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A Review of Ecological Models of Potential Use in Environmental Forecasting

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FOREWORD

This review of ecological models has been produced by WRc at the request of the National Centre for Risk Analysis and options Appraisal. WRc have attempted to survey the range of ecological models available, primarily as software implementations, from a variety of mostly European sources. The report highlights the range of environmental management applications for which ecological software models have been developed. The review is not meant to be a comprehensive review of either modelling as a discipline, or a review of all those models which might find applications in environmental impact forecasting. Nor does the review attempt to evaluate the robustness of these models, their applicability to the UK, or the availability of suitable datasets.

The NCRAOA aim to develop robust, state-of-the-art techniques for forecasting the future state of environmental ecological quality, and for extrapolating these assessments over a range of spatial and temporal scales. The NCRAOA would welcome any comments on this report, and more generally on the need for particular ecological models that might assist the Agency in meeting its responsibilities.

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EXECUTIVE SUMMARY

The National Centre for Risk Analysis and Options Appraisal of the Environment Agency has an objective to ensure that a comprehensive suite of environmental models is available for predicting the effects of current and future human activities. To this end, a review has been conducted of European ecological models that may be of relevance (including UK models), focusing on those with biological (or biologically orientated) end-points. The review was wide-ranging, reflecting the environmental remit of the Agency and covering all principal environmental media. Some US models were also investigated.

An enormous array of potentially relevant models has been identified, highlighting the huge resource being invested in such modelling in Europe and the US. These include practical and relatively simple models that are principally geared to management applications (such as environmental forecasting), in addition to more complex software that is largely geared to research applications. Summary information has been gathered on each model, with more detailed information being produced for some of the most promising ones. The model listings produced provide a useful first step in identifying models that may ultimately be of use to the Agency in environmental forecasting, but cannot be considered definitive. There are likely to be many other models in existence or under development that are, or will be, of potential use to the Agency. In addition, it should be noted that the application of many of the models listed could entail considerable investment by the Agency, in terms of collecting datasets and modifying software for UK/Agency use.

In order to target further review work it will be necessary to define likely scenarios of model use in my case more detailed consideration and comparison of models is required before recommendations concerning specific models could be made.

KEY WORDS

ECOLOGICAL MODELS, ENVIRONMENTAL FORECASTING.

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1. INTRODUCTION

1.1 Background and objectives

As part of its responsibilities towards 'environmental forecasting' within the Environment Agency, the National Centre for Risk Analysis and Options Appraisal aims to ensure that a comprehensive suite of environmental models is available for predicting the effects of current and future human activities. Owing to the wide range of Agency activities and duties, this suite of models needs to cover potential impacts on the air, soil and water environments, the latter including rivers, lakes, estuaries and coastal waters.

Many environmental models that are currently available are purely physico-chemical in nature, but the Agency is also interested in the possibilities for forecasting potential impacts upon biological communities. This requires the identification of ecological models with biological (or biologically-orientated) end-points, which either have additional capabilities in physico-chemical modelling or can be linked to other models with such capabilities. The Centre therefore commissioned WRc to undertake an initial review of such ecological models, which can be used as the foundation for further action.

The main objective of the work was:

> 'to undertake a comprehensive review of ecological models in use or under development across Europe and assess their suitability for use in environmental forecasting.'

A brief investigation of US models was also requested, to be undertaken as time allowed.

1.2 Scope of review

The term 'ecological model' is often used very broadly in the scientific community and it is therefore important to define boundaries to the review, particularly in the light of the huge investment in such modelling in Europe and the US. Many environmental models that have only physico-chemical end-points (such as nitrate concentrations in rivers) are often described as 'ecological' models, in that they simulate both biotic and abiotic processes to derive their output. The wholesale inclusion of this type of model in this review would increase the number of models to be considered manyfold, making the study impossible with the budget available. In any case, reviews of physico-chemical models have recently been undertaken for the Agency in relation to various issues (such as agricultural pollution - see Mainstone *et al.* 1994).

Figure 1.1 indicates the mechanistic links between physico-chemical change and biological effects upon which this review has concentrated. Exceptions have been made for those models that couch physico-chemical end-points in terms of consequences for, or risks to, the biota (see Section 3.1). Models that deal with links between human activity and physico-chemical change are dealt with where they are known to have links to 'true' ecological models, thereby permitting predictions of the biological effects of human activity. Socio-economic models, which allow changes in human activities (such as land use and resource exploitation) to be forecast, are dealt with in the same way.

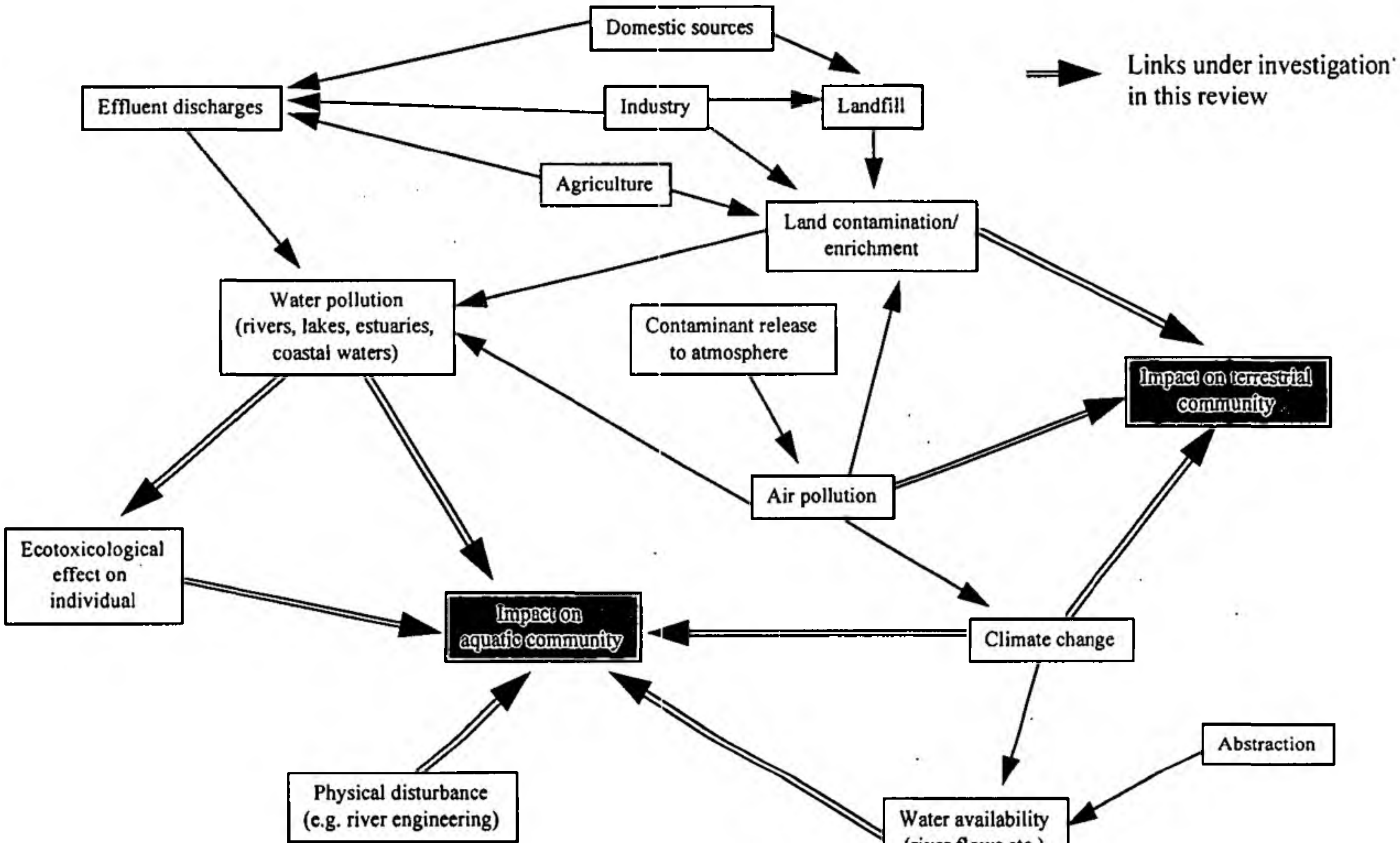

Figure 1.1 Major links between human activities and ecological effects, showing the mechanistic links most relevant to the current review.

2. METHODS OF WORKING

Four main avenues of investigation were used, as outlined below.

1. A search of the published literature was conducted using relevant databases on the DIALOG host, including BIOSIS, Oceanic abstracts, Aquatic Sciences and Fisheries Abstracts, Water Resources Abstracts, Waternet and CAB Abstracts. The most productive source of information was the journal, Ecological Modelling, published by the International Society for Ecological Modelling and devoted entirely to the subject.

2. Key European information sources were investigated on the internet. The most informative were:

   - the UFIS database of ecological models (see Knorrenschild *et al.* 1996), administered by the University of Kiel in Germany and holding information on nearly 500 models from across the world, including relevant models held on the CAMASE Register of Agro-ecosystem models (also on the internet);

   - the European Commission's CORDIS homepage (Coordinated R&D Information Service), providing information on numerous R&D projects funded by the various directorates of the Commission.

   The European Environment Agency's CDS homepage (Catalogue of Data Sources) was also investigated, but the system is as yet relatively unpopulated with information. Data input for this system is largely the responsibility of individual Member States; it may be useful in the future, but this will depend upon the enthusiasm of relevant organisations in each State.

3. Suitable European contacts were identified by the above search procedures (via relevant home pages on the internet) and through the European Topic Centre on Inland Waters (based at WRc and having a good knowledge of European research organisations). Efforts were focused on countries in north west Europe, where major research initiatives are concentrated and environmental conditions are most similar to the UK. All communications were via e-mail. A full list of those organisations and individuals contacted is given in Appendix A.

4 Information on relevant UK research was gained from existing contacts and a search of the World Wide Web home pages of key organisations, such as IFE, ITE, the Institute of Hydrology and the Plymouth Marine Laboratory. Web searches were followed up by e-mail with relevant research staff.

3. DISCUSSION OF FINDINGS

3.1 Summary of modelling approaches

Before discussing the models identified by the review, it is useful to consider model characteristics and how they relate to modelling objectives. The review revealed an enormous amount of effort being expended on ecological models across Europe, differing widely in the ecological issues covered, model design, complexity, purpose, mode of application and ease of applicability to new situations. Inevitably, all of these model characteristics are interlinked, in that model design and complexity are driven by the purpose of the model and the knowledge of the end user. Seemingly very relevant models can reveal themselves as highly complex with applications only in the detailed investigation of ecological processes, rather than the practical management of real systems or the pragmatic prediction of impacts upon them.

Ecological models represent a formal attempt to describe some components of the natural world with a mathematical function whose parameters can be adjusted so that the function closely describes a set of empirical data. A **mechanistic** model is usually based on well-understood biological, chemical and physical mechanisms, and its parameters have real world interpretations. By contrast, **statistical** or **empirical** models are statistical descriptions of ecological data, where a particular mathematical function is selected purely for its ability to best illustrate those empirical data. Extrapolation from mechanistic models usually (but not always) carries higher confidence than extrapolation using empirical models. However, the prediction of ecological change with empirical models often requires no extrapolation outside of the dataset upon which the model is based (as long as the environmental conditions that are being simulated exist somewhere and are included in the model). In practice, many ecological models are hybrid, with both mechanistic and empirical components.

A model that can describe the temporal change of an ecological system as a result of changes in external, 'forcing' environmental variables is termed a **dynamic** model. **Static** models are generally simpler, and represent relationships between internal model variables as a result of different, non-changing values of external environmental variables. While many potentially useful ecological models may not require computer implementation, the more complex, dynamic ecological models do require computer-based numerical techniques in order to solve the model equations.

Jorgensen (1994) provides a table of contrasting pairs of model qualities (Table 3.1) that is useful in that it contains the majority of terms that are likely to be encountered by Agency staff who may require the services of a model. The first pairing (**research versus management**) seems an ideal basis for selecting models for this review, but unfortunately available literature is not usually explicit about the purpose of a model. In any case, the division between the two is heavily blurred, since most models have some potential application to management even if it is not easy to realise in practice (owing to the costs of developing a software application and supporting it with data). In addition, model developers can be enthusiastic about the potential applicability of their model to management situations, if only to justify the heavy investment made in development.

A wide range of combinations of model characteristics is possible, making it difficult to generalise. However, **dynamic models** are typically **causal**, often complex and are more difficult to transfer to other situations, with more research applications than **management** applications. In contrast, **black-box models** tend to be **static**, simple and generic, geared more towards management than research. Dynamic, complex models may be the only valid approach to predicting the effects of some types of environmental change, which can present difficulties in terms of providing strategic forecasting with national relevance. An example of this is the effect of climate change, for which simple **black-box** models are difficult to build since the changes which may occur cannot easily be observed. In situations where complex models are appropriate, and extensive datasets are needed to parameterise and drive the model, the availability of a small number of representative case study datasets may help inform the decision-making process, while avoiding the high costs associated with developing additional site-specific implementations. Some dynamic models actually cover large geographical areas, such as the North Sea or English Channel (see Section 3.3.4), and in such cases model outputs may be adequate for strategic forecasting.

Many of the models used in environmental management today are statistical models. These are essentially of the black-box type, in that the models are developed using a general understanding of the processes affecting the model end-point, but these processes are not modelled mechanistically. Such models often use a relatively large dataset of observations and typically use techniques such as multiple regression analysis (such as HABSCORE), or cluster techniques followed by discriminant analysis (such as RIVPACS), or simple correlation analysis (such as some of the predictive systems for terrestrial vegetation change in relation to land use) to identify relationships between environmental parameters and the biological factors of interest that can be used for predicting change.

There is by no means a consensus within the modelling community as to which type of model is required to address a specific problem. Some theoretical modellers will argue that it is necessary to understand causal mechanisms fully before any meaningful predictions of ecological change can be made, and that therefore dynamic causal models should lie at the heart of environmental management. However, Scheffer and Beets (1994) point out that the parameterisation of complex causal models can lead to good results for the wrong reasons, thereby providing misleading information on causal mechanisms and giving false confidence in predictive capacity in new situations. Causal mechanisms are often extremely difficult to understand, and it is often the case that black-box, statistical models can provide satisfactory results in a less resource-intensive way.

Scheffer and Beets (1994) point to a perceived division between theoretical and applied ecological modellers, the former expounding the virtues of dynamic causal models and the latter focusing on black-box, generic models. Environmental managers are wise to be wary of the different modelling approaches that are available when considering models for their own purposes. The key is to decide upon the management questions that need to be answered and then choose the least complex model that will answer the questions at an appropriate level of detail and reliability. Where a simple black-box model is based on a sound theoretical knowledge of the system being modelled, and the answers it provides are suitable for the management questions at hand, there is no need to look at higher model complexity. Complex models should only be considered when they are essential to address the management problem.

Table 3.1 Model characteristics listed in contrasting pairs (after Jorgensen 1994)

Model characteristic	Description
Research	Used as a research tool
Management	Used as a management tool
Deterministic	Predicted values are computed exactly
Stochastic	Predicted values depend on probability distributions associated with model input variables and/or parameters
Compartment	Defining variables quantified by time-dependent differential equations
Matrix	Use matrices in the mathematical formulation
Reductionistic	Include as many relevant details as possible
Holistic	Use general principles
Static	Defining variables not dependent on time
Dynamic	Defining variables are a function of time (and/or perhaps space)
Distributed	Parameters are considered as functions of time and space
Lumped	Parameters are within prescribed spatial locations and time and are considered constant
Linear	First-degree equations are used consecutively
Non-linear	One or more of the equations are not first degree
Causal	Inputs, states and outputs are inter-related using causal relations
Black-box	The input disturbances affect only the output. No causality is required.
Autonomous	Derivatives are not explicitly dependent on time
Non-autonomous	Derivatives are explicitly dependent on time

Quite apart from the formal descriptions of modelling approaches given in Table 3.1, ecological models can be categorised in terms of the type of output, which is ultimately the most salient feature of a model to the end user. Here again, a number of categories can be distinguished, each of which may be appropriate to environmental forecasting depending upon circumstance. The models identified by this review can be divided into three categories of biological relevance, each of which is exemplified by a well-known model used in the UK:

1. those that can be used to predict change in communities, populations or the status of individual organisms as a result of physico-chemical changes to the environment (such as HABSCORE);

2. those that simulate changes in habitat conditions that relate directly to the requirements of target species or communities (such as PHABSIM);

3. those that predict physico-chemical change in relation to ecological thresholds or scales of risk that are derived from a knowledge of biological impact (such as models dealing with eutrophication risk, e.g. MINDER).

For many management applications, it might be considered important to be able to predict actual quantitative changes in the biological resource. Fish stocks are a particular case in point, where a range of human activities are dependent upon resource availability (e.g. angling and commercial fisheries). In other instances, it may be acceptable to assume a simple relationship between habitat availability and population size and use habitat as the end-point of a model. In yet other situations, particularly in the realm of water quality impacts, it may be sufficient to append ecological thresholds to ensure 'no-effect', or to use ecological risk categories. The type of effects likely to occur if a certain threshold is exceeded are known, but there is perhaps no need to model these effects directly.

Another important type of software that should be highlighted is that which brings ecological models together so that their use in management can be facilitated - this type of product might be termed 'umbrella software' (see Section 3.5). This may involve linking physico-chemical models to models with biological end-points, or bringing a range of ecological models together to cover a range of environmental issues within the same package. They are typically user-friendly Decision Support Systems (DSSs), but in their most sophisticated form they are integration platforms that provide detailed software links between models.

3.2 Discussion of review process

The review identified an almost bewildering array of ecological models in the broader sense (see Section 1.2), many of which are complete and publicly available. There is perhaps an emphasis on complex (often dynamic) models, many of which may have limited application to environmental management in England and Wales. The reason for this emphasis may be that much more theoretical modelling is being undertaken, or that simple, black-box models are just not prominently featured in available information sources. For instance, the journal Ecological Modelling seems to be more focused upon theoretical modelling of ecological processes, rather than applied modelling of human-induced ecological change. This said, it contains more applied models than many other environmental journals that publish papers on ecological modelling. Simplistic empirical models for management purposes may possibly be most often judged as 'too dirty' for inclusion in what are essentially academic publications.

Summary information on potentially relevant models identified by the review are given in Tables 3.2 to 3.6. No model identified by this review with a relevant biological end-point has been omitted from this list, in case there may be an application within the Agency (now or in the future) for which it may be suited. In the time available this cannot be considered an exhaustive search, particularly considering the enormous amount of modelling work being conducted, the wide remit of the review and the lack of response from some contacts in key organisations. However, it does provide a good starting point for the Agency in this area.

Particularly helpful contacts were found in **The Netherlands**, who have undertaken a good deal of relevant work on management-orientated modelling systems, including the decision-support system Nature Planner, which acts like an integration platform for ecological models covering a range of environmental issues (Section 3.5). Dutch organisations are also undertaking extensive modelling of the interactive effects of nutrients and toxicants on aquatic ecosystems (Kramer *et al.* 1997), a subject which has not really been addressed in the UK (generic models are not currently available).

A year-long review of simulation models of potential use in the management of the aquatic environment has just been completed in **France**. Unfortunately, the Agences de l'Eau (the funding body) will not release this report until the second phase of work has been completed, scheduled for this summer (see Appendix A for the relevant contact point). Contacts in **Sweden** revealed interesting collaborative work in Scandinavia to develop black-box predictive systems for unimpacted (reference) macroinvertebrate, fish and macrophyte communities, using similar techniques to those used for RIVPACS, but there do not seem to be plans to develop them further into predictors of environmental change.

Contact with the European Topic Centre for Nature Conservation revealed work underway on the development of a forecasting model based on indicators of biodiversity. This research is being led by the UK's ITE, but attempts to contact the project leader (Dr Barry Wyatt) by e-mail have been unsuccessful. The model is potentially highly relevant to the Agency and therefore needs to be investigated further.

The search of the internet identified the Projektzentrum Oekosystemforschung (PZO), a research initiative attached to the University of Kiel in **Germany**, which brings together 22 organisations across the country in collaborative ecosystem research. One of the main objectives of the initiative is to develop an information system that allows environmental impacts relating to human land use and the use of natural resources to be predicted. There are therefore close parallels with the objectives of the National Centre in terms of environmental forecasting. However, so far only one model seems to be under development that is relevant to this review (relating to the simulation of changes in wetland vegetation - see Section 3.3.3).

Most of the models identified use traditional modelling approaches, with very few examples of more modern techniques such as neural networks and genetic algorithms. In the future, such techniques are likely to become much more prevalent in ecological modelling (particularly applied modelling), since they are extremely flexible in their approach to identifying empirical relationships that can be used in predicting biological change.

A brief discussion of the models in Tables 3.2 to 3.6 is given in subsequent sections, divided into major environmental media (as are the tables). It should be noted that some models are multi-media and will appear in more than one table. Within the time available it has not been possible to undertake in-depth assessments of the relative merits and disadvantages of individual models, although some judgement as to their likely value to the Agency is made where possible. Appendix B provides more detailed descriptions of some of the models that would appear to be of most interest to the Agency (excluding ones that are already in operational use).

3.3 Models with aquatic/wetland biological end-points

3.3.1 Rivers

Various riverine models of potential interest have been identified by the review, including ones from Europe and the US and covering issues such as eutrophication risk, physical impacts and toxic effects (Table 3.2). Those models already in use within the Environment Agency (PHABSIM, RIVPACS and HABSCORE) are included in the table.

It is fair to say that **RIVPACS** is of little value in environmental forecasting in its current form, since it only predicts clean water communities and not communities under different levels of anthropogenic stress. Its current value in this area is restricted to the prediction of the effects of certain coarse physical changes, such as the removal of gravel substrates from a site. However, further versions of RIVPACS may be produced in the future which tackle the prediction of different types of impact (such as acidification and organic pollution). **HABSCORE** again makes predictions in relation to clean water conditions (this time of salmon and trout abundance), but uses detailed assessments of physical habitat quality in the predictive process. It can therefore be used to predict the effects of deteriorations in detailed physical habitat, although its use in this way at a strategic level is hampered by a lack of survey sites across England and Wales. **PHABSIM** can be used to predict the effects on habitat availability of reduced river flows, but again the data demands are quite high and the model is therefore only used in site-specific investigations. The establishment of a network of representative study sites across England and Wales for both HABSCORE and PHABSIM would help greatly in their use at a strategic level.

MINDER for Rivers and CECOSECOM deal with the prediction of eutrophication problems in rivers as a result of enhanced nutrient inputs. Both deal in eutrophication risk, rather than direct prediction of biological changes. **MINDER for Rivers** has been applied to the Don catchment in Scotland and adapted to utilise environmental data available in Eastern Europe. It was then applied to river systems in Romania, Slovakia and Hungary. However, it requires further refinement in terms of its use of pollutant export coefficients and the assessment of ecological risk. **CECOSECOM** (Coupled ECOlogical and Socio-ECOnomic Model) brings together the forecasting of human activities with the simulation of ecological consequences in order to analyse future scenarios of eutrophication risk, covering both river reaches and coastal areas associated with the Rhone River basin. It considers factors such as agricultural production, overall population, intensity of urbanisation and industrial activity, but the output parameters are unclear from available information. The project was scheduled to end in 1996 so it assumed that the model is complete.

BINOCULARS (BIogeochemical Nutrients Cycling in LArge River Systems) is another nutrient-based river model that is geared towards analysing land use scenarios in river basins. Although it is unclear from the information available how model outputs are expressed, it does consider impacts on the ecological functioning of the river as well as predicting changes in nutrient status. The aim of model development was to assist in the formulation of policies on integrated river basin management, and as such is of potential relevance to the Agency in environmental forecasting. It has been built on seven case study catchments in Europe (including the Axe).

Table 3.2 Summary information on models of interest relating to rivers

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
ALGAL GROWTH	USA	Compartment model	Algae	Effects of nitrates, phosphate, turbidity, pH, temperature, ammonia, alkalinity and light on algal growth.	Operational	Aquatic ecosystems	Generic	UFIS database
ASRAM	Canada	Empirical	Atlantic salmon	Recovery as low pH streams remedied	Operational	River reaches	Generic	Jørgensen *et al* 1996
BINOCULARS	France/ Greece/UK/ Netherlands	Mechanistic	Ecological process in relation to nutrient cycling	Eutrophication	Presumed operational	River basins, spatial resoln. unclear.	Applicable	EC CORDIS homepage
CECOSECOM	France/UK	Coupled socio-economic and dynamic ecological model	Lower trophic groups	Eutrophication risk	Presumed operational	River basin	Specific to Rhone Basin and Gulf of Lions	EC CORDIS Homepage
CemoS/water	Germany	Steady state compartment model	Contaminant concentrations in biota (including fish)	Predicts exposure concentrations of hazardous chemicals	Operational	river ecosystems	Generic	UFIS database
CL-CCE	Netherlands	Expert system	Forest soils and surface waters	Model calculates critical loads of acidity and sulphur	Operational	Ecosystems - areas of variable size	Generic	UFIS database
ECOFATE	Canada	Dynamic (ordinary differential equations)	Contaminant concentrations in biota - including fish	Ecological or human health risk of chemical emissions	Operational (ECOFATE Home page)	Freshwater and marine ecosystems	May be specific to Canadian species	UFIS database
FGETS	USA	Compartment model (ordinary differential equations)	Fish	Predicts time taken for body concentrations of toxins to reach lethal concentrations	Operational	Fish populations	Generic	UFIS database

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
HABSCORE	UK	Empirical	Salmon and trout	Physical changes in fish habitat	Operational	100m reaches	Already in use	Wyatt *et al.* 1995
MEDUSA	UK	Empirical	Macrophytes, invertebrates, fish, birds	Ecological impact of changing acidity	Under long-term development	Welsh streams	Applicable	Rundle *et al.* 1995
MINDER For Rivers	UK	Empirical	Risks of algal growth	Eutrophication	Development halted	Catchment-scale	High	Woodrow *et al.* 1994
QUAL2EU (enhancement of QUAL2E)	USA	Can be operated as either steady state or dynamic	Algal productivity	Effects of conventional pollutants on algal productivity	Operational - available through US EPA	Stream sections and well mixed lake systems	Generic	UFIS database EPA Homepage
PHABSIM	USA	Empirical	Salmonids and other target species	Effect of flow regimes on habitats for selected species	Operational	River stretches	Already in use	Gustard and Elliott (1997) for use in UK
RBM10	USA	Dynamic	phytoplankton, zooplankton, macrophytes, benthic animals	Ecosystem risk in relation to point and diffuse sources	Operational	River Basins	Generic	Jørgensen *et al* 1996
RIVEG & linked models	Netherlands	Empirical	Riparian vegetation and key animal spp.	Positive effects of river rehabilitation	Under development	River reaches	Unknown	Duel *et al.* 1994
RIVPACS	UK	Empirical	Invertebrates	Crude physical changes in substrate etc.	Operational	Site-based but national database	Already in use	Wright *et al.* 1984 and subsequent developments
Trout mortality	Germany	Empirical	Brown trout	Effects of turbid water and low oxygen concentration on trout mortality	Operational	Rivers/lakes	Generic	Jørgensen *et al* 1996
Flood disturbance model	USA	Compartment model	Food web (predator-resistant grazing insects, top predators)	Effects of flooding disturbance on food web interactions	Operational	river systems	Applied specifically in US	Wootton *et al* 1996

QUAL2EU (see Appendix B for further details) is a US model that predicts the effects of toxicants on algal growth in both rivers and lakes. It has been integrated into an important USEPA modelling package called **BASINS** (see Section 3.5), which also includes the major non-point source model HSPF and the toxicity model TOXIROUTE. Models of algal growth in rivers have also been developed in the UK (e.g. Whitehead *et al.* 1997), although not to the point where a generic model is available. The river phytoplankton model RIVERSTRAHLER has been applied to several European rivers (e.g. Billen *et al* 1994), but would not be widely applicable in the UK without further development.

MEDUSA and ASRAM both deal with the prediction of the biological effects of acidification. **MEDUSA** (Models of Ecosystem Dynamics Under Stream Acidification), developed by the University of Wales under the Welsh Acid Waters Monitoring Programme, deals with various components of riverine communities including invertebrates, macrophytes, the density and survival of fish populations and the presence/absence of river birds. It comprises a family of empirical models based upon biological communities across a range of acidified and unimpacted sites. The models were produced in the same way as the RIVPACS package, sites being grouped biologically according to cluster analysis and then these groupings being explained by abiotic factors using multiple discriminant analysis. MEDUSA models can be linked to the physico-chemical acidification model MAGIC so that predictions of ecological change can be attempted based on changes in atmospheric emissions. Unfortunately, the reliability of model outputs is relatively low, particularly due to the inability of the models to accommodate transient acid events (which are known to heavily influence community structure). The Canadian model **ASRAM** deals with the more specific issue of salmon recovery following the application of measures to ameliorate acidification problems.

An alternative approach to the direct modelling of acidification impacts on the biological community is to use models of critical loads, which have been developed in the UK (by ITE) and elsewhere (such as **CL-CCE** in the Netherlands - see Appendix B for further details). These are based on the buffering capacity of catchment soils and levels of acidification that are likely to cause ecological damage. They are useful in terms of mapping the spatial distribution of problem areas, and provide a national-scale overview that is valuable for environmental forecasting.

Some models have been identified that deal with the accumulation of contaminants in biological organisms, one specifically aimed at river systems (**CemoS/Water**) and others aimed more widely at aquatic environments (**ECOFATE** in freshwater and marine environments and **FGETS** in fish populations generally). CemoS/Water is part of an extensive model package called **CemoS** (see model summary sheet in Appendix B), which aims to estimate exposure concentrations of hazardous chemicals in air, soil and water environments.

Only one model was identified that tackled the ecological effects of flooding on river systems (Wooton *et al.* 1996), developed and applied in the US and simulating the whole food web. The ecological importance of flood events needs to be better understood and integrated within water level management plans in England and Wales, but it is not possible to gauge the value of this particular model to the Agency from the limited information available.

Physical river rehabilitation is an increasingly important component of the Agency's work, but initiatives are currently rather piecemeal and not quantitatively integrated into catchment modelling activity (such as for flood defence). Models are being developed in the Netherlands for simulating the effectiveness of river and floodplain rehabilitation (Duel *et al.* 1994), including **RIVEG** for predicting the development of riparian vegetation, models of habitat suitability for key animal species, and an expert system (**MIMIKRI**) for storing and using existing ecological knowledge on a given river system. The model package deals with such issues as the creation of backwaters and changes in the frequency and duration of flooding, and is aimed at integrating river rehabilitation with flood defence and water quality planning.

3.3.2 Lakes

Ecological models specific to lakes (Table 3.3) are mostly targeted at eutrophication issues (such as PCLake, LAVSOE, LEEDS and PROTECH), some dealing only with eutrophication risk (in terms of threshold nutrient concentrations) and others being more complex and dealing with simulations of various biological components (such as phytoplankton, zooplankton, macrophytes and fish). However, there is also a range of toxicity models developed purely for lake systems (including TOXFATE, SIM-PEL and LERAM) as well as the more generally applicable models of aquatic toxicity (such as FGETS for fish populations).

The Dutch dynamic model **PCLake** (see Appendix B for further details) simulates changes in lake communities as a result of changes in nutrient loading, particularly focusing on shifts between the two alternative stable states of the lake ecosystem (one comprising phytoplankton-dominated turbid water and the other comprising clear water dominated by submerged macrophytes). Modelling of alternative stable states is now a key component of lake modelling in relation to eutrophication and restoration, and is not accommodated by traditional eutrophication models. PCLake is currently being linked to a water transport model DUFLOW so that catchment problems can be investigated (pers. comm. L. van Liere, the Dutch National Institute of Public Health and Environmental Protection - RIVM), and links to PCDitch (see Section 3.3.3) are also being developed.

PROTECH (developed by IFE) is currently used by the Environment Agency as its standard lake eutrophication model. This goes further than basic nutrient/chlorophyll regression analyses (e.g. OECD 1982), since it predicts chlorophyll levels associated with functional groups of phytoplankton throughout the year. It does this by updating information on growth conditions in 10 cm horizons throughout the water column. Thus, it is able to predict chlorophyll-a levels at any time of year and to predict what group of algae is likely to dominate. The downside of such a model is that it is data-hungry, requiring bathymetric, biological, hydrological, chemical and meteorological inputs. PROTECH may be used in conjunction with PACGAP - a simple expert system which uses data on lake morphology, biology, retention time and nutrient concentrations to predict the most suitable eutrophication control method(s).

Table 3.3 Summary information on models of interest relating to lakes

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
AQUAMOD	Italy	Dynamic (ordinary differential equations)	Algae, macrophytes, zooplankton	Effects of nutrient and oxygen fluxes	Operational	Not specified	Generic	UFIS database Hull and Lagonegro 1988
AQUAMOD1, AQUAMOD2 + AQUAMOD3	Czech Republic	Dynamic	Phytoplankton and zooplankton (fish predation)	Effects of water quality variables on production	Operational	Lakes and reservoirs	Generic	Jørgensen *et al* 1996
ALGAL GROWTH	USA	Compartment model	Algae	Effects of nitrates, phosphate, turbidity, pH, temperature, ammonia, alkalinity and light on algal growth.	Operational	Aquatic ecosystems	Generic	UFIS database
FGETS	USA	Compartment model	Fish	Predicts time taken for body concentrations of toxins to reach lethal concentrations	Operational	Fish populations	Generic	UFIS database
The Glumsø model	Denmark	Dynamic	Phytoplankton and zooplankton	Eutrophication	Operational	Eutrofied and/or shallow lakes	Generic	Jørgensen *et al* 1996
ICHORS	Netherlands	Empirical	Plant species	Influence of chemical and hydrological factors on species composition	Operational	Wetlands and lakes	Generic	Hooghart and Posthumus 1993
LAVSOE	Denmark	Dynamic	Algae	Eutrophication	Operational	Shallow eutrophic lakes	Generic	Jørgensen *et al* 1996
LEEDS	Sweden	Empirical eutrophication management model	Phytoplankton	Effects of P on biomass	Operational	Large lakes	Generic	Jørgensen *et al* 1996
LERAM	US	Complex, dynamic	Growth rates in different compartments of the food web	Effects of chemical exposure	Requires further development	Lake systems only	Generic	Hanratty and Stay 1994

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
PCLake	Netherlands	Compartment, mechanistic	Lake vegetation (algae and higher plants)	Effects of nutrient loading and management measures on species dominance	Operational	Individual lakes	Generic and relevant to UK communities	Janse 1997
PROTECH	UK							
SIM-PEL	Germany	Compartment model	Algae/fish	Effects of environmental factors (temp and radiation) and xenobiotics on biomass	Operational	Lake pelagic area	Generic	UFIS database
SALMO	Germany	dynamic	Phytoplankton and zooplankton	Effects of water quality variations on productivity	Operational	Lakes and reservoirs	Generic and applicable to UK	Jørgensen *et al* 1996
SAM	Germany	Dynamic	Phytoplankton (5 taxa), zooplankton (5 taxa)	Effects of nutrients and pesticides on Phyto- and zooplankton populations	Cannot be purchased at present	Ponds	Generic	Jørgensen *et al* 1996
TOXFATE	Canada	Compartment model (ordinary differential equations)	Phytoplankton, zooplankton, fish	Toxic accumulation of pollutants	Operational	Completely mixed lakes	Generic	UFIS database Halfon *et al.* 1984
3DWFGAS	Finland	Dynamic	Phytoplankton, zooplankton, zoobenthos, fish	Effects of water quality changes	Operational	Natural and artificial lakes	Applicable (covers lakes in N&C Europe)	Jørgensen *et al* 1996
Ecological risk simulation models	Germany	Stochastic and compartment models	Plankton communities	Ecological risk of toxins	Operational	Plankton communities in lakes	Generic	Hommen *et al* 1993
Lake eutrophication model	Denmark	Simple	Phytoplankton, zooplankton, fish	Effects of N, P and climate	Operational	Lake ecosystems	Generic	Jørgensen *et al* 1996
Lake fishery management	Denmark	Not specified	Fish (3 species)	Effects of climate, available food and water quality on fish growth rate and mortality	Operational	Lakes	Generic	Jørgensen *et al* 1996

The forecasting of blue-green algal problems is a particularly important issue for the Agency. PROTECH is able to predict the likely times of dominance and the standing crops of the functional groups containing toxic blue-green algae, but modelling of toxin production is altogether different. There is a two-thirds chance of a potentially toxic blue-green algal bloom being toxic, but the factors controlling toxin production appear not to be sufficiently well understood for the process to be accurately modelled, although such models have been attempted. However the effects of light-driven buoyancy on blue-green algal populations (mediated by gas vacuole inflation/deflation) have been successfully modelled (albeit in a nutrient-saturated isothermal water column - Belov and Giles 1997). This model requires further validation and a user-friendly front end before it could be used by non-modellers, but the general model of Belov and Wiltshire (1995) could be very useful in predicting the likely effect of mixing system operation on blue-green algal populations, and hence be of use to both the Environment Agency and water companies.

LERAM (Littoral Ecosystem Risk Assessment Model) is a relatively complex compartment model that simulates the effects of various chemicals on the growth rates of different sectors of the biological community (as functional groups). However, the model uses only acute toxicity data and assumes a linear exposure-response relationship. Further development is required to improve the way in which the model deals with toxic effects (van Wensum 1997). **SIM-PEL** is a similar model, focusing on pelagic areas of lakes and dealing with toxic effects on biomass in different biological compartments. **TOXFATE** is yet another compartmental food web model addressing toxic exposure, but only considers bioaccumulation rather than additionally relating body burdens to toxic effect.

3.3.3 Wetlands

Large amounts of effort have been invested in wetland modelling by organisations in the Netherlands, particularly in relation to the effects of anthropogenic alterations to the height of the water table. Table 3.4 is dominated by Dutch models, some of which appear to overlap heavily in the nature of their application.

- **ICHORS** (Influence of Chemical and Hydrological factors On the Response of Species) uses site-specific data on the distribution of plant species and various (about 25) associated abiotic variables (such as water depth above or below ground level, pH and soil/sediment content of parameters including magnesium and bicarbonate), computing probability functions for selected plant species in relation to the most important abiotic factors (selected by multiple regression). In this way, it may be compared to the PHABSIM model for rivers, with its probability functions being similar to Habitat Suitability Curves. Unfortunately, the large number of parameters it uses makes it expensive to apply, and when scenario-testing many parameters are very difficult to predict.

- **WSN** (Water-Site-Nature conservation value) is based on the first Dutch ecohydrological model WAFLO (WAter-FLOra) and concentrates on water management issues. It uses Ellenburg's scales of wetland character, which are based on soil moisture, acidity and nutrient availability and are applied to individual wetland plant species. These are used to identify ecological species groups (together with potential conservation value) under different combinations of the three abiotic variables, and physico-chemical models are used to predict changes in the abiotic environment. Where predictions of abiotic change take a site from one species group to another, the site is reclassified and a new potential conservation value is assigned.

- **MOVE** (Model for the Vegetation - see summary sheet in Appendix B) combines the statistical approach of ICHORS with Ellenburg's indicator values. The Ellenburg scales are calibrated to abiotic site factors, such as soil moisture and pH, which are predicted in scenario-testing using dynamic models such as SMART2. MOVE and SMART2 are both incorporated into the decision support system Nature Planner (Section 3.5).

- **DEMNAT-2.1** (see summary sheet in Appendix B) is a national-scale model that uses national datasets on soils, groundwater and plant species distributions to develop empirical relationships that are then used in scenario-testing, considering changes in soil moisture conditions, nutrient availability, acidity and salinity.

The two models of greatest apparent applicability are DEMNAT and MOVE, with the former seeming to be of more utility in terms of environmental forecasting simply due to its large scale of application. This allows more strategic, national-level predictions of change, although it does rely on certain national datasets being available in an appropriate format. Although both models are used by RIVM to analyse water management scenarios, there is some concern that MOVE is not ready for operational use (pers. comm. F. Witte, RIVM). A pc version of DEMNAT has recently been produced which is to be sent to the regional water boards of the Netherlands for operational applications.

The Projektzentrum Oekosystemforschung in Germany is developing a similar modelling approach for managing wet grasslands (Schrautzer *et al.* 1996), consisting of an expert system, a database of 1300 sites and autecological information on 200 plant species. Rules concerning autecological preferences, vegetation types and likely succession stages are built into the expert system and used to simulate likely biological changes as a result of possible alterations to environmental conditions. Whilst the system seems to be more orientated towards determining what changes are required to achieve a pre-defined target vegetation type, it can presumably be used to determine what floristic changes would occur if environmental conditions were altered in different ways. It differs from Dutch models in having no abiotic modelling capability (although this is planned for the future), and is largely geared to identifying meadow restoration options.

PCDitch (see Appendix B for further details) is a Dutch model that has been developed to simulate the adverse consequences of nutrient enrichment in the drainage networks typically associated with wetland systems. Enrichment of ditch systems, and the consequent loss of the typically diverse assemblages of submerged macrophytes, is an important issue and one that has been poorly researched to date. This model, whilst requiring further development, provides an opportunity to place ditch management on a more objective footing.

Table 3.4 Summary information on models of interest relating to freshwater wetlands (including ditch systems)

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
BERI	Netherlands/ UK/Finland/ Switzerland/ Sweden/Italy	Process-oriented	Plant communities in bogs	Effects of atmospheric CO_2 composition, N deposition and climate on plant biodiversity, C-sequestration and methane emission	Under development	Bog areas	Applicable to bogs across Europe	EC CORDIS homepage
CALM	USA	Spatially explicit dynamic simulation model	Algae, periphyton, macrophytes, consumers	Effects of varying hydrological and nutrient regimes on landscapes	Recently developed	Landscapes (0.25 km^2 cells)	Developed for Everglades - may not be applicable	UFIS database
DEMNAT-2.1	Netherlands	Empirical	Wetland plant spp.	Impact of hydrological changes on vegetation type	Operational	Regional	Generic and relevant to UK spp.	Witte 1998
ELM	USA	Spatially explicit dynamic simulation model	algae, periphyton, macrophytes and consumers	Landscape responses to varying hydrological and nutrient regimes	Under development	Landscapes	Possibly too specific (Everglades model)	UFIS database
ICHORS	Netherlands	Empirical	Plant species	Influence of chemical and hydrological factors on species composition	Operational	Wetlands and lakes	Generic and relevant to UK spp.	Hooghart and Posthumus 1993
MOVE	Netherlands	Empirical	Vegetation	Effects of stresses imposed by different environmental problems e.g. nutrient availability, soil moisture	Operational	Geographical units	Generic and relevant to UK spp.	Cited in Hooghart and Posthumus 1993
PCDitch	Netherlands	Compartment, mechanistic	Ditch vegetation (algae and higher plants)	Eutrophication	Under development	Site-level	Generic and relevant to UK communities	Janse (In press)
SIMO-NEW	Netherlands	Dynamic	River marginal wetland	Effects of athropogenic activities on wetland functioning	Operational	"units" within a wetland as well as wetland "sites"	European wetlands	Jørgensen *et al* 1996
WSN	Netherlands	Empirical	Plant species	Soil wetness, nitrogen, pH	Operational	Sites or catchment level	Generic and relevant to UK spp.	Kemmers 1993

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
Ecological-Economic wetland model	UK/ Netherlands/ Sweden/ Greece	Wetland management model type not specified	Wetland ecosystems	Effects of different use and preservation options on wetland ecosystems	Under development	wetland areas	Applicable to wetlands within the EU	EC CORDIS homepage
Wet grassland model	Germany	Empirical	Wet grassland plants	Effects of changes in abiotic conditions	Under development	Site-based but can be applied rapidly	Generic and relevant to UK spp.	Schrautzer 1996
Fen model	Netherlands	Dynamic	Vegetation	Effect of nutrients and organic matter on vegetation type	Operational	Landscapes	Generic	Jørgensen *et al* 1996

3.3.4 Estuaries and coastal waters

The review has identified a number of models dealing with the simulation of phytoplankton and/or macroalgal populations that are of potential use in forecasting Man-induced change. These include a predictive model for *Phaeocystis* blooms, which are a major feature of coastal areas of England and Wales. Phytoplankton simulation models have been developed in Norway, France, Germany and Italy, whilst **EROS 2000** is a collaborative European model that deals with eutrophication in coastal areas. **COHERENS** is a management-orientated dynamic model of coastal ecosystems, developed by Belgium and the UK, that is particularly worthy of further investigation (see Appendix B for further details).

ERSEM and **MIKE21 EU** both simulate carbon and nutrient cycling processes through the food web in the North Sea. Their applicability to the analysis of eutrophication problems has been compared by Baretta *et al.* (1994), concluding that both are relevant at different geographical scales. MIKE21 EU has a high spatial resolution (18.5x18.5 km), whereas ERSEM is mechanistically more complex (with 70 state variables) but of coarse spatial resolution. MIKE21 EU is therefore more appropriate for identifying problem areas, whilst ERSEM is better suited to analysing the mechanisms and nature of likely changes. Further details of the ERSEM model are provided in Appendix B.

The EU-funded JEEP-92 (Joint European Estuarine Project) Project has produced a model of ecological processes in European estuaries that may be of value in environmental forecasting. The ecological model **MOSES** simulates basic pelagic and benthic processes relevant to carbon and nutrient cycling, including primary production, degradation processes, zooplankton grazing and macrobenthic feeding (Heip and Herman 1995). The model is said to be sufficiently generic to apply easily to other estuaries, and has potential applications in simulating the impacts of possible future changes in the loads of organic material and nutrients. MOSES is linked to a hydrodynamic model that calculates loads to the system.

Several OECD-type empirical models (linking chlorophyll-a levels to nutrient concentrations) have been produced for coastal waters (e.g. Lack *et al* 1990, Gowen and Ezzi 1992, Gowen *et al* 1992, Giovanardi and Tromellini 1992), the first of which includes the use of site-specific flushing factors to account for phytoplankton loss from dynamic systems. This substantially improved the accuracy of the model for use in Hong Kong coastal waters, but the approach is not known to have been used in estuaries.

The loss of eel-grass beds is of concern in some UK coastal areas, and a European model has been developed under the EU 3rd Framework Programme to simulate the mechanisms causing transition from *Ulva* (sea lettuce) to eel-grass that may be of value to the Agency.

Few models of anthropogenic impact exist that deal with mudflats, despite the high ecological importance of mudflat ecosystems. **ECOFLAT** is a collaborative European model that simulates the ecological effects of global environmental change, and may be of future use to the Agency.

Table 3.5 Summary information on models of interest relating to estuaries and coastal waters

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
CECOSECOM	France/UK	Coupled socio-economic and dynamic ecological model	Lower trophic groups	Eutrophication risk	Presumed operational	River basin	Specific to Rhone Basin and Gulf of Lions	EC CORDIS Homepage
COHERENS	Belgium/UK	Integrated 3-D dynamic model	Pelagic and benthic ecosystems	Diagnostic and prognostic management tool (including bloom formation)	Under development	Marginal seas and ocean basins	Highly applicable	EC CORDIS homepage
ECOFATE	Canada	Dynamic (ordinary differential equations)	Contaminant concentrations in biota - including fish	Ecological or human health risk of chemical emissions	Operational (ECOFATE Home page)	Freshwater and marine ecosystems	May be specific to Canadian species	UFIS database Gobas 1992
ECOFLAT	Netherlands/ UK/Belgium/ France	Dynamic, mechanistic model	General mudflat ecosystems	Prediction of ecological consequences of global change	Under development	Estuarine intertidal mudflats	Applicable	EC CORDIS homepage
ECOWIN	Portugal	Object-orientated ecological box model	Phytoplankton/benthos, zooplankton/benthos	Impact of a range of physical/chemical variables on communities	Operational	Estuaries (present application)	Generic	Ferreira 1995
ELISE	France	Box model	Phytoplankton	Effects of hydrodynamics, climatic conditions and biological factors on biogeochemical processes	Operational	Bay of Brest	Generic	Lepape and Menesguen 1997
EROS 2000	France/UK/ Ireland/Spain /Belgium	Dynamic	Biogeo-chemical and ecological flux models - eutrophication	Long-term influences of man-induced changes in inputs of organic and inorganic compounds	Operational	Land/ocean interface	Applicable	EC CORDIS homepage
ERSEM	Denmark	Dynamic, complex	Carbon and nutrient cycling within ecosystem compartments	Eutrophication	Operational	Regional seas (North Sea), coarse scale	Applicable	EC CORDIS homepage, Radford and Blackford 1996
HEAVY ROCK	Norway	Empirical	Benthic algae (*Ascophyllium nodosum*)	Uptake of heavy metals (Cu, Zn) in *Ascophyllium nodosum* as a function of growth rate, mortality and concentration of meal in ambient medium	Operational	Rocky shores	Applicable (species found in UK)	Jørgensen *et al* 1996

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
MIKE21 EU	Denmark	Dynamic	Carbon/nutrient cycling in lower trophic levels	Eutrophication	Operational	High resolution, applied to North Sea	Applicable to North Sea	Baretta et al. 1994
MOSES	Netherlands	Dynamic, complex	Pelagic/benthic processes in estuaries	Changes in organic loading	Operational	Individual estuaries	Reasonably generic	Heip and Herman 1995
SEABIRD	Norway	Not specified	Seabirds	Impact of oil spills on the distribution, abundance and recovery of seabird populations	Operational	Coastal areas	Applicable	Jørgensen *et al* 1996
SENSI	Denmark	Dynamic	Brown algae (*Fucus vesiculosus*)	Quantification (estimates) of the concentrations and turnover of radioactive metal contaminants by a brown alga	Operational	Vicinity of radioactive effluent	Applicable (species found in UK)	Jørgensen *et al* 1996
Model of 1[c] production - Cen. North Sea	Germany	Dynamic	Phytoplankton	Effects of physical, chemical and biological (grazing) on standing crop	Operational	Upper layer model - central North sea	Applicable	Jorgensen *et al* 1996
Fjord ecosystem model	UK	Dynamic	Pelagic ecosystem	Effects of marine farming and other activities on productivity	Operational	Fjords and associated coastal areas	Applicable to Western British Isles	Jørgensen *et al* 1996
Oyster bioaccumulation model	USA	Dynamic/ stochastic	Oysters	Simulation of radionuclide concentrations in oysters maintained in the effluent of a nuclear plant	Operational	Vicinity of radioactive effluent	Generic	Jørgensen *et al* 1996
Phytoplankton simulation model	Norway	Empirical	Phytoplankton: diatoms and flagellates	Effects of light and anthropogenic nutrients on populations	Operational	Coastal areas	Generic	Aksnes *et al* 1995
Ecological model - English Channel	France	Dynamic ecological box model	Phytoplankton:diatoms and dinoflagellates	Biogeochemical cycles of elements limiting primary production	Operational	Shelf seas	Generic	Ménesguen and Hoch 1997
Predictive model to assess impact of waste dumping	UK	Empirical model	Demersal fish and benthic fauna	Impact of waste dumping on marine ecosystems	Operational (developed in 1985)	Coastal regions	Applicable	EC CORDIS homepage

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
Predictive eutrophication model	Belgium	Dynamic	Algae (*Phaeocystis*)	Effects of nutrient fluxes on *Phaeocystis* dynamics	Operational	Coastal areas	Applicable (Southern North Sea)	EC CORDIS homepage
Marine universal structural model	Denmark/ Portugal/Italy	Dynamic	Macrophytes	Factors responsible for structural dynamic changes (transition from Ulva to Eel grass)	Operational	Shallow marine waters	Generic	EC CORDIS homepage
Ecosystem model - North Adriatic	Italy/UK -	Not specified	Algae	Effects of increases in nutrient supply and climatic factors on algal growth and mucilage formation	Operational	River basins and marginal seas	Generic	EC CORDIS homepage
Mercury-pollution	Denmark	Steady state model	Phytoplankton, fish	Effects of mercury discharges and climatic factors on accumulation in estuarine ecosystems	Operational	Estuaries	Generic	Jorgensen *et al* 1996

3.4 Models with terrestrial biological end-points

The review has identified some advanced management-orientated systems for strategic ecological prediction in the terrestrial environment, involving the linkage of physico-chemical and biological models and even economic models. In many cases the model component with the biological end-point is an associative (empirical) model linking plant species occurrence with habitat type, in much the same way as many of the wetland models outlined in Section 3.3.3 operate. There are also numerous complex dynamic models that are aimed at predicting the impacts of climate change and other factors on natural and semi-natural vegetation, including grasslands and forest stands.

ITE undertake modelling of changes in terrestrial communities as a result of land use change, using a matrix-based associative model to predict the likelihood of occurrence of species and species assemblages. This involves the use of national digital datasets of vegetation types and species distributions (at 1 km resolution) and works within the decision support system NELUP (see Section 3.5). Such modelling is being taken further, into the effects of factors such as habitat fragmentation, under the ITE's LANDECONET programme (LANDscape-ECOlogical NETwork).

There are numerous models dealing with the impact of climate change on terrestrial vegetation, some coarsely lumped and relating to the global scale (such as **HYBRID, FBM, IMAGE** and **HRBM**), some to the regional scale (**GVM, CARBON** and **CENTURY**), others to individual forest areas (such as **ECOCRAFT, CARDYN, TEMFES** and **BIOME-BGC**) and one at the level of the individual tree (**TREGRO**). Other models incorporate simulation of the effects of both climate change and land use change, such as the UK model **MEDRUSH** and the German/US model **SWIM** (see Appendix B for more details on both models).

One model funded by the EU 3rd Framework programme and developed collaboratively by the UK and France is aimed at simulating the abiotic conditions required for the development of woody riparian vegetation. The re-establishment of floodplain woodlands is a highly topical subject at present in England and Wales, and modelling to predict changes in the floodplain environment that would affect the success of such woodland is of potential value to the Agency.

Various models deal with the exposure of terrestrial organisms to hazardous substances and subsequent accumulation in biological tissues, including a number of models in the German **CemoS** package and another German model, **PLANTX. CATS** (Contaminants in Aquatic and Terrestrial Systems) is a complex, process-orientated Dutch model that deals with the accumulation of chemicals in the food web, divided into a number of functional groups. Whilst toxic effects are not simulated, they could be predicted by relating toxicological data to information on threshold tissue concentrations. **ACAC** and **PEF** simulate exposure of foraging animals as a result of soil and hence soil invertebrate contamination, with ACAC dealing with individuals and PEF focusing on populations.

Table 3.6 Summary information on models of interest relating to terrestrial ecosystems

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
ACAC	USA	Simple	Foraging animal species	Uptake of hazardous chemicals through foodweb	Operational	Single contaminated sites	Unknown	Freshman and Menzie 1996
BIOME-BGC	USA	Compartment model	Forests	Effects of climate change	Operational	Forests	Generic	UFIS database Hunt *et al.* 1996
CARDYN	Belgium	Compartment model	Forest stands	Impact of climate change on carbon fluxes	Operational	Forests	Generic	UFIS database Veroustraete 1994
CARBON	Netherlands	Compartment model (ordinary differential equations)	Woody and herbaceous vegetation (6 types)	General carbon cycle model	Operational	Global/regional	Generic	UFIS database
CATS	Netherlands	Compartment model	Bioaccumulation within different compartments of the food web	Exposure to chemicals	Presumed still under development	Covers habitats such as grassland, scrub, forest and aquatic habitats	Generic	Traas and Aldenberg 1992
CemoS/Chain	Germany	Compartment model	Chemical degradation and accumulation in consumers/producers	Exposure to environmental chemicals	Operational	Non-spatial	Generic	UFIS database
CemoS/Level1	Germany	Compartment model	Steady state distribution of chemicals in plants, fish, soil etc.	Exposure concentration estimates of environmentally hazardous chemicals	Operational	Ecosystems	Generic	UFIS database
CemoS/Plant	Germany	Compartment model	Plants	Exposure concentration estimates of environmentally hazardous chemicals	Operational	Organism	Generic	UFIS database
CENTURY	USA	Compartment model (ordinary differential equations)	Grasslands and agro-ecosystems	Impact of regional climate change on a variety of important grassland ecosystems	Operational	Regional	Generic	UFIS database Parton *et al.* 1993
CL-CCE	Netherlands	Expert system	Forest soils and surface waters	Model calculates critical loads of acidity and sulphur	Operational	Ecosystems - areas of variable size	Generic	UFIS database

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
ECOCRAFT	UK & 8 collaborating countries	Process-based, deterministic	European trees	Impacts of rising CO_2 and temperature on forest stands	Under development	Forest stands	Applicable (UK lead project)	EC CORDIS homepage
EXPECT	Netherlands	Modelling system comprising dynamic and empirical models	Forests and heathlands	Effect of environmental policy scenarios on acidification, growth and overfertilization	Operational but extension work halted	Regional (districts)	Developed for the Netherlands	Bakema *et al* 1994
FBM (Frankfurt Biosphere model)	Germany	Compartment model	32 vegetation types	Seasonal and long term carbon dynamics (exchange between terrestrial ecosystems and atmosphere	Operational	Global/regional	Generic	Jørgensen *et al* 1996 Ludeke 1997
GVM	USA	Static model	Biomes	Impact of climate change on geographic extent of biomes	Operational	Coarse scale (0.5^{deg} X 0.5^{deg})	Requires IIASA global climate database as input	UFIS database
HRBM	Germany	Dynamic	Terrestrial vegetation	Carbon cycling through terrestrial vegetation in response to climate and CO_2 forcing	Operational	Regional to global scale	Generic	Jørgensen *et al* 1996
HYBRID	UK	General global ecosystem model	Generalised plant types (grass, broadleaf and coniferous trees)	Effect of environmental factors on carbon, nitrogen and water cycle	Operational	Global ecosystem	Applicable	UFIS database
IMAGE	Netherlands	Unknown	Vegetation	Climate and land use change	Unknown	Global	Unknown	Pers comm J Wiertz, RIVM
MEDRUSH	UK	Dynamic GIS-based distributed process model	Vegetation (growth and distribution)	Effects of seasonal/annual and long term climate and land use variations on vegetation growth and distribution	Under development	Areas up to 5000 km^2	Applicable	UFIS database
NELUP	UK	Biological component is empirical	Species and species assemblages	Land use change	Operational	1 km grid suitable for regional/national scale	High	O'Callaghan 1996
PEF	USA	Simple	Foraging animal species	Uptake of hazardous chemicals through foodweb	Operational	Individual contaminated sites	Unknown	Freshman and Menzie 1996
PLANTX	Germany	Compartment model	Plants	Accumulation of anthropogenic chemicals in roots, stem and leaves	Operational	Landscapes	Generic	UFIS database

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
RAMAS	USA	Not specified	Wildlife populations	Human impact on wildlife populations	Operational	Landscape	Generic	UFIS database Kingston 1995
SAEM	Not specified	Empirical (2-D stepwise regression model)	Forests (predicts number of species)	Impact of environmental characteristics on biodiversity (e.g. annual rainfall, human population density)	Operational	Regional landscapes	Generic (relatively little information provided)	UFIS database
SWIM	Germany/ USA	Dynamic, distributed model	Vegetation (growth)	Effects of climate change and land use change on hydrology and water quality (and subsequently plant growth)	Operational	Watersheds (100 to 20000 km^2)	Generic	UFIS database
TEMFES	USA	Process-oriented model	Forests	Transient response of unmanaged forest systems to long-term changes in climate and atmospheric CO_2 concentration	Should be completed	Forests	Generic	Jorgensen *et al* 1996
TREGRO	USA	Dynamic process model	Most tree species	Response (growth and patterns of carbon allocation) to levels of ozone, nutrient stress and water availability	Operational	Individual trees	Generic	UFIS database Weinstein and Yanai 1994
European terrestrial modelling activity	Sweden/UK/ Italy/Germany/France	Modular modelling framework	Vegetation	Human impact and natural disturbance - ecosystem-planetary boundary layer interactions, CO_2 and H_2O fluxes	Under development	Simulation of ecosystem at "patch" scale (<0.1 km) or regional scale (10-100 km)	Applicable	EC CORDIS homepage
Integrated vegetation and economic model	UK	Empirical	Upland plant communities	Costs of achieving a given area of desired vegetation	Operational	Upland area of River Tyne catchment	Applicable	Moxey *et al* 1995
Model of woody riparian vegetation	UK/France	Dynamic, GIS-based model	Woody riparian vegetation species	Germination and establishment in relation to hydrological and ecological determinants	Operational	Floodplains	Applicable	EC CORDIS homepage

Model name	Country of origin	Model type	Biota modelled	Modes of impact addressed	Status	Area/habitat covered and spatial scale	Ease of application in E&W	Reference
ECOCRAFT	UK & 8 collaborating countries	Process-based, deterministic	European trees	Impacts of rising CO_2 and temperature on forest stands	Under development	Forest stands	Applicable (UK lead project)	EC CORDIS homepage
EXPECT	Netherlands	Modelling system comprising dynamic and empirical models	Forests and heathlands	Effect of environmental policy scenarios on acidification, growth and overfertilization	Operational but extension work halted	Regional (districts)	Developed for the Netherlands	Bakema *et al* 1994
FBM (Frankfurt Biosphere model)	Germany	Compartment model	32 vegetation types	Seasonal and long term carbon dynamics (exchange between terrestrial ecosystems and atmosphere	Operational	Global/regional	Generic	Jørgensen *et al* 1996 Ludeke 1997
GVM	USA	Static model	Biomes	Impact of climate change on geographic extent of biomes	Operational	Coarse scale (0.5^{deg} X 0.5^{deg})	Requires IIASA global climate database as input	UFIS database
HRBM	Germany	Dynamic	Terrestrial vegetation	Carbon cycling through terrestrial vegetation in response to climate and CO_2 forcing	Operational	Regional to global scale	Generic	Jørgensen *et al* 1996
HYBRID	UK	General global ecosystem model	Generalised plant types (grass, broadleaf and coniferous trees)	Effect of environmental factors on carbon, nitrogen and water cycle	Operational	Global ecosystem	Applicable	UFIS database
IMAGE	Netherlands	Unknown	Vegetation	Climate and land use change	Unknown	Global	Unknown	Pers comm J Wiertz, RIVM
MEDRUSH	UK	Dynamic GIS-based distributed process model	Vegetation (growth and distribution)	Effects of seasonal/annual and long term climate and land use variations on vegetation growth and distribution .	Under development	Areas up to 5000 km^2	Applicable	UFIS database
NELUP	UK	Biological component is empirical	Species and species assemblages	Land use change	Operational	1 km grid suitable for regional/national scale	High	O'Callaghan 1996
PEF	USA	Simple	Foraging animal species	Uptake of hazardous chemicals through foodweb	Operational	Individual contaminated sites	Unknown	Freshman and Menzie 1996
PLANTX	Germany	Compartment model	Plants	Accumulation of anthropogenic chemicals in roots, stem and leaves	Operational	Landscapes	Generic	UFIS database

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Other models in the table deal with acid and sulphur deposition onto terrestrial and/or freshwater systems, identifying critical loads above which ecological damage is likely to occur (the **UK Critical Loads** mapping programme, **CL-CCE** and **EXPECT**). EXPECT differs from the critical loads approach in that biological effects (on forests and heathlands) are predicted, rather than the likelihood of impact being related to threshold values of loads. Whilst EXPECT was to be extended to cover freshwaters, development was halted in favour of other modelling systems, particularly NELUP (pers. comm. J. Wiertz, RIVM).

3.5 Umbrella software

Umbrella software can provide important user-friendly links between environmental managers and the models required in the process of predicting changes in human activities, thence changes in the physico-chemical environment, and thence changes in biological communities. In the future, such software should bring ecological modelling much closer to the users of model outputs and thereby make environmental forecasting a more efficient and direct process. This type of software can vary from simple decision support systems to complex integration platforms.

Nature Planner is a decision support system under development at RIVM in the Netherlands, acting as an integration platform for a number of ecological models and aimed at assisting the formulation of environmental policy decisions. It is therefore a highly relevant system in terms of environmental forecasting. Nature Planner deals with the combined effects of eutrophication, acidification, water table draw-down, landscape fragmentation, climate change and pollution by toxic substances, in relation to both species and ecosystems (pers. comm. J Wiertz, RIVM). It includes the wetland model MOVE.

The Institute of Terrestrial Ecology has developed **NELUP** (NERC/ESRC **Land Use** Programme), a decision-support system for use in assessing the ecological implications of policy changes concerning land use. NELUP brings together an economic model, hydrological models and an ecological model. Land use changes are predicted by economic appraisals, and the hydrological implications of these changes can be simulated by hydrological models at high resolution, small-scale (SHE-TRAN) or low resolution, regional/national scale (NUARNO). The hydrological predictions alone are of great potential value for environmental forecasting within the Agency, indicating potential water resource problems associated with possible future changes in land use. Ecological modelling, as outlined in Section 3.4, does not appear to be linked to hydrological simulations.

The USEPA's **BASINS** package takes an important step in linking non-point source (NPS) models to models of environmental fate and ecological impact. The review of NPS models conducted by Mainstone *et al.* (1994) highlighted that many packages were of reduced value in pollution prevention and control because they stopped at the land/water interface. BASINS brings together a high-powered US NPS model (HSPF) with the important aquatic models QUAL2EU and TOXIROUTE to allow detailed agricultural management scenarios to be linked to ecological consequences for the riverine environment. In terms of environmental forecasting, HSPF is perhaps not the best choice of NPS model, since it has a very high spatial resolution and consequently only models one field at a time (unless it has been modified extensively since 1994). However, it could be used to test general scenarios on a range of

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4. CONCLUSIONS

1. The review has revealed a large array of models with biological end-points (or physico-chemical end-points couched in biological terms) that are of potential value to the Environment Agency in environmental forecasting, including models of the effects of:

    - climate change on terrestrial vegetation and aquatic ecosystems;
    - land use change on terrestrial vegetation;
    - eutrophication in the full range of environmental waters (including ditch systems);
    - exposure to hazardous substances in all environmental media;
    - acidification;
    - dehydration of wetlands;
    - physical changes to river and floodplain ecosystems.

2. In addition to the models identified, there are numerous European contacts and data sources highlighted by this review that will be of value to the Agency in the future consideration of models for environmental forecasting. The World Wide Web has proved to be a particularly important source of information on modelling activity worldwide, including one database devoted solely to ecological models.

3. Whilst the review has provided a good starting point in the identification of suitable models, it must be treated as a preliminary exercise only. The lists of models produced is not definitive, due to the wide remit of the review (covering all environmental media, all biological components and all types of potential impact), the huge amount of modelling work being undertaken in Europe and the US, and difficulties in obtaining responses from some key organisations.

4. If the information that has been gathered is any reflection of the progress made by individual European countries, the Netherlands stands out as being most advanced in developing models with biological end-points that can be used for the type of large-scale, strategic assessments assumed to be of most relevance in environmental forecasting.

5. In general, it has not been possible within the time available to draw meaningful comparisons between different models that fulfil similar functions. Such comparisons need detailed attention to both the nature of the predictions required and the characteristics of the models being compared, neither of which has it been possible to address within the current brief study.

6. Assuming that environmental forecasting will normally be undertaken at a strategic level covering large geographical areas (either regional or national), simple empirical models will generally be of more value that complex dynamic models. However, there may be no alternative to the use of complex models in certain situations.

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APPENDIX A - LIST OF EUROPEAN CONTACTS TO WHOM INFORMATION REQUESTS WERE SENT

Country/Name/Position	Organisation	Relevance
The Netherlands		
Jaap Wiertz	RIVM (National Institute of Public Health and Environmental Protection)	Responsible for most of RIVM's ecological modelling for planning purposes
Remco van Ek	RIZA (Institute for Inland Water Management)	Project Leader for DEMNAT
J.P.M. Witte	University of Wageningen	Technical contact for DEMNAT and other ecohydrological models
Frans Claessen Head of Groundwater and Regional Waters	RIZA (Institute for Inland Water Management)	Involved in DEMNAT development and use.
L van Liere	Laboratory of water and drinking water research, RIVM	Contact for models such as PCLake and PCDitch
France		
G. Decatheaugrue	L'Agence Seine-Normandie	Project Leader for a major review of French models of relevance to the integrated management of aquatic systems.
Germany		
F. Hosenfield Database administrator	Projektzentrum Oekosystemforschung, Ecosystem Research Centre, University of Kiel	General contact for this major German initiative.
M. Asshoff	Projektzentrum Oekosystemforschung	Technical contact for modelling issues, mainly involved in wet grassland modelling.
C Steinburg, Director	Institute for Aquatic Ecology and Inland Fisheries	No responses to information request received
Sweden		
R Johnson	University of Agricultural Sciences, Uppsala	Involved in a Nordic programme of research to develop predictive systems for fish, invertebrates and macrophytes.
G Persson	University of Agricultural Sciences, Uppsala	Involved in eutrophication research. No response to information request received
T Ebenhardt	The Swedish Biodiversity Centre	No response to information request received.
Norway		

Country/Name/Position	Organisation	Relevance
M Johannesen	NIVA	No response to information request received
Denmark		
S Jorgensen Editor-in-Chief of the Journal of Ecological Modelling	Royal Danish School of Pharmacy, Copenhagen	No response to information request received
T Moth Iversen	NERI, Roskilde	No response to information request received
UK		
P Leed-Harrison	Silsoe College	Involved in wetland modelling. No response to information request received
P Armitage	Institute of Freshwater Ecology, Rivers Laboratory	Involved in RIVPACS and also ecohydrological requirements in rivers.
S Ormerod	University of Wales	Involved in acidification impacts and the development of MEDUSA.
M Dunbar	Institute of Hydrology	Involved in PHABSIM. Recently reviewed methodologies for setting ecologically acceptable river flows.
L Firbank	Institute of Terrestrial Ecology	Involved in the LANDECONET initiative on ecology and landscape.
A Stebbing	Plymouth Marine Laboratory	No response to information request received.
A Harrison	Institute of Terrestrial Ecology	Possible contact for impacts of soil biota. No response to information request received.
T Ashenden	Institute of Terrestrial Ecology	Possible contact for impacts of atmospheric pollution on terrestrial vegetation. No response to information request received
B Wyatt	Institute of Terrestrial Ecology	Head of modelling research on biodiversity. No response to information request received
D Moss	Institute of Terrestrial Ecology	Involved in vegetation/habitat mapping and application spin-offs.

APPENDIX B

SUMMARY SHEETS FOR SELECTED MODELS

Model summary sheet

Model name: CemoS

Model type: Compartment

Environments covered: Air, soil, water

Aspects of the biota addressed: Food chain, fish, plants

Country of origin: Germany

Created by: Institute of Environmental Systems Research, University of Osnabrueck

Modes of impact addressed: A suite of models for estimating the exposure concentration of environmental chemicals

Spatial scale: Variable, depending on which model is applied

Status: Operational

Software/hardware: PC, Operation System: MS-DOS

Outline description

The model package CemoS is a program system that has been developed to estimate the exposure concentration of environmental chemical. The package contains the eight models described briefly below.

CemoS/Chain - is a food chain model consisting of three levels: producer, consumer 1 and consumer 2. Chemical degradation and accumulation in consumers is calculated after a single input of a chemical into the producer occurs. The change of the mass of a chemical in the producer and the consumers is described by a linear differential equation system with constant coefficients. Analytical solutions from the concentrations of the chemical in producer, consumer 1 and consumer 2 are given.

CemoS/Air - is a box model for calculating the atmospheric transport of a chemical after aerial emission (e.g. city). As well as the stationary chemical concentration in a rectangular box (area of emission source and height of atmospheric mixing layer), chemical deposition, photodegradation, advection, and annual inhalation dose are estimated.

CemoS/Buckets - is a cascade model for the description of transport and residing of chemicals in soil. In the model, the soil column is partitioned into different layers and the amount of the chemical and the water content in each soil layer is determined daily by difference equations.

CemoS/Level 1 - calculates the steady state distribution of a chemical in the compartments "water", "air", "soil", "sediment", "suspension", "fish" and "plant", assuming immediate equilibrium. All compartments are regarded as homogeneously intermixed. Partition coefficients between all media and one reference medium (e.g. water) are calculated. From this and from the volumina of the compartments, chemical concentrations and chemical mass in the compartments are calculated.

CemoS/Plant - calculates uptake of anthropogenic organic chemical form soil and air into the above ground part of plants as well as chemical losses from plant by volatilisation and metabolism in a given time. The concentration of a chemical in the plant as well as the concentration in the particles on the plant is governed by a first-order linear differential equation with constant coefficients.

CemoS/Plume - calculates the atmospheric transport of chemicals following point emission (e.g. from a chimney). assuming that atmospheric and meteorological properties are constant. Advective transport by wind and as well as dilution by atmospheric dispersion is also taken into account. The model is derived from the dispersion-advection equation.

CemoS/Soil - is a dynamical model for the description of the transport and the residing chemical in a soil column. The model can be used in three situations: 1. a single input of a chemical at the soil surface; 2. transport from a contaminated soil layer into deeper layers; 3. transport and residing in the case of continuous injection. The basis of the model is a one dimensional advection-diffusion/dispersion -equation.

CemoS/Water - is a steady-state model for the estimation of the pollution of a river by a chemical caused by a single continuous pollution source such as the discharge of sewage effluent into a river. The concentration profile and the mass balance of the chemical in the river, as well as the concentrations in the sediment and in the biota living in the river (e.g. fish), are calculated. The concentration profile of a chemical in the river, caused by a single emission, is described by an analytical equation derived from the mass balance in the river. All elimination processes are described by an aggregated first-order degradation rate. The sorption of the chemical on suspended material as well as the concentrations in the sediment and in the fish are calculated from the concentration in the water with the help of partition coefficients.

References

The above information was derived from the UFIS database of ecological models, administered by the University of Kiel in Germany.

Model summary sheet

Model name: CL_CCE (Critical loads model of the CCE)

Model type: Expert system

Environments covered: Forest soils and surface waters

Aspects of the biota addressed: Ecosystems

Country of origin: The Netherlands

Created by: National Institute of Public Health and Environmental Protection, Coordination Centre for Effects (RIVM, CCE)

Modes of impact addressed: Calculates Critical loads of acidity and sulphur

Spatial scale: National (forest soils and surface waters)

Status: Operational

Software/hardware: dBase for using European background data (if no national data available)

Files: FOREST.DBF; critical loads related data on forests. SOIL.DBF; critical loads related to data on soils.

Outline description

The model calculates critical loads of acidity and sulphur. It summarises the work of the National Institute of Public Health and Environmental Protection, Coordination Centre for Effects (RIVM, CCE) and a number of National Focal Centres (NFC). A critical load has been defined as "the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function".

The model considers the following ecosystems: countries submitting national data on calculated critical loads for either forest soils, surface waters or a combination of the two. For countries not submitting national data, critical loads for forest soils are computed, using European data bases which are described by Downing *et al.* (1993). All maps show the 5-percentile critical load, i.e. the deposition level needed to protect the most sensitive 95% of ecosystem area in each grid cell. (As a basis of the computation of the 5-percentile, the actual ecosystem area rather than the total area of the grid cell is used). Three equations deal with critical loads for aquatic ecosystems.

References

The above information was derived from the UFIS database of ecological models, administered by the University of Kiel in Germany.

Downing, R.J., Hettelingh, J.-P., de Smet, P.A.M. (eds) (1993) Calculation and mapping of critical loads in Europe: Status report 1993. RIVM Report: 259101003 (1993), ISBN 90-6960-047-1.

Model summary sheet

Model name: COHERENS

Model type: Coupled hydrodynamical-ecological model

Environments covered: Coastal

Aspects of the biota addressed: Plankton (phytoplankton and microplankton)

Country of origin: Belgium/UK

Created by: Currently being developed under the EC 4th Framework Programme by the Institute for Hygiene and Epidemiology (Belgium), The Natural Environmental Research Council (UK) and Napier University (UK).

Modes of impact addressed: Interaction of physics, microbiology and sedimentology of coastal and shelf seas

Spatial scale: Regional and shelf seas

Status: Under development, due for completion end of April, 1999

Software/hardware: Not specified

Outline description

The objective of COHERENS (Coupled Hydrodynamical-Ecological model for Regional and Shelf Seas) is the dissemination and exploitation of an integrated three-dimensional model which couples the physics, microbiology and sedimentology of coastal and shelf seas. the model has been developed over the period 1990-1996 within two MAST-supported projects by a multinational European group, and used to simulate conditions in stratified coastal areas with an important river input to the North Sea. The model will be made available to the scientific and coastal management communities for further diagnostic use and for testing as a prognostic and management tool.

The model has four major components: 1. a physical component with a general module for solving advection-diffusion type equations; 2. a biological module describing the cycling of carbon and nitrogen through microplankton and detrital compartments, with corresponding changes in nitrate, ammonium and oxygen concentrations; 3. a sediment module describing the deposition and erosion of suspended organic and inorganic material through a "fluff" layer; 4. an Eulerian and Lagrangian transport module for contaminants. The modular design allows easy updating of any particular process, the inclusion of an alternative solution method or the addition of new processes. a series of switches is implemented allowing the user to select whichever processes are required.

References

The above information was obtained from the European Commission's CORDIS (Coordinated R&D Information Service) homepage.

Model summary sheet

Model name: DEMNAT 2.1

Model type: Empirical

Environments covered: Fresh and brackish water wetlands

Aspects of the biota addressed: Plant species/vegetation

Country of origin: The Netherlands

Created by: Wageningen Agricultural University (in association with others)

Modes of impact addressed: Dehydration and associated water quality effects.

Spatial scale: National/ regional

Status: Ready for use (in Dutch) but a further version is being prepared.

Software/hardware: GIS-based.

Linked physico-chemical models: NAGROM and MOZART

Outline description

DEMNAT 2.1 is used by the Dutch Government for national-scale predictions of the effects of long-term changes in the hydrology of wetlands. The system uses 1:50 000 scale soils data aggregated into 52 ecologically relevant soil units, and a 6-class groundwater classification, which are used to define abiotic 'ecoseries'. In parallel with this, the national botanical database FLORBASE is used to produce vegetation maps of community-based species groups and indicate the level of 'completeness' of the community at individual sites. These maps are combined with ecoseries to link vegetation with environmental conditions. The combination of a species group with an ecoseries is termed an 'ecoplot', which is a site-level characteristic. Effects are computed at the site level and then aggregated up to 1 x 1 km grid cells so that local information is not lost. Predictions can be made of the effects of changes in spring groundwater level, upward seepage, the water level of small surface waters and the inlet of river water into local systems.

Predictions of changes in moisture conditions, nutrient availability, acidity and salinity are made for each soil type for a given hydrological 'dose' (or change). These are then related to vegetational changes through empirical relationships derived through FLORBASE. These two steps allow the derivation of a 'dose-effect' function for each ecoplot, which allows changes in hydrology to be translated into likely local effects. Dose-effect relationships for soils are based on small-scale process-based studies and so are more reliable than relationships typically used in national assessments. Hydrological changes are simulated by a national groundwater model NAGROM and a hydrological model of the unsaturated zone, MOZART. Vegetational changes can be converted into numbers relevant to nature conservation, with indices calculated on the basis of species rarity and richness.

The model is undergoing further development to allow predictions of vegetation recovery, which will require a better understanding of seed dispersal and the persistence of seed banks, as well as information on vegetation management. A PC version will soon be ready (in Dutch) which will be used nationally and will also be sent to the regional water boards of The Netherlands for medium-scale applications.

References

van Ek, R., Witte, J.P.M., Runhaar, J., Klijn, F., Nienhuis, J.G. and Pakes, U. (1996) DEMNAT 2.1 - Latest innovations on a national dose-effect model for the analysis of dehydration of wetlands in The Netherlands. Poster paper No. 90182 at Hydro GIS '96, Vienna, Austria.

Witte, J.P.M. (1998) National water management and the value of nature. Doctoral thesis, Wageningen University, the Netherlands.

Model summary sheet

Model name: ERSEM (European Regional Seas Ecosystem Model)

Model type: Dynamic comprehensive ecosystem model

Environments covered: Coastal

Aspects of the biota addressed: Carbon and nutrient cycling within ecosystem compartments

Country of origin: Denmark

Created by: Netherlands Institute for Sea Research

Modes of impact addressed: Eutrophication

Spatial scale: Regional seas (North sea) coarse scale

Status: Operational

Software/hardware: Runs on a UNIX workstation using the SESAME simulation modelling package

Outline description

ERSEM is a comprehensive ecosystem model which dynamically simulates the large-scale cycling of organic carbon, oxygen and the macronutrients nitrogen, phosphorous and silicon over the seasonal cycle in the North Sea. The model consists of an interlinked set of modules, describing the biological and chemical processes in the stratified or non-stratified water column and in the benthic system, as forced by light and temperature. Physical transport is included by driving the model with the output of physical circulation and dispersion models.

The model is generic in that it can be set up for any temperate shelf sea area by replacing the physical description of the North Sea by the appropriate description of another area. The biological and chemical processes contain no site dependence.

References

The above information was obtained from the European Commission's CORDIS (Coordinated R&D Information Service) homepage.

Model summary sheet

Model name: MEDRUSH

Model type: GIS-based distributed process model

Environments covered: Terrestrial

Aspects of the biota addressed: Vegetation

Country of origin: Joint - European Community (EC)

Created by: EC - as part of the Mediterranean Land Use and Desertification Project (MEDALUS)

Modes of impact addressed: Vegetation growth and distribution in response to land use and climatic factors

Spatial scale: Areas up to 5000 km^2

Status: Currently under development

Software/hardware: No information

Outline description

MEDRUSH is a combined geographical information system and large scale distributed process model that is intended to be applicable to areas of up to 5000 km^2 and for periods of up to 100 years. It is intended to provide scenarios of vegetation growth and the distribution of function types and to forecast water runoff, sediment yield and the ways in which these factors evolve in response to short-term sequences of storms, seasonal and annual variations in climate and long-term trends in climate and land use.

The development of this model is being funded by the European Community as part of the Mediterranean Land Use and Desertification Project (MEDALUS).

Reference

The above information was derived from the UFIS database of ecological models, administered by the University of Kiel in Germany.

Model summary sheet

Model name: PCDitch

Model type: Compartment-based, process-orientated but relatively simple

Environments covered: Ditch systems

Aspects of the biota addressed: Macrophyte and algal communities

Country of origin: The Netherlands

Created by: RIVM

Modes of impact addressed: Eutrophication

Spatial scale: Small drainage networks

Status: Under further development

Software/hardware:

Outline description

PCDitch has been developed from PCLake and simulates the competitive interactions occurring between algae and different functional groups of macrophytes. Algae are treated as one functional group, whilst macrophytes are divided into rooted submerged angiosperms, non-rooted submerged angiosperms, charophytes (stoneworts), non rooted floating plants (essentially the duckweeds but also water fern), and rooted plants with floating leaves. The processes simulated by the model include nutrient transport between sediment and water column, phosphorus adsorption, mineralisation of detritus, nitrification and denitrification. Model input parameters are flow rate of water, external nutrient load, water depth, and various sediment characteristics. The model simulates competition between functional groups using light availability, nutrient availability (both water column and sediment pools) and flow rate through the ditch system. The principal model output is dry weight of tissue residing in each functional group, which is converted into plant cover.

The model has been optimised with field data from the Netherlands and has had some success in modelling the effects of different rates of nutrient loading on the balance between submerged macrophytes and duckweed. Unfortunately, results were less reliable for charophytes and algae. So far it has only been used to model semi-stagnant, unmanaged ditches. Further developments proposed by the developers would account for management regime and a range of other factors (including water level fluctuations and ditch interconnectivity).

References

Janse, J.H. (In press) A model of ditch vegetation in relation to eutrophication. *Water Science and Technology*.

Model summary sheet

Model name: PCLake

Model type: Compartment-based, process-orientated but relatively simple

Environments covered: Lakes

Aspects of the biota addressed: Phytoplankton and submerged macrophytes.

Country of origin: Netherlands

Created by: RIVM

Modes of impact addressed: Changes in nutrient loading.

Spatial scale: Single lake

Status: Not fully operational

Software/hardware: ACSL Version 10

Outline description

PCLake accommodates the theory of alternative stable states in lake systems, whereby a lake can exist in one of two states (phytoplankton-dominated or submerged macrophyte-dominated) that possess inertia to change through a number of biological feedback mechanisms. It simulates changes in the competitive balance between the phytoplankton and macrophyte communities in response to changes in nutrient loading and the application of methods of biomanipulation. The model strikes a compromise between traditional eutrophication models (that deal only with nutrient cycling) and detailed biological models. The food web is described by a number of functional groups, comprising phytoplankton (divided into 3 groups - cyanobacteria, diatoms, and other small edible algae), zooplankton, macrozoobenthos, whitefish and predatory fish. The processes of sedimentation, resuspension, diffusion, burial and chemical adsorption are all simulated. The model calculates chlorophyll a, transparency, phytoplankton types and the density of submerged macrophytes.

The value of the model lies in its ability to simulate the effects of a range of lake management scenarios (including not only changes in external nutrient loading but dredging and fish population management) and to successfully account for the crucial role of trophic structure in the balance between phytoplankton and macrophytes. PCLake is currently being linked to a water transport model DUFLOW so that catchment problems can be investigated (pers. comm. L. van Liere, RIVM). It is also being linked to PCDitch, so that the integrated modelling of lake and drainage systems can be undertaken. Given the uncertainty inherent in lake ecosystems, it may be that in the future model outputs are couched probabilistically in terms of ecological risk (scenarios of degradation) or likelihood of lake recovery (scenarios of improvement).

Reference

Janse, J.H. (1997) A model of nutrient dynamics in shallow lakes in relation to multiple stable states. *Hydrobiologia*, **342/343**, 108.

Model summary sheet

Model name: QUAL2EU - The Enhanced Stream Water Quality Model

Model type: Ordinary Differential Equations - can be operated as either a steady-state or dynamic model

Environments covered: Branching streams and well mixed lakes

Aspects of the biota addressed: Algal production

Country of origin: The United States of America

Created by: United States Environmental Protection agency (USEPA)

Modes of impact addressed: Water quality and eutrophication (major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the DO balance)

Spatial scale: Stream and lake systems

Status: Operational and widely used in the US

Software/hardware: Original DOS Operating system now with Windows interface.

Outline description

The Enhanced Stream Water Quality Model (QUAL2E) is applicable to conventional pollutants in branching streams and well mixed lakes. It can be operated either as a steady-state or dynamic model and is intended for use as a water quality planning tool. The model can be used to study impact of waste loads on instream water quality and identify magnitude and quality characteristics of non-point waste loads. By operating the model dynamically, the user can study diurnal dissolved oxygen variations and algal growth. However, the effects of dynamic forcing functions, such as headwater flows or point source loads, cannot be modelled with QUAL2E. QUAL2EU is an enhancement allowing users to perform three types of uncertainty analyses: sensitivity analysis, first order error analysis and Monte Carlo simulation.

The QUAL2E Windows interface was developed to make the model more user friendly. It provides input screens to facilitate preparing model inputs and executing the model. It also has help screens and provides graphical viewing of input data and model results. Examples with datasets are included which illustrate how to use the windows interface to enter the model inputs, run the model and plot its results.

QUAL2E forms an integral component of the USEPA's BASINS (Better Assessment Science Integrating Point and Non-point Sources) model used widely as an environmental analysis system in watershed and water quality based studies where it allows fate and transport modelling for both point and non-point source loadings.

Reference

The model and associated files can be downloaded from the USEPA home page at http://www.epa.gov.

Model summary sheet

Model name: SMART2/MOVE

Model type: Process-based/Empirical.

Environments covered: Terrestrial habitats

Aspects of the biota addressed: Plant and bird species

Country of origin: The Netherlands

Created by: RIVM, National Institute of Public Health and Environmental Protection.

Modes of impact addressed: Changes in nitrogen availability and pH due to nitrogen deposition, water management and vegetation development.

Spatial scale: National/ regional

Status: Operational for predicting national and regional policy scenarios.

Software/hardware: ?

Outline description

SMART2/MOVE are linked models simulating the combined effects of acidification, eutrophication and desiccation on vegetation. They work within Nature Planner, a Decision Support System and integration platform developed for environmental policy decisions. The aim of Nature Planner is to provide assessments of the combined effects of eutrophication, acidification, water table draw-down, landscape fragmentation, climate change and pollution by toxic substances on ecosystems and species. It is currently operational for plant and bird species, but it may be extended to other biological groups.

SMART2 is a simple process-orientated soil model, evaluating the changes in nitrogen availability and pH due to changes in N deposition, water management and vegetation development. MOVE uses the output from SMART2 and predicts the probability of occurrence of plant species using a database of species distributions and soil conditions. The system operates at a maximum spatial resolution of 250 x 250 metres.

Reference

Outline description provided in:

Witte, J.P.M. (1998) National water management and the value of nature. Doctoral thesis, Wageningen University, the Netherlands.

Model summary sheet

Model name: SWIM

Model type: Dynamic distributed model

Environments covered: Terrestrial

Aspects of the biota addressed: Vegetation

Country of origin: Germany

Created by: V. Krysanova, D.-I. Müller-Wohlfeil and A. Becker - Potsdam Institute for Climate Impact Research, Germany

Modes of impact addressed: Analysis of climate change and land use change impacts on hydrology and water quality at the regional scale

Spatial scale: Mesoscale watersheds(from 100 km^2 to 20000 km^2)

Status: Operational (SWIM users manual not yet available)

Software/hardware: Operating system: UNIX

Outline description

The objective of the Soil and Water Integrated Model (SWIM) is to simulate the hydrological cycle, erosion, vegetation growth and nutrient transport in mesoscale watersheds (from 100 km^2 to 20000 km^2); to analyse climate change and land use change impacts on hydrology and water quality at the regional scale.

The modelling approach utilises a three-level scheme of spatial disaggregation at basin, sub-basin and hydrotope levels. The soil profile is represented by a maximum of ten soil layers. A SWIM/GRASS (GRASS is a Geo. Information System) interface is used to initialise the model by extracting distributed parameters of elevation, land use, soil, climate, and to create hydrotope structure and routing structure files. The meteorological parameters used to drive the model are daily precipitation, air temperature (average, minimum and maximum) and solar radiation. The model operates within a daily timestep. SWIM can be used either for hydrological modelling only, or for integrated/crop, hydrological erosion, hydrological/water quality modelling.

SWIM is based on two previously developed models: SWAT (Arnold *et al*, 1993) and MATSALU (Krysanova *et al*, 1989) as direct application of both models for German watersheds was not possible (SWAT was specific to US datasets and MATSALU was specific to Matsalu Bay in Estonia). The model includes modules from both predecessors and attempts to combine the advantages of both.

The following hydrological processes are included: precipitation; snow melt; evapotranspiration; surface runoff; lateral subsurface flow (interflow), percolation to groundwater, groundwater contribution to stream flow, streamflow routing. The following geo- and hydrochemical processes are included; input of fertilisers, mineralisation, denitrification and nitrification, sorption/desorption (for phosphorus), crop uptake of nutrients, leaching to groundwater, transport with surface flow, transport with subsurface flow.

References

The above information was derived from the UFIS database of ecological models, administered by the University of Kiel in Germany.

Arnold, J.G., Allen, P.M. and Bernhardt, G.T. (1993) A comprehensive surface-groundwater flow model. *Journal of Hydrology*, **142**, p47-69.

Arnold, J.G., Engel, B.A. and Srinivasan, R. (1993) A continuous time, grid cell watershed model; In: Proceedings of Application of Advanced Technology for the Management of Natural Resources, sponsored by the American Society of Agricultural Engineers, June 17-19. 1993, Spokane, WA.

Krysanova, V. and Luik, H. (eds.) (1989) Simulation modelling of a system watershed-river-sea bay. Tallinn, Valgus, 428 pp, (in Russian).

Krysanova, V., Meiner, A., Roosaare, J. and Vasilyev, A. (1989) Simulation modelling of coastal water pollution from an agricultural watershed, *Ecological Modelling*, **49**, 7-29.