



Loose One-Way Coupling of Land Use and Nutrient Emission Models to Assess Effects of Regional Development Scenarios on Catchment Water Quality

Eva M Mockler¹ · Harutyun Shahumyan² · Brendan Williams² · Michael Bruen³

Received: 1 September 2018 / Accepted: 2 March 2020 / Published online: 4 May 2020
© The Author(s) 2020

Abstract

Nutrient enrichment and eutrophication can increase when urbanisation and intensification of agriculture production occurs without accompanying mitigation measures to offset impacts from land use transitions. The identification of measures to protect or restore water quality is a challenging exercise, particularly in the context of increasing population and urbanisation. Hence, decision-makers need adequate tools to better understand and evaluate the effects of policy interventions on water management and quality control in urban regions. A model integration method was developed to assess future scenarios of urban development on water quality using land use model Monitoring Land Use/Cover Dynamics and nutrient emission model Source Load Apportionment Model. A case study application investigated how projected changes in urban land use in the most populated region of Ireland, the Greater Dublin Region, impact on water quality. Results for all scenarios indicate increasing losses to water for both phosphorus (18–25%) and nitrogen (9–12%). However, as these scenarios assume that wastewater treatment efficiencies remain static into the future, this study highlights that the magnitude and distribution of investment in urban wastewater collection and treatment will have the greatest impact on changes in future nutrient emissions to water in this urban region. The differences between the development scenarios for diffuse nutrient losses were small in comparison, even though the location of specific land uses varied broadly across scenarios. It was found that the decline of agricultural land cover and replacement with urban development in Dublin region by 2026 as represented by four modelled scenarios resulted in substantial increases in diffuse phosphorus emissions, but only slight changes in diffuse nitrogen emissions. It was shown that the scales of impact from sources of nutrients vary from scenario to scenario and that these should be considered alongside planned mitigation of point sources of nutrient emissions to water. Such information can support physical planners, catchment managers and policy makers to plan accordingly to get the best possible environmental outcomes. The case study application demonstrated that the loose one-way coupling of a land use model and a nutrient emission model can be an effective and inexpensive approach to improve understanding of the effects of urbanisation on water quality and assist in the strategic planning of catchment management and infrastructure investment.

Keywords Urban development · Land use change · Nutrient emissions · Model coupling · Dublin region · MOLAND · SLAM

1 Introduction

A key challenge for a sustainable future is to protect or restore water quality whilst supporting a growing population with its resulting food production and land use change demands. Urbanisation and intensification of agriculture production encourage land use transitions that can substantially impact on water quality and freshwater resources. Agricultural activities may degrade water quality through excessive soil loss (erosion) or export of fertilisers and pesticides [10]. Urbanisation increases the impervious area resulting in higher stormwater flows and more contaminants in runoff that add to already

✉ Eva M Mockler
e.mockler@epa.ie

¹ Catchment Science and Management Unit, Environmental Protection Agency, Clonskeagh, Ireland

² School of Architecture, Planning and Environmental Policy, University College Dublin, Belfield, Ireland

³ School of Civil Engineering and Earth Institute, University College Dublin, Belfield, Ireland

increased municipal wastewater discharges that, all together, can have a negative effect on stream water quality [45].

Anthropogenically influenced nutrient enrichment and eutrophication is impacting on freshwater and marine ecosystems around the globe [11, 72]. The sources of the nitrogen (N) and phosphorus (P) driving this eutrophication are closely related to human activities, including direct discharges from wastewater treatment facilities or septic tanks, and emissions from diffuse nutrient sources, such as agriculture, forestry and artificial surfaces, such as roads, buildings and car-parks. Eutrophication remains the main cause of inadequate water quality in rivers, lakes and coastal waters in Ireland [56].

Environmental managers and decision-makers need to identify and quantify the sources of nutrient emissions to better understand and evaluate the effects of policy interventions on water quality [49]. The European Union has adopted the Nitrates Directive [32] and Water Framework Directive [33] aiming to have a good quality of all waters by 2027. The relationship between land use and water quality is studied widely across the world [6, 36, 63]. Some of the studies use hydrologic/water quality models such as Soil and Water Assessment Tool [2], Hydrological Simulation Program-Fortran [41] and Agricultural Nonpoint Source [89] models. Others use statistical models such as principal component analysis, ordinary least squares and geographic weighted regression. Similarly, there is increasing applications of land use and urban models for policy analyses and scenario simulation [77]. Among those models, the ones based on cellular automata are particularly powerful because of their ability to reproduce complex spatial and temporal dynamics. A large number of applications use existing modelling frameworks, such as the SLEUTH [13], the CLUE [76] and Metronamica/Monitoring Land Use/Cover Dynamics (MOLAND) [30] models.

Developing a new state-of-the-art model is an expensive and demanding process. Calibrating a comprehensive integrated model for a new study region is also a complex task [75]. Many of the abovementioned and other models are powerful, well tested and used in many countries. However, their adaptation and calibration for a new study region is quite time-consuming and often requires special expertise. Therefore, if there are multiple models already adapted and calibrated for a region, then their loose coupling can be an effective and quick solution for integrated decision-making with limited resources [67].

Research into the impacts of land use change on the environment has examined a range of processes including hydrologic (e.g. [47, 78]) and water quality impacts [43, 51, 52, 83]. For example, Zhang et al. [90] have coupled CLUE-S (the Conversion of Land Use and its Effect at Small regional extent) and SWAT (Soil and Water Assessment Tool) models to simulate pollution loads under different land use scenarios in the watershed of Miyun Reservoir in China. They showed that land

use changes under different scenarios have significantly affected the non-point source pollution load. Modelling methodologies have also been explored with, for example, Yalew et al. [88] arguing that coupling land use and hydrologic models may not be always necessary as they found that dynamic feedback between the SITE (Simulation of Terrestrial Environments) and SWIM (Soil and Water Integrated Model) models resulted in only marginal improvements in results. Recent research by Wagner et al. [78] advocates for the inclusion of dynamic land use information to improve the accuracy of the assessed hydrologic changes. This research analysed the frequency of required land use information, highlighting that non-linear land use change over time periods greater than 5 years is difficult to approximate with static land use change assessments.

The rise of interest in such model integration is linked with the potential benefit for urban and river basin planners who can examine the present and future characteristic of a specific watershed through analysing effects of land use change on water resources in an integrated manner [88]. The approach used in this research allows the application of existing models from different disciplines in an integrated manner and provides a template that can be implemented for other relevant models available for the same study region.

This study developed a tailored model integration to support decision-makers in assessing how Regional Planning Guidelines' projected changes in urban land use in the most populated region of Ireland, the Greater Dublin Region (GDR), may impact on water quality in its main catchments.

2 Methodology

The key objectives of the study were to (i) couple two independent models developed and previously calibrated for the study region and (ii) estimate the annual nutrient (N and P) emissions to surface waters for different future regional development scenarios. Hence, the selection of the land use model MOLAND and water quality model Source Load Apportionment Model (SLAM) was mainly based on their availability for the study region.

2.1 Study Area

The Greater Dublin Region (GDR) is Ireland's most densely populated region with a population of 2 million within and area of 7815 km². It was the principal beneficiary of the strong economic and population growth from the late 1990s to 2007; followed by a severe economic recession from 2007 to 2014; and a strong recovery from 2014 to 2019 [17]. By 2019, unemployment has fallen from over 16 to 5% and migration to the region has dramatically increased leading to a need to increase provision of infrastructure and housing to cater for increased demand.

In Ireland, the experiences of integrated planning and development systems internationally have been used to shift what was a highly localised and development led planning system towards the incorporation of national and strategic approaches. The first planning strategy on a regional basis, the Strategic Planning Guidelines, dates from 1999 in Ireland. The first National Spatial Strategy [54] adopted and adapted concepts from the European Spatial Development Perspective such as balanced regional development and regional infrastructure provision. This developed the role of spatial coordination to include concepts including a national spatial level coordination of public policy by linkages with national development planning and investment decisions incorporated in a National Development Plan which committed capital spending to designated infrastructure projects. The replacement for that national planning strategy is the new National Planning Framework [24], incorporating both national and regional strategic infrastructure provisions with additional specific outcome and target-based objectives; e.g. brownfield and vacant sites targets have been set nationally and locally.

In the meantime, a lack of housing close to the economic core areas created a continuing push of employment-related housing demand at increasing distances from Dublin [84]. The dispersal of housing, retail and employment activities in a fragmented manner across the GDR has major implications for the environment, infrastructure and service provision. Moreover, the population in the GDR is projected to further increase by over 400,000 by 2031 and is expected to account for 42.4% of the total population in Ireland [16], raising water demands beyond current supply capabilities and creating challenges for water resources management [44, 85].

This study is focused on the core 3567 km² of the GDR, defined by the river catchments of the Nanny-Delvin Rivers in the north, the Avoca-Vartry Rivers in the south, the Liffey to the west and Dublin Bay to the east (Fig. 1). A total population of 1,555,078 was reported for this area in 2011 [15]. Its dominant land use type is pasture (42.3%), followed by arable land (15.6%) and urban surface (11.5%) in 2012 [31], with the majority of urban and pasture lands contained in the Liffey and Dublin Bay catchments (Figs. 2 and 3).

2.2 The MOLAND Model

The MOLAND land use model has been developed by the Research Institute for Knowledge Systems (RIKS) as part of an initiative of the EC Joint Research Centre [3]. It generates alternative future scenarios informing urban planners and policy makers on the possible implications of their decisions in terms of land use change.

The MOLAND model is based on the GEONAMICA framework [40] and stands out from other urban models because of its capability of simulating up to 32 land uses,

conforming with the Co-ORDinated INformation on the Environment (CORINE) land cover classification system [48].

It comprises two dynamic sub-models with a common temporal increment of 1 year but working at different spatial scales. At the macro scale, the model allocates regional population and jobs among its sub-regions. At the micro scale, the provision for population and jobs is translated into demand for various land use classes using a constrained cellular automaton [80]. Six of the land use classes (road and rail networks, airports, mineral extraction sites, dump sites, artificial non-agricultural vegetated areas and water bodies) represent fixed features in the model and are assumed not to change and which therefore do not participate in the dynamics. They do, however, affect the dynamics of the active land uses, since in the cell neighbourhood, they may represent an attractive or repulsive effect. Another eight (arable land, permanent crops, pastures, heterogeneous agricultural areas, forests, shrub, sparsely vegetated areas and wetlands) are passive functions that participate in the land use dynamics, but the dynamics is not driven by an exogenous demand for land. They appear or disappear in response to land being taken or abandoned by the active functions. The urban land uses (residential; industrial areas; commercial areas; public and private services; port areas; construction sites and abandoned land) are the active land uses and are forced by demands for land generated exogenously to the cellular automaton, in response to the growth of the urban area [29].

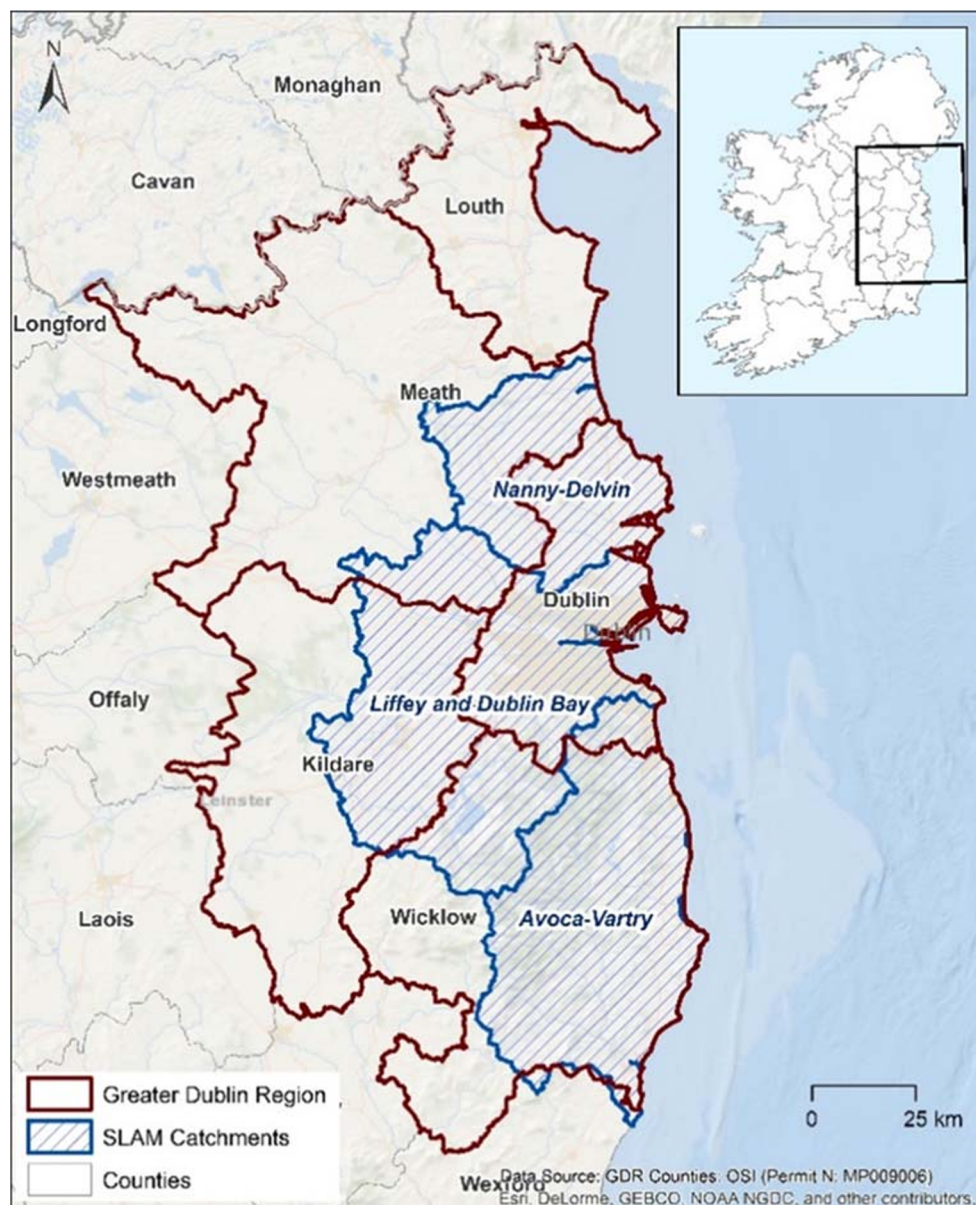
For the GDR, this consists of (i) a land use raster grid with 200 m cell size and 23 classes from which 7 urban classes are actively modelled, (ii) a set of factors influencing the allocation of land use change such as suitability, zoning, accessibility and neighbouring land uses (Fig. 4) and (iii) transition rules determining the attraction and repulsion between land uses [29]. The model also includes a stochastic parameter which insures the generation of realistically heterogeneous land use patterns. The combined effects of all those factors in the cellular automata are reflected in the transition rule defined by the expression (1):

$$P(k, x, y, t) = v(t) S(k, x, y)^{\sigma_1} Z(k, x, y, t)^{\sigma_2} A(k, x, y, t)^{\sigma_3} R(k, x, y, t)^{\sigma_4} \quad (1)$$

where $v(t)$ is the scalable stochastic perturbation term; $S(k, x, y)$ is the suitability of cell (x, y) for land use k ; $Z(k, x, y, t)$ is the Zoning; $A(k, x, y, t)$ is the accessibility and $R(k, x, y, t)$ is the contribution of the cellular automaton (CA) transition rules in the calculation of the transition potential of cell (x, y) for land use k at time t ; σ -s are the exponents determining whether the effects of suitability, zoning and accessibility; and the CA transition rules are (= 1) or are not (= 0) taken into consideration in the calculation of the CA transition potential [29].

The robustness of the model is demonstrated in numerous applications worldwide [3, 4, 21, 60, 71, 80]. For the GDR,

Fig. 1 Study area



the MOLAND was calibrated based on datasets for the years 1990, 1996, 2000 and 2006 [69]. For validation of the calibration results, the Fuzzy-kappa map comparison method was applied, showing high degree of agreement between actual and simulated land use maps (Fig. 5). Additionally, the MOLAND results were tested against the land use map generated by random (i.e. model free) cell changes through the Random Constraint Match model from the Map Comparison Kit [38]. Particularly, the Random Constraint Match model was used to generate a land use map of the region by minimally adjusting the 2000 actual map giving it the same frequency distribution of the land use categories as the 2006 actual map. As a result, the random model interprets the frequency distribution of the 2006 actual map as constraints and

imposes these constraints by randomly modifying the 2000 map, but only as little as strictly necessary. The comparison of the 2006 actual map with the Random Constraint Match map gave a Fuzzy-kappa value of 0.798, which is lower than the 0.836 value given by the MOLAND-generated map comparison. The MOLAND performed also quite well in terms of regional estimates of population and activities, which compare favourably with actual estimates and constant share projections [69].

Following calibration for the Greater Dublin Region, the MOLAND model was applied extensively in a number of studies [70, 71, 74, 86] and has formed an important part of the review of the Dublin and Mid-East Regional Planning Guidelines [19].

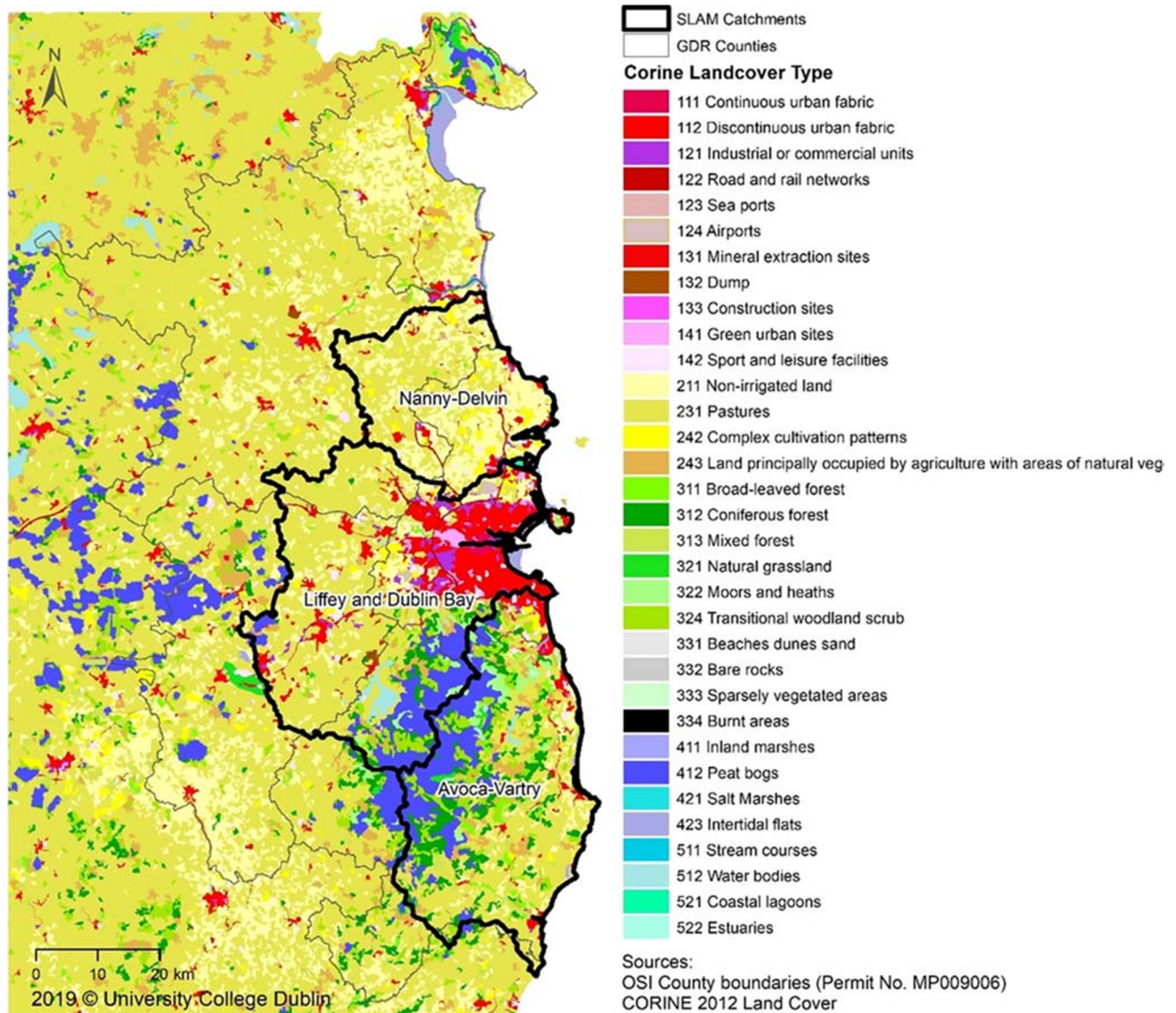


Fig. 2 Land use map of the region in 2012

2.3 The Source Load Apportionment Model

The Source Load Apportionment Model (SLAM) framework [50] is a geospatial modelling framework to quantify and apportion the sources of nutrient exports to rivers and coastal waters in Ireland. It was used by the Irish EPA during the Water Framework Directive characterisation process to support the identification of significant pressures on water bodies, feeding into the Irish River Basin Management Plan (2018–2021) [23]. The SLAM uses a source-orientated approach that incorporates reported emission data to calculate point source loads and geospatial models of diffuse pollution based on detailed land management data and export coefficients that vary with catchment characteristics (e.g. [42, 73]). It calculates the annual average N and P emissions to surface waters from nine source types including point discharges from urban

wastewater treatment plants, industry and septic tank systems, and diffuse sources include emissions from agriculture, forestry and peatlands. In contrast to modelling approaches that rely

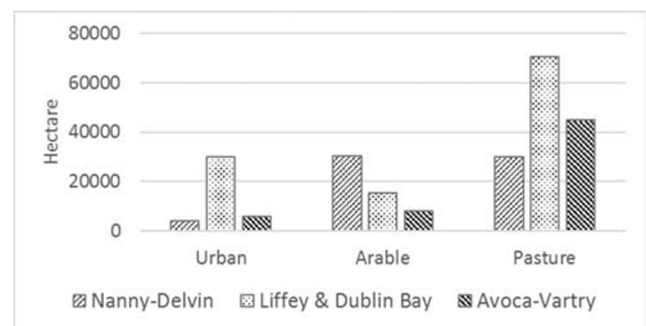


Fig. 3 Urban, arable and pasture land use areas within catchments in 2012

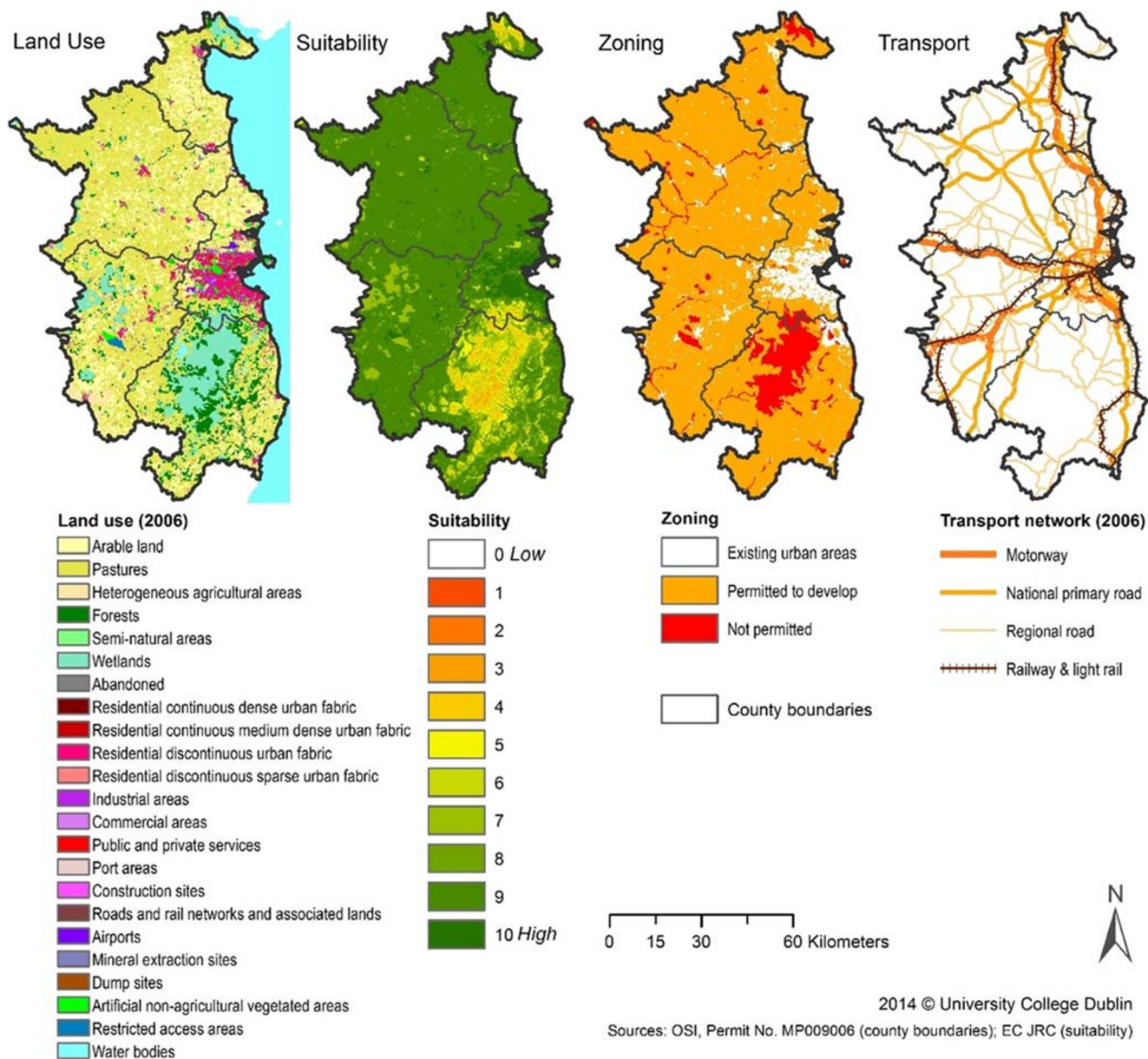


Fig. 4 The MOLAND model input layers

on measured in-stream data for model calibration, this approach allows the model to be applied throughout Ireland irrespective of the availability of monitoring data.

The SLAM input data included national inventory and reporting data, including data for over 1000 wastewater treatment plants and each of the over 130,000 farms in Ireland, in combination with export coefficients linked to catchment characteristics such as the soil and subsoil permeability and groundwater recharge [50]. The agriculture (pasture and arable) and septic tank systems modules incorporated the outputs from geospatial models: the Catchment Characterisation Tool (CCT) [1, 59] and SANICOSE models [35], respectively. Loads from point source discharges were calculated from data

collected by the EPA, including Annual Environmental Reports, the EPA Licensing Enforcement and Monitoring Application (LEMA) and the Pollutant Release and Transfer Register (PRTR) database. The total annual nutrient load at the outlet of each sub-catchment ($L_{N,P}$) was calculated as:

$$L_{N,P} = (\text{Point}_{N,P} + \text{Diffuse}_{N,P}) \times (1 - \text{Lake}_{N,P}) \tag{2}$$

where $\text{Point}_{N,P}$ = the sum of nutrient loads discharged from wastewater treatment plants, industrial discharges and emissions from septic tank systems; $\text{Diffuse}_{N,P}$ = the sum of diffuse nutrient losses from agriculture, forestry, peatlands, urban areas and atmospheric deposition; and $\text{Lake}_{N,P}$ = the

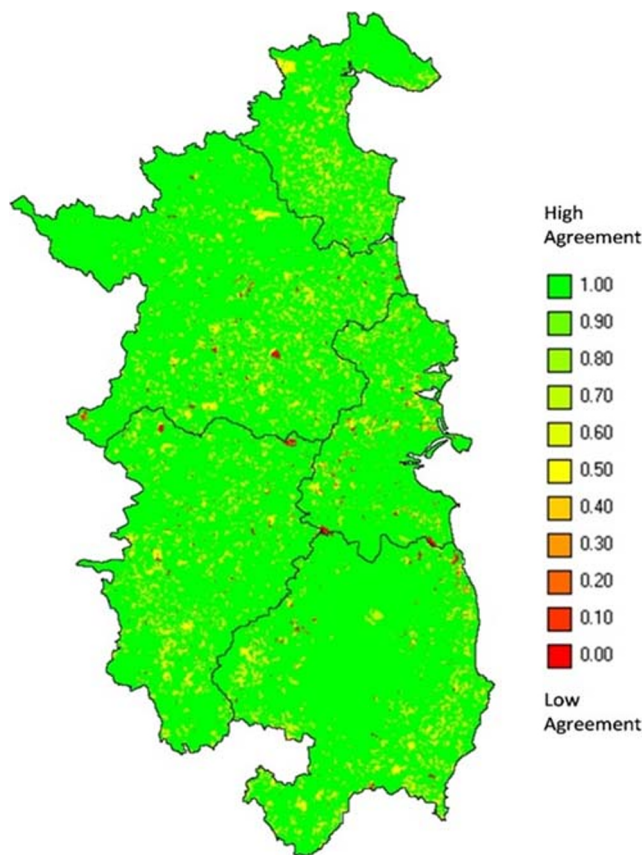


Fig. 5 The MOLAND model calibration assessment through Fuzzy-kappa comparison of Greater Dublin Region 2006 actual land use map and simulated land use map

estimated nutrient lake retention factor. The 2012 CORINE [46] level 3 land cover data were used for the baseline in the forestry, peatlands and urban sub-models with various export coefficients (Table 1) applied to estimate the annual diffuse nutrient emissions to water, calculated as:

$$\text{Diffuse}_{N,P} = \text{Area} \times \text{Export}_{N,P} \quad (3)$$

where Area is the area of the land cover category (ha) and $\text{Export}_{N,P}$ is the appropriate export coefficient for nitrogen or phosphorus ($\text{kg ha}^{-1} \text{ year}^{-1}$). The SLAM nutrient emissions were assessed against monitoring data for 16 major river catchments covering 50% of the area of Ireland with satisfactory coefficient of determination (r^2) for annual TP ($r^2 = 0.78$, $p < 0.01$, $n = 16$) and TN ($r^2 = 0.82$, $p < 0.01$, $n = 16$) [50].

2.3.1 Data Exchange for Scenarios

Originally, the SLAM calculated diffuse nutrient emissions from forestry, peatlands and developed urban areas based on CORINE land cover dataset. However, CORINE is available only for limited years and not for future scenarios. Therefore, a land use forecasting model is required to feed the SLAM with the required information on land use changes. In this

research, the land cover change, represented by MOLAND for the GDR, was incorporated as an input to the SLAM framework to estimate annual nutrient losses from diffuse sources for alternative future scenarios.

Population projections from MOLAND were used to estimate emissions from point source discharges for each scenario. As this study is in the most densely populated region of the country, it is assumed that all of the new developments in the GDR will be connected to municipal sewerage networks and hence the number of septic tank systems was not increased in the 2026 scenarios. The emissions from municipal wastewater plants were increased pro rata to reflect the scenario population projections for each catchment based on the levels of treatment efficiency reported in the 2014 annual environmental reports to the Irish EPA. Planned infrastructure investment in the study area was not accounted for in the scenario emission predictions as the details of the load reductions for individual plants were unavailable. However, the results were compared with indicative reductions expected from capital investment in Section 3.2.2.

2.4 Model Coupling

Brandmeyer and Karimi [7] have classified model coupling approaches into the following categories: manual data transfer, loose coupling, shared coupling, joined coupling and tool coupling. Each of these approaches has its benefits and limitations. For example, manual data transfer is the least demanding approach, with minimal cost and time requirements. However, it is error-prone and not convenient when multiple runs are expected. Loose coupling automates the data exchange between the models with minimal changes in the model codes. However, it is very sensitive to the changes in the model output formats. The selection of the coupling method depends on many factors including the characteristics of the selected models, project goals, available resources, data exchange direction and frequencies [68].

The MOLAND and SLAM models were developed independently in different software environments (Table 2). The SLAM was developed as an ArcGIS tool and although having an open source code, it requires ESRI ArcGIS licence to run. The MOLAND model is developed as proprietary software (GEONAMICA) with restricted access to its code. Therefore, changes to the MOLAND code are not practical as change requests require developers' resources.

Models have approximately similar run time on a typical personal computer (i5 or i7 Intel processor or equivalent AMD, 8-GB RAM). It takes about 2 min for the MOLAND to simulate annual land use change in the GDR over 20 years. Whilst for the SLAM, modelling the phosphorus and nitrogen emissions to surface waters for a particular year takes about 13 min.

Table 1 Nutrient export rates from diffuse sources used in the SLAM model [50]

Land cover	CORINE code	Area (ha)	% area of Ireland	Rates (kg ha ⁻¹ year ⁻¹)	
				N	P
Urban					
Continuous urban fabric	111	3100	<0.0	5	1.4
Discontinuous urban fabric	112	111,914	1.6	5	0.86
Industrial or commercial units	121–124	13,003	0.2	5	1.88
Mine, dump, construction sites	131–133	304	<0.0	5	2.15
Green urban areas, sport and leisure	141,142	3573	0.4	5	1.4
Forestry					
Broad-leaved, coniferous, mixed forest	311–313	376,450	5.3	5.42	0.33
Natural grassland, moors, heathland	321,322	141,118	2.0	5.42	0.33
Transitional woodland-shrub	324	289,767	4.1	3.71	0.565
Peat					
Inland marshes	411	19,392	0.3	2	0.325
Peat bogs	412	1,033,832	14.7	2	0.2
Agriculture—export rates vary based on CCT model			65	NA	NA

These models have independent paths of development by independent group of researchers. Therefore, the only way of keeping the integrated suite compatible with the future versions of the models was to hold them separate in the coupling suite. Besides, the models run sequentially, and there is a one-way data flow from MOLAND to SLAM as it is assumed that changes in water quality do not influence land use change. More specifically, MOLAND simulates population, jobs and land use data for a specific year and passes it to SLAM. MOLAND runs internally in 1-year increments. SLAM takes the data for a specific year and generates the emission estimations for that year. Technically, SLAM can run for every year MOLAND runs for. However, it takes years to fully realise the impacts of development on the ground such as the buildout of a residential neighbourhood. For scenario comparison purposes, it is sufficient to use the outputs of the SLAM for the final year of the simulation, to assess all the impacts of the developments.

Consequently, a loose coupling method was identified as the most appropriate approach for linking MOLAND and SLAM models. Indeed, in loose coupling, the data exchange between models is automated but the models work independently. Then, loose coupling has a low initial cost and requires minimal or no changes to source codes, and the models still can be developed independently [87]. This will insure the compatibility of the future versions of the models.

There are some established model integration tools supporting loose coupling, such as the Open Modelling Interface (OpenMI) [37], Model Coupling Toolkit (MCT) [79], Community Surface Dynamics Modelling System (CSDMS) [58], Earth System Modelling Framework (ESMF) [39], Framework for Risk Analysis Multimedia Environmental Systems (FRAMES) [66], PCRaster [65] and ICMS [62]. However, these tools have their specific requirements for operation systems, programming languages, data formats and licences. Hence, none of those tools could have been applied to couple MOLAND and SLAM, mostly because of absence of support for the Windows environment or the requirement to be able to change the model source codes.

We aimed to couple the MOLAND and SLAM with minimal resources, without changing their codes whilst still preserving their capability of visualisation. Both models are based on geographic information systems (GIS) and use GIS for data preparation and output analysis. Particularly, the MOLAND land use, suitability and zoning maps are raster files stored in ASC format, and the road network is an ArcGIS shapefile (Fig. 3). SLAM also uses ArcGIS shapefiles for its input. Therefore, we have organised their coupling through a GIS, which has already proved to be an effective tool for loose model coupling in other studies with several applications for environmental models including soil erosion

Table 2 Main characteristics of the models

Model	Programming environment	Operation system	Simulation years	Total runtime (min)
MOLAND	GEONAMICA	Windows	2006–2026	2
SLAM	ArcGIS	Windows	2012, 2026	13

[8], land use change [12], hydrologic modelling [22, 64] and water quality modelling [5, 27]. As the SLAM model was developed in ArcGIS environment, this was used to organise data transfer between the MOLAND and SLAM (Fig. 4). Particularly, the MOLAND outputs the projected land use maps in ASC format raster files, which were passed to the ArcGIS Model Builder and the required numbers on land use areas per catchment were calculated and transferred to SLAM (MOLAND Landuse2SLAM in the Fig. 6). The MOLAND saves the projected population and employment numbers in Excel file, which was imported into SLAM using a Python script (MOLAND Activities2SLAM in the Fig. 6). Using ArcGIS made the data exchange process smoother and allowed us to capitalise on its data management and visualisation functionality.

Even if the models are comparable in terms of data being exchanged, it is rare that one model output identically matches the input format required by the other model [26]. MOLAND provides the population and job numbers organised by counties. In the meantime, SLAM requires those numbers at the catchment area level. As can be seen in Fig. 1, the catchment areas in the Greater Dublin Region intersect with two or more counties. Hence, this transition requires special treatment. A tailored geoprocessing tool (MOLANDActivities2SLAM) was developed to re-aggregate such data; in this case, it counts population and job density per county based on the MOLAND output; then, those are used with the SLAM catchment boundaries to estimate the number of people and number of jobs by catchment areas. Similarly, areas of various land use by catchments were re-aggregated using an analogous tool (MOLANDLanduse2SLAM).

The outputs of the MOLAND-SLAM integrated run were compared with the outputs of the standalone runs of each model. The results were ensuring that the link between the models works correctly.

2.5 Scenarios

In an effort to ensure that the strategies outlined by the Regional Planning Guidelines (RPG) in 1999 [18] remained relevant in the context of an unstable economic situation, the Dublin and Mid-East Regional Authorities (D&MERA) reviewed the RPGs in 2009 [19]. The following four scenarios were constructed for evaluation as part of the Strategic Environmental Assessment (SEA) process; whilst the MOLAND model was used to model those scenarios illustrating the effects of future policy directions on the GDR up to 2026 [9]:

1. Business as usual (BU) scenario explores the consequences of continuing the current settlement patterns.
2. Finger expansion (FE). Development is focused within the metropolitan footprint, with minimal growth in other

areas and expansion of the metropolitan footprint along key transport corridors.

3. Consolidation of key towns and the city (CKT) scenario explores a settlement pattern similar to that proposed in the original Strategic Planning Guidelines [18]. This settlement pattern entails development to be consolidated within the existing metropolitan footprint and a small number of development centres along major transport routes. The metropolitan footprint is not expanded along these corridors.
4. Managed dispersal (MD). Dispersal of development is managed by focusing new growth within the existing metropolitan footprint and several development centres across the region. Strictly enforced strategic green belts were used to prevent the merger of towns and ensure corridors remained between urban and rural natural areas.

The scenarios were based on national (Irish) storylines briefly described in D&MERA [19] and developed using five driving forces, namely: population change, economic trends, urbanisation, transport and overall trends [9, 61]. The base year of the MOLAND simulation was 2006, and 2026 was set as the final year, facilitating the use of and aligning with official population projections [14]. Whilst those scenarios use the same population and job projections for 2026 (Table 3), they have extensively different zoning policies and transportation network updates leading to drastically different urban development patterns [9].

The MOLAND outputs for those scenarios were used to feed the SLAM model and to explore likely nutrient emissions to surface waters and relevant effect on the water quality in the region by 2026.

3 Results and Discussion

3.1 Land Use Change

The MOLAND output maps showing the urban development between 2006 and 2026 illustrate significant differences in potential development patterns for different scenarios (Fig. 7). The key contribution that this type of research is that it provides a scientific basis to discussion of the complex changes brought about by changing urban land development patterns. The coupling of models allows critical issues such as future water quality be assessed given the potential future scenarios being considered by planners and policy makers. The engagement of such stakeholders is essential in both the development of this research and in validating the outputs. In particular, the dispersed settlement pattern and merger of formerly separate urban areas are observed in the BU scenario, whilst in the case of the FE scenario, new urban development is focused into the Dublin metropolitan footprint and a few

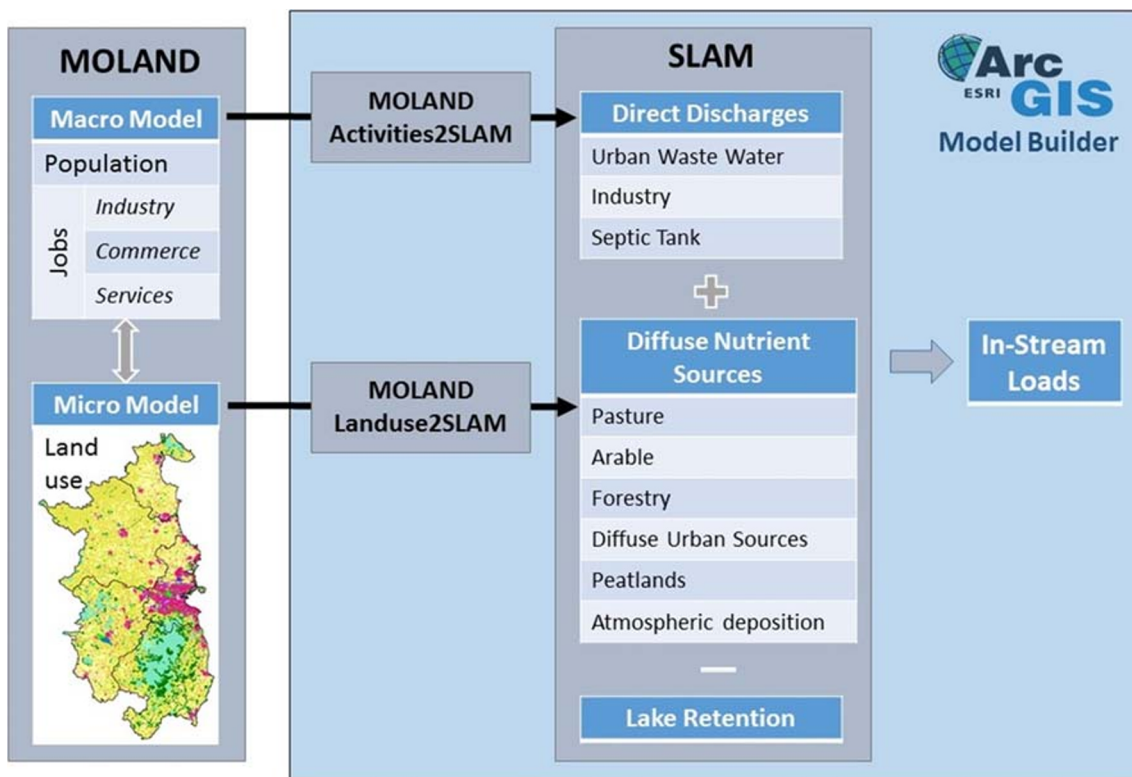


Fig. 6 The MOLAND-SLAM coupling framework

growth centres along major transport routes. Development to the West of Dublin city is significant. In the case of the CKT scenario, the urban development is consolidated into several growth centres. Development to the west of the city is less intense than in FE scenario, with this development focused into the growth centres of Drogheda, Navan, Naas, Wicklow and Arklow towns. Finally, the MD scenario shows dispersed development similar to the BU scenario with larger overall urban growth. Whilst development is dispersed across the region, it is consolidated into several growth centres of Arklow, Balbriggan, Drogheda, Navan, Naas, Newbridge and Wicklow. This contrasts with BU scenario, where development is widely dispersed in small pockets across the region. Coastal development close to Dublin city is also more pronounced in FE, CKT and MD scenarios.

The population and jobs per catchments for the modelled scenarios were estimated based on the MOLAND density figures (Fig. 8). Though the projected total population for the GDR is the same for all scenarios, the population distribution

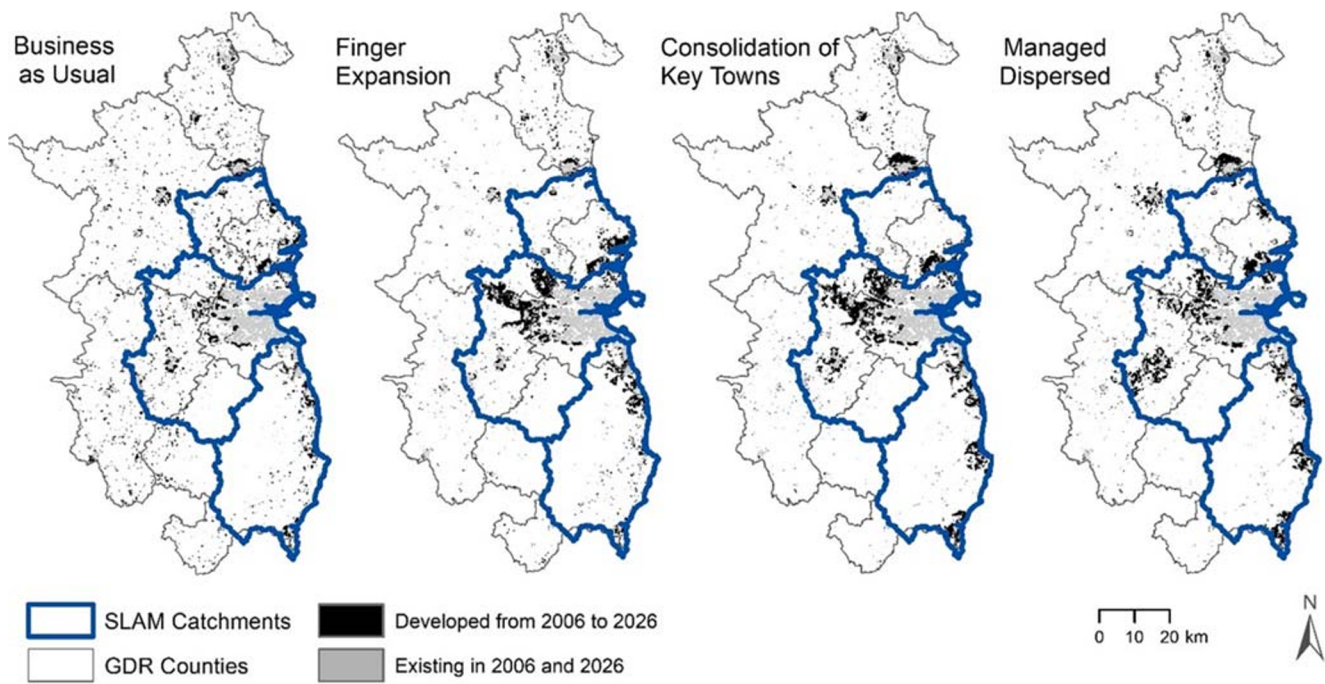
in the catchment areas varies significantly. The population growth between 2011 and 2026 in the studied three catchment areas is predicted to rise from 22% in the case of BU to 31% in the case of the FE and CKT scenarios. In all scenarios, the biggest population growth happens in Avoca-Vartry catchment ranging from 39% for BU and 64% for the MD scenario. The Liffey and Dublin Bay catchment has the least growth ranging from 8% for BU and 21% for the CKT scenarios.

Compared with the base year of 2006, by 2026 BU, FE, CKT and MD scenarios get correspondingly 52, 73, 75 and 70% increase in urban land uses within the study region (Fig. 8). The majority of urban growth occurs in the Liffey and Dublin Bay catchment.

Arable and pasture lands are decreased by 2026 for all scenarios (Fig. 8). The predicted loss of arable land is 11% for BU, 12% for MD and 13% for the FE and CKT scenarios. Similarly, the least loss of pasture land is observed for the BU scenario (7%), followed by FE and MD (11%), and then by the CKT (12%) scenarios.

Table 3 GDR population and jobs for 2006 and projections for 2026 scenarios

Scenario	Population (millions)	Jobs (thousands)		
		Industrial	Commercial	Service
Baseline in 2006	1.8	260	322	212
Scenarios in 2026	2.4	352	518	335



2019 © University College Dublin (Source of county boundaries: OSI, Permit No. MP009006)

Fig. 7 Comparison of GDR urban development in 2006 and 2026 scenarios

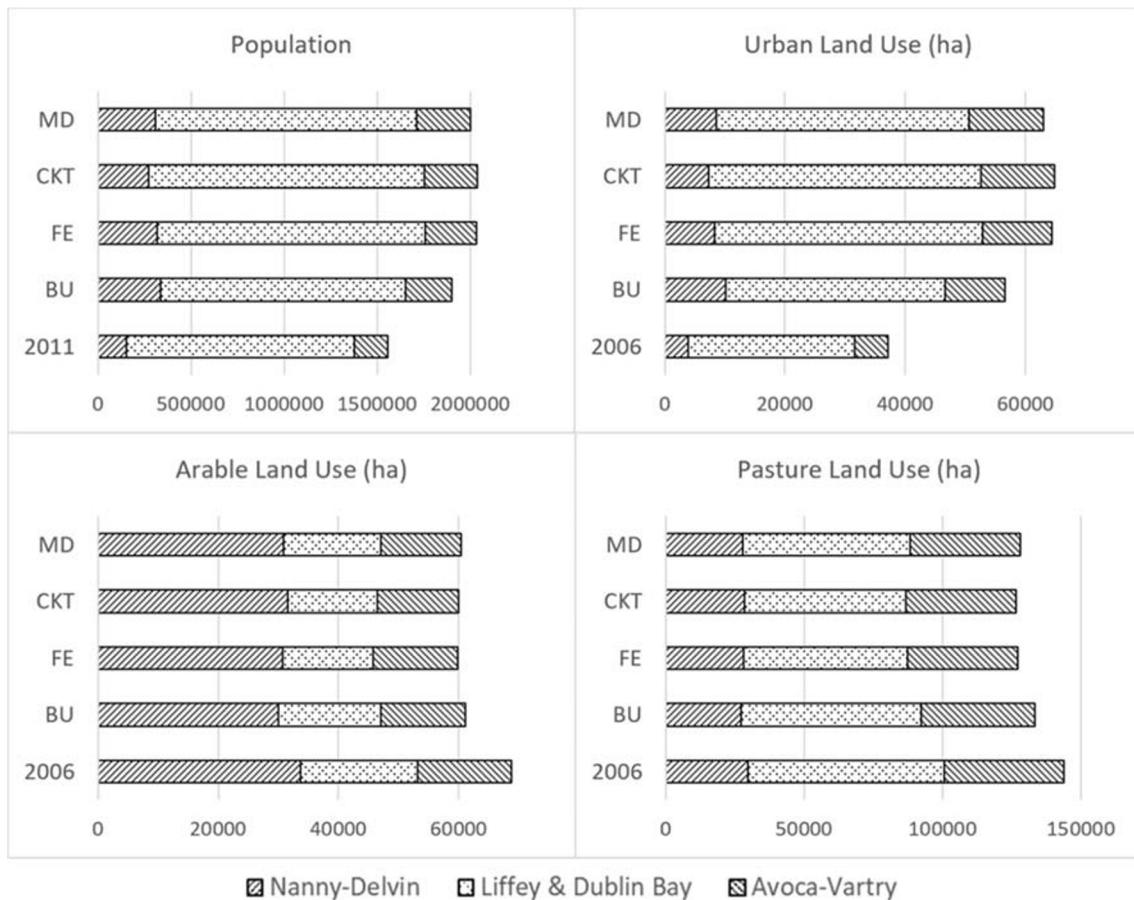


Fig. 8 Population and land uses per catchment and scenario

3.2 Water Quality

3.2.1 Changes in Diffuse Nutrient Sources

The MOLAND actively models urban land uses and assumes that new agriculture land use will not occur in this region. Hence, the baseline model for agriculture based on 2012 data was used in the scenario calculations. The spatial extents of urban cover from the scenarios were used to remove areas of pasture and arable land modelled in the SLAM.

The decline of agricultural land cover and replacement with urban development has a similar impact on phosphorus emissions for all scenarios with increases in diffuse sources in each catchment (Fig. 9). The greatest emissions are in the Liffey and Dublin Bay catchment and for the FE and CKT scenarios, which have the highest increases in urban fabric. This is due to the relatively high phosphorus emission rates from diffuse urban sources in the SLAM model compared with the moderately intensive pasture and arable land cover that it replaced and is in line with Irish and international nutrient emission studies [34, 50]. However, it is noted that the heterogeneity of the urban environment makes the identification of export coefficients more difficult compared with other land cover types [81, 82], as diffuse urban P loads originate from a variety of sources including atmospheric deposition, construction sites, lawn fertilisers, leaf litter, grass clippings, sewer leakage and pet waste.

The average net impact of land cover changes as represented by all four development scenarios resulted in slight changes in nitrogen emissions in all three catchments ranging from -3 to $+4\%$ (Table 4). This reflects trade-offs in emissions from agriculture and urban emissions.

3.2.2 Changes in Wastewater Discharges

The population increases predicted by the development scenarios, ranging from 22 to 31% over 15 years, will increase the quantity of wastewater generated in the region. In the study region, the baseline average treatment efficiency rates are approximately 62% and 56% for P and N, respectively. Assuming the treatment efficiency rates at wastewater treatment plants remain similar in the next decade, the average additional emissions from these scenarios equate to an additional 350 t/year of phosphorus and 2000 t/year of nitrogen added to watercourses. Of course, the nutrient emissions from municipal wastewater treatment plants can deviate greatly from the linear extrapolation used in this study due to operational management changes or capital investment in treatment infrastructure. Wastewater treatment in Ireland has improved in recent decades and further upgrades are planned through Irish Water's capital investment programme. This magnitude of the offset of emission increases in the study area will depend on the investment programme and on the availability of

funding. In the Liffey and Dublin Bay catchment, major improvements at the Ringsend wastewater treatment plant are outlined in Irish Water's investment programme as this plant is operating above capacity and effluent is impacting on Liffey Estuary and Dublin Bay [23]. Upgrades to this plant will provide substantial P and N emission reductions. However, the catchments north and south of Dublin city may not have such substantial planned investment to offset population increases. These scenarios highlight the continued need for investment in infrastructure in the GDR, particularly for the rapidly expanding populations north of Dublin city.

3.3 Uses and Limitations of Modelled Scenarios

The benefit of scenario analysis at catchment scale is that sources of emission increases can be compared, and the relative impact of sector-specific measures are put into the catchment context. Catchments are constantly evolving as human activities and climate are changing. Numerical modelling can provide information about the effectiveness of measures and the possible response of water bodies to future actions. For the modelled scenarios to inform changes to water quality status under the Water Framework Directive, further assessments of the ecological implication of the changes in nutrients would be required. For example, models of estuaries and coastal waters can be used to identify the magnitude of nutrient reductions required to achieve Good status, thereby supporting the selection of appropriate mitigation measures [53, 55].

In this study, the future changes in nitrogen and phosphorus emissions to water expected reflect the likely outcomes of the socio-economic changes and related planning decisions covered by those scenarios. The described patterns result from the assumptions made for each scenario and converted into the model through population and employment projections, transport network updates and zoning adjustments. As a result, they reflect the likely outcomes of socio-economic changes and planning decisions covered by those scenarios. Moreover, the location of specific land uses, population and jobs varies broadly across scenarios, meaning that those scenarios would have different environmental effects and nutrient emissions. As the MOLAND model simulates land use change based on the parameters calibrated on historical datasets, it cannot anticipate unforeseen events such as an economic crash and recovery or emigration crisis unless it is specifically implemented in the scenario projections.

Modelling nutrient emissions to water in a catchment requires detailed knowledge of the spatial and temporal distribution of anthropogenic pressures and hydrological processes. The SLAM results performed well to-date when tested independently against national monitoring data in 16 Irish catchments. However, uncertainties can arise due to several sources including the following: errors or outdated information in input datasets; inadequacy of extrapolated attenuation parameter

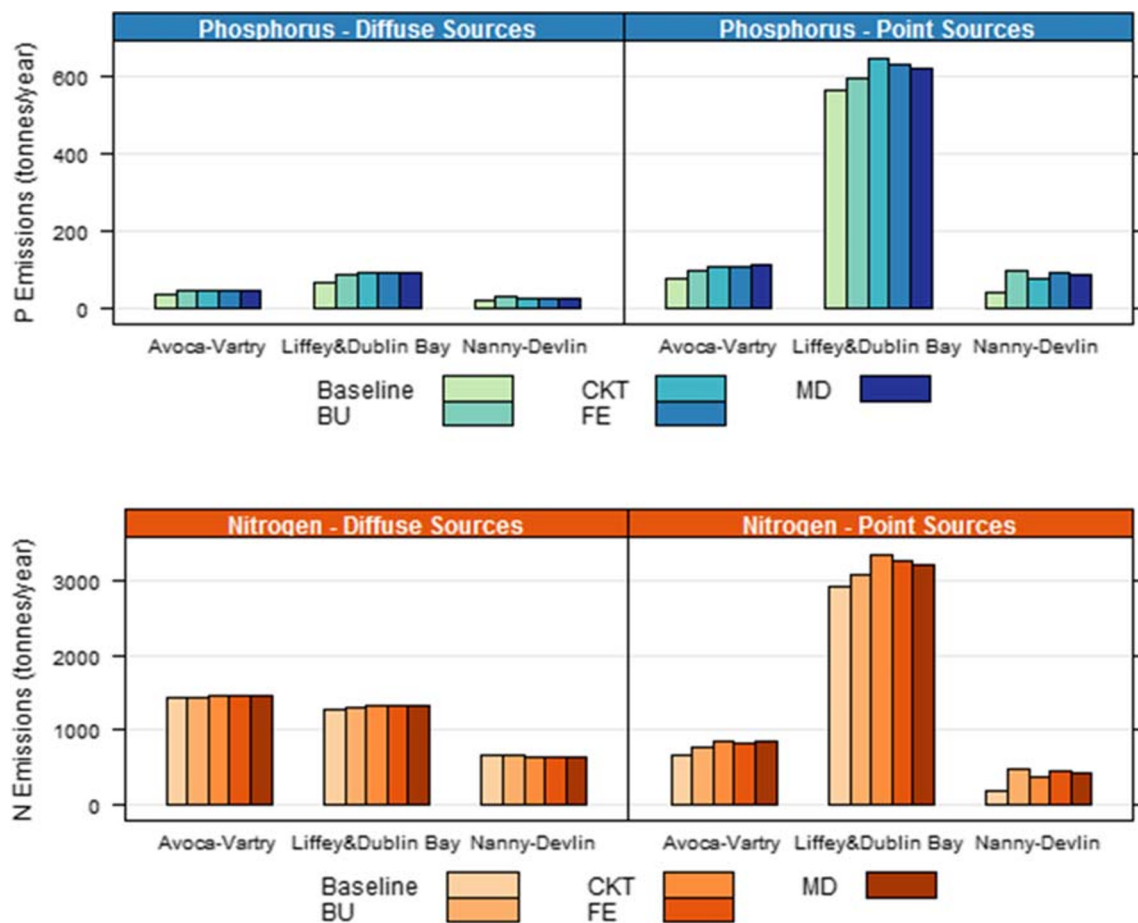


Fig. 9 Impact of land cover change on nutrient emissions in four scenarios relative to the baseline numbers of 2014

values; and unknown pressures in a catchment not accounted for in the model, e.g. accidental spills or overflows on farmyards or wastewater treatment plants [50].

Forecasting the changes in nutrient pressures in the next decade is particularly challenging for diffuse (non-point) pollution sources as in addition to the spatial distribution of farmlands, the stocking rates and technologies are evolving in response to economic drivers. There are forecasted increases in the national cattle numbers by 2026 [20, 25]; however, these increases are expected to be focused outside of the GDR and so were not included in this study.

Diffuse urban phosphorus loads originate from a variety of sources including atmospheric deposition, runoff from roads, roofs, construction sites and gardens. The heterogeneity of the urban environment makes the identification of export coefficients more difficult compared with other land cover types [81, 82]. Several sources may not be captured by this modelling approach, including localised practices and incidental spills. For example, a review of sewer misconnections by Ellis and Butler [28] found typical rates of misconnection in the UK and Ireland ranging from 1 to 6%. Hence, sewer misconnections are a potential source of nutrient losses from urban areas not explicitly modelled in the scenarios.

For municipal wastewater treatment plants, the additional wastewater generated by the population scenarios was assumed to be treated at the current efficiency rate. This assumption does not consider the treatment capacity of each plant, or possible future operational changes that may impact the treatment efficiency rate.

3.4 Implications for Water Quality Management

Population increases and associated municipal wastewater will be the main driver of water quality change in this region. The highest increases of emissions from point sources are predicted in the Nanny-Devlin, north of Dublin city. The national water utility, Irish Water, is currently investing in wastewater projects in this catchment that will increase the capacity within the wastewater network and will cater for future development of the area and growth in population whilst reducing the number of combined sewer overflows. The scenario results presented here highlight the importance of investment in this area to provide sustainable infrastructure in the coming decades.

The magnitude and distribution of investment in urban wastewater collection and treatment will have the greatest

Table 4 Baseline phosphorus (P t year⁻¹) and nitrogen (N t year⁻¹) emissions and percentage change from point and diffuse sources for four development scenarios by catchments (values displayed are rounded)

	P			N		
	Diffuse	Point	Total	Diffuse	Point	Total
Study area						
2014 baseline (t year ⁻¹)	122	673	795	3374	3753	7127
2026 BU	26%	17%	18%	1%	15%	9%
2026 FE	32%	23%	24%	2%	21%	12%
2026 CKT	33%	23%	25%	2%	21%	12%
2026 MD	31%	21%	23%	2%	20%	11%
Nanny-Devlin (8)						
2014 baseline (t year ⁻¹)	20	37	57	658	166	824
2026 BU	32%	160%	114%	-1%	183%	36%
2026 FE	25%	143%	101%	-2%	165%	32%
2026 CKT	21%	102%	73%	-3%	117%	21%
2026 MD	26%	136%	97%	-2%	156%	30%
Liffey and Dublin Bay (9)						
2014 baseline (t year ⁻¹)	66	562	628	1287	2931	4218
2026 BU	28%	5%	8%	1%	5%	4%
2026 FE	40%	12%	15%	4%	12%	10%
2026 CKT	41%	15%	17%	4%	15%	11%
2026 MD	36%	10%	13%	3%	10%	8%
Avoca-Vartry (10)						
2014 Baseline (t year ⁻¹)	36	73	109	1429	656	2085
2026 BU	20%	30%	27%	1%	17%	6%
2026 FE	23%	44%	37%	2%	25%	9%
2026 CKT	25%	48%	40%	2%	28%	10%
2026 MD	25%	50%	42%	2%	29%	11%

impact on changes in future nutrient emissions to water. Overall, the differences in results between the development scenarios were small, even though the location of specific land uses, population and jobs varied broadly across scenarios. Ideally, urban planning and investment in urban wastewater treatment should be coordinated to target the agglomerations with the greatest projected shortfall in treatment capacity.

Aggregated to the catchment scale, the reduction in the point sources of nutrients is expected to offset the increases in population and diffuse sources in the Liffey and Dublin Bay catchment. However, there is a spatial mismatch as the point sources are mainly at the catchment outlet and the increases in diffuse sources will impact on water quality in the upstream rivers and tributaries in the catchments, prior to their reaching the outlet. The increased inclusion of Sustainable Drainage Systems (SuDS) in urban developments is recommended to offset some of these projected increases. O'Sullivan et al. [57] reported that perceived barriers limiting the use of SuDS include uncertainty around ownership and maintenance and that although incorporating sustainability principles in stormwater management will require efforts at policy, design and management stages, there are clear opportunities to increase SuDS in Ireland.

4 Conclusions

Coupling the MOLAND and SLAM models helps to better represent complex interactions observed empirically between land use and water quality in the Dublin region. An increase in nutrient emissions was shown across all scenarios for nitrogen (9–12%) and phosphorus (18–25%). However, as these results assume that wastewater treatment efficiencies remain static, this study highlights that the magnitude and distribution of investment in urban wastewater collection and treatment will have a greater impact on future nutrient concentrations in water compared with changes in other nutrient sources in this urban region. In addition, increased diffuse sources of nutrients from urban land may be counterbalanced by removal of agricultural from these areas and an increased uptake of SuDS.

This research was initiated to identify the impact of land use on water quality at river catchment scale for policy and planning purposes, with consideration of varying socio-economic indicators. It demonstrated that the loose one-way coupling of a land use model and a nutrient emission model can improve understanding of the effects of urbanisation on water quality and assist in the strategic planning of infrastructure investment. Integrated application of land use and nutrient

emission models can assess urban planning scenarios in the context of future changes and possible mitigation measures, by supporting decision-making both in the urban planning and water management domains.

From a policy perspective, the relevance of research in this area has increased in recent years in Ireland, as a sustained period of economic recovery from 2014 to 2018 has seen a substantial growth in both employment and population for this region. A new National Planning Framework [24] and supporting capital expenditure programmes specifically adopt regional policy approaches in solving critical local infrastructure deficits including in water supplies. There will always be a certain level of uncertainty around the effectiveness of new policies, particularly in the context of a changing climate, economic developments and population increases. Integrated scenario modelling can be used as a tool to inform policy and support the selection of measures based on the best available information.

Funding Information The authors received 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. This work was supported by Marie Curie International Outgoing Fellowship (GeoSInPo) within the 7th European Community Framework Programme, by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 713567, and in part by a research grant from Science Foundation Ireland (SFI) which is co-funded under the European Regional Development Fund under grant number 13/RC/2077.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Archbold, M., Deakin, J., Bruen, M., Desta, M., Flynn, R., Kelly-Quinn, M., Gill, L., Maher, P., Misstear, B., Mockler, E., O'Brien, R., Orr, A., Packham, I., & Thompson, J. (2016). Contaminant movement and attenuation along pathways from the land surface to aquatic receptors (pathways project). Synthesis report 2007-WQ-CD-1-S1 STRIVE report 165. Environmental Protection Agency (Ireland).
2. Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., Van Griensven, A., Van Liew, M. W., Kannan, N., & Jha, M. K. (2012). SWAT: model use, calibration, and validation. *Transactions of the ASABE*, 55, 1491–1508.
3. Barredo, J., & Demicheli, L. (2003). Urban sustainability in developing countries' megacities: modelling and predicting future urban growth in Lagos. *Cities*, 20, 297–310.
4. Barredo, J. I., Demicheli, L., Lavalle, C., Kasanko, M., & McCormick, N. (2004). Modelling future urban scenarios in developing countries: an application case study in Lagos, Nigeria. *Environment and Planning B-Planning & Design*, 31, 65–84.
5. Basnyat, P., Teeter, L. D., Lockaby, B. G., & Flynn, K. M. (2000). The use of remote sensing and GIS in watershed level analyses of non-point source pollution problems. *Forest Ecology and Management*, 128, 65–73.
6. Bouraoui, F., & Grizzetti, B. (2014). Modelling mitigation options to reduce diffuse nitrogen water pollution from agriculture. *Science of the Total Environment*, 468–469, 1267–1277.
7. Brandmeyer, J. E., & Karimi, H. A. (2000). Coupling methodologies for environmental models. *Environmental Modelling & Software*, 15, 479–488.
8. Brazier, R. E., Heathwaite, A. L., & Liu, S. (2005). Scaling issues relating to phosphorus transfer from land to water in agricultural catchments. *Journal of Hydrology*, 301, 330–342.
9. Brennan, M., Shahumyan, H., Walsh, C., Carty, J., Williams, B., & Convery, S. (2009). Regional planning guideline review: using MOLAND as part of the strategic environmental assessment process. UCD Urban Institute Ireland Working Paper Series.
10. Carpenter, S. R. (2008). Phosphorus control is critical to mitigating eutrophication. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 11039–11040.
11. Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge*, 4(4).
12. Clarke, K. C., & Gaydos, L. J. (1998). Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographical Information Science*, 12, 699–714.
13. Clarke, K. C., Hoppen, S., & Gaydos, L. (1997). A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. *Environment and Planning B Planning and Design*, 247–261.
14. CSO. (2008). *Population and labour force projections 2011–2041*. Dublin: Central Statistics Office (CSO).
15. CSO. (2011). *Census 2011, principal demographic results*. Dublin: Government of Ireland, Stationary Office.
16. CSO. (2013). *Regional Population Projections 2016–2031. CSO statistical release* [Online]. Available: http://www.cso.ie/en/releasesandpublications/er/rpp/regionalpopulationprojections2016-2031/#.UwTe4v1_tc8.
17. CSO. (2017). *Census of Social, Economic and Housing Data 2006–2016*. In OFFICE, C. S. (ed.). Dublin: Stationery Office.
18. D&MERA. (1999). *Strategic planning guidelines for the greater Dublin area*. The Regional Planning Guidelines Office: Dublin & Mid-East Regional Authorities.
19. D&MERA. (2010). *Regional planning guidelines for the greater Dublin area*. The Regional Planning Guidelines Office: Dublin & Mid-East Regional Authorities.
20. DAFM. (2015). *Food Wise 2025. A 10-year vision for the Irish Agri-food industry*. Department of Agriculture, Food and the Marine.
21. Demicheli, L., Lavalle, C., Kasanko, M., Barredo, J. I., McCormick, N., & Sagris, V. (2003). *Creation of territorial and environmental data sets for the county of Harjumaa (Estonia) and the corridor Tallin-Parnuu*. EC Joint Research Centre: Institute for Environment and Sustainability.
22. Devantier, B. A., & Feldman, A. D. (1993). Review of Gis applications in hydrologic modeling. *Journal of Water Resources Planning and Management-Asce*, 119, 246–261.
23. DHPLG. (2018a). *River basin management plan for Ireland 2018–2021*. Department of Housing, Planning and Local Government.

24. DHPLG. (2018b). Project Ireland 2040. National Planning Framework. In DEPARTMENT OF HOUSING, P. A. L. G. (ed.).
25. Donnellan, T., Hanrahan, K., & Breen, J. P. (2014). Development and application of economic and environmental models of greenhouse gas emissions from agriculture: some difficult choices for policy makers. In C. Zopounidis, N. Kalogeras, K. Mattas, G. Van Dijk, & G. Baourakis (Eds.), *Agricultural cooperative management and policy: new robust, reliable and coherent modelling tools*. Cham: Springer International Publishing.
26. Droppo, J. G., Whelan, G., Tryby, M. E., Pelton, M. A., Taira, R. Y., & Dorow, K. E. Methods to register models and input/output parameters for integrated modeling. International Congress on Environmental Modelling and Software, 2010 Ottawa, Canada. 2010 International Environmental Modelling and Software Society (iEMSs).
27. Elliott, A. H., Semadeni-Davies, A. F., Shankar, U., Zeldis, J. R., Wheeler, D. M., Plew, D. R., Rys, G. J., & Harris, S. R. (2016). A national-scale GIS-based system for modelling impacts of land use on water quality. *Environmental Modelling & Software*, 86, 131–144.
28. Ellis, J. B., & Butler, D. (2015). Surface water sewer misconnections in England and Wales: pollution sources and impacts. *Science of the Total Environment*, 526, 98–109.
29. Engelen, G., White, R., & Uljee, I. (2004). The MOLAND model for urban and regional growth. RIKS bv: Research Institute for Knowledge Systems.
30. Engelen, G., Lavalley, C., Barredo, J. I., Van Der Meulen, M., & White, R. (2007). The MOLAND modelling framework for urban and regional land-use dynamics. *Modelling Land-Use Change: Progress and Applications*, 90, 297–319.
31. EPA. (2012). CORINE Landcover 2012 Dataset. In AGENCY, I. E. P. (ed.).
32. EU. (1991). Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.
33. EU. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.
34. Ghane, E., Ranaivoson, A. Z., Feyereisen, G. W., Rosen, C. J., & Moncrief, J. F. (2016). Comparison of contaminant transport in agricultural drainage water and urban stormwater runoff. *PLoS ONE*, 11.
35. Gill, L. W., & Mockler, E. M. (2016). Modeling the pathways and attenuation of nutrients from domestic wastewater treatment systems at a catchment scale. *Environmental Modelling & Software*, 84, 363–377.
36. Giri, S., & Qiu, Z. Y. (2016). Understanding the relationship of land uses and water quality in twenty first century: a review. *Journal of Environmental Management*, 173, 41–48.
37. Gregersen, J. B., Gijbsbers, P. J. A., & Westen, S. J. P. (2007). OpenMI: Open modelling interface. *Journal of Hydroinformatics*, 9, 175–191.
38. Hagen-Zanker, A., Engelen, G., Hurkens, J., Vanhout, R., & Uljee, I. (2006). *Map comparison kit user manual*. Maastricht: Research Institute for Knowledge Systems (RIKS bv).
39. Hill, C., DeLuca, C., Balaji, Suarez, M., & Da Silva, A. (2004). The architecture of the earth system modeling framework. *Computing in Science & Engineering*, 6, 18–28.
40. Hurkens, J., Hahn, B., & Van Delden, H. (2008). Using the GEONAMICA® software environment for integrated dynamic spatial modelling. In M. Sánchez-Marrè, J. Béjar, J. Comas, A. Rizzoli, & G. Guariso (eds.), *iEMSs 2008: International Congress on Environmental Modelling and Software*. International Environmental Modelling and Software Society (iEMSs).
41. Johanson, R., Imhoff, J., Kittle Jr., J., & Donigan, J. A. (2004). *Hydrological simulation program-fortran (HSPF): Users manual for release 8.0*. Washington, D.C.: U.S. Environmental Protection Agency.
42. Jordan, C., & Smith, R. V. (2005). Methods to predict the agricultural contribution to catchment nitrate loads: designation of nitrate vulnerable zones in Northern Ireland. *Journal of Hydrology*, 304, 316–329.
43. Karlsson, I. B., Sonnenborg, T. O., Refsgaard, J. C., Trolle, D., Borgesen, C. D., Olesen, J. E., Jeppesen, E., & Jensen, K. H. (2016). Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change. *Journal of Hydrology*, 535, 301–317.
44. Kelly-Quinn, M., Blacklocke, S., Bruen, M., Earle, R., O'Neill, E., O'Sullivan, J., & Purcell, P. (2014). Dublin Ireland: a city addressing challenging water supply, management, and governance issues. *Ecology and Society*, 19.
45. Kennen, J. G., Riva-Murray, K., & Beaulieu, K. M. (2010). Determining hydrologic factors that influence stream macroinvertebrate assemblages in the northeastern US. *Ecohydrology*, 3, 88–106.
46. Lydon, K., & Smith, G. (2014). CORINE Landcover 2012 Ireland Final Report. Environmental Protection Agency (Ireland). http://www.epa.ie/pubs/data/corinedata/CLC2012_IE_Final_Report.pdf Accessed 19 March 2020.
47. McColl, C., & Aggett, G. (2007). Land-use forecasting and hydrologic model integration for improved land-use decision support. *Journal of Environmental Management*, 84, 494–512.
48. McCormick, N., Lavalley, C., & Barredo, J. An example of the application of spatial dynamics modeling for evaluating the future impact of land use development decisions. 4th Seminar of the PlanNet Europe Network on Strategic Environmental Assessment (SEA) of Urban Plans and Programs, 2005 Brussels. Ministry of the Brussels, pp. 47–55.
49. McGonigle, D. F., Harris, R. C., McCamphill, C., Kirk, S., Dils, R., Macdonald, J., & Bailey, S. (2012). Towards a more strategic approach to research to support catchment-based policy approaches to mitigate agricultural water pollution: A UK case-study. *Environmental Science & Policy*, 24, 4–14.
50. Mockler, E. M., Deakin, J., Archbold, M., Gill, L., Daly, D., & Bruen, M. (2017). Sources of nitrogen and phosphorus emissions to Irish rivers and coastal waters: estimates from a nutrient load apportionment framework. *Science of the Total Environment*, 601–602, 326–339.
51. Monier, E., Kicklighter, D., Ejaz, Q., Winchester, N., Paltsev, S., & Reilly, J. (2016). Integrated modeling of land-use change: the role of coupling, Interactions and Feedbacks between the Human and Earth Systems. AGU Fall Meeting Abstracts.
52. Narasimhan, B., Allen, P., Coffman, S., Arnold, J., & Srinivasan, R. (2017). Development and testing of a physically based model of streambank erosion for coupling with a basin-scale hydrologic model SWAT. *JAWRA Journal of the American Water Resources Association*, 53, 344–364.
53. Ni Longphuir, S., Mockler, E., O'Boyle, S., Wynne, C., & Stengel, D. B. (2016). Linking changes in nutrient load source apportionment to estuarine responses: an Irish perspective. *Biology and Environment*, 116B, 295–311.
54. NSS. (2002). National spatial strategy for Ireland 2002–2020 : People, Places and Potential. In GOVERNMENT, D. O. T. E. A. L. (ed.). Dublin: Stationery Office.
55. O'Boyle, S., Wilkes, R., Mcdermott, G., Ni Longphuir, S., & Murray, C. (2015). Factors affecting the accumulation of phytoplankton biomass in Irish estuaries and nearshore coastal waters: a conceptual model. *Estuarine, Coastal and Shelf Science*, 155, 75–88.
56. O'Boyle, S., Trodd, W., Bradley, C., Tierney, D., Wilkes, R., Longphuir, S. N., Smith, J., Stephens, A., Barry, J., Maher, P., McGinn, R., Mockler, E., Deakin, J., Craig, M., & Gurrie, M. (2019). *Water quality in Ireland 2013–2018*. Environmental Protection Agency.

57. O'Sullivan, J. J., Bruen, M., Purcell, P. J., & Gebre, F. (2012). Urban drainage in Ireland - embracing sustainable systems. *Water and Environment Journal*, *26*, 241–251.
58. Overeem, I., Berlin, M. M., & Syvitski, J. P. M. (2013). Strategies for integrated modeling: the community surface dynamics modeling system example. *Environmental Modelling & Software*, *39*, 314–321.
59. Packham, I., Mockler, E., Archbold, M., Mannix, A., Daly, D., Deakin, J., & Bruen, M. (2019). Catchment characterisation tool: prioritising critical source areas for managing diffuse nitrate pollution. *Environmental Modeling and Assessment*.
60. Petrov, L. O., Lavallo, C., & Kasanko, M. (2009). Urban land use scenarios for a tourist region in Europe: applying the MOLAND model to Algarve, Portugal. *Landscape and Urban Planning*, *92*, 10–23.
61. Petrov, L., Shahumyan, H., Williams, B., & Convery, S. (2011). Scenarios and indicators supporting urban regional planning. *Procedia - Social and Behavioral Sciences*, *21*, 243–252.
62. Rahman, J. M., Cuddy, S. M., & Watson, F. G. R. (2004). Tarsier and ICMS: two approaches to framework development. *Mathematics and Computers in Simulation*, *64*, 339–350.
63. Rhodes, A. L., Newton, R. M., & Pufall, A. (2001). Influences of land use on water quality of a diverse New England watershed. *Environmental Science & Technology*, *35*, 3640–3645.
64. Rógenes, P., Pontes, M., Mainardi Fan, F., Santos Fleischmann, A., Cauduro Dias de Paiva, R., Costa Buarque, D., Alencar Siqueira, V., Frediani Jardim, P., Viana Sorribas, M., & Collischonn, W. (2017). MGB-IPH model for hydrological and hydraulic simulation of large floodplain river systems coupled with open source GIS. *Environmental Modelling & Software*, *94*, 1–20.
65. Schmitz, O., Karssenber, D., van Deursen, W. P. A., & Wesseling, C. G. (2009). Linking external components to a spatio-temporal modelling framework: coupling MODFLOW and PCRaster. *Environmental Modelling & Software*, *24*, 1088–1099.
66. Shah, A. R., Castleton, K. J., & Hoopes, B. L. (2004). Framework for risk analysis in multimedia environmental systems: modeling individual steps of a risk analysis process. *Msv'04 & Amcs'04, Proceedings*, 38–44.
67. Shahumyan, H., & Moeckel, R. (2015). *Integrating models for complex planning policy analysis: challenges and a solution in coupling dissimilar models. Proceedings of the 14th Conference on Computers in Urban Planning and Urban Management (CUPUM), 7–10 July 2015*. Cambridge: MIT.
68. Shahumyan, H., & Moeckel, R. (2016). Integration of land use, land cover, transportation, and environmental impact models: expanding scenario analysis with multiple modules. *Environment and Planning B: Planning and Design*.
69. Shahumyan, H., White, R., Twumasi, B., Convery, S., Williams, B., Critchley, M., Carty, J., Walsh, C., & M., B. (2009). The MOLAND model calibration and validation for the Greater Dublin Region. UCD Urban Institute Ireland Working Paper Series.
70. Shahumyan, H., White, R., Petrov, L., Williams, B., Convery, S., & Brennan, M. (2011). Urban development scenarios and probability mapping for Greater Dublin Region: the MOLAND model applications. *Lecture Notes in Computer Science (LNCS)*, *6782*, 119–134.
71. Shahumyan, H., Williams, B., Petrov, L., & Foley, W. (2014). Regional development scenario evaluation through land use modeling and opportunity mapping. *Land*, *3*, 1180–1213.
72. Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*, 126–139.
73. Smith, R. V., Jordan, C., & Annett, J. A. (2005). A phosphorus budget for Northern Ireland: inputs to inland and coastal waters. *Journal of Hydrology*, *304*, 193–202.
74. Van de Voorde, T., van der Kwast, J., Poelmans, L., Canters, F., Binard, M., Cornet, Y., Engelen, G., Uljee, I., Shahumyan, H., Williams, B., Convery, S., & Lavallo, C. (2016). Projecting alternative urban growth patterns: The development and application of a remote sensing assisted calibration framework for the Greater Dublin Area. *Ecological Indicators*, *60*, 1056–1069.
75. van Vliet, J., Bregt, A. K., Brown, D. G., VAN Delden, H., Heckbert, S., & Verburg, P. H. (2016). A review of current calibration and validation practices in land-change modeling. *Environmental Modelling & Software*, 174–182.
76. Verburg, P., & Overmars, K. (2009). Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecology*, *24*, 1167–1181.
77. Verburg, P. H., Schot, P., Dijst, M., & Veldkamp, A. (2004). Land-use change modeling: current practice and research priorities. *GeoJournal*, *61*, 309–324.
78. Wagner, P. D., Bhallamudi, S. M., Narasimhan, B., Kumar, S., Fohrer, N., & Fiener, P. (2019). Comparing the effects of dynamic versus static representations of land use change in hydrologic impact assessments. *Environmental Modelling & Software*, *122*, 103987.
79. Warner, J. C., Perlin, N., & Skyllingstad, E. D. (2008). Using the model coupling toolkit to couple earth system models. *Environmental Modelling & Software*, *23*, 1240–1249.
80. White, R., & Engelen, G. (1997). Cellular automata as the basis of integrated dynamic regional modelling. *Environment and Planning B-Planning & Design*, *24*, 235–246.
81. White, P. J., & Hammond, J. P. (2006). Updating the estimate of the sources of phosphorus in UK waters. Defra funded project WT0701CSF.
82. White, P. J., & Hammond, J. P. (2009). The sources of phosphorus in the waters of Great Britain. *Journal of Environmental Quality*, *38*.
83. Wijesekara, G. N., Gupta, A., Valeo, C., Hasbani, J. G., Qiao, Y., Delaney, P., & Marceau, D. J. (2011). Assessing the impact of future land-use changes on hydrological processes in the Elbow river watershed in southern Alberta, Canada. *Journal of Hydrology*.
84. Williams, B., & Nedovic-Budic, Z. (2016). The real estate bubble in Ireland. Policy context and responses. *Urban Research and Practice*, *9*, 204–218.
85. Williams, B., Shahumyan, H., Boyle, I., Convery, S., & White, R. (2012). Utilizing an urban-regional model (MOLAND) for testing the planning and provision of wastewater treatment capacity in the Dublin Region 2006–2026. *Planning Practice and Research*, *27*, 227–248.
86. Willuweit, L., O'Sullivan, J. J., & Shahumyan, H. (2015). Simulating the effects of climate change, economic and urban planning scenarios on urban runoff patterns of a metropolitan region. *Urban Water Journal*, 1–16. <https://doi.org/10.1080/1573062X.2015.1036086>.
87. Wong, I., Lam, D., Booty, W., & Fong, P. (2009). *A loosely-coupled collaborative integrated environmental Modelling framework. Americas Conference on Information Systems*. AIS Electronic Library.
88. Yalaw, S. G., Pilz, V., Schweitzer, C., Liersch, S., van der Kwast, J., van Griensven, A., Mul, M. L., Dickens, C., & van der Zaag, P. (2018). Coupling land-use change and hydrologic models for quantification of catchment ecosystem services. *Environmental Modelling & Software*, *109*, 315–328.
89. Young, R. A., Onstad, C. A., Bosch, D. D., & Anderson, W. P. (1989). AGNPS: a non-point-source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation*, *44*.
90. Zhang, P., Liu, Y., Pan, Y., & Yu, Z. (2013). Land use pattern optimization based on CLUE-S and SWAT models for agricultural non-point source pollution control. *Mathematical and Computer Modelling*, *58*, 588–595.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Reproduced with permission of copyright owner. Further reproduction prohibited without permission.