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Title	Development of a Nutrient Load Apportionment Modelling Toolbox
Author(s)	Mockler, Eva M.
Publication date	2016-07-14
Conference details	International Environmental Modelling & Software Society (iEMSS) 8th International Congress on Environmental Modelling and Software, Toulouse, France, 10-14 July 2016
Link to online version	http://www.iemss.org/sites/iemss2016/
Item record/more information	http://hdl.handle.net/10197/7887

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Development of a Nutrient Load Apportionment Modelling Toolbox

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Abstract: Where surface waters are impacted by excess nutrients, understanding the sources of those nutrients is key to the development of effective, targeted, mitigation measures. In Ireland, nutrient emissions remains the top suspected cause of surface waters not achieving the required Good Status, as defined by the Water Framework Directive (WFD). Hence, a toolbox has been developed to predict the sources of nutrients contributing to these emissions, and to assess future pressures and the likely effectiveness of targeted mitigation scenarios. This Source Load Apportionment Model (SLAM) supports catchment managers by providing scientifically robust evidence to back-up decision-making in relation to reducing nutrient pollution. The SLAM is a source-oriented model that calculates the nitrogen & phosphorus exported from each sector (e.g. pasture, forestry, wastewater discharges) that contribute to nutrient loads in a river. The SLAM was built as a modular framework in ArcGIS ModelBuilder to encourage continuous development by a range of scientific experts without the need for programming skills. Model output is presented as maps and tables showing the proportions of nutrient emissions to water attributed to each sector in each sub-catchment. Results for the Suir catchment, in the South East of Ireland, indicate that diffuse losses of nutrients from pasture are the dominant source of nitrogen and both wastewater discharges and losses from pasture are dominant for phosphorus. The Irish EPA has incorporated these model results into the WFD characterisation process for Irish catchments.

Keywords: Nutrient Load Apportionment Modelling; Phosphorus; Nitrogen; Integrated Catchment Management; Water Framework Directive

1 INTRODUCTION

A key challenge for ensuring a sustainable future is to increase food production and population with minimal impact on water quality, biodiversity, and climate, etc. In Ireland, eutrophication remains the top suspected cause of rivers and lakes not achieving Good Status, as defined by the Water Framework Directive (WFD) (Bradley et al., 2015). Hence, assessments of sources of nutrient emissions are important in the WFD characterisation process. These assessments are one component of the integrated catchment management (ICM) approach that has been adopted in Ireland for implementation of the WFD (Daly et al., 2016).

Nutrient load apportionment modelling can identify the sources of nutrients using pressure data combined with various models (e.g. MCOS, 2002; Smith et al., 2005; Campbell and Foy, 2008; Ní Longphuirt et al., 2015), or alternatively, with statistical methods using monitoring data (e.g. Grizzetti et al., 2005; Greene et al., 2011; Grizzetti et al., 2012). As surface waters typically do not have high resolution monitoring data, methods based on pressure data are more suitable for modelling at a national scale where data are limited. Hence, the Source Load Apportionment Model (SLAM) (Mockler et al., submitted) has been developed to predict the sources of nutrients in Irish water bodies, using the pressure data (source) approach.

In this paper, the structure of the SLAM toolbox is outlined along with areas of on-going development. Results for the Suir catchment are presented, illustrating how the model outputs can support the identification of significant pressures.

2 MODEL STRUCTURE & DATA

The SLAM has been developed as an ArcGIS toolbox that uses the best available Irish data and models to quantify annual nutrient losses from both point discharges from urban wastewater, industry and septic tank systems, and diffuse sources including agriculture, forestry, etc. (Figure 1). The total annual nutrient load at the outlet of each sub-catchment (L_j) is calculated as;

$$L_j = (Point_j + Diffuse_j) * (1 - Lake_j) \quad (1)$$

where,

$Point_j$ = sum of nutrient loads discharged from point sources

$Diffuse_j$ = sum of diffuse nutrient losses

$Lake_j$ = estimated nutrient lake retention factor

An outline of the calculation methods for each sector and primary data sources are given in Table 1. Alternative data can replace the primary data sources, once the field mapping in the toolbox is updated. This facilitates the updating of pressure datasets e.g. with new emission values from annual environmental reports, and also enables modelling of historical data. For example, CORINE datasets from 2000 and 2006 can be combined with historical census data to model the sources of long term nutrient monitoring data. Ní Longphuirt et al. (submitted) used the SLAM toolbox in this manner to evaluate the changes in nutrient sources over a ten year period in 17 catchments in Ireland.

2.1 Direct Discharges

For direct discharges, the main data source is from monitoring of nutrients in effluent discharged by individual municipal or industrial facilities. Annual environmental performance reporting provides these estimates of annual nutrient loads which are spatially associated with the point of discharge. Where monitoring data is not available, loads are estimated from the population equivalent (PE) of the facility. For the septic tank systems sub-model, results of the SANICOSE model (Gill and Mockler, submitted) are aggregated up to the relevant water body or sub-catchment scale.

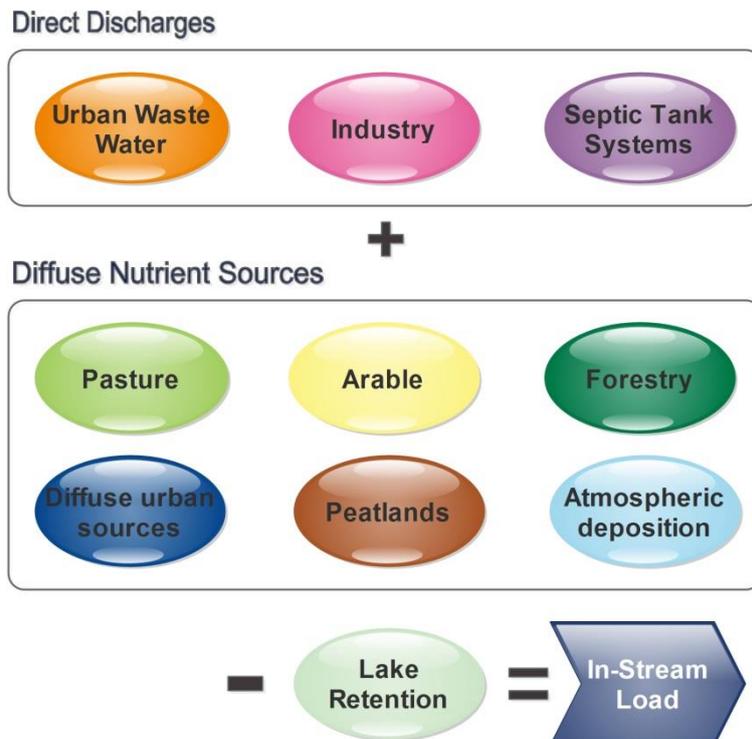


Figure 1. Sub-models of the Source Load Apportionment Model (SLAM) Framework.

Table 1. Data sources and calculation methods for sub-models of the SLAM framework.

Sub-model	Calculation Methods	Primary Data Sources
Waste water discharges	Annual nutrient load emissions reported to EPA for 2014 OR calculation based on 2014 PE and assumed figures for nutrient production and treatment efficiency.	2014 Annual Environmental performance Reports OR 2014 Population Equivalent (PE)
Diffuse urban sources*	Export coefficient model based on land cover	2012 CORINE land cover
Industrial discharges	Three year average of annual reported nutrient emissions OR calculation based on 25% of licenced limits	2011-2013 PRTR database OR EPA licenced limits
Septic Tank Systems	Export coefficient model (SANICOSE) with 3 transport pathways: 1. Inadequate percolation 2. Near surface (subsoils) 3. Groundwater	Non-sewered house dataset, surface water bodies (EPA, OSi) and catchment characteristics including aquifer vulnerability and subsoil permeability (from Geological Survey of Ireland)
Pasture (diffuse agriculture)	Export coefficient model (CCT) with 2 transport pathways: 1. Near surface (soils/ subsoils) 2. Groundwater (sub surface pathways)	2012 LPIS (DAFM), Good Agricultural Practices (GAP) Regulations (S.I. 31, 2014) and catchment characteristics including soil drainage properties and depth to bedrock.
Arable (diffuse agriculture)	Export coefficient model (CCT) with 2 transport pathways (same as Pasture sub-model).	2012 LPIS (DAFM), fertilizer application rates (Lalor et al., 2010) and catchment characteristics
Forestry*	Export coefficient model based on land cover	2012 CORINE land cover
Peatlands*	Export coefficient model based on land cover	2012 CORINE land cover
Atmospheric deposition	Direct deposition on lakes	Nitrogen deposition from map from Henry and Aherne (2014) & Lakes map (EPA)

* Sub-model structure under review.

2.2 Diffuse Nutrient Sources

Ireland is predominantly covered by agricultural land, with significant areas of forestry and wetlands (Table 2). The 2012 CORINE land cover data (Lydon and Smith, 2014) is used in the SLAM toolbox to estimate nutrient emissions to water from areas of forestry, peatlands and artificial surfaces.

The pressure information for diffuse agriculture is mainly from the Land-Parcel Identification System (LPIS) provided by the Department of Agriculture, Food and the Marine (DAFM). The pasture and arable sub-models aggregate the relevant results from the Catchment Characterisation Tool (CCT) (Archbold et al., 2016 and reference therein). Both the SANICOSE (for septic tank systems) and the CCT models produce simple estimates of nutrient loads in groundwater, which the SLAM toolbox combines to give an indication of the percentage of nutrients that are delivered to surface waters via groundwater pathways. See Mockler et al. (submitted) for further details on the calculation methods for each sub-model.

Table 2. CORINE 2012 land cover by area and percentage area of Ireland.

CORINE 2012	Area (km ²)	%
Artificial Surfaces	1,747	2.5
Agricultural Areas	47,879	68.1
Forestry and semi-natural areas	8,073	11.5
Wetlands	11,069	15.8
Water	1,502	2.1
Total	70,271	100

2.3 SLAM Toolbox Interface

The SLAM toolbox interface is opened through the ArcToolbox panel in ArcGIS (Figure 2). Firstly, the user is required to indicate whether nitrogen (N) or phosphorus (P) is to be modelled. Users can select any polygon shapefile to represent the catchments, and results will be reported using the 'CatchID' field in the attribute table. In addition, a SQL expression can be provided to indicate a sub-set of polygons in the catchment shapefile.

Users can then select the preferred datasets for the sub-models, including;

- the CORINE land cover data,
- the SANICOSE and CCT results,
- wastewater treatment plants shapefile,
- industrial discharges shapefiles, and
- parameter tables.

The parameter tables are provided in Excel spreadsheets, and can be easily edited and updated by users.

The SLAM results are provided in tables and shapefiles, and are saved to the folder indicated by the 'Results Out Path', using a file name including text specified in the 'NameOut' field.

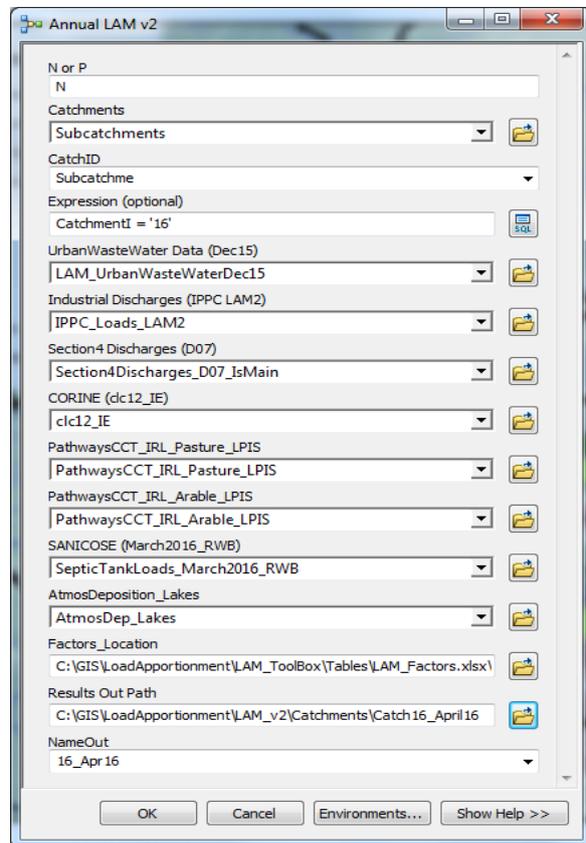


Figure 2. Input screen for SLAM ArcGIS toolbox.

Results are displayed spatially using standard ArcGIS functions to produce pie charts of sources of nutrients (Figure 3). In addition, tabular results are easily exported into other software.

3 CASE STUDY: PHOSPHORUS IN THE SUIR CATCHMENT

The Suir catchment is in the South-East of Ireland and has predominantly agricultural land cover with some areas of forestry and peatlands. It has a total area of 3500 km² divided into 29 sub-catchments (Figure 3). The total population is approximately 200,000, with the largest town, Waterford, located at the mouth of the estuary. The average density of septic tank systems in the catchment is 8 per km².

Results for the Suir catchment indicate that diffuse losses of nutrients from pasture are the dominant source of nitrogen and both wastewater discharges and losses from pasture are dominant for phosphorus. The overall annual phosphorus emissions are dominated by a large municipal discharge at the mouth of the catchment (Figure 3).

The main sources of phosphorus varies considerably between sub-catchments depending on the anthropogenic activities, with pasture, municipal wastewater and industrial discharges typically contributing the highest proportions of load on an annual basis. For example, urban wastewater contributions range from between 1% to 90% of phosphorus in sub-catchments of the Suir, typically reflecting the locations of more densely populated areas.

Load apportionment results for nitrogen showed less variation between sub-catchments, compared to phosphorus, with pasture being the dominant source throughout. These results have been used to inform WFD characterisation and the identification of significant pressures for waterbodies at risk of not meeting WFD objectives due to elevated nutrient concentrations.

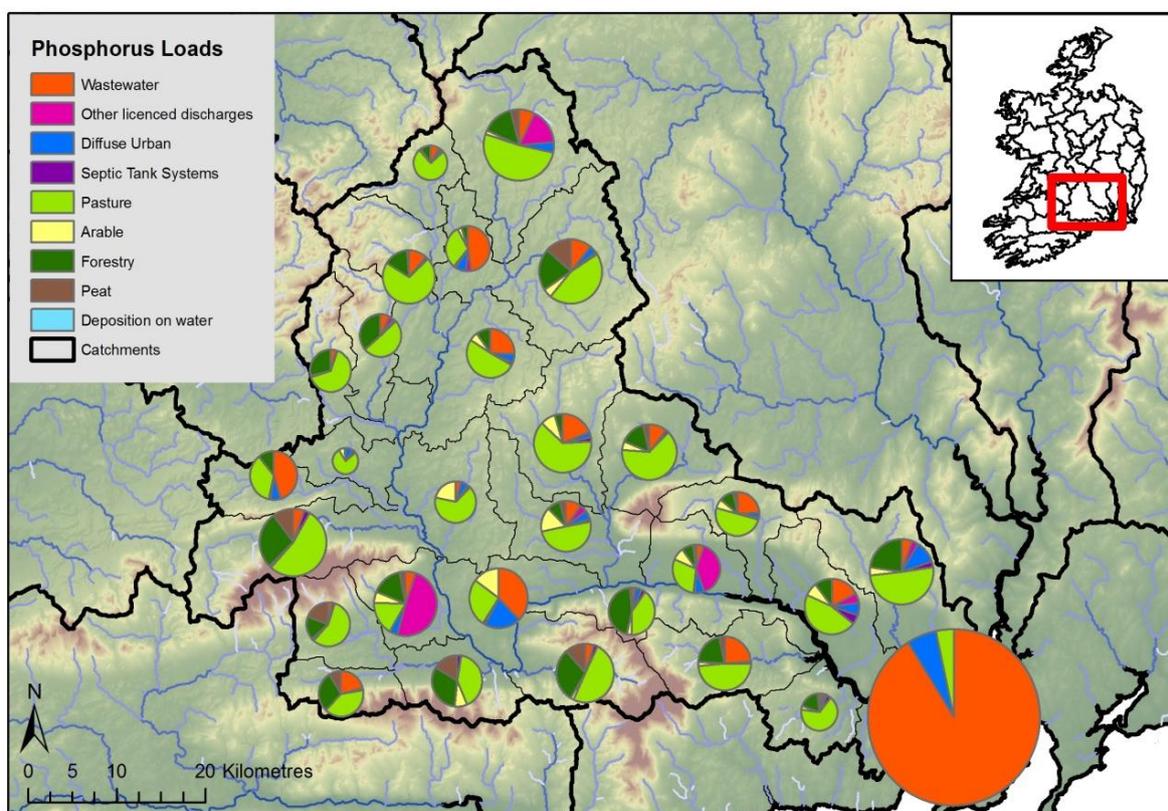


Figure 3. Phosphorus load apportionment results for the Suir catchment (size of pie indicates relative contribution of annual loads from each sub-catchment).

4 DISCUSSION

4.1 Model Software Selection

The objective of the SLAM toolbox is to support catchment managers by providing scientifically robust evidence base to back-up decision making in relation to reducing nutrient pollution. This model is being developed by the EPA *CatchmentTools* Project (2014-2017), and builds on previous research from the EPA *Pathways* Project which produced both numerical (Mockler et al., 2014; Mockler et al., 2016) and GIS-based water quality models for Irish catchments (Archbold et al., 2016).

Bruen and Mockler (2012) outlined the motivations for the development of a decision support system, the Catchment Modelling Tool, built on a flexible hydrological model. However, this water quality model is relatively time and data intensive (Mockler et al., 2013), and is more suited to detailed assessments that require tracking the short-term variation in nutrient quantities and relationships with time-varying drivers. An initial scoping exercise in 2014 identified that the load apportionment model proposed by the Irish EPA was required to;

- (i) produce national results using available datasets,
- (ii) include a user-friendly interface,
- (iii) facilitate continuous development, and
- (iv) be available to the EPA after only one year of development.

After testing several options, the optimal software solution was identified as ArcGIS toolbox developed using ModelBuilder. ArcGIS is the most common GIS software used by the relevant stakeholders, and provides a user-friendly interface with limited development. Using this software, sample results were easily produced which were used to elicit feedback from stakeholders and hence to ensure that all of the requirements of the stakeholders were met.

4.2 Model Development

The SLAM toolbox was designed with individual sub-models for each sector to facilitate engagement with relevant stakeholders and scientific experts. For example, while the septic tank system sub-model was in development, several alternative options were tested and compared within the toolbox. The alternative results that these models produced were presented to stakeholders, to highlight the impacts of model improvements on the overall load apportionment results.

Further development is on-going with the forestry, peatlands, diffuse urban and lake retention sub-models to incorporate recent research findings and higher resolution datasets.

4.3 Supporting Integrated Catchment Management

As detailed risk assessments are not feasible at national scale, simple tools can be used to prioritise resources for catchment management. The average annual model results produced by the SLAM are used in combination with monitoring data and local knowledge to highlight the likely sources of issues within a sub-catchment (Daly et al., 2016). Additional detailed assessments may be required in some cases where, for example, seasonality or local conditions have a potential ecological impact.

5 CONCLUSIONS

The SLAM framework has been developed to produce nutrient load apportionment in Irish catchments based on the best available national models and data. The framework was developed as an ArcGIS toolbox using ModelBuilder, with individual sub-models for each sector. This design was chosen because of the possibility for contributions to model development from a broad range of scientists, without the need for experience in programming.

The results presented here have been reproduced at national level and are incorporated into the Irish EPAs WFD characterisation process. In addition to the identification of significant pressures, the SLAM toolbox can be used to assess scenarios of changes in pressures and mitigation measures, thereby supporting decision making in the water domain.

Using local knowledge in conjunction with scientific evidence, such as provided by the SLAM, effective, targeted measures can be identified to reduce nutrient losses to water. This will potentially lead to improvements in the health of our aquatic environment and valuable ecosystem services for citizens.

ACKNOWLEDGMENTS

The author acknowledges funding for the *CatchmentTools* Project from the Irish Environmental Protection Agency (project ref. 2013-W-FS-14) on behalf of the Department of the Environment, Community and Local Government. We thank EPA laboratory and scientific staff, Met Éireann and OPW for providing national datasets integral to this research. The author would particularly like to acknowledge members of the EPA Catchment Science and Management Unit.

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