06 - PULLING IT ALL TOGETHER: INFORMATION FROM FSU AND EPA DATASETS IN PARAMETERISING HYDROLOGY IN THE PATHWAYS CATCHMENT MANAGEMENT TOOL

Eva Mockler, Ian Packham & Michael Bruen*
UCD Dooge Centre for Water Resources Research, School of Civil, Structural and Environmental Engineering, University College Dublin, Ireland.
Corresponding author Michael.Bruen@ucd.ie

Abstract

The Pathways Catchment Management Tool (CMT) is being developed for environmental managers interested in water quality modelling and critical source area identification. The CMT is a Geographical Information System (GIS) based application that helps decision makers manage water at catchment scale by predicting fluxes of water and contaminants separately through all of the hydrological pathways and identifying critical source areas (CSAs). This management tool integrates a considerable amount of national datasets and research from a broad range of disciplines into an annual GIS model and a dynamic water quality model to simulate fluxes of water, sediment and nutrients entering a river along various flow paths.

Three levels of user interaction are facilitated in the interface to match the complexity of the available information and analysis required, and the user's level of experience. In Level 1 of the tool, users can view national data sets, delineate a catchment of interest and generate reports summarising the data. Level 2 involves the generation of static CSA maps using the intersection of spatial loadings and susceptibility datasets for the contaminant under investigation. The third level of interaction allows investigation of dynamic CSAs by modelling hydrological flow paths and the associated transport and attenuation of pollutants in catchments. The CMT tool can assist environmental managers in identifying CSAs for contaminants, evaluating alternative strategies for land use and their impacts on aquatic ecosystems, and targeting areas for enforcement of regulations.

Hydrological modelling can give a complete picture of the transfer of pollution from the land surface via both surface and sub-surface pathways to our water courses, i.e. (1) overland flow, (2) Interflow, (3) shallow groundwater flow, and (4) deep groundwater flow. Most flood forecasting models focus on predicting total outflows from a catchment and often can do this well without getting the distribution between individual pathways correct. However, modelling of water flow paths within a catchment, rather than its overall response, is needed to investigate the physical and chemical transport of matter through the various elements of the hydrological cycle. Thus the CMT Level 3 contains a hydrological model, specially designed for this purpose. Analysis from work packages of the Flood Studies Update have been used to parameterise some hydrological components of this dynamic water quality model in order to facilitate predictions in ungauged basins. For instance, the Base Flow Index

(BFI_{soil}) ungauged dataset and slope indices, among others, have been incorporated into the regionalisation study of the semi-distributed model in the CMT.

1. INTRODUCTION

1.1 Integrated Catchment Management

Ireland is demanding more agricultural output under increasingly strict environmental regulations than ever before. The Food Harvest 2020 (FH2020) policy is intending to increase output from the agri-food industry in Ireland, while achieving the environmental objectives of the EU Water Framework Directive (WFD), Floods Directive, Nitrates Directive etc. Achieving both of these goals is feasible through sustainable planning and Integrated Catchment Management (ICM) (Daly, 2013).

Geographical Information Systems (GIS) and remote sensing enable a broad overview of catchment characteristics at a range of scales. Many regional and national projects investigating hydrological processes e.g. flooding, sediments, nutrients and pollution, have produced datasets which have potential use outside the original scope, and communicating and disseminating these data can facilitate cross pollination of information. National GIS data sets of hydrological and geological data from the Environmental Protection Agency (EPA), Office of Public Works (OPW) and Geological Survey of Ireland (GSI) are combined in the Pathways Catchment Management Tool (CMT) to develop a greater understanding of hydrological processes and facilitate management of Irish catchments.

1.2 The STRIVE Pathways Project

The Pathways Project objectives are the identification and quantification of flows of significant hydrological pathways within Irish catchments and following on from this, the identification of significant pathways for diffuse pollutant transport and attenuation with particular emphasis on the attenuation of nutrients (nitrogen and phosphorus species), and sediments. The Pathways Catchment management Tool incorporates this knowledge in a modelling framework to inform the identification of critical source areas (CSAs) in Irish catchments.

The project inception report (Archbold *et al.*, 2010) outlined the knowledge gaps in relation to flow paths in Irish catchments, including the lack of field data for overland flow, interflow and interaction of surface water with ground water. Furthermore, the absence of reliable, long term stream flow data in small catchments and groundwater level data in poorly productive aquifers were also noted. The Pathways Project addressed these through investigations in four study catchment, which included detailed monitoring with instrumentation for meteorological data, flow and water quality in groundwater borehole clusters, subsoil and in-stream. The development of water quality equations has been informed by field data collected from the project to investigate flow and contaminants along different flow paths in Irish catchments, which are combined with the hydrological model described here to produce the final CMT Level 3 water quality model.

This paper introduces the Pathways CMT, including an overview of data and the three levels of interaction. A broad range of datasets are incorporated in the Pathways CMT to facilitate and inform Integrated Catchment management (ICM), including spatial and temporal national datasets which were used in the modelling calibration and regionalisation. The hydrological model in Level 3 of the CMT is detailed, with a focus on the national parameterisation of hydrology using catchment characteristics from these datasets.

2. THE PATHWAYS CATCHMENT MANAGEMENT TOOL

The Pathways Catchment Management Tool (CMT) is a GIS-based platform for environmental managers interested in water quality modelling and its environmental consequences. The Source-Pathway-Receptor model is commonly used to describe the transport and attenuation of contaminants through our environment, and is used in the CMT to identify critical source areas (CSAs). These are areas which contribute a disproportionally higher amount of contaminant to the receptor, and will vary for each combination of contaminant and receptor investigated. The Pathways CMT can identify CSAs for a particular receptor by combining loadings information representing the source of a particular contaminant with knowledge of transport and attenuation along the likely pathways to the groundwater or surface receptor, referred to as the pathway susceptibility.

Multiple levels of interaction with the system can accommodate a range of end-users interests, taking account of their level of experience and of the information and analysis required. The three tiered structure of the Pathways CMT (Figure 1) allows the user to balance the time invested in the analysis with the level of detail required, while allowing projects to be saved and re-visited. In this manner, catchment analysis can be shared among environmental managers, thereby improving communication and ultimately understanding of hydrological processes in our environment.

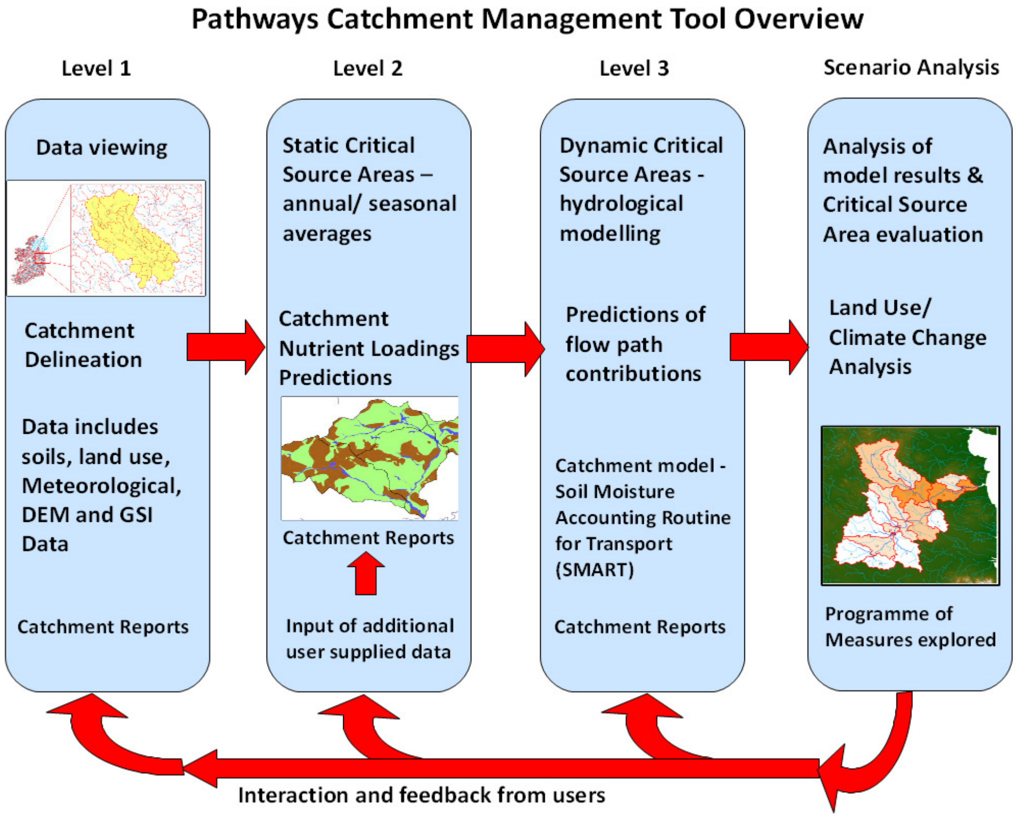

Figure 1. *Levels of interaction with the Pathways Catchment Management Tool*

2.1 Level 1: Data Exploration

A user can select a catchment of interest using the CMT interface and explore the various relevant data sets, e.g. hydrological, geological, soils, land-use, population, pollution sources, etc. for that catchment. Level 1 incorporates GIS layers from the EPA WFD database and maps provided by the Geological Survey of Ireland (GSI). These GIS data include soil and subsoil characteristics, bedrock aquifers, gravels, vulnerability data and Corine land cover. Point datasets can include waste water treatment plants, CSOs, Landfills and other licensed facilities, along with agricultural information which is combined to estimate nutrient loadings in Level 2.

Selection of information is controlled in the top right panel of the CMT interface and summary information is displayed below this (Figure 2). The map is seen in the centre of the display and the colour legend is shown on the left hand side.

2.2 Level 2: Static Critical Source Areas

Analysis of data in Level 2 can produce annual average mapping of nutrient application or estimated nutrient loading to groundwater. The system will produce a map of the critical source areas in the selected catchment for a selected contaminant, generally useful for loadings to groundwater or for preliminary surface pathway studies.

Loadings are calculated following the Groundwater Task Team (GTT) loadings tool methodology (GTT, 2010) adapted for Irish conditions by the EPA. The GTT tool uses available public data to estimate the amount of Nitrogen and Phosphorous loadings applied to Rural and Urban areas. Data sources include the Central Statistics Office of Ireland (CSO, 2006) for population information, Teagasc for Fertiliser application (Lalor et al. 2010) and the Department of Agriculture, Fisheries and Food (DAFM) for crop usage and animal population figures. Data is continuously updated to benefit from the latest available sources.

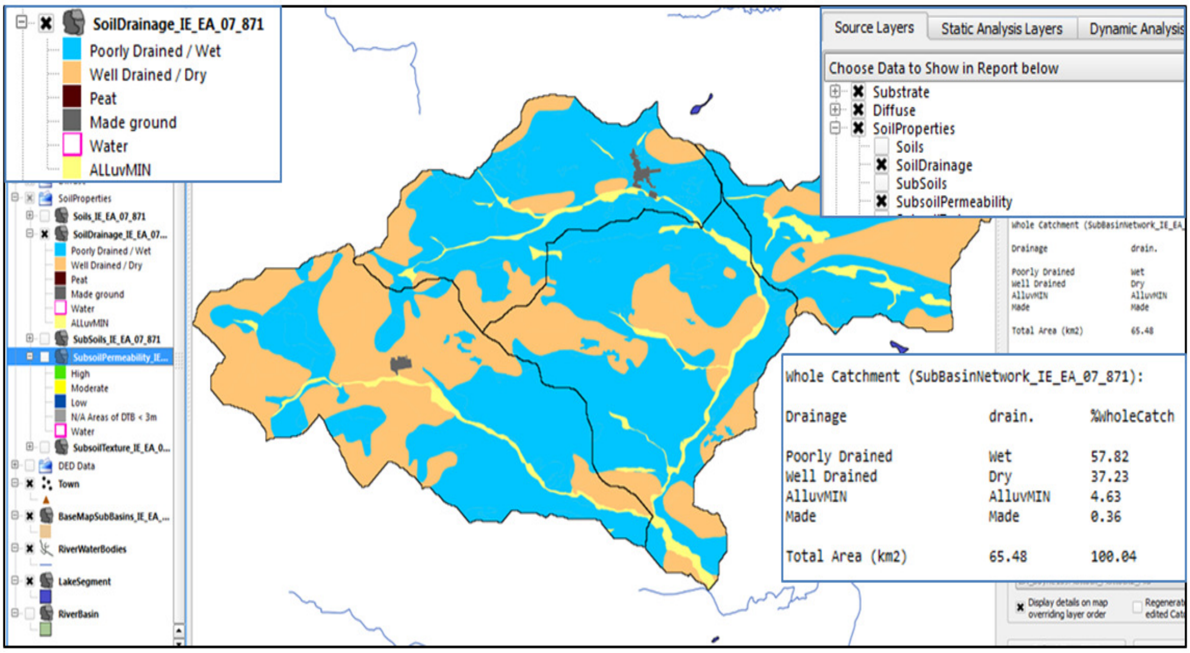

Figure 2. CMT interface showing soil drainage GIS layer for Mattock catchment.

2.3 Level 3: Dynamic Critical Source Areas

The Pathways CMT Level 3 model incorporates the more complex processes of lateral transport and attenuation, e.g. in overland flow, interflow and lateral groundwater movement. The Pathways Computational Engine (PACE) model is linked to the user interface through text files. The CMT can assist users in simulating hydrological flows and contaminant transport in Irish catchments by generating the required input files from national datasets. Semi-distributed models for the selected catchment are generated by the tool based on Irish EPA defined River Sub-Basins which have a mean area of 10km^2. The model network structure is initially determined from GIS data. An advanced user will be able to further adjust connections within the model network to test hypotheses on hydraulic connectivity. The CMT can visually identify CSAs for selected contaminants dynamically, using the hydrological model for investigating the transport and attenuation of pollution.

2.4 Scenario Analysis

Land use and climate change scenarios can be explored with both Level 2 and 3 of the CMT, by altering the spatial loadings or meteorological input data respectively. This can be used to explore alternative programme of measures and assess future risks in Irish river basins.

3. HYDROLOGICAL CATCHMENT MODELLING

Hydrological modelling can give a complete picture of the transfer of pollution from the land surface via both surface and sub-surface pathways to our water courses. Modelling of water flow paths within a catchment, rather than overall response, is needed to investigate the physical and chemical transport of matter through the various elements of the hydrological cycle. The main conceptual hydrological flow paths that excess rainfall can take to contribute to stream flow can be identified as (1) overland flow, (2) Interflow and (3) groundwater flow.

Developed from an earlier hydrological model, SMAR (Tan and OConnor, 1996), from NUI Galway, the Soil Moisture Accounting Routine for Transport (SMART) model is used in the Pathways Computational Engine (PACE) Framework to simulate the movement of flows and contaminants both vertically and horizontally through our river basins. The CMT acts as a user-friendly interface to the model to aid environmental managers in identifying critical source areas for contaminants, particularly where dynamic simulation of hydrological processes is required to evaluate CSAs. The SMART model simulates four hydrological pathways with 10 parameters which are populated with values related to GIS layers from the CMT, informed by a national regionalisation study. These include six soil moisture accounting parameters and four routing parameters (shown in square brackets, Figure 3).

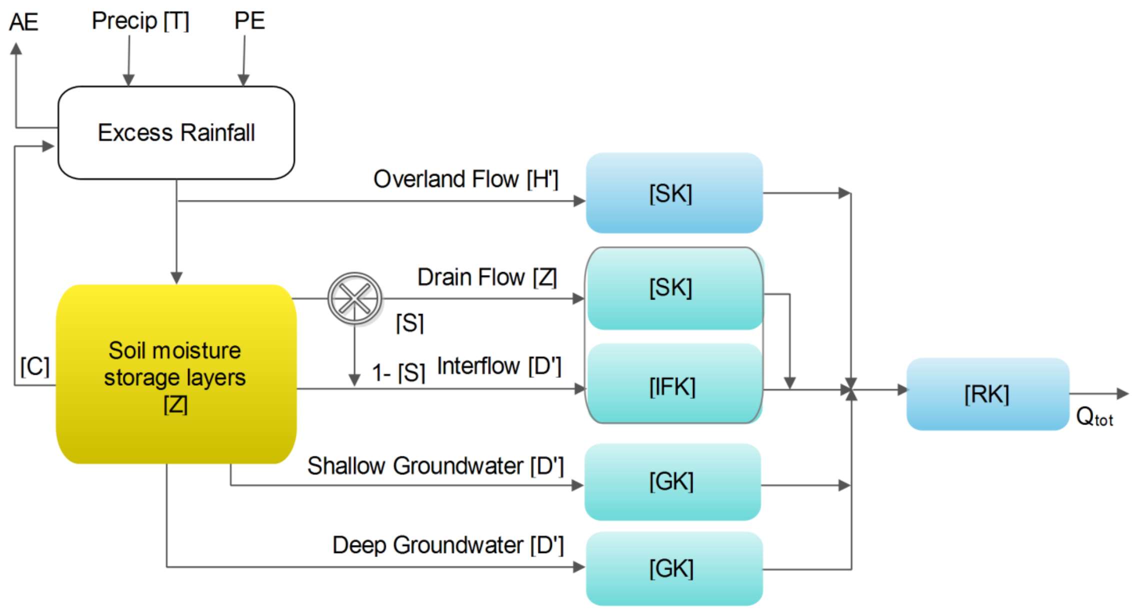

Figure 3. *SMART model schematic including lumped catchment model and river routing*

3.1 Water Quality Simulations

Hydrology is the driver of contaminants in the Pathways CMT models. Time series of rainfall and potential evapotranspiration are used as inputs to the Level 3 hydrological model, typically in the range of sub-hourly to daily as availability allows. Daily values of these time series are included in the CMT's database for a range of stations across Ireland as default inputs when local data is not supplied by the user. The CMT defines initial parameter values linked to geological, soils and vegetation information to determine the distribution of flows along surface and groundwater pathways. Actual evaporation and flows are produced as outputs from the model at the same time step as the temporal input data.

Diffuse loadings calculated in Level 2 are used as a basis for the pollutant source data, and combined with available point source data in the catchment. Equations describe the transformations of this source along each conceptual pathway within the sub-catchment, with parameters of the water quality components of the model linked to spatial GIS data when appropriate. Water quality equations for the PACE model are informed by existing state-of-the-art models, including the INCA-N model (Wade *et al.*, 2002), and are being reviewed and refined for Irish conditions.

3.2 Functional Role of Parameters in Conceptual Models

Each process in a conceptual model is a simplification of a dynamic naturally occurring hydrological process at catchment scale. Ideally, these process equations and associated parameter(s) should therefore aim to describe only the water movement of the specific natural process as intended. But as the exact movement of water for each process are unknown at catchment scale, our models cannot be calibrated for each internal process. When attempting to determine parameter values for several processes simultaneously, many combinations of parameters can produce similar results.

In the CMT Level 3 model, GIS data sets were used to directly determine parameter values for the hydrological model where a parameter is not easily identifiable from the hydrograph time-series. A comparison of uncertainties related to parameter estimation from hydrograph time-series and remote sensing shows that determining values from GIS data directly can improve the identification of other model parameters.

3.3 River Routing in Conceptual Hydrological Models

Flood estimation studies have analysed hydrographs for many decades in order to develop relationships between flows and catchment characteristics. Although there are many studies investigating the flood routing, there is great difficulty in separating out river routing from the routing of hydrological flow paths with gauging data alone. All of the relationships derived from observed data result in catchment routing that combines quick flow routing and river routing. This did not satisfy the requirements of the SMART hydrological model, which aims to identify each component distinctly. Therefore it was decided to determine the river routing parameter from a semi-theoretical model (Manning's equation) related to the river geometry and slope.

4. STUDY CATCHMENTS AND DATA

Data associated with hydrological modelling include (i) stream flow measurements, (ii) meteorological observations and (iii) physical catchment descriptors to relate conceptual model structures and parameters to river catchments. Hydrological observations are transformed during modelling exercises, with these results then compared to other hydrological observations. As such, they are the core of catchment modelling, and influence every stage of model development. Errors in hydrological observations are ubiquitous, but understanding this and accounting for it in data interpretation allows for the full potential of data to be exploited.

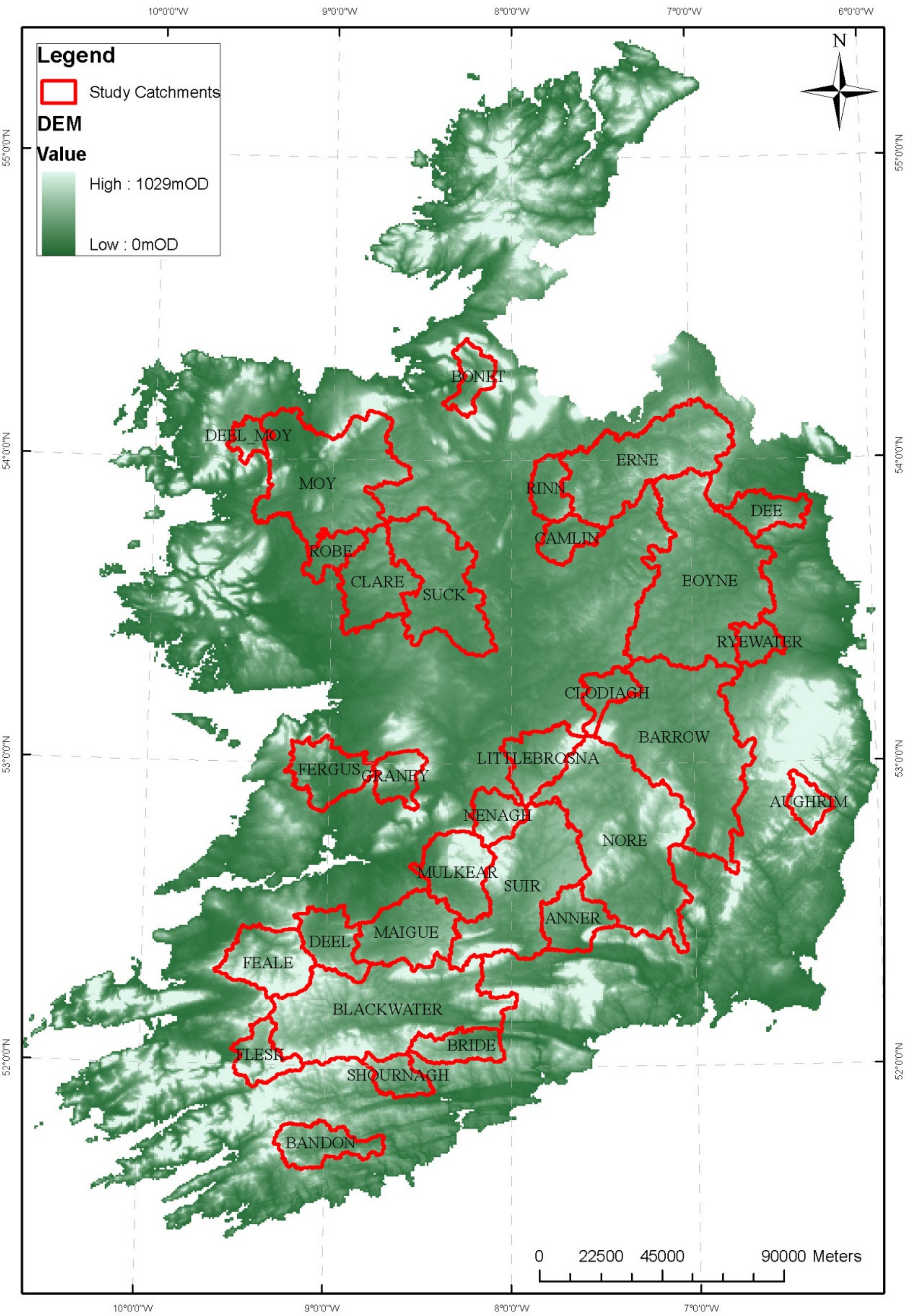

Figure 4. *Locations of the 31 study catchments*

4.1 Study Catchments

Selection of study catchments followed from the RPS study, 'An Integrated Approach to Quantifying Groundwater and Surface Water Contributions of Stream Flow' (RPS, 2008). This study included a review of hydrological data for a large number of catchments used in the national study of the project, and 31 suitable catchments were selected from this set to be used in the national regionalisation of the PACE model. This data consists of values of daily mean flows originating from the OPW and the EPA. Meteorological data consisted of daily rainfall and Pan Class A potential evapotranspiration values, originating from Met Éireann. A range of hydrological settings are included in the 31 selected catchments to represent the variety of meteorological and geological conditions across Ireland, covering over 35% of the country.

These 31 catchments have been used to carry out analysis at a national scale using temporal datasets at a daily time step. The time series datasets are typically comprised of daily of rain, PE and flow data, with some borehole levels and water quality data available for some locations.

4.2 Incorporation of National Datasets

GIS datasets are vital for hydrological modelling in ungauged catchments, for estimating both the conceptual model and parameter values. The characteristics known to influence hydrological and hydrological flows in Irish catchments include slope, soil type, land cover, subsoil permeability, depth to bedrock, aquifer class and groundwater vulnerability (RPS, 2008).

The Flood Studies Update (FSU) project was coordinated by the OPW and developed on a GIS framework, using national datasets from multiple sources including Ordinance Survey of Ireland (OSi) and the EPA. National standard datasets on rivers and lakes used for the WFD were used to facilitate interoperability between national initiatives. Hydrological and spatial catchment descriptors were derived nationally for gauged and ungauged catchments. Catchment descriptors, including those from the FSU dataset, were used to regionalise the parameters of the CMT Level 3 model to facilitate integrated catchment management.

5. METHODOLOGY FOR DETERMINISTIC PARAMETER IDENTIFICATION

The river routing parameter (RK) represents the time lag of the river component in the conceptual model (Figure 3). To reduce the uncertainty, this parameter was removed from the statistical regionalisation procedure and estimated *a priori* using a separate river routing model. A method was developed to determine the river routing parameter from a semi-theoretical model (Manning's equation) related to the river geometry and slope, as detailed below.

5.1 River Routing Parameter from Manning's Equation

The river routing parameter (RK) is the time lag of the linear reservoir routing component of the hydrological model can be determined from the river reach length L (m) and the mean velocity v (m/s), as:

$$RK\ (s) = \frac{L}{v}$$ **Equation 1**

The cross sectional area of natural channels is often approximated by a rectangular cross section with channel width W and channel depth h. The mean velocity v (m/s) for such a channel is related to discharge (Q) as:

$$v = \frac{Q}{W\boldsymbol{h}}$$ **Equation 2**

National data sets for the river reach length (L) and mean discharge (Q) values are available, but river cross sectional dimensions are not readily available at a national scale. River cross sectional geometry is a complex topic, but simplifications can be made for the purposes of determining the river routing parameter of a conceptual model, including the assumption of a wide rectangular channel.

Manning's Equation can be used to estimate the average cross-sectional velocity from the hydraulic radius, average discharge, slope and Manning's roughness coefficient n. If the assumption of a wide rectangular channel is accepted, the method only requires dimensions for the cross section width. The errors related to coupling the Manning's equation with an empirical estimate of river width have been reported as limited in comparison to other sources of uncertainty (Pistocchi and Pennington, 2006). The Manning formula is an empirical formula estimating open channel flow driven by gravity, first presented by the French engineer Philippe Gauckler in 1867 and later re-developed by the Irish engineer Robert Manning in 1890. Manning's equation can be written in terms of water discharge (Q)

$$Q = \frac{AR^{\frac{2}{3}}S^{\frac{1}{2}}}{n}$$ **Equation 3**

where:

Q is the cross-sectional average discharge (m^3/s)
A is the cross sectional area of the channel (m^2)
R is the hydraulic radius (m) = cross sectional area of the channel / wetted perimeter
S is the slope of the water surface (m/m)
n is the Manning coefficient, estimated as 0.03 for natural channel

Assuming a wide rectangular channel, the hydraulic radius can be approximated as the depth h. Many studies (e.g. Hey and Thorne, 1986; Pistocchi and Pennington, 2006) have correlated river width with representative discharges using a power law equation following Leopold and Maddock (1953), with α and β as regression parameters:

$$W = \alpha Q^{\beta}$$ **Equation 4**

Hey and Thorne (1986) studied 62 sites in the UK and determined the parameters as $\alpha = 3.67$ and $\beta = 0.45$ with $r^2 = 0.7784$. Substituting these values into Manning's equation (Equation 5) gives velocity in terms of Q, S and n only:

$$v = \frac{Q^{\frac{2}{5}}\, S^{\frac{3}{10}}}{[3.67Q^{0.45}]^{\frac{2}{5}}\, n^{\frac{3}{5}}} \qquad \textbf{Equation 5}$$

Pistocchi and Pennington (2006) investigated the regression parameters for the power law equation at European scale using mean annual Q data from the European Environmental Agency (EEA) and river width measurements estimated from coarse aerial photography. A 'representative' river geometry value was chosen for each river reach rather than a single station, based on research by Stewardson (2005). The study fitted width and discharge data pairs using the least trimmed squares (LTS) regression method, and included a sub-group of Irish and British catchments represented by 15 river sections. Regression parameters were determined for Irish and British rivers as $\alpha = 11.9$ and $\beta = 0.3766$ with an r^2 of 0.663. The authors commented on the potential insufficient representation of the width-discharge relationship in the data, referring to the superior results of the Hey and Thorne (1986) study in this region.

6. RESULTS AND DISCUSSIONS

An average value of 15 hours was determined for the river routing lag parameter (RK) (Table 1), with two catchments having values of values greater than 30 hours (Barrow and Suck) due to the flat slopes of these large catchments.

Table 1. *Calculations of average width (W), average velocity (v) and lag time parameter (RK).*

WATERBODY	AREA	AAR	Mean Q	MSL	S1085	Avg Width	Avg v n=0.04	RK n=0.04
	(km2)	(mm/yr)	(m3/s)	(km)	(m/km)	(m)	(m/s)	(hr)
Anner	437	913	6.8	37.4	3.5	8.7	1.15	9.1
Aughrim	203	1423	5.7	25.0	7.9	8.1	1.41	4.9
Bandon	424	1576	14.9	58.2	2.1	12.4	1.17	13.9
Barrow	2419	865	33.2	114.5	0.5	17.7	0.88	36.3
Blackwater (Mun)	2334	1255	59.7	129.1	1.3	23.1	1.39	25.9
Bonet	264	1670	10.8	34.2	4.1	10.7	1.33	7.2
Boyne	2460	903	37.8	93.7	0.7	18.8	1.03	25.3
Bride	334	1305	9.5	46.2	3.8	10.1	1.27	10.1
Camlin	253	884	3.9	35.8	0.5	6.8	0.57	17.6
Clare	700	1146	16.0	65.7	0.9	12.8	0.91	20
Clodiagh	254	904	3.9	31.7	6.0	6.8	1.19	7.4
Dee	334	918	4.3	54.0	2.6	7.1	0.95	15.8
Deel (Moy)	151	1922	6.7	33.1	4.6	8.6	1.24	7.4
Deel (Mun)	439	1191	10.7	46.8	1.9	10.6	1.06	12.3
Erne	1492	1008	30.2	78.6	1.2	17	1.15	19
Feale	647	1532	22.0	50.5	4.3	14.8	1.58	8.9
Fergus	511	1135	10.4	40.4	1.2	10.5	0.92	12.2

Flesk	329	1897	14.4	45.1	9.4	12.2	1.82	6.9
Graney	280	1384	7.7	37.3	3.9	9.2	1.22	8.5
Little Brosna	479	962	8.3	44.2	1.5	9.5	0.92	13.3
Maigue	763	1018	13.0	50.2	1.9	11.7	1.1	12.6
Moy	1975	1313	58.8	88.9	0.7	23	1.15	21.5
Mulkear	648	1244	15.5	53.2	4.1	12.6	1.44	10.3
Nenagh	293	1041	6.4	38.1	4.8	8.5	1.24	8.5
Nore	2418	962	39.6	117.4	0.9	19.2	1.14	28.6
Rinn	281	1027	5.7	34.8	1.1	8.1	0.78	12.4
Robe	238	1220	6.2	44.8	1.0	8.3	0.78	16
Ryewater	210	820	2.4	24.9	2.1	5.4	0.78	8.8
Shournagh	208	1213	5.1	26.5	8.4	7.6	1.4	5.3
Suck	1207	1061	25.2	107.4	0.4	15.7	0.81	37
Suir	1583	1113	34.0	85.4	1.0	17.9	1.12	21.1

AAR = Annual Average Rainfall, Mean Q = Mean Discharge, MSL = Main Stream Length, S1085 = Slope index

This method of determining the river routing lag parameter for the routing component of the SMART model uses the main stream length, and therefore implies that routing in ditches and streams are included in the overland flow component and the associated overland flow routing lag parameter (SK).

6.1 River Routing Parameter - Sources of Uncertainty

In the application of Equation 5 for this study, errors in the estimation of the average velocity are related to the discharge, slope and the width regression coefficients. The determination of specific Manning's coefficients for each river reach, rather than using the estimate of 0.035 or 0.04, may improve the estimation of velocity. Slope indices (S1085) of the main stream length (MSL) from the OPW FSU dataset exclude the top 10% and bottom 15% of the river. This can mask the impacts of flat stretches of river reach near the outlet of a catchment, which may have a notable impact on the overall routing time.

Pistocchi and Pennington (2006) highlight that the roughness and width parameter are much more sensitive than slope in Manning's equation for calculating velocity (indicated by the power values). The authors estimate that their 'quick yet well tested' method can calculate velocity within a factor of 2 of the absolute value. This error factor is estimated to be greatly reduced in this study as the slope parameter values used are determined from high quality national data, and the width parameters have been sourced from a more successful regression study. The regression parameters selected to determine the cross-sectional width could be improved with a more detailed Irish study using improved resolution data and an increased number of river reaches.

6.2 Statistical Parameter Regionalisation

The methodology outlined above for the river routing lag parameter was combined with similar analysis for the drain flow parameter (S), thereby reducing the number of parameters in the statistical regionalisation study to eight. Hydrological data from the four Pathways study catchments and 31 national study catchments, as detailed above, were used to identify the plausible range of hydrograph splits using the SMART model. This constrained calibration acts as the first stage in the two-step regionalisation method, with the second step relating physical catchment descriptors to the calibrated parameter sets.

7. CONCLUSIONS

Critical Source Area (CSA) identification is a key tool for environmental managers using a risk-based approach to decision making. The Pathways CMT is described here as a three-tiered management tool for analysing national datasets for investigation CSAs. Level 1 and 2 are investigation of GIS layers, including an annual average GIS-based model for identifying CSAs. The Level 3 of the CMT incorporated a flexible network model for identifying contaminant transport along hydrological flow paths. The model is housed in a GIS based tool for viewing and analysing Irish national spatial data and for incorporating expert knowledge relating to flow pathways and contaminant transport along these pathways. The GIS tool acts as the user interface for the model, which can be used in a semi-distributed manner to investigate the hydrological pathways and contaminant processes and pathways at sub-catchment scale.

A regionalisation study of the SMART hydrological model incorporated data from the EPA, OPW and GSI to enable hydrological predictions nationally. The associated nutrient and sediment simulations are being tested and refined for Irish conditions. The Pathways CMT assists in pollution risk assessment in river basins, and can inform decision making in catchment management. The source-pathway-receptor model is used to identify and quantify the linkages between pollutant sources, hydrological pathways and receptors to evaluate the presence of a risk of contamination. Combining multi-disciplinary knowledge and national data sets with a user-friendly interface, the Pathways CMT can present informative risk maps of CSAs to environmental managers, to assist in risk assessment, mitigation, monitoring and review of contaminants in Irish catchments.

8. ACKNOWLEDGEMENTS

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