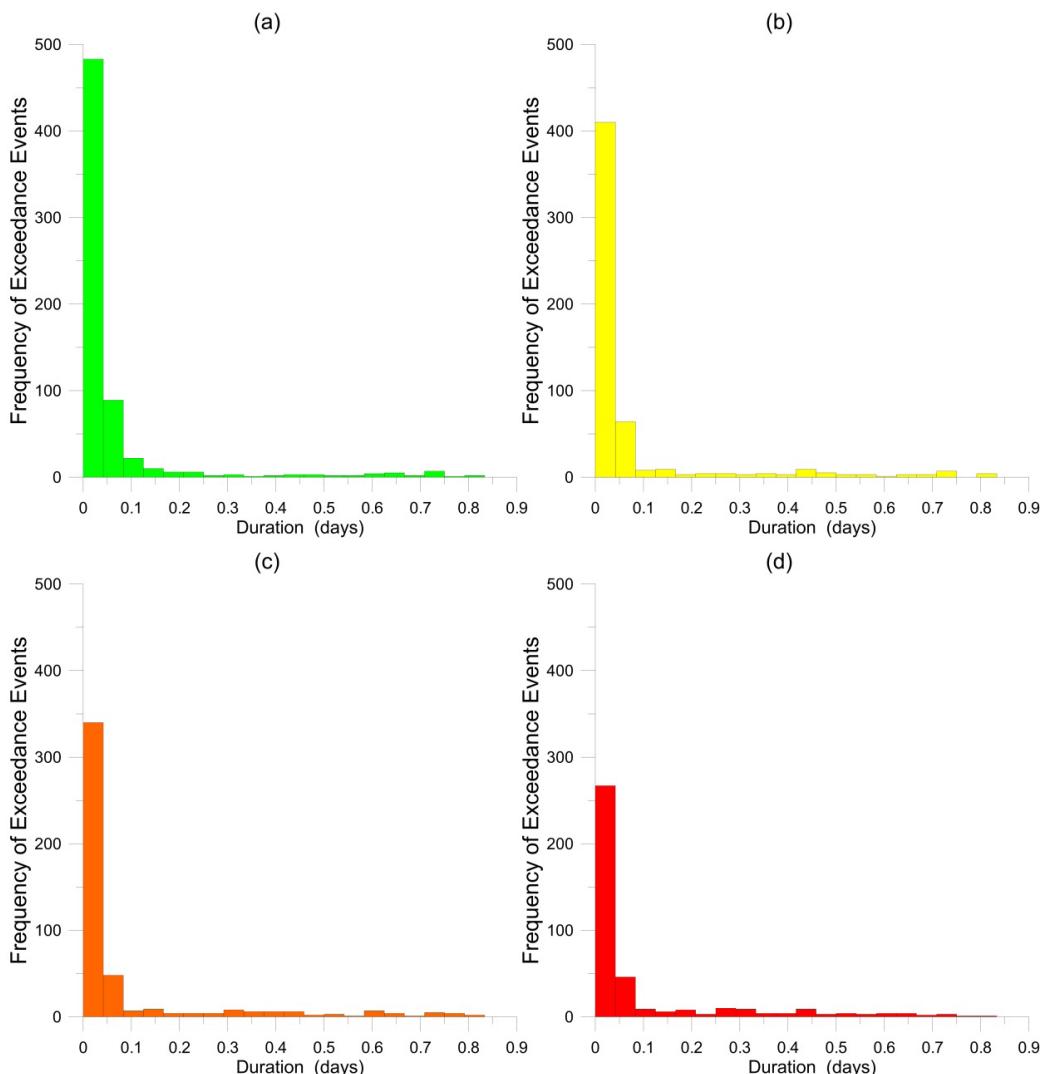
Figure 2.4. Mattock catchment histograms detailing the frequency of exceedance events above threshold concentrations and the duration of each event in days for (a) 10 mg/L, (b) 15 mg/L, (c) 20 mg/L and (d) 25 mg/L (Thompson *et al*., 2014).

via preferential flow paths, and the supply became exhausted as the event progressed. P was also delivered from small point sources directly into ditches, or the transition zone if the depth to rock was shallow. However, P concentrations were low in cases in which the drainage intercepted rising groundwater. A first flush effect for both P and NO_3 was seen in land drains after dry periods.

These findings highlight that the drainage networks contribute significantly to the flow and nutrient transport processes in the catchment. This research has provided new evidence to suggest that the origin of the drainage water, specifically its hydrogeological setting, has a significant bearing on the dynamics of nutrient transfers in drainage waters at the catchment scale (Deakin, 2014).

Faecal indicator organisms

Although faecal indicator organisms (FIOs) were not a main contaminant of interest within the Pathways Project, a component of the research looked at the benefits of using an approach involving FIOs to assist with the characterisation of catchment-scale processes. A campaign of monthly microbial sampling was carried out across both the Glen Burn and Mattock catchments to investigate the spatial and temporal variations in concentrations and loads of FIOs. Temporal variations were anticipated as a result of land use measures aimed at limiting the inputs of organic fertiliser/manure during the winter period. This included a closed period in which the application of organic fertiliser was not permitted and livestock were housed. (However, other sources of FIO contamination were unchanged during this period.)

Multiple locations were sampled on 13 occasions throughout the year and were analysed for *Escherichia coli*, enterococci, sulphate-reducing-bacteria (SRB), total coliforms and total viable counts at 22°C and 37°C.

The results revealed the presence of FIOs in samples collected all year round, even during the closed land-spreading season. Similarly, measurements of FIO fluxes increased gradually as sampling moved downstream, pointing to multiple contributions between the stream headwaters and the catchment outlet. This

is consistent with the findings of specific electrical conductance profiles generated in both water courses. On the other hand, comparisons of FIO concentrations determined from grab samples during open and closed periods for organic fertiliser spreading failed to reveal significant differences (Figure 2.5). This is thought to be the result, in part, of contrasting hydrological conditions.

Analyses of the relative concentrations of *E. coli* (short lived), enterococci (longer lived) and SRB (aged faecal material) show that, in samples collected across the
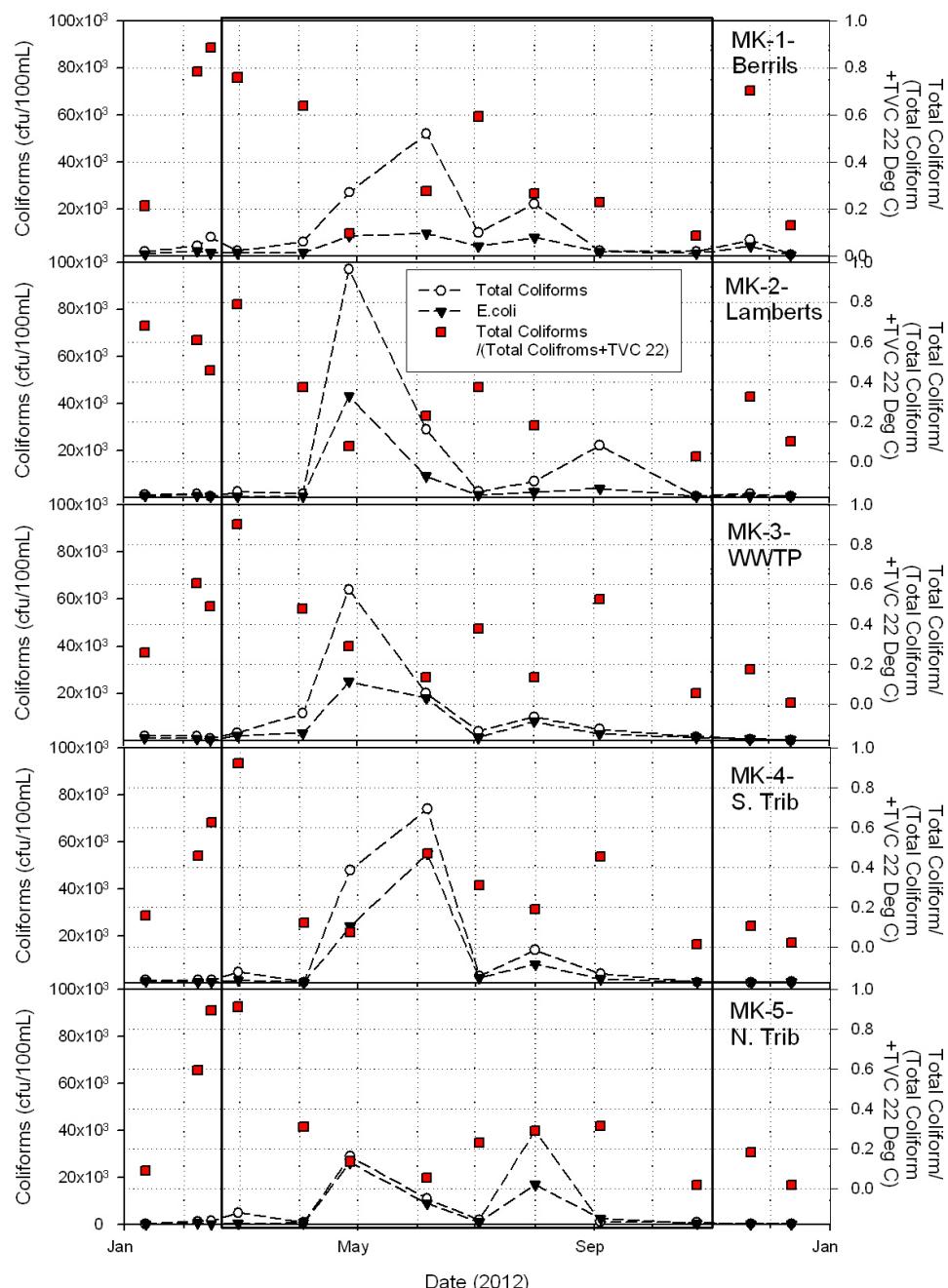
Figure 2.5. Coliform counts in samples taken from the Mattock catchment in 2012. (The period when animals are outdoors grazing (March to October) lies within the area of the black box.)

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Mattock catchment throughout the year, levels of *E. coli* predominate, and suggest that the faecal material inputs in the stream are relatively fresh (Figure 2.5). Analysis of samples collected from the Glen Burn catchment during the open season for spreading display a similar pattern. By contrast, levels during the closed season proved far more variable and suggest a greater contribution from more aged sources than from baseflow fluxes.

Event-based sampling carried out at the catchment outlet of the Glen Burn suggested that microbial signatures could change over short periods during energetic hydrological events. Results of analyses of samples collected before the event revealed high proportions of SRB, relative to either enterococci or *E. coli*. This changed during the event with peak flow, and corresponded to an increased relative abundance of *E. coli*. This declined with event recession, only to rise again during a second flood peak, which occurred before the end of the first recession limb. The results suggest a sustained contaminant source controlled by transport-limited delivery, rather than source depletion. The findings suggest that fresh faecal waste is delivered persistently throughout the open season for organic waste application in both catchments. Although this signature continues to dominate monitoring data through the winter in the Mattock catchment, aged waste plays a more dominant role during the closed season in the Glen Burn catchment. This sustained contribution is overprinted by pulses of fresh material during hydrologically energetic events. Moreover, the high levels of coliforms corresponded to increased fluxes of both N and P (Figure 2.6). The strong association between faecal waste and nutrients helps explain the similar responses in N and P fluxes observed during event-based sampling, and suggests that sustained sources of P and N discharge to surface water during storm events.

Nitrate attenuation in groundwater pathways

A national- and catchment-scale study investigated the influence of hydrogeological setting on the fate and transport of NO_3 in agricultural catchments. Although there are several studies of NO_3 in groundwater, few have studied the influence of hydrogeological settings on the fate of NO_3.

Statistical analyses carried out on a national Environmental Protection Agency (EPA) groundwater quality monitoring database showed that groundwater NO_3 concentrations are controlled by a combination of factors, including the hydrogeological setting (aquifer class), which incorporates transmissivity and flow path length, land use pressure, soil type, subsoil thickness and permeability, and groundwater oxidation reduction potential conditions (Orr, 2014).

The national-scale study provided baseline information to inform the investigation of NO_3 attenuation in two hydrogeologically distinct study catchments: the Nuenna catchment, underlain by a regionally productive diffuse karst (Rk_d) aquifer, and the Glen Burn catchment, underlain by a poorly productive aquifer. The contribution from contaminant sources other than groundwater to baseflow was investigated. Based on analysis of NO_3 concentrations and loads from baseflow and event-targeted sampling in the Nuenna catchment, it was concluded that point sources are not a significant influence on water quality in terms of N concentrations and loads. In contrast, in the Glen Burn catchment, point sources, including farmyards, a septic tank, a tributary and slurry spreading, all have a significant influence on stream water quality. This contribution from point sources increases as the water table rises, creating greater connectivity between the sources and the stream. However, during rainfall events and high groundwater levels, discharge from the shallow groundwater can contribute to the dilution of the point sources, creating a more diffuse contribution to the stream's N flux. The Glen Burn catchment near-surface N dynamics are controlled by biogeochemical processes and groundwater levels, whereas hydrogeological characteristics have a greater influence in the Nuenna River (Orr, 2014).

Following on from these findings, further investigations were undertaken to assess the attenuation of N with depth in both study catchments. Many previous studies using NO_3 isotopes focused on a single bedrock type and few studies have investigated the progression of N dynamics with depth in bedrock. The research presented here shows that denitrification occurs with depth in the poorly productive aquifer underlying the Glen Burn catchment, evident as a result of preferable hydrochemical conditions and an isotopic enrichment ratio of 1.7:1 between $\delta^{15}N$ and $\delta^{18}O$ (see Figure 2.7). In contrast, in the Nuenna catchment, hydrochemical and isotopic analyses show that nitrification is the dominant biogeochemical N processing event.

The policies and catchment management tools implemented to achieve good water quality status should be
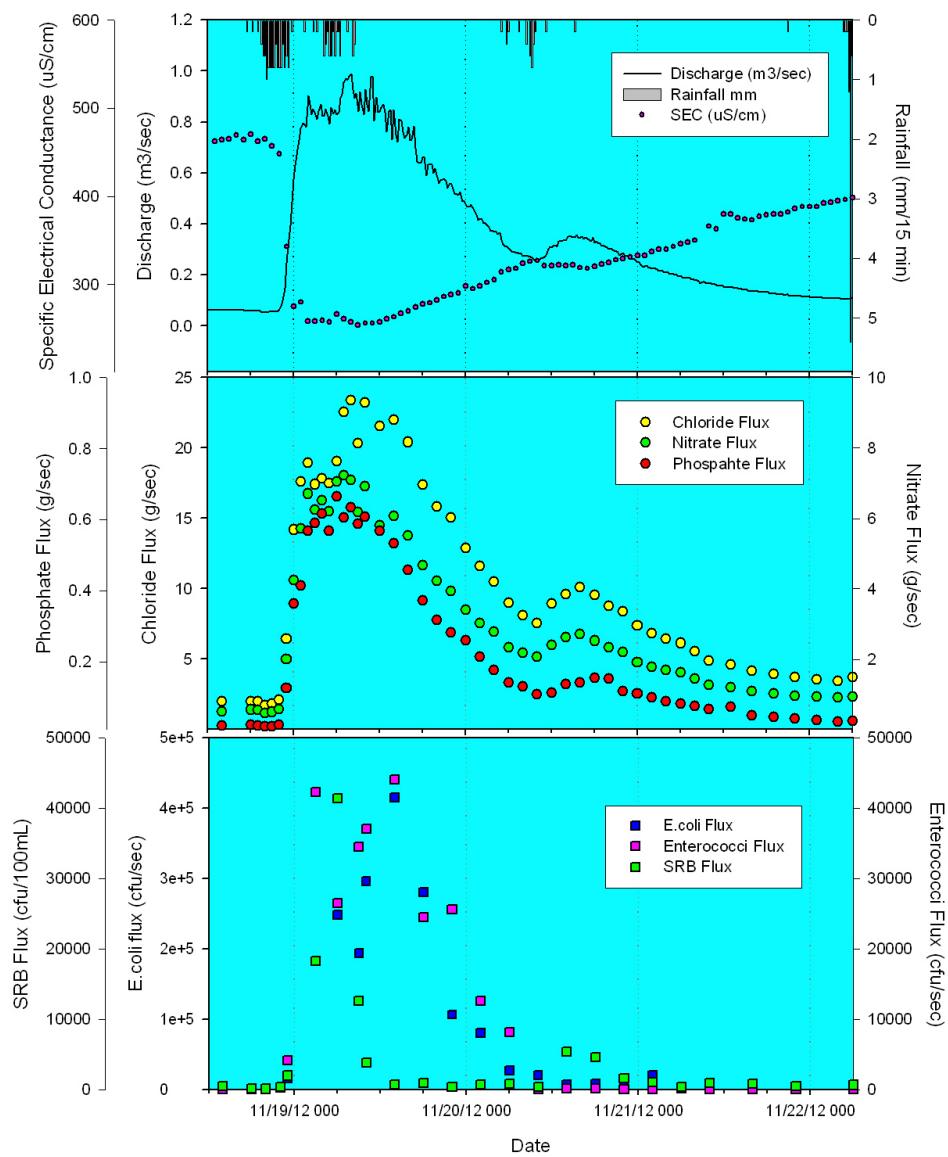
Figure 2.6. Plot of flow, nutrient and selected FIO fluxes with time for samples collected at the Glen Burn catchment outlet during the November 2012 sampling event. Note that the second peak in flow generates a corresponding rise in nutrient and FIO fluxes suggesting sustained contaminant source(s).
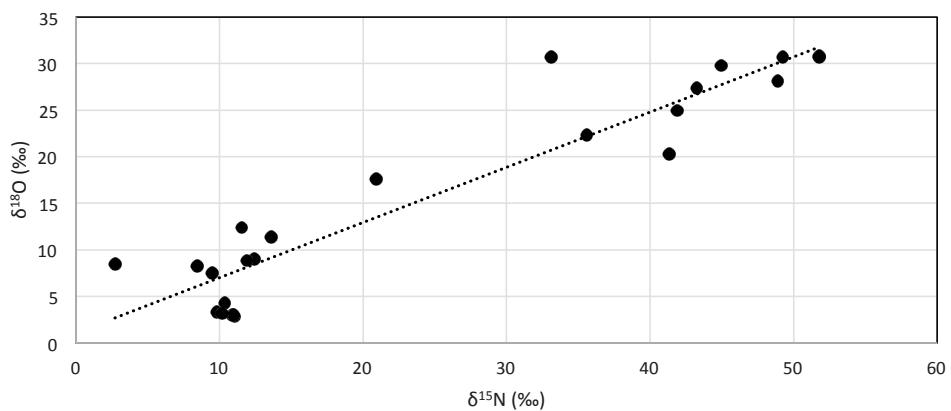
Figure 2.7. Nitrate isotopic signatures in the groundwater of a poorly draining aquifer with a low transmissivity aquifer (Glen Burn catchment).

underpinned by a good understanding of the fate and transport of N. This research highlights the differences in N dynamics between catchments with very different hydrogeological settings, and the drivers for these differences should be considered when developing a conceptual understanding of N dynamics in Irish catchments.

Aquatic ecology

Macroinvertebrate community analysis was undertaken at a number of sites along the length of the river channels in the four catchments (Mattock, Gortinlieve, Nuenna and Glen Burn) in an attempt to relate pollutant inputs to ecological water quality. Sampling was undertaken on seven occasions, May 2010, June 2010, July 2010, October 2010, January 2011, May 2011 and September 2011, yielding a total of 525 samples. Community structure and a range of biological metrics were compared between dates, sites and rivers. The results highlight dynamic seasonal changes within catchments and striking differences among catchments. The Glen Burn catchment exhibited consistently poor water quality throughout the study period (Figure 2.8a), whereas most other sites showed some recovery during the winter/spring (Figure 2.8b). The latter is typical of streams in agricultural catchments throughout Ireland.

In the absence of continuous nutrient data, it is difficult to link the observed deterioration in water quality to specific inputs. The results tentatively suggest that chronic levels of nutrient pollution, including NO_3, may reduce water quality in the study catchments, but there is also some evidence of responses to acute pollution inputs. Furthermore, flow appears to be an important factor in determining whether or not nutrient inputs will elicit an ecological response.

Overall, the results highlight the challenges associated with linking hydrochemical conditions to ecological responses, especially if multiple stressors are involved, very often on different temporal scales. The loss of ecological quality in the headwater of river systems may have implications for downstream recovery, the potential to achieve 'good status', as well as overall catchment biodiversity. Further research should aim to identify the conditions that drive deterioration in water quality through intensive biological sampling of streams with continuous measurement of key pollutants, coupled with controlled experiments designed to disentangle the effects of the various stressors.

2.4 Hydrograph Separation: Combined Approach

2.4.1 Physical hydrograph separation and flow pathways modelling

Physical hydrograph separation methods and flow pathways modelling were undertaken to assist with the interpretation of the field investigation results and the refinement of the catchment conceptual models used in the development of the CMST.

Water balances were developed for the four study catchments using the project catchment rainfall and discharge data. A number of physical hydrograph separation techniques were employed, and later modified, to quantify the flows through each of the four pathways (deep and shallow groundwater, interflow and overland flow). These included the recharge coefficient approach (Misstear *et al.*, 2009), master recession curves, digital filtering algorithms (O'Brien *et al.*, 2013a) and the application of temperature data to split the river flow hydrograph. Flow modelling was carried out using the
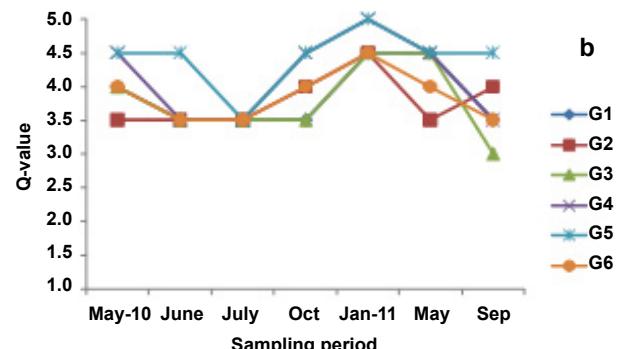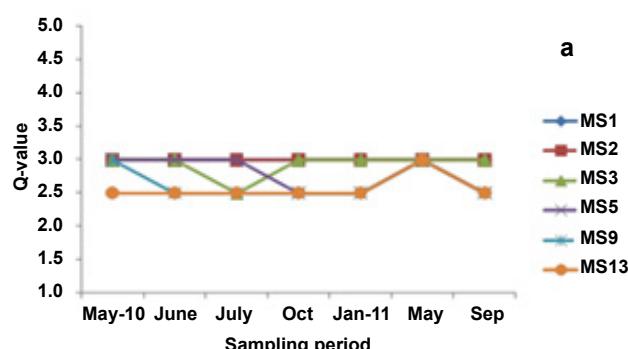
Figure 2.8. Variation in Q-values (biotic indices of water quality) for (a) the Glen Burn catchment and (b) the Gortinlieve catchment from May 2010 to September 2011.

Danish lumped hydrological precipitation run-off model, NAM. A distributed hydrogeological model, MODFLOW (the United States Geological Survey's Modular Three-dimensional Finite-difference Groundwater Flow Model), was applied in one study catchment to test the assumption that there are rarely sufficient data available for Irish catchments to justify the application of fully distributed groundwater models.

Once the pathway separations had been determined from the hydrological modelling, the NAM parameters were related to the different catchment characteristics (i.e. soil, subsoil, slope, aquifer type, etc.). This was accomplished using multiple linear regressions that related each parameter to a selection of catchment descriptors, enabling NAM to be implemented in ungauged catchments of similar types to the study catchments and the supplementary catchments used in this research. A sensitivity analysis was carried out to assess the importance of the NAM parameters. This provided a ranking of the parameters that are most important for implementing the model, particularly for calibrating it.

The combined use of the different techniques enabled the physical hydrograph separations to be consistent with the geological setting of the catchment in question. The physical separations were based largely on response times, in which the fastest responding

pathway was interpreted as 'overland flow', with 'interflow', 'shallow groundwater' and 'deep groundwater' then identified, in turn, as the next fastest responding pathways.

A 'one-parameter' algorithm was modified to identify the four hydrogeological pathways (O'Brien *et al.*, 2013a; Figure 2.9). The flashy nature of the Glen Burn catchment can be observed, with overland flow and interflow providing the largest flow contributions to the hydrograph.

The NAM was found to be effective at separating the hydrograph into its constituent response-time flow pathways, reflecting the results of the physical separation techniques and, in general, maintaining a satisfactory correlation between simulated and observed river discharge. The comparison between observed and simulated flows was evaluated using various objective functions with good results, as shown by the example from the Gortinlieve catchment (EPA weir subcatchment) in Figure 2.10. In this example, interflow dominated for all of the different discharge levels, with 'overland flow' becoming an important contributing pathway during rainfall events if discharge was peaking. These results also show that 'interflow' responded faster than the two groundwater pathways, with 'shallow groundwater' responding faster than 'deep groundwater'. This dominance of 'interflow' is most likely a result of the land
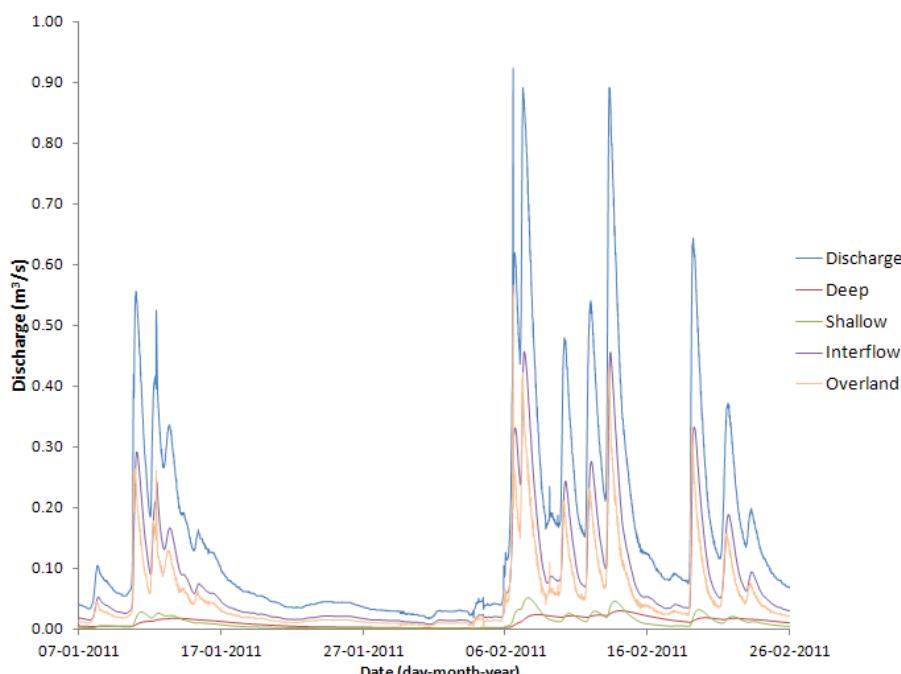
Figure 2.9. Modified Lyne and Hollick algorithm separations, shown with observed total discharge for the Glen Burn outlet catchment (January 2011–February 2011).

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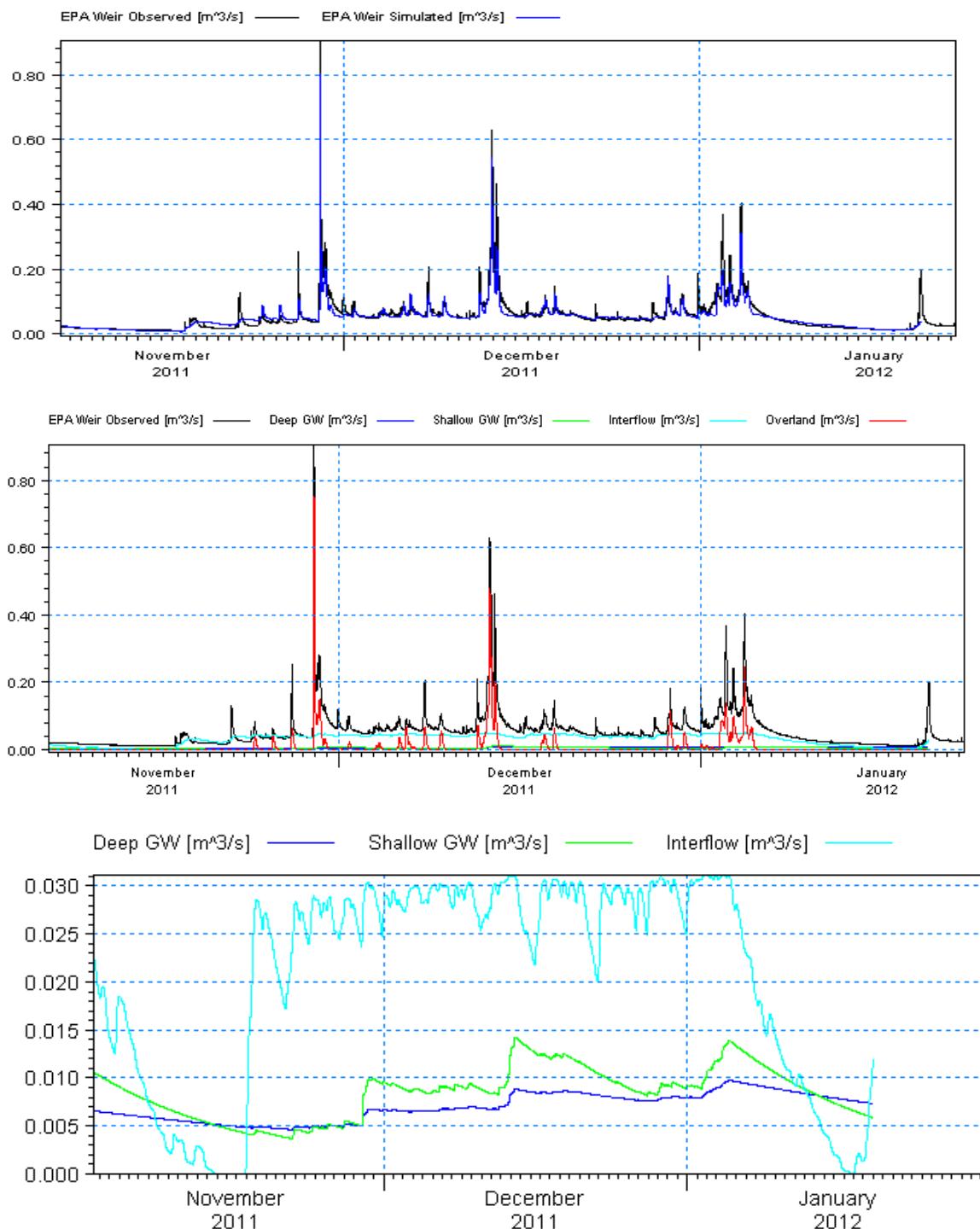
Figure 2.10. Gortinlieve EPA weir (G6) subcatchment modelled flows. Observed discharge with simulated discharge (top), simulated pathway flows with observed discharge (middle), and simulated subsurface pathway flows (bottom) (see Pathways Project Final Report Volume 2).

drains that are installed in the fields because of the poorly draining nature of the catchment (see Chapter 5 of Pathways Project Final Report Volume 1). These land drains encourage subsurface flow that produces the 'interflow' dominance in this catchment and in the other 'flashy' study catchments, as described in Pathways Project Final Report Volume 1. The 'deep' and 'shallow groundwater' contributions maintain the river discharge during periods of low flow.

However, in cases in which different pathway contributions had similar response times, it was not possible to distinguish the contributions using physical methods

alone. This was illustrated by the use of temperature data in the Mattock catchment, which suggested that the other methods, including the NAM, underestimated the contribution of interflow – as fast drain flow – to the river. Therefore, the results of the physical approaches were combined with those from chemical hydrograph separation methods.

2.4.2   Combining chemical and physical hydrograph separation methods

Chemical hydrograph separation methods provide information on the origin and pathways of water contributing to streams that complements the physical hydrograph separation approaches. Suitable chemical tracers representing the different hydrogeological pathways were selected on a catchment-by-catchment basis using the data from the background water chemistry monitoring programmes and the catchment conceptual models. Stream and hydrogeological pathway chemistry was sampled regularly during the monitored rainfall events, and mixing analysis was carried out to determine the contribution of the pathways to the stream. An example of the pathway separations based on chemistry for the Mattock catchment is provided in Figure 2.11.

The results suggest that in the poorly drained catchments under low flow conditions, the majority of stream flow originates from the interflow pathway (including drain flow), with the remainder coming from groundwater. However, the relative proportion of groundwater increases as antecedent conditions become wetter and water tables rise. At high flows, when antecedent

conditions were relatively dry, the majority of the flow was from overland flow; however, as the catchment conditions became wetter, the relative proportion of interflow increased during the event peaks and even exceeded overland flow on occasion. In the Mattock catchment, which was larger than the other two poorly drained catchments, there was also a scale effect, with a higher proportion of groundwater at the catchment outlet than in the upper catchment. In the steeper Gortinlieve catchment, the transition zone was the dominant pathway under all flow conditions; however, in the groundwater discharge area in the lower catchment in wetter antecedent conditions, the relative proportion of groundwater increased. The artificial drainage network was an important delivery pathway for interflow delivery in all catchments, but especially in the low-lying drumlin topography area of the Glen Burn catchment.

Combining the results of the chemical hydrograph separation data with the physical hydrograph separation data (Figure 2.12) provided additional insights into the pathway contributions. For example, in the Gortinlieve catchment during a winter event in December 2012, both methods identified that the highest proportion of flow in the stream was from the overland flow pathway. However, during the larger and higher rainfall intensity event in November 2011, during which antecedent conditions were wetter and water tables were higher, the chemical approach identified that, despite the similarly rapid response times, the largest proportion of flow to the stream at peak flow came from the transition zone. The increase in water levels in the transition zone at all monitoring points throughout the catchment increased the
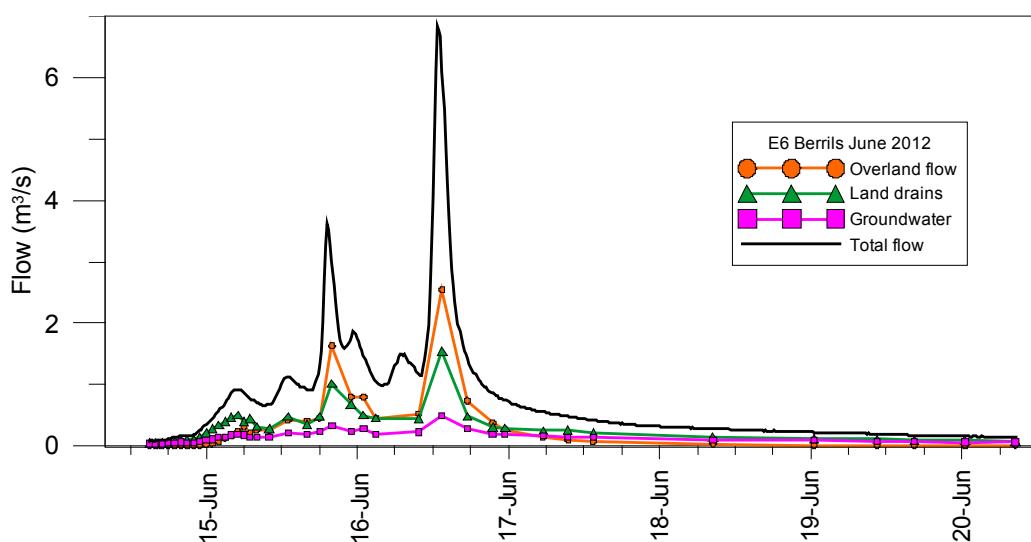
Figure 2.11. Chemical pathway separation at the Mattock catchment outlet (June 2012).

G6 sub	G6 % Pathway contribution		
Nov 2011	Pre event	Peak flow	Total
OF	8	26	23
TZ	53	69	63
GW	39	5	14

G6	% Pathway contribution (NAM)		
Nov 2011	Low flow	Peak flow	Total flow
OF	0	95	58
IF	70	3	27
Sh GW	15	1	9
D GW	15	1	6

G1 outlet	% Pathway contribution		
Nov 2011	Pre event	Peak flow	Total flow
OF	10	39	31
TZ	35	62	47
GW	54	0	22

G1	% Pathway contribution (NAM)		
Nov 2011	Low flow	Peak flow	Total flow
OF	0	93	61
IF	67	4	25
Sh GW	18	1	9
D GW	14	1	5

G6 sub	% Pathway contribution		
Dec 2012	Low flow	Peak flow	Total
OF	5	88	22
TZ	64	8	57
GW	31	4	21

G6	% Pathway contribution (NAM)		
Dec 2012	Low flow	Peak flow	Total flow
OF	0	84	34
IF	78	13	48
Sh GW	11	2	10
D GW	11	2	8

G1 outlet	% Pathway contribution		
Dec 2012	Low flow	Peak flow	Total flow
OF	2	88	28
TZ	62	9	50
GW	36	3	22

G1	% Pathway contribution (NAM)		
Dec 2012	Low flow	Peak flow	Total flow
OF	0	87	42
IF	76	10	41
Sh GW	13	2	10
D GW	11	1	7

Figure 2.12. Comparison of the chemical (left) and equivalent NAM-modelled (right) pathway separations for the November 2011 and December 2012 events in the Gortinlieve catchment. D, deep; GW, groundwater; IF, interflow; OF, overflow; Sh, shallow; TZ, transition zone.

proportion of transition zone water that was discharged to the stream, although much of it was delivered over the land surface based on the field observations and the dominant quick flow response times from the NAM. The review of the water chemistry data highlighted that this water was important for the delivery of NO_3 to the stream from the transition zone, but not particularly important for TP, potassium or ammonium delivery, as would be assumed with an overland flow pathway origin.

Thus, combining the NAM-modelled outputs with the chemical analysis improved the constraints on both the origins of the water and the delivery pathways, which were useful for informing the catchment conceptual models (Pathways Project Final Report Volume 1) and the development of the CMST.

In the Nuenna catchment, the source–pathway–receptor linkages were heavily influenced by the underlying karst limestone. Dye-tracing studies identified that there were rapid underground connections between the poorly drained Namurian shales in the upland regions and the Nuenna River via sinking streams, swallow holes and karst conduits. This means that there is a direct connection between water and nutrients in the catchment area to the sinking streams in the upper catchment and the river. The water balance calculations were therefore modified to more accurately constrain the model. A two-component mixing model, together with longitudinal stream profiles of flow and chemistry, borehole sampling and geophysics, showed that over 90% of the flow during low-flow periods is derived from groundwater discharging at major springs, while during

peak-flow periods, the fresher surface water inputs contribute 40% to the flow. The interflow and transition zone flow pathways are negligible in this catchment as the soils, subsoils and bedrock have high relative permeabilities.

Although the NAM was successfully employed for splitting flows into the four pathways identified in the project conceptual model, it was recognised within the Pathways Project that the NAM would not be easily adaptable to simulating the transport and attenuation of contaminants along those pathways. Therefore, for the computational engine included as part of the Catchment Modelling Tool (CMT), the SMART (Soil Moisture Accounting and Routing for Transport) model was developed, as described in detail in Pathways Project Final Report Volume 4. Although using MODFLOW for the lumped hydrological modelling exercise provided some useful insights into catchment behaviour, the results confirmed the limitations of a distributed groundwater flow modelling approach if the necessary data required to populate the model are not available at the scale of the catchment being investigated, that is if the available data are insufficient to shed significant additional insight on hydrological processes. It should be added that, in an Irish context, the Mattock catchment would be considered a relatively well-instrumented catchment, so the inapplicability of a data-hungry finite difference groundwater model to this catchment supported the adoption of a lumped modelling approach in this project (Pathways Project Final Report Volume 2).

2.4.3 Extrapolation of the event flow pathway estimates to annual average estimates

Annual average estimates of flow path contributions were extrapolated from chemical hydrograph separations in each of the Pathways Project study catchments, using a flow duration curve (FDC) method. The results are presented in Pathways Project Final Report Volume 4 and are compared with results from the hydrological models and values from the Geological Survey of Ireland (GSI) recharge map.

The FDC method combined the chemical hydrograph separations with continuous flow data, collected over approximately 2 years, to estimate flow path contributions from overland flow, interflow and groundwater flow in each of the catchments. A very simple approach was adopted, which incorporated the conceptual understanding of the fieldwork team, as the data were limited to two events in each catchment over a 2-year period. Representative flow splits were identified for two to four flow regimes in each catchment. In the three catchments underlain by poorly productive aquifers (Pathways Project Final Report Volume 1), representative high-, medium- and low-flow hydrograph separations were identified based on combined interpretation of the field and modelled data by both project field scientists and modellers. Using FDCs of the continuous flow data available (approximately 2 years), these separations were used to calculate the overall average annual estimates (Figure 2.13). A similar method was also applied in the Nuenna catchment, but with just two dominant hydrological pathways, identified as groundwater flow (diffuse and conduit) and quick flow.
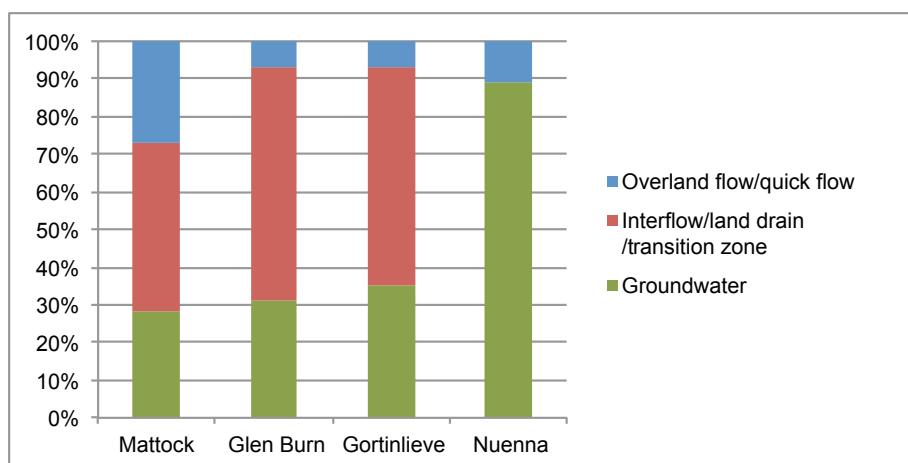
Figure 2.13. Annual average flow pathway estimates for the four Pathways Project study catchments.

These estimated annual average flow path contributions to stream flow were an independent comparison for the modelled hydrograph separation techniques, and were compared with both results from the Monte Carlo analysis and optimised simulations of the SMART (see Section 2.5.3) and NAM models.

2.5 Catchment Management Support Tools

The Pathways Project developed a suite of Pathways CMSTs, intended for use by environmental, water resource and catchment managers (for example, those working for the EPA, local authorities and river basin districts) interested in identifying CSAs for nutrients and sediment from diffuse sources in Irish catchments. Individual elements of the CMSTs build upon one another (Figure 2.14), with more complex combinations relying on the outputs from more basic tools. Consequently, the CMSTs may be employed to address issues of varying levels of complexity, without

any need to resort to advanced elements; that is, the use of the CMST's basic elements can provide stand-alone outputs.

CMST development was informed by the catchment studies and subsequent modelling summarised in the previous sections. The CMST is based on a GIS that acts as a user-friendly interface for hydrological and water-quality models to assist with the prediction of fluxes of water and contaminants along various flow paths in order to identify CSAs for selected contaminants. It can help with catchment characterisation and allows managers to target areas for the enforcement of regulations and to evaluate mitigation strategies. The tools in the CMST include base maps in GIS and two modelling tools: the Catchment Characterisation Tool (CCT), described in Pathways Project Final Report Volume 3, which is concerned with long-term annual average fluxes; and the CMT, which deals with the dynamic variation of the fluxes over time and is described in Pathways Project Final Report Volume 4.

Pathways Catchment Management Support Tools (CMST) Overview
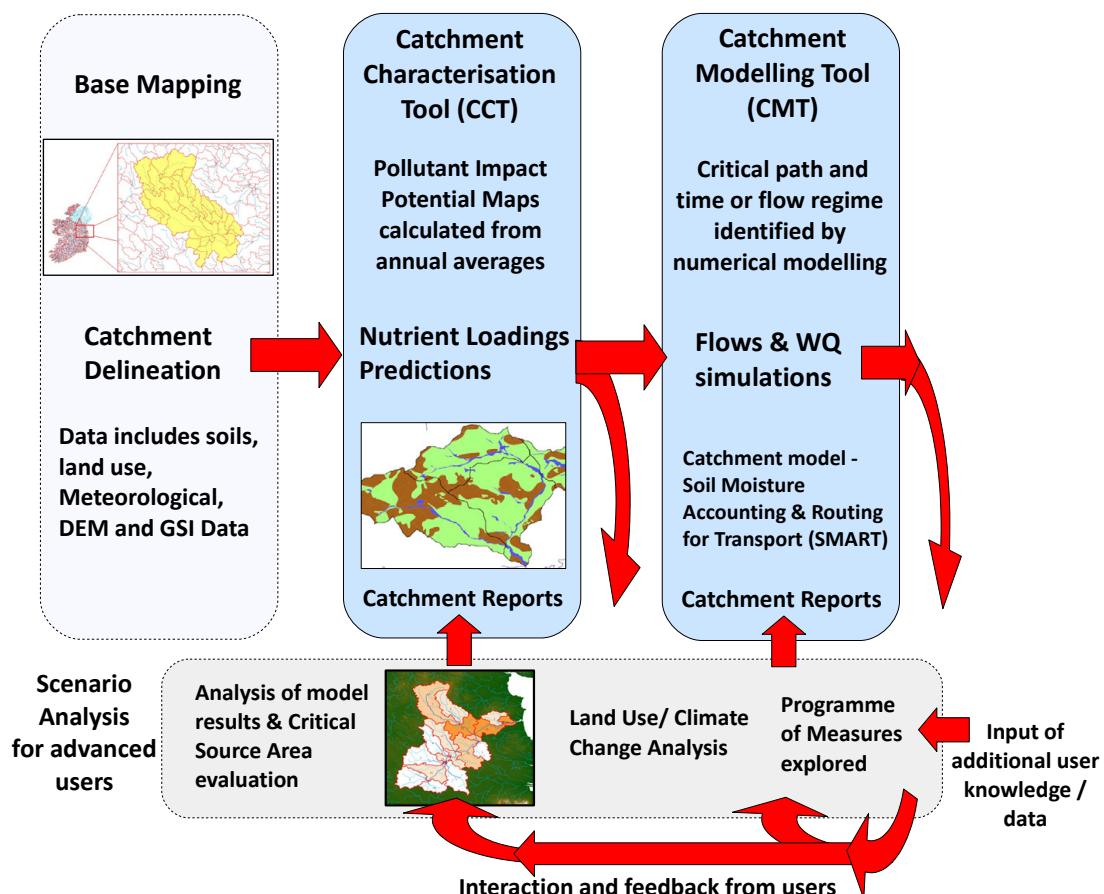
Figure 2.14. Overview of the Pathways Project Catchment Management Support Tools.

The CMST structure is shown in Figure 2.14. The following sections provide details on the main functions of each component of the CMST and how they can be utilised to assist with water resource and catchment management.

2.5.1 Base maps in GIS

Base maps in GIS contain all the source map layers employed by the CCT and allows the user to choose a catchment for study. Currently, the choice of catchments is determined from subcatchments delineated for the EPA. The average subcatchment size is approximately 10 km^2, but there is considerable variation across the country; for example, it is possible to view whole river catchments or entire river basin management districts. Once the catchment of interest is selected, there are a number of base maps on land use, soil and geological properties, and point sources that can be viewed in the Base Map Exploration Tool for the catchment by simply selecting the layer of interest. A summary of the layers used withing the CMST is provided in Table 2.2, while a detailed list is provided in Pathways Project Final Report Volume 3. The source GIS data are supplied mainly by the EPA and the GSI for the catchment of interest. The user can view the individual layers of interest by simply selecting a layer. Summary statistics can then be generated, which provide catchment details on the various maps that have been selected and viewed. The whole catchment or individual subcatchments can be chosen for viewing and reporting. Summary statistics can be provided for each layer of interest, thus providing the user with an overview of the properties of the catchment. For example, the proportion of wet soils versus dry soils will be displayed on the soil drainage map, and, with regard to land use, the highest proportion Corine category will be displayed, followed by the next highest, etc. The number and type of point sources is also displayed, giving an indication of the pressures in the catchment.

2.5.2 Catchment Characterisation Tool

Overview

The CCT is a risk assessment tool developed to identify CSAs in catchments and to assist catchment managers with targeting investigations and possible mitigation measures. A lumped annual average model in the CCT links the GIS layers and datasets with transport and

Table 2.2. Summary of dataset types contained within the CMST

Groundwater abstraction locations
Corine land use update 2006
County boundaries
Combined sewer overflow locations
Domestic waste water treatment system (septic tank) locations
Groundwater body boundaries
Location of integrated pollution prevention control licensed facilities
Lake segment boundaries
Landfill locations
Mining locations
Quarry locations
River basin boundaries
River basin district boundaries
River segment network (lowest order of rivers included)
River subcatchment boundaries
River water body network
Geological formation boundaries
Location of Section 4 licensed facilities
Sewered area boundaries
Soil types and attributes
Natural soil drainage map
Town locations
List of catchment descriptors for points on the EPA river segments
Location of waste facilities
Water treatment plant locations
Waste water treatment plant locations
Digital terrain map, hydrologically corrected
Potential denitrification map
Aquifer bedrock boundaries
Depth to bedrock map
Gravel aquifer boundaries
Location of karst features
National groundwater vulnerability
Subsoil permeability map
National recharge map
Boundaries of electoral divisions
National statistics broken down by electoral divisions
Agricultural statistics broken down by electoral division
Land drains potential map
Sediment rainfall erosivity factor
Sediment soil erodibility

delivery factors derived from field and literature data, and expert knowledge. Applied loadings are calculated using an adapted version of the Groundwater Task

Team loadings tool (GTT, 2010) for NO_3 and soluble P, and the Revised Universal Soil Loss Equation for sediment (Renard *et al*., 1997). The NO_3 and soluble P application rates are taken to be the maximum recommended fertilisation rates of available nutrients from good agricultural practice regulations (S.I. No. 31/2014 from Irish Statute Book, 2014).

The CCT produces pollution impact potential (PIP) maps, which are derived by ranking the possible source areas of contaminants contributing to surface water and groundwater receptors in accordance with source–pathway–receptor methodology.

Transport and delivery factors for each nutrient and pathway, informed by the literature review and field studies, are associated with surface and subsurface pathways. These factors are displayed as susceptibility maps in the CCT, giving the proportion of the applied nutrient that will reach the receptor for a given pathway. The loadings are calculated and combined with the susceptibility maps to give pathway loading maps. The loadings are then converted to concentrations to generate the final PIP maps using estimates of annual

amounts of effective rainfall and recharge from previous research (Hunter Williams *et al*., 2013). Concentration ranges are divided into discrete risk categories, ranging from low to very high for each contaminant. Each source area is assigned a risk category based on its concentration and is ranked in terms of risk to the receptor. The areas in the highest category are the CSAs for the catchment; these represent the areas of highest risk of pollution impact on the receptor. An example of a PIP map for the surface water receptor in the Nuenna catchment is shown in Figure 2.15.

PIP maps for each catchment highlight the relative source areas of pollutant impact to the groundwater and local surface water receptors for nutrients. For nutrients, three PIP maps can be displayed:

1. the subsurface pathway that delivers to the groundwater receptor;

2. the near-surface pathway contribution to the local surface water receptor;

3. the combination of both pathways that deliver to the local surface water receptor.
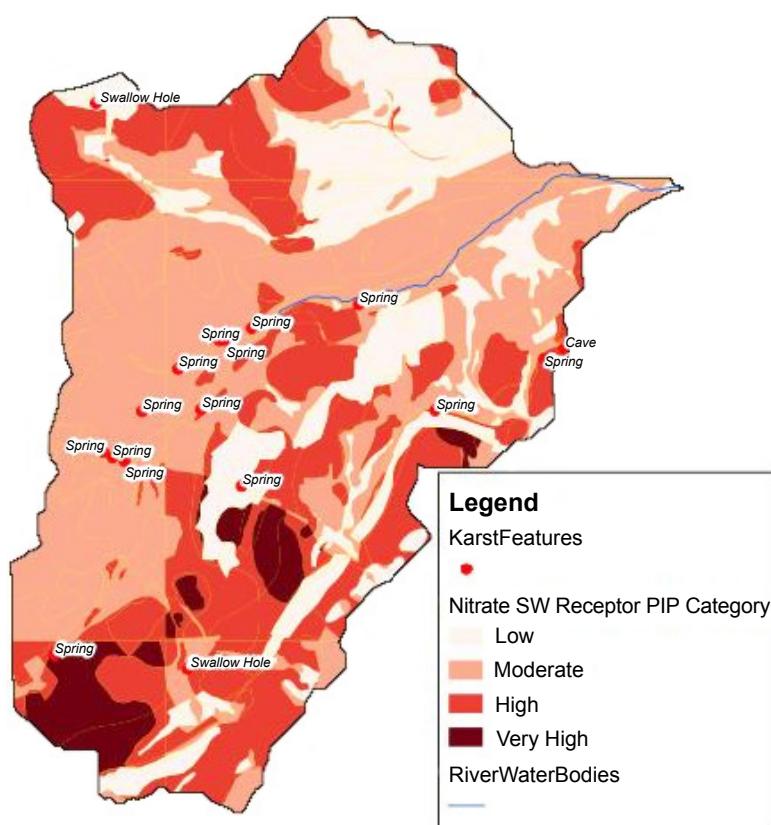
Figure 2.15. Nitrate pollution impact potential map for the surface water receptor in the Nuenna catchment. (Please contact catchments@epa.ie for details of PIP maps updated since completion of the Pathways Project.)

The model is conservative, in the sense that the factors are designed to highlight potential problem areas of nutrient impact. The CCT ranks the relative calculated concentrations and displays a colour risk rank on the maps. The areas with the highest risk ranks are the CSAs for the catchment. Intermediate maps that are used to create the PIP maps, such as susceptibility and pathway loading maps, can provide additional information to assist with catchment management and planning a programme of measures.

This tool can be used by an end-user with some GIS experience, although it is envisaged that a working GIS knowledge would be required to alter the input files required for catchment management scenario testing.

Fieldwork and hydrograph separation

The results of the Pathways Project field studies and hydrograph separation were used to inform the CMST modelling framework. In the CCT, the near-surface pathway encompasses overland flow and interflow (including drains and ditches), while the shallow and deep groundwater pathways are lumped together in the subsurface pathway. The output from the CCT broadly matched the observed Pathways Project field data in both magnitude and trend, giving confidence in the ranking of CSAs for the different pathways. Further testing using field data from other Irish study catchments will continue. Initial results suggest that the CCT maps and output reflect the catchment conceptual models, and that the nutrient loadings are realistic. Table 2.3 shows a comparison of measured NO_3 data versus modelled NO_3 data for the Nuenna catchment. The measured data has been lumped together to reflect the modelled subsurface pathways and surface water receptor.

Benefits of the CCT

The CCT is a powerful tool, which can assist with meeting WFD objectives, especially 'characterisation', under Article 5 of the WFD (EC, 2000; EPA, 2005). The CCT has been developed to reduce the time taken to identify CSAs in catchments and to provide the user with the added benefit of being able to quickly assess some potential mitigation measures for the catchments.

In addition, scenario testing may be carried out with this tool; this may include, for example, changing the land use or nutrient loading within a catchment to determine if and how changes in catchment management scenarios alter the CSAs. Scenario change analysis, using the CCT, can assist with the assessment of potential mitigation measures. Intermediate outputs from the CCT, such as susceptibility and pathway loading maps, can provide the end-user with additional information and help focus measures on the most relevant pathways.

The flexible platform structure means that the CCT can be modified and adapted for use by, for example, agricultural scientists, planners and climate change scientists for catchment and water resource management. The CMST is currently populated with datasets from Ireland, but the flexibility of the CMST structure means that the CCT can be modified for use in other EU member states that are also obliged to meet WFD objectives.

The base maps and CCT should be continually developed and updated to realise their full potential. Currently, work is ongoing on the next versions, which will incorporate the Land Parcel Identification System (LPIS) dataset, in order to improve loading estimations and possibly allow impacts of farmyards to be considered. Furthermore, a method is being developed to determine if it is possible to combine the loading from small point

Table 2.3. Nuenna nitrate concentrations comparison of Pollutant Impact Potential output with field data (see Pathways Project Final Report Volume 3, Section 7)

Pathway	Minimum (as N, mg/L)	Maximum (as N, mg/L)	Mean (as N, mg/L)	PIP map receptor	Modelled NO_3 (as N, mg/L)
Nuenna deep and shallow GW combined	0.22	5.77	3.72	Subsurface pathway	5.23
Subsoil	4.29	5.93	5.17		
Springs	0.20	6.30	4.88	Local surface water receptor	4.60
Surface water catchment outlet	1.80	5.90	4.98		
Near-surface pathway	Near-surface pathway was not sampled			Near-surface pathway	3.96

GW, groundwater.

sources, such as domestic waste water treatment systems, directly with the diffuse loadings. Testing with data from other Irish catchments is ongoing. These tools are being developed to provide an indication of the presence and location of CSAs in catchments, as shown on PIP maps. Catchment walks, inspections and/or monitoring will be undertaken to confirm the CSAs, and no decisions should be based on PIP maps alone.

2.5.3   *Catchment Modelling Tool*

Overview

Dynamic water quality simulations based on hydrological modelling can be particularly useful for assessments of catchments with multiple sources (diffuse and point) of nutrients with different attenuation and delivery mechanisms. Estimates of nutrient source apportionment on the subcatchment scale can be produced when data for all sources, including large point sources, are available for input into the model.

The CMT is a combined hydrological and water quality numerical model for investigation of time-varying flows of water, nutrients and sediment. It was developed as

a dynamic model, capable of tracking the short-term variation in these quantities and their relationship with time-varying drivers. Results can be analysed for high-, medium- or low-flow periods, and by month or season. Flow pathway relationships were determined by numerical equations, the parameters for which were identified from the literature and the analysis of observed data. The temporal output from the model currently includes water flows and contaminant amounts travelling along all the modelled pathways.

The CMT simulates subcatchments as nodes in a network, linked together with river water bodies. Hydrological connectivity is interpreted from GIS data for surface water bodies, resulting in a semi-distributed representation of the catchment (Figure 2.16). In the CMT, the hydrological flow pathway separation for each subcatchment is determined by the SMART numerical model. This model was developed following a comparative study with the NAM and SMARG (Soil Moisture Accounting and Routing with Groundwater component) models (Mockler and Bruen, 2013; Mockler *et al*., 2013). The parameters for each catchment simulation are estimated from catchment characteristics, such as soil and aquifer categories, using regression equations derived
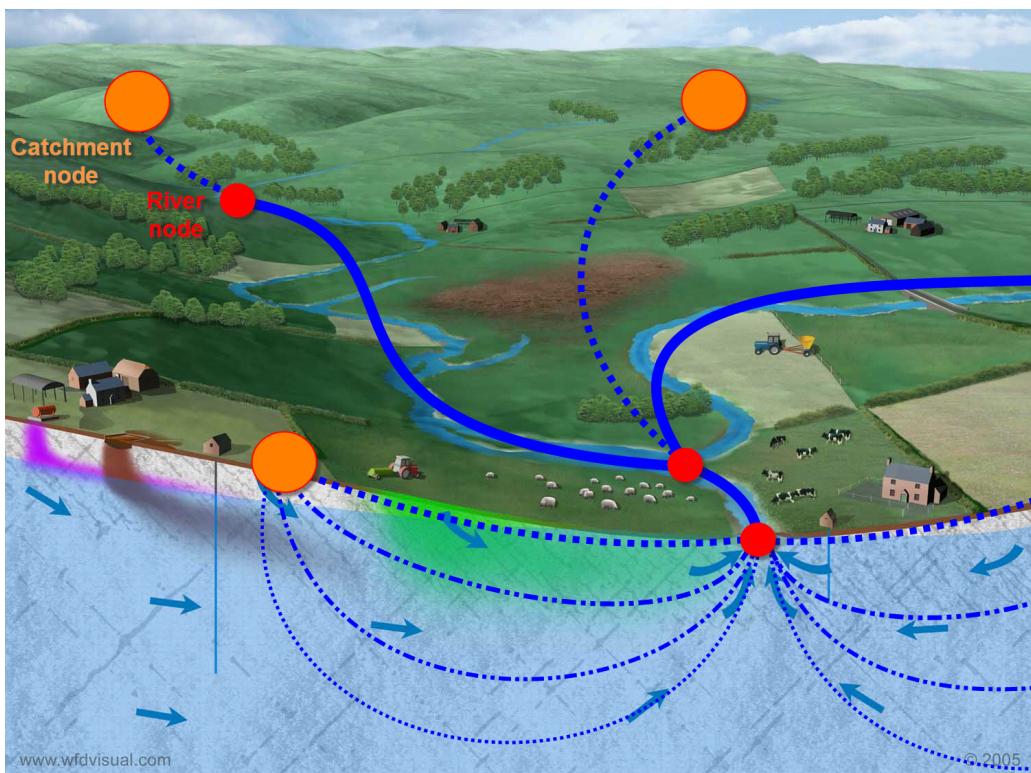

Figure 2.16. Illustration of the CMT representation of a catchment using connected nodes (base image from WFDvisual.com).

from a national study using 31 catchments, detailed in Chapter 6 of Pathways Project Final Report Volume 4.

Annual nutrient loadings calculated by the CCT are passed to the CMT. The movement of nutrient loadings through the catchments and river network is driven by the simulated hydrological flows. Water quality attenuation equations simulate the transformations of nutrients along the modelled flows. These equations provide information on fluxes and concentrations at all nodes in the model. These water quality equations are based on existing models, especially the Integrated Nutrients from Catchments (INCA) – Nitrogen (INCA-N) model (Whitehead *et al.*, 1998; Wade *et al.*, 2002a; Wade, 2004) and the INCA – Phosphorus (INCA-P) model (Wade *et al.*, 2002b).

The results for the annual average export of NO_3, estimated by the CMT, for each subcatchment can be visualised through the CMST interface. Some of the results for the extended Mattock catchment are combined in Figure 2.17, which shows the 18-year average NO_3 loads exported. This illustrates the benefits of a semi-distributed model, able to show the differences between subcatchments with different physical characteristics and meteorological conditions. This knowledge can then inform the identification of the important pathways and flow regimes that influence CSAs within a catchment.

Testing with Pathways Project and national data

The Pathways Project fieldwork confirmed findings in international literature (e.g. Jayatilaka and Gillham, 1996) by showing that physical hydrograph separation techniques and conceptual modelling reliant on lag time to determine flow path contribution may not capture all processes seen in the field. The SMART model structure drives the flows and nutrients in the CMT, and was required to be compatible with both contaminant and hydrological modelling, while being amenable to parameter regionalisation.

The development of SMART was informed by the conceptual understanding of the four Pathways Project study catchments, principally through dialogue between modellers and the fieldwork team. Such interactions between field scientists and modellers is vital for improving conceptual models of hydrological processes (McDonnell, 2003). Drain flow was identified as an

important factor during the course of the field research, and, therefore, was included in the interflow pathway of SMART. Analyses of chemical hydrograph separations from event sampling in the four Pathways Project study catchments were used to estimate annual flow path contributions to stream flow. These annual estimates were extrapolated from results of two events in each catchment. Monte Carlo simulation results were analysed to assess and compare the range of plausible flow path contributions from the models, as well as parameter value ranges (Mockler, 2014). Flow path modelling results for the Pathways Project study catchments are detailed in Chapter 4 of Pathways Project Final Report Volume 4, including comparisons with the NAM and SMARG models, which informed the development of the SMART model.

The SMART model was developed and tested at a range of spatial and temporal scales. Along with testing in the Pathways Project study catchments, testing was also carried out across a wide range of hydrological conditions in 31 catchments, ranging from 150 to 2500 km^2 in area. The parameters of the new hydrological model were successfully regionalised using regression equations with catchment characteristics, to facilitate predictions for catchments outside of this study. Regionalisation included the development of two methods of deterministic parameter estimation that are applicable nationally.

The development and testing of the water quality aspects of the CMT are ongoing. The results from nutrient simulations are presented in Chapter 8 of the Pathways Project Final Report Volume 4 and show the potential of the model. The general water quality model structure has been developed, but further work on the loading inputs and model testing is required. This development of the CMT has been taken forward through an EPA research fellowship (the Catchments Project).

Benefits of the CMT

The CMT can inform catchment scientists about the timing and pathways of pollution delivery at the subcatchment scale. This information can be used with the CCT maps to identify the potential location, pathway and timing of a pollutant reaching a receptor.

Water quality simulations incorporating hydrological connectivity can be used to assess many sources of pollution in an integrated manner. This type of
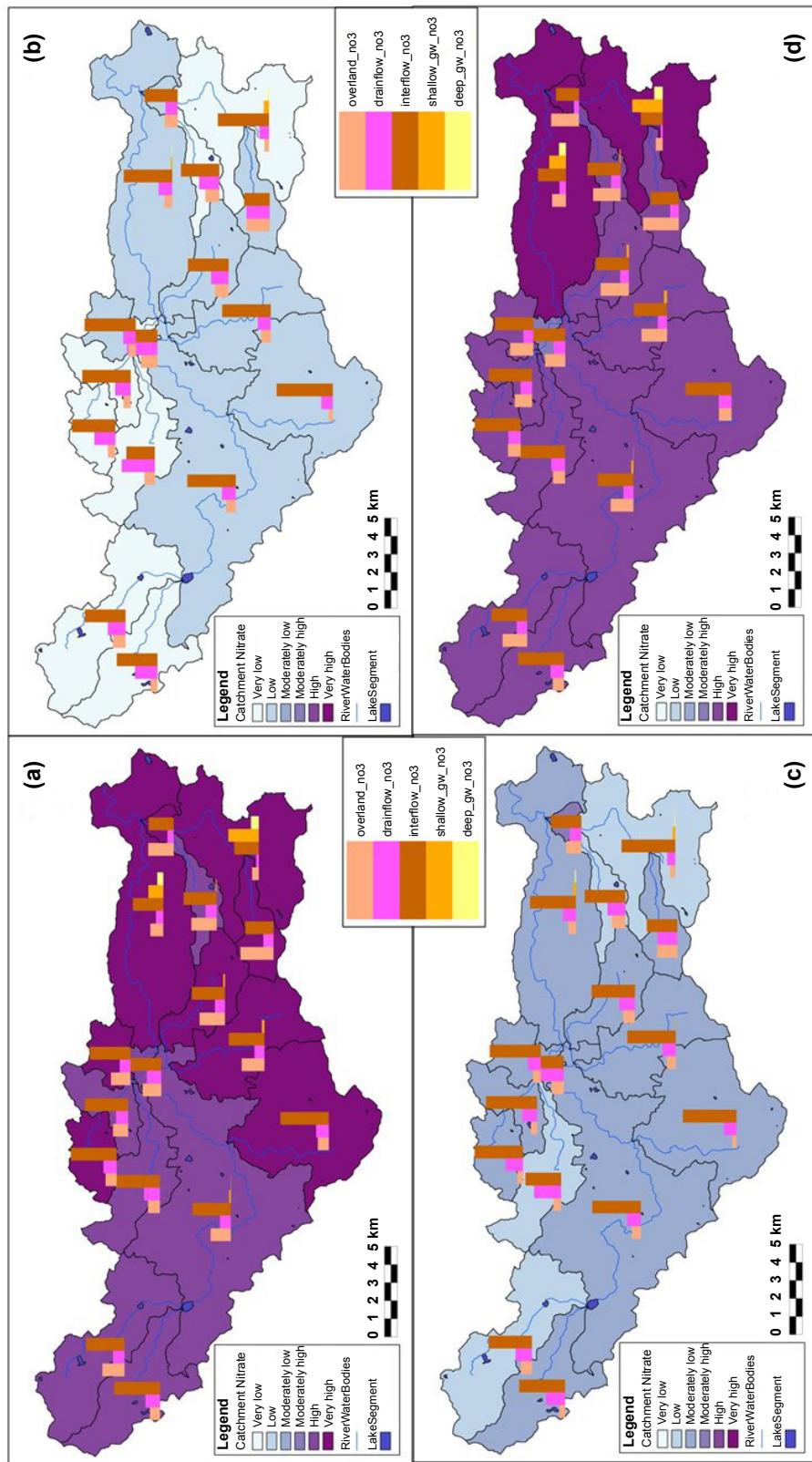
Figure 2.17. Nitrate catchment and pathway contributions: (a) annual total, (b) high flows, (c) medium flows, (d) low flows.

analysis is particularly useful for detailed assessments of contaminant attenuation and delivery mechanisms at catchment scale, and it is envisaged that it will be used in catchments with significant water quality issues. Scenario analysis could then be used to assess and compare the impacts of applying measures with both the CCT and CMT.

The CMT is especially suitable for producing risk rankings of critical pathways, flow regimes and critical seasons, because its outputs include nutrient source apportionment at the subcatchment scale. These outputs are currently for diffuse sources, but, in the future, outputs for small and large point sources could also be added as data availability allows. Scenario analysis using the CMT can facilitate the assessment and comparison of intended mitigation measures, and their potential effects on the relative source apportionment at subcatchment scale. Examples of such scenario analyses include:

- analysis of loadings
  - loading rate change scenarios (e.g. land use stocking density and inorganic fertiliser loadings);
  - changes in the timing of fertiliser applications;
- sensitivity of flow regimes
  - assessment and comparison of some management measures (e.g. increased attenuation in overland flow from buffer strips);
  - changing climate assessment by adjusting rainfall/temperature using monthly factors;
- future developments
  - in-stream point source (and abstraction) effects and downstream sensitive water bodies;
  - assessment of the impact of timing of delivery of pollutants (e.g. from waste water treatment plants (WWTPs));
  - comparison of downstream results before and after upgrades of WWTPs.

The CMST interface allows CMT users to simulate hydrological flows and contaminant transport in Irish catchments by generating the input files required by the CMT's hydrological and water quality models from national datasets. Input files for the selected catchment are generated by the CMST. The GIS interface of the CMST can superimpose results on a catchment map so that the spatial variation in results for subcatchments, produced by the CMT, can be visualised by the user.

2.6 Outputs from the Pathways Project

This section highlights the main outputs from the Pathways Project and is broken down into the following types of output:

- published papers;
- PhD and MSc theses;
- workshops.

The following peer reviewed papers are based on Pathways Project research:

Flynn, R., Deakin, J., Archbold, M., *et al.*, 2015. Using microbiological tracers to assess the impact of winter land use restrictions on the quality of stream headwaters in a small catchment. *Science of the Total Environment* 541: 949–956.

Mockler, E.M. and Bruen, M., 2013. Parameterizing dynamic water quality models in ungauged basins: issues and solutions. *Understanding Freshwater Quality Problems in a Changing World* 361: 235–242.

O'Brien, R.J., Misstear, B.D., Gill, L.W. *et al.*, 2013a. Developing an integrated hydrograph separation and lumped modelling approach to quantifying hydrological pathways in Irish river catchments. *Journal of Hydrology* 486: 259–270.

Thompson, J., Doody, D.G., Flynn, R. *et al.*, 2012. Dynamics of critical source areas: does connectivity explain chemistry? *Science of The Total Environment* 435–436: 499–508.

Thompson, J., Cassidy, R., Doody, D.G. *et al.*, 2013. Predicting critical source areas of sediment in headwater catchments. *Agriculture, Ecosystems and Environment* 179: 41–52.

Thompson, J., Doody, D.G., Cassidy, R. *et al.*, 2014. Assessing suspended sediment dynamics in relation to ecological thresholds and sampling strategies in two Irish headwater catchments. *Science of the Total Environment* 468–469: 45–357.

The following MSc and PhD theses were completed as part of the Pathways Project research:

Crockford, L., 2009. Conceptual model of the Mattock catchment. Unpublished MSc thesis. School of Planning, Architecture and Civil Engineering, Queen's Univeristy Belfast, Belfast.

Deakin, J., 2014. The role of the near surface pathways in the delivery of flow and contaminants to streams in Irish catchments. PhD thesis. Department of Civil, Structural and Environmental Engineering, Trinity College, University of Dublin, Dublin.

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Kennedy, E., 2010. An analysis of evapotranspiration calculations in South East Ireland. Unpublished MSc thesis. Department of Civil, Structural and Civil Engineering, Trinity College, University of Dublin, Dublin.

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McDonald, J., 2011. N dynamics of the Glen Burn catchment. Unpublished MSc thesis. School of Planning, Architecture and Civil Engineering, Queen's Univeristy Belfast, Belfast.

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Thompson, J., 2013. The dynamics of hydrological connectivity, phosphorus and sediment delivery – a field and modelling approach. Unpublished PhD thesis. School of Planning, Architecture and Civil Engineering, Queen's Univeristy Belfast, Belfast.

Travers, P., 2011. Stream Flow Analysis of the Nuenna. Unpublished MSc thesis. Department of Civil, Structural and Civil Engineering, Trinity College, University of Dublin, Dublin.

Walsh, P., 2011. Investigation of Point Recharge, Flow and Nutrient Levels in a Lowland Karst System in the South-East of Ireland. Unpublished MSc thesis. Centre for the Environment, Trinity College, University of Dublin, Dublin.

The workshops undertaken as part of the Pathways Project are detailed in Table 2.4.

Table 2.4. Workshops undertaken as part of the Pathways Project

Workshop	Date
Catchment Management Tools Overview Workshop	15 March 2011
Pathways Catchment Management Support Tools Workshop	13 December 2013
Pathways Project Final Workshop	14 October 2014

All datasets and listed resources, including Final Technical Reports, are available from http://erc.epa.ie/safer/reports.

3 Conclusions and Recommendations

3.1 Conclusions

The research has shown that use of the four-pathway conceptual model is broadly appropriate for the four study catchments. Within this framework, field research identified that the transition zone, between the upper bedrock and the overlying subsoils, and the artificial drainage networks provide important flow and nutrient transport pathways in poorly drained catchments. The dominant transport pathways for NO_3 include the groundwater, the transition zone and the artificial drainage pathways, while both P and sediment transport are primarily delivered via the nearer-surface pathways, that is by overland flow and the artificial drainage system. Physical and chemical hydrograph separation methods, and hydrological modelling using NAM and a newly developed SMART model, were used to quantify the contributions from each of the pathways to the streams.

These findings informed the CMST, which comprises a CCT that considers the near-surface and subsurface pathways using long-term average data and a CMT that models all four main pathways on a temporal basis. The CCT produces PIP maps, ranking the areas from the highest to the lowest risk with regard to impacts of N and P to the surface and groundwater receptors in a catchment, thus providing a spatial overview of the CSAs. While focusing on the spatial distribution of risk areas within a catchment, the CCT is complemented by the CMT, which simulates the variation in contaminant transport along pathways seasonally, as well as highlighting when mitigation measures should be implemented within a catchment. The CMT can inform catchment scientists with regard to the timing and pathways of pollution delivery at the subcatchment scale. This information can be used with the CCT maps to identify the potential location, pathway and timing with regard to a pollutant reaching a receptor. Scenario analysis with both CCT and CMT outputs can then be used to assess and compare impacts of applying measures. The flexible structure of the CMST ensures that new findings and updated datasets can be incorporated into the tool. Although designed as a tool to assist with WFD water resource management, there are numerous other potential applications and potential end-users. For example, this tool could be developed for future climate change assessment, and also as a land use planning tool.

3.2 Recommendations for Future Research

On the basis of the project conclusions, expert opinion and team reflections, this section provides a summary and overview of the main research areas that require additional research, while the Pathways Project Final Report Volumes 1–4 provide more detailed recommendations for future work.

- The outcomes of the Pathways Project highlight the importance of considering a bottom-up approach in terms of flow pathways and nutrient transport. A deeper integration of the full hydrogeological profile in catchment studies is recommended.
- Temporal water quality (chemical and biological) sampling during events was found to be very useful for assessing nutrient delivery along different pathways, and it is recommended that both high-resolution flow and nutrient data is obtained in future catchment studies.
- For both the CCT and CMT, water quality equations for nutrients and sediment were adopted from existing state-of-the-art international models. However, the restricted availability of appropriate data was a major limitation for what could be achieved by the CMT. Further research is required to permit inputs to be applied with greater confidence.
- Further research and collaboration with the Department of Agriculture, Food and the Marine and Teagasc on the nutrient loadings and attenuation and transport factors used in the CMST is recommended.
- The CMT structure has been designed so that it could be developed further to consider point sources, as well as the diffuse sources currently considered (e.g. WWTPs). This issue should be addressed in the near future.
- The age or residence time of water and contaminants in each of the major pathways should also be

considered. This would permit the determination of lag times between precipitation and water reaching receptors, and therefore provide estimates of how long the impacts of programmes of measures would take to be observed.

- The role of the interface between surface water and groundwater, including the hyporheic zone, was not explicitly examined as part of this research. Future research needs to examine groundwater–surface water interactions in this interval and to characterise its capacity to influence water quality and, more notably, nutrient attenuation.

- Further research and collaboration with the GSI on improving subsurface pathway characterisation is recommended. This includes investigating subsoil variations that could result in interflow not being appropriately reflected in the existing maps, which requires further examination of transition zone properties and how they contrast with shallow and deeper groundwater flow zones.

- Further specific field investigations to characterise the geometry and properties of the transition zone would be useful for determining the influence of the transition zone on nutrient transport and attenuation dynamics in different hydrogeological scenarios.

- Further investigation is required to understand the role of drain flow for nutrient transport. These investigations may identify different conceptualisations for specific land drain issues, such as high or rising groundwater tables.

- Many catchment studies tend to focus on small catchments. However, there is a need to investigate larger catchments, as catchments will be managed at a larger scale for the WFD.

- The CMSTs will benefit greatly from the incorporation of data, such as 5 m Digital Elevation Model, improved topographic (LiDAR, a portmanteau of "light" and "radar") and LPIS data, as these datasets become available.

- It is recommended that resource provisions are made within the EPA to ensure that the tool is routinely updated.

3.3   Ongoing Research Following on from the Pathways Project

The Catchment Tools Project (2013-W-FS-14) is currently building on the Pathways Project findings by continuing the development of the CMSTs (Table 3.1). Along with the continued development of the CCT and CMT, the Catchment Tools Project is developing a new tool called the Irish Source Loading Apportionment Model (SLAM). In addition to considering loadings from agriculture, this model quantifies the relative contributions of multiple sources of nutrients (e.g. agglomerations and forestry) to Irish rivers. All of these models should improve the understanding of catchment processes and identify risks to water bodies in different, but complementary, ways. These tools enable catchment data and information to be considered in an integrated manner, and provide useful outputs that enable the characterisation of source–pathway–receptor relationships in Irish catchments.

Table 3.1. Details of the Catchment Management Support Tools, including the ongoing development by the Catchment Tools Project

Model	CCT	SLAM	CMT
Name	Catchment Characterisation Tool	Source Loading Apportionment Model	Catchment Modelling Tool
Description	The CCT estimates long-term annual average losses of N and P from diffuse agricultural sources using export coefficients based on GIS maps for both the surface and groundwater pathways	SLAM is a source-oriented model that predicts the N and P exported from each sector in a catchment using GIS datasets, including the CCT, and monitoring data if available	The CMT is a dynamic model for tracking the short-term variation in nutrient quantities and their relationship with time-varying drivers
Purpose	To assess spatial variations in diffuse nutrient pollution from agricultural sources	To rank the sources (e.g. agriculture, WWTP, etc.) contributing to nutrient loads in a catchment	To assess short- and long-term dynamics of flows and concentrations in catchments
Output	PIP maps showing CSAs for NO_3 and phosphate for the groundwater and local surface water receptor	Maps and charts showing magnitude and proportion of nutrients attributed to each sector	Maps and time-series showing concentrations of nutrients attributed to each flow path

3.4   Recommendations for Policy

The Pathways Project has highlighted the variation in nutrient transport pathways that link CSAs to receptors across Ireland. Furthermore, it has highlighted that there may be variations in transport pathways across a subcatchment and although one management strategy may work in one area of a subcatchment, it may not be suitable in another area of that same subcatchment. Therefore, for mitigation measures and management strategies to be successful, it is essential that these transport pathways are identified and understood at a subcatchment scale and that mitigation measures and management strategies are pathway specific. The outputs of the CMST have been developed to inform the WFD characterisation process that will lead to the development of the programme of measures for the river basin management plans. It is recommended that these tools are also used to model and assess the proposed programme of measures before finalisation.

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Abbreviations

CCT	Catchment Characterisation Tool
CMST	Catchment Management Support Tools
CMT	Catchment Modelling Tool
CSA	Critical source area
EPA	Environmental Protection Agency
FDC	Flow duration curve
FIO	Faecal indicator organism
GIS	Geographical information system
GTT	Groundwater Task Team
GSI	Geological Survey of Ireland
INCA	Integrated Nutrition from Catchments (model)
LPIS	Land Parcel Identification System
MODFLOW	Modular Three-dimensional Finite-difference Groundwater Flow Model
N	Nitrogen
NAM	Danish lumped hydrological precipitation run-off model (Nedbør-Afstrømnings Model)
NO$_3$	Nitrate
P	Phosphorus
PIP	Pollution impact potential
SMARG	Soil Moisture Accounting and Routing with Groundwater component
SMART	Soil Moisture Accounting and Routing for Transport (model)
SRB	Sulphate-reducing bacteria
SSC	Suspended sediment concentration
SSY	Suspended sediment yield
TP	Total phosphorus
WFD	Water Framework Directive
WWTP	Waste water treatment plant

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Contaminant Movement and Attenuation along Pathways from the Land Surface to Aquatic Receptors: the PATHWAYS Project

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Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

In order for Ireland to meet its obligations under the Water Framework Directive (WFD) we need to understand how diffuse nutrients reach water bodies and impact on Irish aquatic ecosystems. By combining information on hydrological and hydrogeological pathways with land use pressures, a conceptual understanding was developed in the Irish context which provides a basis for assessing the impacts of land use on water quality. This knowledge provides a foundation for identifying the areas in Irish catchments that contribute the greatest proportion of nutrients to water bodies (receptors). These areas are referred to as critical source areas. Locating critical sources areas helps ensure that appropriate management strategies are targeted to maintain and/or improve water quality by (1) reducing the nutrient loading in critical source area and/or (2) breaking the pathways linkage between the critical source area and the receptor. Understanding the transport pathways linking the diffuse nutrients source to the receptor is vital in determining the most appropriate management strategies/mitigation measures.

Informing Policy

Findings from the *PATHWAYS Project* have informed the Environmental Protection Agency's WFD characterisation approach with both surface and subsurface pathways considered in the risk assessment process. The findings have also permitted the development of a suite of catchment management support tools to assist environmental/water resources/catchment managers in defining critical source areas for diffuse contaminants and assessing appropriate measures for protection and/or improvement of water quality. Outputs from the catchment management support tool include a national suite of pollution impact potential (PIP) maps that delineate critical source areas for nutrients (PO_4 and NO_3) and these maps have been refined since the completion of the Pathways Project for use by the EPA and local authorities in catchment management.

Developing Solutions

The *PATHWAYS Project* developed the following:

- A suite of catchment management support tools capable of assisting catchment managers in identifying critical source areas.

- Preliminary Pollution Impact Potential (PIP) maps.

- Integrated hydrological/hydrogeological models to simulate flow along surface and groundwater pathways to water bodies.

- A comprehensive, consolidated database of water quality and discharge data for both base flow and storm events in four study catchments that identifies conditions where nutrient transport pathways are most likely to contribute to water bodies (receptors).