A DECISION SUPPORT TOOL FOR INTERNATIONAL DIFFUSE POLLUTION MANAGEMENT

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ABSTRACT

We present a framework for a decision support tool (DST), which can be applied globally to assess the sources and significance of diffuse pollution without the need for detailed monitoring or modelling on a local basis. The DST will be built around an empirical loading model and global data sets that provide information on demography, land use, climate and terrain. The loading model will be reliant on the use of coefficients that will be derived from the global data sets to ensure that the DST is transferable to any region in the world. The loading model and the global data sets will be structured into a tiered spatial system, in which the world's landmasses are mapped into a grid. The top tier estimates loads for grid squares that are hundreds of kilometres across, and uses broad land use categories and corresponding coefficients to calculate the loads. The loads from each grid may be summed to produce loads for entire countries, continents or regional areas defined by geographic, political or economic boundaries. In contrast, the lower tiers estimate diffuse pollutant loads for smaller grid squares (smaller blocks of land) and are therefore designed to operate at the smaller catchment scale, and in areas where relatively more data are available. In these lower tiers, pollutant loads for each grid square will be estimated by characterising the squares into more defined land use types and using narrowly defined or specific coefficients.

Keywords Diffuse pollution; decision support tool; empirical models; export coefficient; global data sets

INTRODUCTION

Recent statistics on the impacts of diffuse pollution highlight the continued severity of the problem and the continued need to identify and manage the polluting sources (see GESAMP, 2001). Partly as a result of transboundary effects, there is also a consensus that diffuse pollution problems need to be managed at a variety of spatial scales (Lawrence, 2002). Water quality has long been assessed through field monitoring, suggesting that sufficient data may now exist in some areas to form the basis of management decisions. However, it has been recognised that while these data exist, they invariably originate from small catchments or sub-catchments because of the large effort and high costs associated with the data collections. Moreover, the information or conclusions that may be formulated from these data sets are greatly influenced by the temporal and spatial scales in which they were collected. Not surprisingly, a large number of water quality models are now available and used by various regulatory authorities, agencies and research institutions to supplement water quality measurements (Table 1). Diffuse pollution is often managed with the aid of loading and receiving water models which provide estimates of diffuse pollution loads and simulate the movement of the pollutant in the waterway, respectively (Novotny, 2003). Loading models are particularly useful as they assist in identifying priorities, which is an essential first step in the hierarchy of actions involved in water quality management. Unfortunately, many loading models are still optimised to work at the relatively small catchment scale (Table 1), meaning that the models are unlikely to be suitable, or have not been demonstrated to be suitable, for management of transboundary ecosystems.

Here we present a framework for a loading model that will be built into a web-based decision support tool (DST) specifically designed to assist in the management of transboundary diffuse pollution problems (*e.g.* Rhine, Danube). The loading model operates in a similar manner to the export coefficient model (*e.g.* Johnes and O'Sullivan, 1989; Johnes, 1996), except that it relies on the use of coefficients derived from global data sets. The use of these 'global coefficients' ensures that loads may even be estimated for regions where extensive data sets do not exist or where few resources for data collection are available. Essentially, the DST will be able to produce pollutant load estimates on a global scale, and therefore would be extremely useful for addressing the objectives of organisations such as those of the Global Environment Facility (http://www.gefweb.org/) and the European Union (http://europa.eu.int/comm/environment/water/index.html).

DEVELOPMENT OF A GLOBAL DST FOR DIFFUSE POLLUTION

The framework for our global DST model was influenced by an extensive review of diffuse pollution modelling approaches. Similar to the recent reviews of this literature (*e.g.* Jenkins *et al*., 2000; Novotny, 2003), we found that diffuse pollutant loads are estimated or predicted using empirical or physical-mechanistic based models (Table 1). Empirical models predominantly rely on the use of coefficients that have been developed from statistical relationships between the pollutant input and output, whereas the physical-mechanistic models rely on parameters or variables that explain the key processes affecting the transport of the pollutant from the source to the waterway, and may additionally consider in-stream processes. Both types of models may be categorised into lumped models which treat the catchment as one homogenous unit, or distributed models which divide the catchment into smaller units sharing similar characteristics such as land use, topography and geology (*e.g*. Leon *et al*., 2002). Many empirical and physical-mechanistic models are optimised to work at small spatial scales and have been shown to be extremely useful for local catchment management (Table 1). The very few models that operate at larger spatial scales are based predominantly on the empirical modelling approach (*e.g.* Seitzinger and Kroeze, 1998; Caraco and Cole, 1999; Heathwaite *et al*, 2003; Table 1), presumably as a consequence of the low data requirements of the empirical models, and the ease with which the empirical models may be refined to estimate loads at various spatial scales (Johnes, 1996). While we are cautioned by the fact that the loads provided by the empirical models are only indicative, policy makers and managers often use these models as they are particularly amenable for developing frameworks with which to base research priorities, mitigation strategies or long-term scenario testing (Jenkins *et al*., 2000; Lepisto *et al*, 2001).

The choice of models is generally recognised as being dependent on the question(s) to be addressed in the study, the water body being studied, the type of pollutant sources, and/or the properties of the pollutants (Novotny, 2003). However, the choice of the model is ultimately constrained by the available data sets required to run the model (Jenkins *et al*., 2000). The basic modelling approach that we adopted for our DST was not only constrained by data availability but also by the necessity to ensure that the DST is globally applicable.

Table 1 Examples of models used for the management of diffuse pollution

	Small catchment models	Larger catchment or regional models	Global models	Examples
EMPIRICAL	export coefficient	export coefficient		Johnes and O'Sullivan, 1989; Johnes, 1996; Worral and Burt, 1999; Hanrahan *et al*., 2001; Lepisto *et al*., 2001; Hilton *et al*., 2002
	SIMPLE	SIMPLE		Schoumans *et al*., 2002
	NLM			Valiela *et al*., 1997
	urban runoff			Chiew and McMahon, 1999
		Input-output		Hetling *et al*., 1999
	regression			Ahl, 1994
	MACRO MODEL			Ichiki *et al*., 1996
		P indicators tool		Heathwaite *et al*., 2003
			DIN and PN model	Seitzinger and Kroeze, 1998; Seitzinger *et al*., 2002
			NO_3 export	Caraco and Cole, 1999
Physical-Mechanistic	LEACHM			http://eco.wiz.uni-kassel.de/model_db/mdb/leachm.html
	ANIMO	ANIMO		Schoumans and Groenendijk, 2000
	SOIL-N/WEKU	SOIL-N/WEKU		Wendland *et al*., 2002.
	CREAMS			http://www.agen.ufl.edu/~klc/abe6254/creamswt01.pdf
	AGNPS	AGNPS		http://www.cee.odu.edu/model/agnps_unix.php
	TOPMODEL			Whelan *et al*., 2002
	urban runoff	urban runoff		Bartosova and Novotny, 1999
	SWMM	SWMM		http://ccee.oregonstate.edu/swmm/
	NTM			Wittgren and Arheimer, 1996
	HBV-N	HBV-N		Arheimer and Brandt, 1998

Indeed, we initially established the following criteria on which to base our final model choice: i) produce a loading model that *operates at a range of spatial scales* to address issues that are either at the catchment scale, transboundary in nature or at the global scale, ii) produce a loading model that is *transferable* to areas where exhaustive data sets are currently lacking and/or where there are less resources for data collection, and iii) adopt a *multi-pollutant* approach to account for varying management priorities. Based on these criteria and the review described above we concluded that the diffuse pollutant loads provided by our DST would be best estimated through the empirical modelling approach.

Perhaps the most referenced and used empirical model is the export coefficient model, which was first developed by Vollenweider (1968) in the late 1960's and has since been optimised to estimate present day diffuse pollutant loads in the United Kingdom (Johnes and O'Sullivan, 1989; Johnes, 1996; McGuckin *et al*., 1999; Worral and Burt, 1999; Hilton *et al*., 2002), United States of America (Frink, 1991; Fisher *et al*., 1998) and numerous countries in Europe (Larsen *et al*., 1999; Brigault and Ruban, 2000; Lepisto *et al*., 2001). The export coefficient model relies on the use of coefficients that describe the amount of pollutant loss per unit area and per unit time for a variety of land uses. Recent studies show that the original export coefficients of Vollenweider (1968) produce load estimates that are comparable to observed or monitored loads (*e.g.* Hanrahan *et al*., 2001; Hilton *et al*., 2002) suggesting that the coefficients are robust and transferable. Other recent studies argue that export coefficients are highly specific to the catchment from which they were derived as the coefficient values may be influenced by the variation in land uses, topography, geology, and climate within the catchment (Lepisto *et al*, 2001). Unfortunately, current approaches with which to apply export coefficients are somewhat subjective, often being based purely on local expert knowledge of the catchment (Reckhow and Simpson, 1980; Johnes, 1999). To estimate pollutant loads over a wide range of spatial scales and geographic regions it would be of particular interest for us to develop a systematic approach with which to apply the published export coefficients, or alternatively create our own coefficients.

Export coefficients have been derived from data collected in process based laboratory studies (*e.g* Sharpley *et al.*, 1982) or from long term field monitoring of in-stream pollutant concentrations and runoff volume (*e.g.* Fisher *et al*., 1998). The data required to derive export coefficients are currently lacking in areas such as the developing countries (GESAMP, 2001). It is likely that the published or existing coefficients are unsuitable for use in these developing countries as the coefficients are predominantly derived from studies conducted in the UK and USA (review: Frink, 1991) where the local climate, terrain, land use practices and level of development differ significantly from those in developing countries. These factors, along with our recognition that there is currently a greater number of export coefficients available to estimate loads for nitrogen and phosphorus compared to other diffuse pollutants (*e.g.* metals, coliforms and pathogenic bacteria, sediments), led to our decision to create a unique set of coefficients from the global data sets that are currently available.

Land use, climate and terrain data have become comprehensive and easily attainable through remote sensing (RS) and geographic information systems (GIS). Organisations such as the World Bank and the Food and Agriculture Organisation also provide relatively comprehensive and up-to-date demographic data on a global scale. These spatial data sets clearly offer an invaluable resource for global models, especially since they are anticipated to improve over time. In the literature there are already examples of empirical models that use GIS/RS data to estimate diffuse pollution loads *e.g.* Fozzard *et al.* (1999), McGuckin *et al.* (1999), Hilton *et al.* (2002). Specifically, land cover data sets have been used to derive the type and magnitude of land use practices within specific catchments. The magnitude or intensity of land uses are usually multiplied by suitable export coefficients. In addition to this 'conventional' use of land cover data, it would be of significance to create export or loss coefficients from a combination of the demographic, GIS and RS data sets. As shown in the early studies of Meybeck (1982), it is possible to derive a type of export coefficient from the relationship between the amount of pollutant produced per capita and the demorphic index of Vallentyne (1978; cited in Meybeck, 1982), which expresses the amount of energy consumed per capita as a function of the amount of energy required per capita.

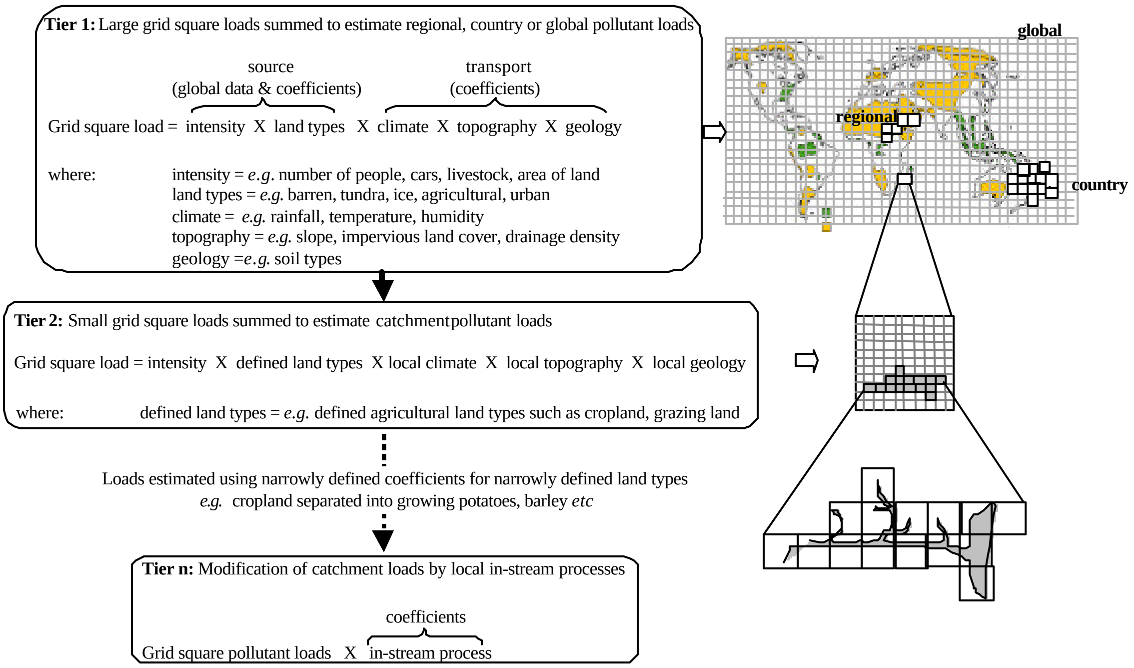

***Figure 1**. Schematic framework for a global decision support tool for diffuse pollution*

FRAMEWORK FOR A GLOBAL DST FOR DIFFUSE POLLUTION

The framework for our global DST will therefore be based around an empirical loading model that uses unique coefficients derived from global data sets, and will be capable of estimating pollutant loads for a variety of diffuse pollutants over a range of spatial scales in any region of the world. Specifically the model will be designed to estimate loads for six pollutant types including nutrients, metals, coliforms and pathogenic bacteria, sediments, persistent organic pollutants and biological oxygen demand. Similar to the export coefficient model, our loading model will be a function of the intensity or magnitude of pollutants produced by the sources, and a series of coefficients that provide a unit measure of the amount of pollutant exported to the waterway. In addition to these model terms (grouped as source terms; Figure 1), our model will also include other terms that may influence the amount of pollutant entering the main waterway *e.g.* topography, climate or geology (grouped as transport terms; Figure 1).

The loading model and the data sets used for the model will be structured into a tiered spatial system (Figure 1), specifically designed to ensure the global application of the DST. The tiered spatial system will be facilitated by mapping the world's land masses into a grid, and characterising each grid square according to types of land use, nature of human activity, terrain, climate *etc*. The first tier (Tier 1) estimates diffuse pollution loads for blocks of land (large grid squares; Figure 1) that are hundreds of kilometres across, and is therefore designed to operate at the larger regional, country and global scale (Figure 1). In this first tier, pollutant loads for each grid square will be estimated from broad land use categories and corresponding 'broad' export coefficients derived from global data sets. In contrast, the lower tiers estimate diffuse pollutant loads for smaller blocks of land (small grid squares; Figure 1) and are therefore designed to operate at the smaller catchment scale and in areas where relatively more data are available. In the lower tiers, pollutant loads for each grid square will be estimated by characterising the squares into more defined land use types and using more narrowly defined or specific coefficients. Users of our global DST will be provided with the option to input their own data, or use a default global data base. This interactive option will allow managers and policy makers to produce better estimates of pollutant loads at the smaller and local catchment scale, and present an opportunity to modify the grid square loads with more localised processes, such as in-stream denitrification (Tier n, Figure 1). The interactive option will also permit the database to be updated as the data becomes available.

CONCLUSIONS

The proposed DST is designed to be used by researchers and managers wishing to determine the sources or root causes of diffuse pollution and is similar to other assessment tools for managing diffuse pollution (*e.g.* Young *et al*., 1995; Elkaduwa and Sakthivadivel, 1999; Heinemann *et al*, 2002). Our DST is unique in that it offers the ability to estimate diffuse pollutant loads at various spatial scales in any region of the world. The tiered design of the DST means that it may coupled to a wide range of models that can only operate at specific spatial scales. For instance, our loading model may provide input data for highly processed hydrological models created for specific catchments, or may provide input data for larger global hydrological models, such as those used for predicting the impacts of climate change.

We are currently refining the source and transport terms in the general loading model, and collating and harmonising global data sets. The next phase of our work will involve the verification of the model by comparing the outputs from each tier to the outputs of existing diffuse pollution loading models, and also to field data collected from a number of test regions that vary with respect climate, level of development and industrialisation (*e.g.* United Kingdom, Central Europe, Mexico, New Zealand). As a consequence, the final DST product will provide measures of uncertainty and variability that may be associated with the load estimates so that these sources of error are also conveyed to the users.

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