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Geographic Information System-based tools in environmental management

Zeinab Bedri
Technological University Dublin, zeinab.bedri@tudublin.ie

Michael Bruen
University College Dublin, michael.bruen@ucd.ie

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Geographic Information System-based tools in environmental management

ZEINAB BEDRI AND MICHAEL BRUEN*

UCD Dooge Centre for Water Resources Research, School of Civil, Structural and Environmental Engineering, University College Dublin, Newstead Building, Belfield, Dublin 4, Ireland

The authors reviewed existing modelling platforms as part of a large study of water and pollution pathways through catchments in Ireland (Irish EPA Pathways project). Worldwide, work on producing catchment management tools (CMTs) has been underway for some time and some of the tools identified here date from as early as 1989. Some of the management problems and model conceptualisations have not changed very much but now there is a stronger emphasis on water quality and more concern about a wider range of contaminants. What has changed substantially is the use of Geographical Information System and Graphical Windows interfaces as technologies supporting a wider practical use of these tools. This review of existing CMTs identified three systems which would be candidates if a CMT had to be deployed immediately in Ireland. All have a rigid catchment model structure and lack the flexibility to include any new scientific information or flow-path conceptualisation that may emerge. The same modelling structure is used for all parts of the catchment, with spatial variation represented by parameter variation only and not variation in model structure. They also have rigid graphical user interfaces which cannot be tailored to match any specific requirements that may emerge from the pathways end-user workshops. Thus a CMT with a more flexible and accessible modelling structure is required if the results of current research are to be incorporated.

Keywords: GIS; Environmental management; Hydrological pathways

1. Introduction

A catchment management tool (CMT) is a computer programme used to design or select appropriate options for managing water at catchment scale. Some tools may focus on water resources management, mainly relating to water quantities and distribution and others may be concerned also with the management of water quality. Because spatial variation is important in catchment information and behaviour, most CMTs require spatial information and thus are associated with a Geographical Information System (GIS); and because of the complexity of catchment behaviour, most CMTs require the use of a catchment model. There are dozens of such models, covering a wide range of scales and processes. The choice must be determined by the range of issues and contaminants to be addressed by the CMT and by the spatial and temporal scales at which detailed information is required by the decision-maker. An inappropriate choice can invalidate the output from the CMT.

Ideally, the choice of catchment modelling approach determines the data requirements. Data may be spatially distributed (e.g. maps) or may change with time (time-series) and

*Corresponding author. Email: michael.bruen@ucd.i.e

both kinds must be managed within the framework of the CMT. Other forms of data include parameter sets, constraint sets and point information. All such data must be carefully managed and therefore a GIS program linked to a formal database system (DBS) is generally used. The use of existing GIS and DBS systems may have the disadvantage of constraining flexibility in the design of the CMT, but has the distinct advantage of proven technology with easier communication in standard data formats with outside data sources.

This paper reviews the state of the art in relation to practical CMTs for managing water quality with the objective to assist water quality managers in making informed decisions in a practical context and it concentrates on (i) CMTs that address water quality management issues and (ii) CMTs for use by scientifically or technically trained people responsible for the design, implementation or management of measures for addressing the quality of natural waters.

2. GIS support and links

Geographic Information Systems are indispensable for hydrological modelling and nutrient management in agricultural catchments because they use the capabilities of modern, high-speed computers to store, manipulate and display large amounts of environmental data in a spatial format. A range of reliable GIS tools are widely available nowadays. Some are free e.g. QGIS, GRASS, PCRaster, MapGuide, Mapwindow and OpenMap, while others are propriety/commercial packages and must be purchased or licensed, e.g. ArcGIS (ArcView and ArcInfo) and MapInfo. Hydrological (catchment) modelling tools are frequently linked with GIS systems. There are four ways to link GIS with catchment models [1].

(1) Isolated coupling, in which the hydrological modelling and GIS systems reside on different hardware platforms, and data transfer is offline. This method is rarely used although isolated systems are the easiest to set up and require the least level of programming knowledge and experience. On the other hand, they are generally the least useful, because of the need to transfer data offline. An example of such a model is WATFLOOD/SPL9 [2–4].

(2) Loose coupling, with online data transfer between software components through data files using special linking programs, or through a common data store. Loose coupling uses the GIS as an aid in developing the input data files for the model. These preliminary input files can be modified in order to produce complete input files in the format required by the model. Thus, both the model and the GIS system can be used without any modification [5]. An example of such a type is TOPMODEL [6].

(3) Tight coupling, with the two systems communicating interactively with each other. A special interfacing program communicates between the GIS and the hydrological model, and serves as a control program issuing commands both to the GIS and the model. Output from the GIS is converted into the proper input format for the model and then read into the model. Output from the model may likewise be converted to a GIS format and then displayed by the GIS. All these operations are controlled by the interface program [5] and, typically, all user interactions are through the GIS interface. Examples are ANSWERS and AGNPS.

(4) Full integration, which does not require a linking program, but the GIS and models share a common data store and user-interface which come up as one software

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product. Typically, with this method, the hydrological model is coded within the built-in programming or macro-language of the GIS and has direct access to the facilities and functions of the GIS. In a fully integrated system, the model is embedded as a component in the host GIS application [7] and therefore modelling is managed entirely within the GIS. Examples of fully integrated catchment models are SWAT, AVGWLF and HSPF (MAPWINDOWS).

The degree of relationship between a model and a GIS has an impact on the reliability and ease of use of the system. Well-integrated systems work as a coherent whole, allowing the experienced user some access to intermediate results and the ability to use his or her own measurements or model outputs where the tool requires inputs, and still afford flexibility for modifying the modelling scenario [7].

3. Most commonly encountered catchment management systems

A literature search for commonly encountered catchment management systems yielded 14 systems for the current review (table 1). Most of these operate on Windows-based PCs, except NELUP which runs on a UNIX operating system. These systems are evaluated and compared in terms of their flexibility, modelling and operating capabilities, and their demand on input and output data:

3.1. Flow modelling capabilities

All reviewed catchment systems have the ability to simulate flow in catchments using hydrological models except for two systems, CMSS and Realta. CMSS is intended to provide a 'first-cut' analysis of the major contributors of sediment or nutrients from a catchment as a result of changes in land-use and/or land-management practices [8]. Its

Table 1. Reviewed catchment modelling systems.

System	Developer
BASINS	US EPA
MIKEBasin	Danish Hydraulic Institute (DHI)
WMS	Aquaveo (http://www.aquaveo.com/wms)
MONERIS	Institute of Freshwater Ecology and Inland Fisheries, Leibniz, Germany
NELUP	The Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, UK under the NERC-ESRC Land-Use Programme
NLCAT	Integrated water and catchment management, Alterra, Wageningen UR, Netherlands
TRK	Swedish Environmental Research Institute and SMHI, Sweden
TCM-Manager	Martens and Associates Pty Ltd., Australia
WAMADSS	Centre for Agricultural, Resource and Environmental Systems (CARES) at University of Missouri-Columbia, USA
CMSS	CSIRO Land and Water, Canberra
SOBEK	Deltares and Delft Hydraulics
Realta	Kirk McClure Morton, Belfast, Northern Ireland
EveNFlow	Agricultual and environmental consultancy ADAS, UK
WEAP	US branch of the Stockholm Environment Institute, Boston, Massachusetts, USA

main limitation is that it is restricted to long-term average behaviour, because it does not consider hydrology or any time-variant components. Realta identifies potential agricultural risk areas at a River Basin District level and quantifies phosphorous export rates from the River Basin District and its sub-catchments. It does not use dynamic rainfall–runoff catchment modelling and does not include in-stream and/or lake retention of pollutants.

Some of the reviewed catchment systems offer a large range of hydrological models (table 2) of varying complexity (e.g. empirical, semi-empirical or physically based). WMS offers the largest number of models (around 15 hydrological and hydraulic models) while some others offer two to three models (e.g. BASINS, MIKEBASIN, NELUP and TRK).

3.2. Water quality modelling capabilities

With the exception of WMS, all reviewed systems include a water quality component. The minimum water quality variables included in these systems are nitrogen and phosphorus (e.g. MONERIS, NELUP, NL-CAT, TRK, REALTA and CMSS). A few models have the capacity to simulate a wider suite of water quality variables. BASINS can simulate pesticides and bacteria, while MIKEBASIN offers bacteria, oxygen, BOD among others. AQ3 SOBEK allows for the simulation of a wide range of water quality variables including bacteria, algae, silica and heavy metals.

Despite the significant role of sediments in the transport of nutrients (Nitrogen and Phosphorus) as highlighted by a large number of studies [9,10], not many of the reviewed systems include sediment transport in their processes.

3.3. Required data

Table 3 shows that the minimum information required by most systems reviewed here is data on the topography, river network, land cover, soils, in addition to information about the pollutant loads. Somewhat surprisingly, independent groundwater data (e.g. water levels and contaminant concentrations) are rarely used. Of the systems reviewed here, BASINS, MIKEBASIN and SOBEK are the most demanding; and CMSS is the system that appears to require the least amount of data.

3.4. Management options

The systems were also compared in terms of their suitability for assessing impacts of (i) land-use changes, (ii) nutrient management options and (iii) water protection measures as a tool to enable catchment managers and planners to examine the impact of land-use changes and management options on the water quality in catchments. Only eight of the reviewed systems (BASINS, MIKEBASIN, NELUP, NL-CAT, TRK, SOBEK, EveNFlow and WEAP) have the ability to assess all three environmental measures. MONERIS, TCM-Manager and CMSS are suitable for assessing land-use changes and management options, but not all changes to water measures.

3.5. GIS support

Most of the reviewed catchment management systems employ GIS as a tool for data handling and visualisation (table 2). The mostly used GIS software in these systems is

Table 2. Modelling and operational details of the reviewed CMTs.

System	BASINS	MIKEBasin	WMS	MONERIS	NELUP	NLCAT	TRK	TCM-Manager	WAMADSS	CMSS	SOBEK	Realta	EveNFlow	WEAP
Flow	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Water quality	N, P, B, Pest	N, P, B, user	No	N, P	N, P	N, P	N, P	N, P, SS	N, P	N, P	N, P, B, Si, Alg., H.M., BOD, O2	P	N	Instream WQ only
Models included	SWAT, HSPF, QUAL2E	MIKESHE, EUROSEM	HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, OC Rational, HSPF, XPSWMM, SWMM	MONERIS	SHETRAN, ARNO	SWQN, AMINO, NUSWALITE, SWAP	SOILNDB, HBV, HBV-N, TRK-P	STORM, ANNUAL	AGNPS, SWAT, CARE	No model	SOBEK-Rural, SOBEK-Urban, SOBEK-River	No model	Soil nitrate model, soil drainage model, drainage routing model	WEAP, QUAL2K, MODFLOW
Model type	Semi-empirical, physically-based	Physically-based	Empirical and semi-empirical	Physically based	Conceptual, physically-based	Physically-based	Empirical	Empirical	Semi-empirical, physically-based	–	Semi-empirical, physically-based	P export rates	–	Semi-empirical, physically-based
Visualisation tool	ArcGIS	ArcGIS	ArcGIS	ArcGIS	Grass	GIS	Own GUI, Outputs to GIS	GIS, own GUI	Own GUI	Own GUI	Open GIS, NETTER	–	No GUI	GIS
Min. spatial scale	F	F	C	10 km^2	0.01 km^2	F	F	Lumped	F	F	Grid resolution 1–50 m	10–15 km^2	1 km^2	C
Min. timestep	Daily	Daily	Daily	–	Daily	Daily	Daily	Event-based, annual	Daily	Annual	Minutes	Annual	Daily	Daily

Notes: N: nitrogen, P: phosphorus, B: bacteria, Pest: pesticides, H.M.: heavy metals, Alg: algae, F: field, C: catchment.

Table 3. Summary of CMT input data requirements.

System	BASINS	MIKEBASIN	WMS	MONERIS	NELUP	NL-CAT	TRK	WEAP	TCM-Manager	WAMADSS	CMSS	SOBEK	Realta	EveNFlow
Topography	R	R	R	N	R	R	R	R	R	R	R	R	R	R
River network	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Overall catchment information of fertiliser, manure, point sources	R	R	N	N	R	O	R	O	R	R	R	R	R	R
Land cover map	R	R	R	N	R	R	R	R	R	R	R	R	R	N
Land management information	R	R	N	N	R	R	R	N	R	R	O	R	N	R
Soil texture map	R	R	R	R	R	R	R	R	R	R	N	R	R	R
Soil hydrogeological map	O	O	N	R	O	N	N	N	R	O	N	R	R	N
Water management information	R	O	N	R	O	R	N	R	N	O	R	R	N	R
Administrative census information of fertiliser, manure, livestock, etc.	R	R	N	R	R	N	R	O	O	O	O	O	N	R
Point sources location map	R	R	O	R	N	R	R	R	R	R	O	R	R	R
Weather monitoring stations	R	R	R	R	R	R	R	R	R	R	N	R	N	R
Surface water monitoring map	R	R	O	R	R	N	R	R	O	R	N	R	R	R
Groundwater monitoring map	O	O	N	O	N	O	O	R	O	R	N	N	N	N

Notes: r: Required data, O: optional, N: not required.

ARCGIS (e.g. MIKEBASIN, WMS and MONERIS). Other GIS softwares used include the UNIX-based Grass GIS used in the NELUP system and Open GIS NETTER used in the SOBEK modelling system. A few of these systems have their own graphical interfaces e.g. CMSS and EveNFLOW. TCM-Manager has its own graphical interface but produces outputs that can be manipulated by standard GIS packages.

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4. Comparison and evaluation of existing CMTs

Table 2 summarises the capabilities of the CMTs reviewed here and lists some of their operating characteristics. Table 3 summarises their input data requirements. All except one (WMS) have some water quality modelling capabilities; but some are limited to sediment, N and P. Those that can simulate more contaminants than sediment, N and P are BASINS, MIKEBASIN and SOBEK. All three can simulate bacteria and other contaminants and could be candidates as a suitable CMT. All three come from organisations with extensive experience of hydraulic and water quality modelling; but each has some individual disadvantages;

(i) BASINS was developed for use in the USA and is written to interface easily with USA data sources. Nevertheless, it is possible to edit Irish data sources to comply with the input formats required by BASINS [11]. This procedure must be done individually for each catchment and might have to be redone each time a new version of BASINS is issued. Although this is not an ideal solution, an experienced GIS user could be trained to perform this step for a catchment manager. To integrate new pathways into the model would require modifying the FORTRAN source code. This procedure has been done in the UCD Dooge Centre for Water Resources Research for some of the models (e.g. SWAT and HSPF), but is difficult and requires a specialist hydrological modeller with computer programming experience.

(ii) MIKEBASIN is based on the MIKE SHE hydrological model. This is a distributed physically based model and is one of the most detailed and complex models available. Since it is a commercial model, the source code is not normally made available to users, who cannot easily incorporate additional pathways or modifications of existing pathways. Such improvements could be incorporated by the model developer in its upgrade cycle, but this would be subject to negotiation between model users and developer. Specific licences would be required for each user. The MIKE SHE approach (as implemented in SHETRAN) has been tested (and compared to two other hydrological models) in some Irish catchments for modelling phosphorus (EPA LS-2.2.2) and its performance was not the best of the models evaluated.

(iii) SOBEK is used in the Netherlands and concentrates more on the process within channels with less focus on modelling processes within the catchment.

Although any of these three models could contribute significantly to catchment management activities, all seem to require a high degree of expertise which militates against their widespread use in Ireland as a CMT. In addition, they focus mainly on surface water flows. Because of this, a CMT was desired that (1) is easier to use by catchment managers and (2) had an increased focus on sub-surface contaminant pathways, so that their influence could be studied in detail.

5. Conclusions

As part of the Irish EPA Pathways project, a literature review of commonly encountered catchment management systems was conducted. The search yielded 14 systems of varying complexity. These were compared in terms of their modelling capabilities, abilities to help decision-makers to examine the impact of land-use changes and management options on the water quality in catchments, and the use of GIS for data handling and visualisation.

Three systems were identified as potential candidates if a CMT had to be deployed immediately in Ireland, namely BASINS, MIKEBASIN and SOBEK. All three come from organisations with extensive experience of hydraulic and water quality modelling. But there are some common disadvantages. All are based on a fixed catchment model structure making it difficult to include any new flow-path or process conceptualisations that may emerge. The same modelling structure is used for all parts of the catchment, with spatial variation represented by parameter variation only and not variation in model structure. They also have fixed graphical user interfaces which cannot be tailored to match any specific implementation requirements that emerge from end-user workshops. Most are intended for use by a specialised modeller rather than by an interested end user. Thus a CMT with a more flexible and accessible modelling structure, particularly of sub-surface pathways, is required if a wider use by a variety of different end users is desired and if the results of current (or future) research are to be incorporated.

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