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Ecological modelling in the Environment Agency: consultation on business needs, science gaps and technical context

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Steve Killeen

Head of Science

Executive summary

The regulation and protection of the water environment in Britain have shifted towards ecological objectives as a result of the Habitats Directive (92/43/EEC), Water Framework Directive (WFD; 2000/60/EC) and the Water Act (2003), along with an increasing realisation that aquatic ecosystems will be highly sensitive to climate change. In the core areas of flood defence, water resource management, abstraction licensing, water quality management and discharge consents, as well as in the developing WFD need for hydromorphological regulation, management decisions must be linked to ecological outcomes.

The protection and enhancement of ecological status and integrity are becoming increasingly important for the Environment Agency. However, current capabilities need bolstering to improve the diagnosis, interpretation and prediction of ecological responses to environmental pressures and the implementation of remedial measures. Modelling ecological impacts and links with physico-chemical drivers is explicit in the WFD Common Implementation Strategy for analysing impacts and pressures. Although reliance on expert judgement may be unavoidable in some cases, this might expose the Environment Agency to problems including lack of consistency, unspecified assumptions, low defensibility and limited quantification, particularly if used in high-risk cases. Outside the Environment Agency, freshwater ecological science, and hence the availability of appropriate evidence, is increasingly limited in key areas in which management tools are required.

Improved capacity in ecological modelling is perceived as a means of improving the Environment Agency's efficiency in meeting its evolving business needs. This project aimed to seek views from key staff in the Environment Agency about the current capability and needs in this respect. This was achieved through a consultation exercise involving 50 staff in key areas of model use, policy and data provision or data archiving and a follow-up workshop involving over 30 Environment Agency staff. Advice on technical issues affecting ecological modelling was also sought from the consultees.

Response to the consultation was excellent (90% of a sample of 50 consulted). There was wide consensus during the consultation and workshop that the Environment Agency cannot continue without effective ecological models. The need to develop Programmes of Measures that will deliver good ecological status using cost-effective methods will, in particular, focus needs on the diagnosis, analysis and prediction of outcomes. The array of water-dependent habitats and species on the Habitats Directive and UK Biodiversity Action Plans (BAP) has also focussed attention on delivery for ecological objectives.

Despite clear business needs for ecological modelling, the staff consulted were aware of many challenges to their effective use in the Environment Agency. At a generic level, these include the poor integration of physical and ecological science in the Environment Agency; poor mutual appreciation of the relative strengths, weaknesses and difficulties of sciences or modelling across these different sectors; the availability and organisation of staff with statistical or ecological modelling expertise; the intrinsic complexity in modelling effects on the distribution and abundance of organisms; and the weakness of models currently in use. There is mixed perception of the value of models.

Although numerous ecologically-oriented 'models' in the Environment Agency were identified, several problems currently limit their value:

- most 'models' with explicit ecological components are indices, screening tools or classification tools;
- many physico-chemical models make limited or no prediction of ecological effects;

- several putative ecological models have been developed without shared inputs from ecologists and physical scientists;
- there is a mismatch between physical and ecological models in their capability to capture key processes;
- links between ecology and physico-chemical drivers are often poorly parameterised;
- models may perform poorly when applied to dynamic circumstances where a range of lags effect affect rates of ecological change;
- few ecological models have been developed to support the Environment Agency's core business needs. Other standard models in the Environment Agency (e.g. RIVPACS) are considered in need of updating and reconfiguring to meet developing business needs for multi-functional management. Some fisheries-oriented models are an exception, and illustrate a range of effective conventional (i.e. frequentist) statistical and Bayesian approaches that have potential for wider use in ecological modelling;
- data quality and data requirements.

We recommend that:

1. the Environment Agency considers six broad options for developing capacity in ecological modelling, supported by tactical data collection and strategic monitoring;
2. the Environment Agency develops a Strategic Framework for developing and using models. This will not specify what models are used, rather it will produce a modelling 'process' that will encourage a structured, risk-based approach;
3. in particular, the Environment Agency should undertake a more detailed review of how ecological models could best be developed to meet its evolving needs. This should appraise the fitness-for-purpose of ecological models currently in use. It should also examine explicitly the strengths and weaknesses of the Environment Agency's data holdings and evolving monitoring strategy on which models might be based;
4. the Environment Agency specifically give early consideration to how and when to best use expert-judgement to develop sound corporate rules and defensibility of this approach;
5. the Environment Agency begins to integrate better the activities of physical scientists and ecologists;
6. the Environment Agency considers the importance of ecological modelling during staff recruitment and training.

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We thank all those staff in the Environment Agency who gave their time to the consultation and workshop, contributing their ideas freely and with open minds. The authors also record their thanks to the Project Steering Group for their guidance throughout.

Contents

1 Background and Introduction

In November 2006, CEH Lancaster and Cardiff University were approached jointly about a project intended to identify the business needs, technical context and capabilities of ecological modelling in the Environment Agency. Recent EU directives, in particular the Habitats and Water Framework Directive, were seen as shifting the basis of regulation and protection of the water environment in Britain from largely chemical focussed to compliance and monitoring based on ecological objectives. However, there was real concern that i) ecological responses to environmental pressures could not be effectively diagnosed or interpreted; ii) the mechanisms through which ecological impairment arose in any given circumstances could not be identified clearly, quantitatively or objectively; and iii) the ecological outcomes, costs and benefits of possible remedial measures or regulation could not be effectively predicted in ways that allowed adequate comparison among competing options. If supported by evidence, these concerns might suggest that the underpinning ecological science was too weak or too poorly linked to other disciplines for the Environment Agency to deliver on its evolving business needs with respect to restoring or maintaining good ecological status. With the Environment Agency's statutory requirements increasingly focussed on either key aquatic species (Habitats Directive) or assemblages of organisms in general (Water Framework Directive), these potential weaknesses could clearly have major ramifications.

This project was commissioned as a consequence of the above concerns, albeit with a small budget and extremely tight timescale (i.e. starting in December 2006 and reporting by March 2007). The project was intended to:

1. Provide business justification for the development of ecological models that could provide evidence to underpin the WFD.
2. Allow external experts on empirical modelling to consult key Agency staff to identify the business and technical context for ecological modelling within the Environment Agency.
3. Allow the external experts to advise upon various aspects of ecological modelling, such as:

- How to discriminate between 'evidence-based approaches', ecological risk assessment, ecological outcome modelling and more formal modelling applications.
- How to determine the most appropriate forms of ecological model for Agency application.
- The availability of underlying ecological science.
- The data requirements for model development and application.

The first and second of these broad aims were to be satisfied in two consultation phases respectively involving i) a questionnaire sent out to around 50 Environment Agency staff and ii) a follow-up workshop at which the initial findings were presented. The workshop, in turn, was intended to:

- disseminate the response to the initial consultation, and to assure its representativeness, completeness and accuracy;
- attain consensus on the top business priorities for ecological modelling;
- identify any gaps in Environment Agency science with respect to ecological modelling;
- propose, explore and agree options for developing ecological modelling capacity in or linked to the Environment Agency.

Parts of the first aim and all of the third aim were to be additionally informed by the consultants' knowledge of Environment Agency business.

This synthesis summarises the project's principle findings, with more detailed notes on the consultation, workshop and technical issues provided in Appendices 1-7.

2 The consultation phases

The consultation phases of this project were intended to identify:

i) Priority areas of Agency business need for ecological modelling, including policy and operational tools;

ii) Opportunities to develop and use ecological models;

iii) Why investment in a model might be necessary, with consideration of whether benefits outweigh costs?

iv) Whether useful data and knowledge exist or can be acquired;

v) The role and potential value of local expertise and expert judgement in Environment Agency decision as an adjunct or alternative to modelling.

For the purposes of this exercise, models were defined broadly as:
"the numerical, conceptual or graphical representations or simplifications of real ecological systems."

We envisaged 'modelling' to encompass a continuum from informal statements about ecological systems, to formalised mathematical descriptions. From the Environment Agency's perspective, we considered models to be tools to assist in the understanding and management of the ecological resources within the Environment Agency's sphere of interest. Thus, classification tools, screening tools and indicator metrics were not specifically excluded since both might have predictive value or might form potential model outputs when linked to other current models.

3 Anticipated business drivers

We expected the main business drivers for ecological models in the Environment Agency would probably focus on the generic need to diagnose, understand, analyse or predict how ecological resources respond to environmental pressures, remedial action or other management drivers. In particular, this could include the needs:

- to allow some comparison of likely ecological outcomes from competing management options in advance of action. Examples might include the need to compare the effectiveness of different actions in areas affected by multiple stressors (for example abstraction, habitat degradation, eutrophication), or the need to evaluate the value of actions at different scales (for example local versus river basin);
- to assist in prioritising possible management options;
- to support the wider aim of integrated catchment science by focussing on delivering river basin management plans;
- to improve the methods for using expert judgement where other methods were unavailable, for example by quantifying how ecological status reflects other environmental measures;
- to anticipate how future environmental changes, notably climate change, will affect ecological resources either directly or through interaction with other pressures;
- to support the core business of the Environment Agency in assessing the consequences of flood defence, water resource management (such as abstraction licensing) and water quality management (such as discharge consents) on ecological resources;
- to deliver a general approach to risk assessment in which ecological objectives are explicit;
- above all, to support key recent legislation, particularly:
  i) River Basin characterisation, classification and classification for Programmes of Measures under the Water Framework Directive (2000/60/EC). The WFD Common Implementation Strategy is explicit about the need to model ecological effects, as well as links between physico-chemistry and ecological effects, in the analysis of pressures and impacts (European Communities 2003).
  ii) The regulation of environmental quality to support the Habitats Directive (92/43/EEC) or UK Biodiversity Action Plan.
  iii) The need to identify and avoid varying degrees of environmental impact linked to abstraction and abstraction licenses as required by the Water Act (2003; ISBN 0 10 543703 4).

There is a need to deliver River Basin Management plans and Programmes of Measures that will deliver good ecological status using cost-effective methods. These will particularly focus on the diagnosis, analysis and prediction of outcomes. The array of water-dependent habitats and species on the Habitats Directive and UK BAP has also focussed attention on delivery for ecological objectives.

4 Consultation methods

The methods, questionnaire design and sample selection during the consultation exercise are outlined more fully in the attached document (Appendix 1: *'Summary of detailed responses to the consultation questionnaire'*). In brief, we divided the consultation questionnaire into 22 questions covering five general areas:

Section A. The current use of ecological models.

Section B. The business need for ecological models.

Section C. Finding a model best suited to the respondents' needs.

Section D. Are the appropriate resources in place?

Section E. Wider technical issues.

A sample of forty-nine respondents was targeted amongst Environment Agency staff. These were spread across functions, areas, regions and were intended to represent i) those likely to be actual or potential users of models; ii) those with links to data provision or data archiving on which models might be based and iii) key areas of policy likely to use model-oriented information. One additional response was received voluntarily. The entire sample was given a choice of responding by telephone or e-mail, with responses divided roughly equally between these two modes.

Many respondents requested that their names and job titles be kept confidential, and consequently all the following results are reported under Chatham House rules, with confidentiality a moral obligation on the consultants' part. Some respondents sent supplementary material or comments following the initial consultation, and these have been used to augment the report as far as possible.

The overall response to the consultation was excellent (90%) which we take to represent widespread interest in the subject matter.

5 Consultation outcome and synthesis: some key points

Specific details of the responses received during the consultation are covered more fully in Appendix 1. This section gives a broader overview of the points arising, with additional views from the consultants.

5.1 Business drivers

The business drivers indicated by the respondents for ecological modelling in the Environment Agency corresponded well with those anticipated in advance of the consultation (outlined in Section 4).

- Applications for models ranged from a local focus on regulatory needs to wider applications to drought, floods, water resource and water quality management for the WFD. To a lesser extent, the Habitats Directive also attracted some modelling effort.
- There was wide consensus that Environment Agency business cannot continue without effective ecological models since this should be a fundamental part of Environment Agency operation.
- The Environment Agency appeared to be recognising the need to develop classification and assessment tools (e.g. under the EMCAR project) better than the need to develop ecological modelling despite major business needs.

5.2 Models in use

The consultation revealed that the Environment Agency uses a wide range of environmental models, although explicit links to ecological response were patchy (Table 1). Among this *sample* of 'models' cited by respondents or known by the consultants to be in Environment Agency use:

i) Eight were biotic indices of various types that indicated environmental quality. We consider these to have a potential role in modelling either as response variables or as indicators whose status 'predicts' other environmental conditions. However, no such use is currently evident.

ii) Nine were classification tools that indicated environmental quality or departure from expected quality. These were divided between those where classification was based on some combination of ecological and physico-chemical variables (for example RIVPACS, LEAFPACS), those where physical features were used to predict conditions for organisms (HABSCORE) and those where ecological conditions are implied but not yet explicitly quantified or predicted (RHS, IRM). Like several respondents, we consider that many of these tools have unexploited potential in ecological modelling. Some will benefit from updating or reconfiguring the array of predictor variables (e.g. RIVPACS); developing better linkages with ecological response (e.g. RHS); by improved linkages with other models in the Environment Agency suite; by improving diagnostic capabilities (All); and by improving general predictive capacity (All).

iii) Beyond these simpler styles of model, there were some examples where ecological response was predicted from physico-chemical drivers (such as. PACGAP, GRC LIFE, DHRAM, PHABSIM, PROTECH). These models were often considered demanding in data requirements, and were frequently site specific rather than transportable. One exception was in fisheries, where a range of statistical models has been developed to predict or analyse population status from physico-chemical variables. The National Fisheries Technical Team (Head Office) has been centrally involved. This strength in fisheries modelling reveals how many of the frequently quoted difficulties associated with ecological modelling can be overcome. We suggest that these examples illustrate the potential opportunities, methodological capability and business value of more generic ecological modelling aimed at other groups of organisms. Most notably these include the other WFD indicators as well as individual species figuring in the HD, and the UK BAP. Both conventional statistical and Bayesian modelling methods were considered most promising and deliverable.

iv) There were several models in use where physico-chemical outputs had no explicit link to ecological response. Examples predicted hydrological behaviour, nutrient behaviour, sediment behaviour, and other aspects of water quality as part of a wide range of regulatory activities. Since impacts on ecological resources were often implied in these cases, we suggest there is both a need and an opportunity to link outputs to specific ecological prediction.

v) The Environment Agency is developing a range of models, often through its Science Programme. Some are being trialled in specific Environment Agency programmes, sometimes with other partners including water companies, universities, CEH and consultancies. We suggest that these, and other, developments across the ecological modelling sphere should be prioritised with respect to the Environment Agency's core business needs.

The consultees and workshop attendees discussed a very wide range of additional problems with current modelling effort. They included weaknesses in addressing error and uncertainty in many existing models, poor model selection, weaknesses in the variables models or their parameterisation with respect to the Environment Agency's business needs (for example reliance on discharge rather than hydraulics, poor quantification of sediment characteristics and hydromorphology in physical models), poor model evaluation and limited *a-priori* phrasing of questions or hypotheses. The past history of ecological models in the Environment Agency has been mixed, with examples such as RIVPACS acknowledged as successful, while investment in other areas is yet to yield major value.

5.3 Gaps in expertise and modelling activity

- With the exception of fisheries, there was much evidence that ecological modelling in the Environment Agency should be strengthened. This reflects views offered by many respondents both from the physical sciences (who were often frustrated at the difficulty of linking their model outputs with ecological response) and from ecology (who considered that the needs for ecological modelling in the Environment Agency had never been greater).
- Most ecological consultees considered themselves users of models or model outputs rather than modellers. Well-developed expertise or leadership in ecological modelling in the Environment Agency is extremely scarce and held by a very small number of staff.
- Respondents were very clear that major needs for modelling activity existed. One of the most widely cited from all sectors was the need to model the links between ecological response and hydromorphology, hydrology and river modifications. This link had been starkly exposed by the needs of the WFD, but also by other core Environment Agency activities (flood defence, drought monitoring, water resources, abstraction licensing,

habitat enhancement and restoration, climate change assessment). Modelling the ecological effects of diffuse pollutants (sediments, nitrogen and phosphorus), and understanding how different pressures interact (e.g. habitat simplification, water quality and abstraction) were also frequently identified. However, these were the only gaps suggested, and there is a wider need to predict ecological response to all environmental pressures (physical, chemical, climatic and biological). Models for lakes and transitional waters were considered weak.

5.4 Other needs exposed by the consultation

- The issue of expert judgement exposed debate, doubt and division within the Environment Agency. Some strengths were suggested, for example the considerable local knowledge of EA staff. However, there were also clear weaknesses with respect to i) low reliability and challenges in quantifying uncertainty; ii) the difficulty in identifying assumptions; iii) the lack of any knowledge base in some key needs on which to form expert judgement; iv) the requirement for regulatory decisions to be defensible, reliable, quantitative and site specific; v) the problem of variation among experts in the judgements they offered. We suggest that the Environment Agency needs guidance over the use of expert judgement, and in particular about where expert judgement offers an acceptable device to support decision making (e.g. where risks are low). In this case, the strengths and weaknesses of this approach should be recognised clearly. Finally, with expert judgement inevitable in some business cases, we suggest that the Environment Agency needs to bolster the basis on which expert judgment is made – for example by using improved generic models linking ecological response to environmental drivers or by developing Bayesian methods. Formalising the use of local expert knowledge in risk assessment or screening could also offer an option in many aspects of Environment Agency casework.
- Respondents suggested the need for other specific developments, notably with respect to basin-scale models of ecological response and models for lakes/small water bodies in general.
- Generic suggestions for improving models included the need to adapt models better to the specific needs of the Environment Agency; the need for models to be less data-demanding; the need for models to report better with respect to uncertainty; and the need to reduce uncertainty.
- A further specific need is to develop a Strategic Framework for developing and using ecological models using a 'tiered' risk-assessment approach. The approach adheres to the UK Risk framework set out in 'Greenleaves 2', guidelines for environmental risk assessement and management (DETR/EA/IEH, 2000).
- There is insufficient help (documentation, training, contacts) within or outside the Environment Agency to support a better understanding of models and their potential uses.
- Staff were rarely aware of exploitable models existing outside the Environment Agency but many think that this was an area where there should be increased awareness.

5.5 Filling the gaps

- Some respondents, often physical scientists, suggested that improved ecological modelling was dependent on better integrating physical sciences with ecology in the Environment Agency. This will require bolstering basic ecological science while encouraging physical scientists to see the ecological relevance of their work and their model outputs. At present, the vast majority of trained ecological staff are focused on routine activities such as operations, casework, monitoring, investigations or ecological appraisal so that staff resources or expertise for model development are not easy to identify.

- Staff with close links to monitoring identified an opportunity to develop conventional statistical or Bayesian models based on the very substantial archive of Environment Agency data. Potential benefits could arise in i) better exploiting past investment; ii) satisfying future regulatory needs by more targeted future monitoring; iii) improved quantification of the physico-chemical conditions most likely to deliver good ecological status. Improving the interface and compatibility across existing Environment Agency data sets was suggested as means of facilitating model development. In general, several important synergies were envisioned that linked effective modelling to effective monitoring and data collection.
- By contrast, some respondents considered that poor quality datasets held in some sectors of the Environment Agency were a potential weakness that could limit modelling progress. Some water quality data and biological data sets were flagged.
- It is highly likely that different modelling approaches will be needed for different tasks within the Environment Agency. However each model needs to be appropriate to the task or question for which it is being used, with questions clearly specified. Data availability and validation need to be defensible should decisions be subsequently challenged. A toolkit of models is needed for different tasks with a simple decision-support system.
- It was considered important to develop better links between Environment Agency science and other sectors involved in ecological modelling (such as CEH and universities) so that the Environment Agency become aware of what tools are available externally and external providers recognise the Environment Agency's business needs.

6 Recommendations: some broad options

Our view is that the Environment Agency now needs to consider how to move forward with respect to the development of ecological modelling. This should be seen as part of a wider strategy for improving the quality of its ecological science, alongside developments such as the structured review of ecological knowledge and data.

In broad terms, the options are:

i) To do nothing, continue with the status quo, and rely on existing capability.

ii) To consider how and when to use alternatives to ecological modelling, such as expert judgement.

iii) To develop a Strategic Framework for developing and using ecological models in the Environment Agency. Having produced a modelling 'process', which encourages a structured approach, this option will then review fitness-for-purpose and potential of existing models. This would be similar to the review recently undertaken in Science Ecotoxicology. It should consider explicitly the strengths and weakness of the Environment Agency's data holdings and monitor strategy on which models might be based.

iv) To develop better ecological modelling capability in-house. Given the limited expertise in ecological modelling at present, collaboration with the wider research community would be a required feature of this option.

v) To develop ecological modelling through substantial targeting from the Environment Agency Science programme.

vi) To develop ecological modelling as part of a wider consortium both of funders (e.g. government/water undertakings) and providers (research institutes and universities).

Given the pressing business needs identified in section 4, we believe that option i) would limit the Environment Agency's professional scope, capability, business efficiency and cost-effectiveness when deciding among competing management options. Option i) is likely also to expose the Environment Agency to real risks associated with scientific credibility and the defensibility of its decision making.

We consider that none of the options from ii)-vi) is mutually exclusive, and all would improve the Environment Agency's business efficiency on a case-by-case basis. However, none of these options can progress effectively without first satisfying option iii) hence **our strongest recommendation is that the Environment Agency seriously considers developing a Strategic Framework for developing and using ecological models in the Environment Agency and conducts a review of fitness-for-purpose and potential of existing models**. We also recommend that the Environment Agency specifically give early consideration to how and when to best use expert-judgement to develop sound corporate rules and defensibility of this approach.

More generically, we also recommend that the Environment Agency begins to integrate better the activities of physical scientists and ecologists to achieve better mutual understanding and parity of esteem across these critical sectors of Environment Agency business. Finally, we recommend that the Environment Agency considers the needs of ecological models with respect to future recruitment and training needs.

Table 1: Examples of environmental models of all types currently used by the Environment Agency. Those marked with * have explicit links to ecological response variables. Those marked ? have ecological response dependent partly or wholly on expert judgment. A glossary of acronyms is in Appendix 1, Table A2.

Ecological indices	Classification tools	Tier-2 (simple) models	Specific models	Tier 3 (heavy) models	Models in development
BMWP* ASPT* LIFE*? CCI* MTR* MFR* CMI* TDI*	RIVPACS* LEAFPACS* PSYM* DARES* DALES* STAR* HABSCORE* FCS* RFHI* RHS IRM	PACGAP* GRC LIFE*? BSEIM CATCHMOD SDSM QUALSOC DHRAM* SIMCAT PRAIRIE SIDO-UK CRITICAL LOADS*	SEPA (176) Specific fisheries models (e.g. SALMODEL; SLM)* CLIO* SIAM REAS Generic statistical models for different groups*	PROTECH* PHABSIM* HUMBER DIVAST	RAM RAPHSA* CERF RPBRN* MIMAS? LAKEMIMAS? TRACMIMAS?

Appendix 1: Summary of detailed responses to the consultation questionnaire

Methods

We divided the consultation questionnaire into 22 questions covering five general areas (see Appendix 2):

Section A. The current use of ecological models.
Section B. The business need for ecological models.
Section C. Finding a model best suited to the respondents' needs.
Section D. Are the appropriate resources in place?
Section E. Wider technical issues.

In an accompanying mail (Appendix 2), respondents were offered the chance of responding by e-mail (considered the most effective way of capturing points directly in the respondent's own terms) or by telephone (considered to allow a more flexible discussion on each question with a well-informed interviewer). In total, 49 consultees (Appendix 3) were suggested by the Environment Agency. They were spread across functions and included area, regional and national staff. They were intended to represent an effective sample of either those likely to be actual or potential users of models or those with links to data provision or data archiving on which models might be based. Cardiff University initially mailed the entire sample, with Cardiff and CEH Lancaster respectively taking responsibility for follow-up contacts of 38 and 11. All except immediate mail respondents were then telephoned to ascertain the preferred response method and, where appropriate, to fix interview times. One other unsolicited response was received from a member of the project steering group and we included this in the total sample of 50.

Many respondents requested that their names and job titles be kept confidential, and consequently all the following results are reported under Chatham House rules, with confidentiality a moral obligation on the consultants' part.

Results

General issues

- Overall response rates were excellent (90%). From the total sample of 50, only four consultees declined to respond on the grounds of workload while another one never responded despite reminders. Overall, 23 responses came by e-mail, and 22 in interviews by telephone or in-person.

- Physical scientists, in general, preferred responding by telephone as they considered a questionnaire on ecological modelling concerned them only peripherally. Nevertheless, several were found to be using ecological models such as PHABSIM (= Physical Habitat Simulation) or were modelling information of direct ecological relevance (e.g. concentrations of potentially toxic contaminants or diffuse pollutants).

- Staff working in policy or data storage also considered the subject concerned them peripherally, and 6/10 in this category did not respond to section A (= *current use of ecological models*).

- Among consultees who felt closer to the subject, many considered themselves users of models or model outputs rather than modellers. In other words, they considered themselves to have some knowledge of models, including their assumptions and limitation, but not modelling skills or hands-on experience of model use.

- Several respondents were unsure about what was meant specifically by an 'ecological model'. For example, several Area staff initially doubted whether classification tools or quality indices should be included, while others offered these as examples. One respondent was unsure whether linear statistics that linked water quality and biological quality represented models. All have been included here.

- Responses on the detailed technical questions (Section E) tended to be poor, with e-mailed responses often ignoring this section. Telephone respondents engaged with these questions only with some difficulty.

- One respondent considered the questionnaire as a waste of time and not relevant to making management decisions.

Section A responses: current use of models

- Models suggested by respondents to be in current use in the Environment Agency are listed with their purpose and business aims in Table A1 and acronyms in Table A2.

- The most common models cited were biotic indices (such as BMWP/ASPT, LIFE), classification tools (RIVPACS, Habscore), PHABSIM and RAM (Resource Assessment Methodology framework) for Catchment Abstraction Managements. Some widely used Environment Agency indicators such as TDI (Trophic Diatom Index were not mentioned explicitly, nor were more recent innovations such as AWIC (Acid Waters Indicator Community). Other widely used models, such as RHS, were mentioned rarely.

- Models in development included:
    - ‘LIFE Response Curves’ which are intended to estimate LIFE scores for invertebrates from flow data
    - RAM (Resources Assessment Methodology) used in catchment abstraction management, currently awaiting an ecological add-on to link flow with ecological status
    - LAKEMiMAS, a screening tool to appraise potential hydro-morphological effects on the ecology of lakes
    - the addition of CERF to RIVPACS
    - RAPHSA (Rapid Assessment for Abstraction) based on PHABSIM
    - RPDS (River Pollution Diagnostic System) for applications in classification (see Table A1).

  Again, some potentially important areas of model development funded by the Environment Agency R & D programme, either alone or with other organisations, were either mentioned infrequently or not at all (e.g. Broad-Scale Ecological Impact Models, CLIO:*Climate Invertebrate Optima*, the MiMAS screening tool).

- Applications for the models ranged from a local focus on regulatory needs (Abstraction Licences) to wider applications to drought, floods and water resource management for the WFD. To a lesser extent, the Habitats Directive (sometimes misidentified by respondents as the ‘Water Habitat Directive) also attracted some modelling effort.

- Satisfaction with models in use was usually good except for PHABSIM, which all users considered expensive, complex and slow. This restricted use to high profile local cases. Similar concerns were also expressed about other complex models like the estuary models (e.g. HUMBER, WASH). There were growing signs of dissatisfaction with the Environment Agency standard tool, RIVPACS, which several respondents noted needed updating and/or reconfiguring, though no respondent said it needed replacing. Other critical comments on specific models included the need to take into account additional driving variables to increase the reliability.

- Generic suggestions for improving models included the need to be better adapt models to the specific needs of the Environment Agency; the need for models to be less data-demanding; the need for models to better reported with respect to uncertainty; and the need to reduce uncertainty. Issues associated with model uncertainty were considered to be growing in importance.

Other specific remarks on existing models included:

- Models have insufficient documentation on limitations, assumptions and applicability;
- Models are often complex, and most cannot be used by Area/Operational staff without training;
- There was some tension between models being sufficiently complicated to capture the main ecological features yet still easy to use.
- There is insufficient help (documentation, training, contacts) within or outside the Environment Agency to support a better understanding of models and their potential uses. For example, very few respondents knew of specialist courses on statistical modelling for ecologists operated in some branches of the Environment Agency (e.g. fisheries). The idea was suggested that it could be helpful to have a library or archive of model examples for different types of problems with documentation on use.
- Models do not always provide simple/understandable answers that help staff in the field. Examples cited included outputs as complex graphs and mathematical equations that were not readily translated into management or decision support.

Business needs for ecological models

- Nearly one third of the consultees, mostly ecologists, were unaware of any business needs for ecological models that were further to the present needs. However, there was wide consensus that Environment Agency business cannot continue without effective ecological models since this should be a fundamental part of Environment Agency operation.

- Respondents were very clear that major gaps existed, with one of the most widely cited from all sectors being the need to model the links between hydro-morphology, hydrology, modifications to rivers and ecological response. Several consultees were explicit that this link had been starkly exposed by the needs of the WFD, but also by other core Environment Agency activities (flood defence, drought monitoring, water resources, abstraction licensing, habitat enhancement and restoration, climate change assessment). Models to assess the effects of diffuse pollutants (sediments, N and P) and to help disentangle the effects of multiple pressures were also flagged. At a generic level, existing models are considered either too coarse (RAM) or too demanding in data to satisfy many key needs (PHABSIM). (*See also 'Resource issues', below*).

- Some respondents suggested that the Environment Agency was facing new and greater challenges than previously. With easier challenges solved, more demanding challenges will require more integrated science, with models crucial.

- In addition to the core areas (e.g. WFD), some respondents suggested that business needs in the Environment Agency are changing with more emphasis on total environmental health and system maintenance. Ecological models, nested from local to national, are crucial to delivery in these new areas.

- Staff with close links to monitoring identified an opportunity to develop models based on the very substantial archive of Environment Agency data (water quality, RHS, BIOSYS….) with the joint purposes of i) better exploiting the past investment in data collection; ii) satisfying future regulator needs through more targeted future monitoring at reduced frequency. Improving interfacing and compatibility across existing Environment Agency data sets and data bases was suggested as means of facilitating model development.

- By contrast, some respondents considered that poor quality datasets held in some sectors of the Environment Agency were a potential weakness that will limit modelling progress in some areas. Water quality datasets were identified as being of poor quality by a number of respondents in terms of limits of detection that were too high to be ecologically useful, while unreliable analyses or inappropriate methods were also flagged (e.g. measuring SRP on unfiltered samples). Issues of quantification, frequency of sampling and the limits of family-level identification were also flagged with respect to biological data. No respondents flagged non-random site selection as an issue affecting data quality.

- A small number of respondents (2) suggested that involvement in modelling should not be restricted to national teams but should also be devolved to Area staff. This would help focus efforts of the collection and analysis of data of higher quality.

- Staff were rarely aware of exploitable models existing outside the Environment Agency but many think that this was an area where there should be improvement. Regularly updated desk manuals on expertise and available models within and outside the Environment Agency were considered potentially useful. Good quality documentation on availability, purpose, running costs, limitations, assumptions, rapidity, reliability and user-access were all considered important. Staff in 'Ecosystem and Health' apparently have this facility.

- Most respondents considered that Environment Agency staff lack training and time to allow them to better use and amend existing models.

- The issue of expert judgement revealed very divergent opinions about fitness for business purpose that could be separated into *pros* and *cons*:

  - Stated *pros* were that i) the Environment Agency benefits from long-standing staff with excellent local knowledge which is often under-exploited; ii) expert judgement, they suggested, could outperform models in the quality of outcomes and costs involved; iii) in some issues and some cases (e.g. transitional/coastal waters), expert judgement was the only affordable option available; iv) expert judgement was considered a potential useful component when included in Bayesian models. One respondent suggested that highly qualified staff should be identified as those from whom expert judgement could be considered most reliable. Some suggest that expert judgment might be used systematically a) to screen problems and assess modelling needs (first tier approach), b) to check the results of model output as is in the 52 risk maps of the WFD program. One respondent suggested capturing expert judgement in expert systems similar to those used by medical diagnosis software.

  - *Cons* included i) low reliability and unquantifiable uncertainty; ii) the difficulty in identifying assumptions; iii) the lack of any knowledge base in some key needs on which to form expert judgement (e.g. hydro-morphology vs ecology); iv) the requirement for regulatory decisions to be defensible, reliable, quantitative and site specific; v) the problem of variation among experts in the judgements they offered. Models were considered by some to be a very powerful way of defending regulatory decisions, carrying more weight that expert opinion in this context.

Finding the best models

- The best model availability was for specific issues that required specific detail application. Models relating to general issues and monitoring were also considered adequate at least for a coarse level of understanding. More substantial needs were identified for models of sufficient detail at intermediate scales – e.g. individual catchments

- In a closely related point, one respondent suggested the need for a hierarchy of models needed with, crucially, a clear and easy-to-use system to help Area and Regional staff decide what level of model is needed for a particular task. Generally there was a trade-off between simple models using national data vs complex, difficult and data hungry models. An increasing requirement is for some models to be easy-enough for Environment Agency staff to use in predictive mode.

- Irrespective of the model type and algorithm, the major constraint on model choice argued by most respondents was that models should offer a quick response at small cost.

- All those who expressed an opinion on the best models types suggested that 'simple' linear models offered an attractive option. One response indicated that statistical models could be a valuable way of modelling in instances where underlying processes - such as fish population dynamics – were known. Another respondent suggested that some of the available data were qualitative and thus not adapted to this purpose.

- Some respondents identified GIS-based models /spatial models as a forward option since quantitative links between GIS layers were underexploited in this domain. Others flagged the importance of spatial and/or map-based representations of model outputs.

- Some respondents suggested that future ecological models should be broader and take more processes into account. This was especially important as ecosystem health was considered increasingly.

- Clearly-defining questions for which a model was being used was considered an important influence on model choice. The need was expressed for a hierarchy of models with clear decision-support systems to identify which might be appropriate for a given problem.

Resource issues

- General limitations to using models that were very widely expressed include lack of time, incomplete training, lack of resources, lack of data and inappropriate software.

- Some specialists felt that resources were sufficient for modelling in their area of work but there was a general perception among non-specialist users of models that more time and training was needed to better develop skill in model use.

- The question of where modelling skills should best be located exercised very considerable debate. Some consider facilities should mainly be within the Environment Agency because consultants do not provide models that are adapted to area and operational staff; there was some argument for new posts as the modellers in place have too little time. Others were content to develop joint collaborations, for example in the field of data mining and statistics. None thought models exclusively created by consultants was an option.

- Modelling expertise was required at different levels. This included outside experts, national teams and regional/area users. It is important to make sure that the Environment Agency management structure promotes effective communication between different modelling developers and users within the Environment Agency. Where outside experts are used, it is good idea to develop models in a consortium with Environment Agency staff (or even the organisations that will be regulated) to pools skills and insights, and to prevent ‘surprises’. The Environment Agency needs credible in-house expertise.

- One respondent suggested that modellers should be involved with the 'customers' within the Environment Agency who are using the model outputs.

- Relevant ecological knowledge to develop ecological modelling was thought only to be ‘partly available’, and not always at the appropriate scales or data to be integrated to the issues at hand. In some areas the science was widely regarded as inadequate to answer the ecological questions.

- Nearly all the staff involved in using models said they had no time to develop, build or better understand models and their applications.

- Most respondents underlined an urgent need to gather the necessary data and improve the science linking ecology to its main drivers (e.g. water quality, hydrology, hydro-morphology) before hybrid hydro-ecological models could be produced. The most sceptical of capabilities in this area were physical scientists.

- The availability of key ecological science (within and, many thought, outside the Environment Agency) was limited and declining. Resourcing this problem was seen as a priority. Classification tools, for instance, are mainly based on hydro-chemical criteria rather than biological, and this could engender inaccuracy. Knowledge gaps for freshwaters and lakes in particular, were flagged.

- One of the current consequences of existing knowledge gaps is that the quality of risk assessments maps for WFD is patchy. Maps linking some pressures (e.g. hydro-morphological degradation) to ecological impacts are 'not very dependable', and this could severely expose the quality of management decisions.

- The Environment Agency data holdings were seen as a valuable resource, but time series aspects were considered weak for some purposes. Models will be poor unless the

Environment Agency continues to invest in the collection of long-term and large-scale data.

- Some respondents noted that modelling complements data collection and is not an alternative. Sometimes making a field measurement was considered more cost-effective or accurate than using a model, and this should be recognised.

Other comments offered by respondents

A range of other less easily categorised comments was offered by respondents. They included:

- There is a risk of fragmentation of Environment Agency science despite the need for integration to tackle more difficult ecological problems. Modelling could be one approach to help integration.

- There is a need to convince politicians that the development of ecological modelling is a large issue that needs funding.

- Bayesian models are a potentially valuable way forward but the approach needs to be understood better by the model users.

- Modellers in the Environment Agency were not easy to access, mostly because of their geographic dispersal; and they had little time available. Communication in general between modellers and operational staff could be enhanced.

- Modellers from hydrology and ecology did not communicate sufficiently (if at all). Both physical scientists and ecologists underlined this issue and suggested work needed to be done in collaboration, starting from section heads and senior staff.

- The data held by the Environment Agency should be better used.

- On data audit measures, the Environment Agency data storage and archiving is considered extremely strong.

- The process of hosting models on the Environment Agency's information system is described as 'onerous and expensive '. The Environment Agency should better manage the maintenance of the models developed either internally or externally. The models used by the Environment Agency, or that could be used by the Environment Agency, should be managed at a national level in a unit analogous to the existing National Data Unit. Management should include the software, the documentation, the data sources, the list of users, the potential, the assumptions…

- “Effective model development and application is a long term undertaking. The instability of Environment Agency structures coupled with the short-term approach of Environment Agency management inhibits the application of ecological models”.

- The computerisation of historical data that exist as paper records is important.

- “Getting the right people to develop the models is difficult. The way that ecology is funded in the Environment Agency doesn't help - in particular the feeding frenzy that happens during tendering for each individual project”

- Some hydrogeologists believe that ecologists would gain from a risk-based, tiered approach to modelling, an approach already used by groundwater modellers and also by staff in Science Ecotoxicology.

- Some respondents offered the names of key people that we have missed during consultation.

Table A1 Some examples of ‘models’ currently in use by the Environment Agency as identified by respondents during the consultation on ecological modelling, January 2007 (see Table A2 for Acronym glossary).

Model name	Model function	Origin/type	Use	Business need	Potential for improvement?
i) Indices					
BMWP/ASPT	Biotic indices	CIES/ index	First tier applications: water quality classification, drought and abstraction investigations, pollution investigation, national reporting	Support for regulatory policy (HD, licensing); for statutory national reporting (GQA, WFD); evaluation for national strategies (CAMS) Operational; Habitat Directive	Indices can highlight areas for closer investigation No idea of effectiveness; diagnostic value limited.
LIFE score	Biotic indices of flow preference	EA/ index			
CCI	Biotic indices for conservation value	EA / index			
MTR & MFR	Mean trophic rank and mean flow rank for macrophytes	EA/ index			
Inter-calibration Common Metric Index	Multimetric river quality index based on river invertebrate data to model overall ecological quality	EU	Calibration with EU partners	WFD	
ii) Routine Classification					
RIVPACS, LEAFPACS	Predictive macro-invertebrate tool to classify water bodies, similar macrophyte tool	CEH-EA	Most ecological monitoring	Monitoring WFD	Needs updating
PSYM	Water quality assessment	Oxford Brooks Univ.	Ecological monitoring of ponds and small lakes	Monitoring	
RHS	Record river biotope character and identify departure from reference conditions	EA	Monitoring/classification	WFD	Links to organisms poorly established. Effects of modification weakly captured.

Habscore	Classification tool to measure and assess the quality of salmonid habitat	Revision under EA/ empirical model	Monitoring	National	Needs updating to improve uncertainty and calibration. Concern over how ‘pristine’ the reference sites were.
DARES and DALES	Diatom based tool to classify water quality	EA-SNIFFER	Monitoring	WFD, Waste WFD	Value of indicating conditions for other organisms unclear. Relative effects of short- and long-term environmental changes not yet established.
STAR	Macrophyte tool of classification	EA/SEPA		WFD	
IRN - Intelligent River Network	GIS based tool to define river network and river catchments from CORINE landuse	CEH	Derive general river attributes (slope, altitude) and configuration, categorisation	WFD maps	
iii) Simple or second tier models					
PACGAP	Simple lake and reservoir management support, inventories freshwater habitats and assesses their sensitivity to change	CEH	Assess probability of the sites becoming infested by toxic blooms	Advice for management	Old model needs updating
GRC General LIFE Response Curves	Link flow curves and LIFE scores	CEH	Water Resource Monitoring link between hydrology and ecology	Monitoring WFD	
BSEIM- Broad Scale Ecosystem Impact Modelling	Collation of data sets giving guidance based on expert judgement	Cascade consulting	Guidance on the environmental consequences of flood defence	Advice for management	
CATCHMOD-Thames Catchment Model	Conceptual water balance (rainfall-runoff) model in Thames catchment.	Thames Water - EA	Predicting runoff, changes in water flow in Thames	Support for AMP5	Need to take uncertainty into account better. No biological link

SDSM - Statistical Downscaling Model	Rapid meteorological downscaling, no biological link	EA	Generates local met data for any UK site	Support for AMP5	Need to take uncertainty into account better
QUALSOC	Simple mass balance water quality model, no biological link	Welsh NRA	Investigate sewage impact on water quality	Compliance to WQ standards	
DHRAM	Assess ecological impact due to hydrological regime alteration	Dundee Univ.	Ecological predictions on the impact of abstraction	Advice for management	
SIMCAT	River water quality model, no biological link	WRc / Monte Carlo simulation approach	Comparison with WQ standards, estimate diffuse load contributions from land	Compliance to WQ standards	Validation issues
PRAIRIE -Pollution Risk from Accidental Influx to Rivers and. Estuaries	Dispersion model for pollution into rivers and estuaries, no biological link	AEA technology			
SIDO-UK	Risk-mapping sediment delivery for river basin characterisation of pressures under WFD, no biological link	USA adapted for UK at Southampton	Dissolved oxygen in sediments and effects of siltation on redds	Delivery of WFD	Not yet fully validated. Needs better data and more funding
Critical load models including some based on MAGIC	Empirical and simple mass balance approaches of pollutants (e.g. nutrients, acid deposition).	External	Assess relative contribution of sources to the total pollution burden on a given ecosystem at a given site	Support regulatory policy Habitats Directive WFD	no measure of temporal change and does not adequately reflect processes within the ecosystem
Metabolake	Stoichiometric model assessing environmental resource most limiting phytoplankton biomass in lakes	CEH	Assess relative importance of different environmental factors in controlling phytoplankton	Support for local management WFD	
iv) Specific models					
SEPA (176)	Nutrient production model, no biological link	SEPA	link nutrient loads to ecology	WFD	

Fisheries models	Wide range of statistical models: models of inter-specific interactions, GLM of habitat-fish relationships, models of salmon egg deposition, regression models between acidification indices and fish abundance, SALMODEL regressions between catchment size indices and salmon/sea trout catches, flow/salmon movement regressions for estuaries, some fish-flow/temperature models in development	EA	Impact assessment, abundance estimation, biological reference points, enforcement, many used routinely	Operational management	Ongoing development on many. Better data will produce better models
Sedimentation models	Sediment tool box models: SIAM, REAS	Nottingham Univ.		Flood risk management	
Other generic models	Statistical correlations between chemical and biological quality in river water		Understand link between pressures and ecological impact	Monitoring	
Other generic models	Regression models relating Total P to ecological attributes			Setting regulatory boundaries for WFD	Moderately satisfactory but R2 ok; needs better data sets
Other generic models	Regression models linking water transparency to Chlorophyll a and macrophyte			Setting regulatory boundaries for WFD	Moderately satisfactory but R2 ok
Other generic models	Models for predicting primary production (eg plankton and macrophyte growth) in Transitional and Coastal Waters		Assessing the impact of nutrients in TRAC waters	Habitats Directive; but also WFD, Urban Wastewater Treatment Directive; Nitrates Directive; Bathing Waters Directive; Shellfish Waters Directive.	Limitations well understood Shortcomings could be rectified: they are tidally averaged, they simplify light climate
Other generic models	Algal dynamics	FBA	Predicting nuisance/toxic algal coastal blooms		
Other generic models	Statistical models of salmon and trout interactions across habitat and density-dependent processes	EA	Impact assessment	Operational management	

Other generic models	Impact of sheep dip model. Risk based model for impacts of sheep dip disposal on wader chicks	Agency R&D	assess potential for typical disposals to impact breeding success of waders	Objective assessment of impact to inform management	
v) Tier 3 heavy models					
PROTECH	Algal modelling unit Tier 3 site specific assessments	CEH	Little current use; Was used to simulate the *in situ* dynamics of phytoplankton in lakes, reservoirs and rivers	Operational management and evidence for cause and effect	Has the potential for Monte-Carlo simulation for a variety of boundary parameter values
PHABSIM	Predict the habitat (depth, velocities, channel indices) conditions in rivers as a function of stream flow, and the relative suitability of those conditions to river organisms	USGS	Little use currently 3rd tier model		Too expensive to run.
Estuary models e.g. HUMBER, DIVAST	Detailed water quality models built for all the estuaries	WRC	3rd tier model	Monitoring	Uses too much data Lack calibration
vi) Models in development					
RAM Resource Assessment Method and environmental weighting add-on	Flow and water levels in relation with abstraction, ongoing development of environmental weighting	Consultant/ Based on expert judgment	Coarse evaluation of flow and water levels to create maps of river sensitivity to flow alteration 1st tier model	CAM -Catchment Abstraction Management	
RAPHSA Rapid Assessment for Abstraction	linear regression based on previous PHABSIM studies	EA/ regression model	Link between hydro and eco 2nd tier model	CAM?	
CERF and CERF add-on	Hydrological model but could have an add-on	EA/Time series model	Link between hydrological and ecological 2nd tier model		

RPDS River Pollution Diagnostic System	Diagnose of causes of stress for river invertebrates	CIES/ pattern recognition AI tool based on MIR-Max	*In development* for classification purposes		Sufficient data not available on pesticides in development
RPBRN River Pollution Bayesian Belief Network	Impact of water quality on river invertebrates	CIES based on probabilistic reasoning AI tool	to evaluate alternative programs of measure for WFD	WFD	
LAKE MIMAS and TRAC MIMAS	Link changes in lake morphology to ecological status	Dundee Univ -SEPA - Irish EA -EA /expert system model	Decision making, risk assessment	WFD	
vii) Other models					
A range of Human health related models (Ashton et al 2007)	-conceptual models (1st tier) -2nd tier food web, population models -3rd tier statistical models	EU and literature review by Ecosystem and Health in EA	Help practitioners to determine if “significant harm” or “significant risk of significant harm” is occurring at a Part 2A receptor location.	Section 57, Part 2A of the Environmental Protection Act 1990 (contaminated land regulations).	The ecological models were severely limited by a lack of relevant data

Table A2: Definition of model and institutional acronyms from Table A1

Acronym	Definition
AEA	Consultant brand
AI	Artificial Intelligence
AMP5	Fifth Periodic Review of Water Price Limits
ASPT	Average Score Per Taxon
BMWP	Biological Monitoring Working Party
BSEIM	Broad Scale Ecosystem Impact Modelling
CAMS	Catchment Abstraction Management Strategies
CCI	Community Conservation Index
CEH	Centre for Ecology and Hydrology
CERF	Continuous Estimation of River Flow
CIES	Centre for Intelligent Environmental Systems
DARES & DALES	Diatom Assessment of River and Lake / Loch Ecological Status
DHRAM	Dundee Hydrological Regime Assessment Method
EA	Environment Agency
EU	European Union
FBA	Freshwater British Association
FCS	Fisheries Classification System
GLM	General Linear Model
GQA	General Quality Assessment
Habscore	Habitat Score
HD	Habitats Directive
LIFE	Lotic Invertebrate Index for Flow Evaluation
MAGIC	Model of Acidification of Groundwaters in Catchmemnts
MFR	Mean Flow Rank
MIMAS	Morphological Impact Matrix Assessment
MIR-Max	Mutual Information and Regression Maximisation
MTR	Mean Trophic Rank
PACGAP	Prediction of Algal Community Growth and Production
PHABSIM	Physical HAbitat SIMulation software.
PROTECH	Phytoplankton RespOnses To Environmental CHange
PSYM	Predictive SYstem for Multimetrics
QUALSOC	QUALity facts of Storm overflows : Consent procedure
REAS	River Energy Audit Scheme
RHS	River Habitat Survey
RFHI	River Fish Habitat Inventory
RIVPACS	River Invertebrate Prediction and Classification System
SALMODEL	EU project: A coordinated approach towards development of a scientific basis for management of wild Atlantic salmon in the North-East Atlantic
SLM	Salmon Lifecycle Model
SEPA	Scottish Environment Protection Agency
SIAM	Sediment Impact Assessment Method
SIDO	Sediment Intrusion and Dissolved Oxygen transport model
SIMCAT	SIMulated CATchment model
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
STAR	Science To Achieve Results
TRAC waters	TRAnsitional and Coastal
USGS	United States Geological Survey
Welsh NRA	Welsh National Rivers Authority
WFD	Water Framework Directive
WQ	Water Quality
WRc	Water Research Centre

Appendix 2: Questionnaire on the Environment Agency current and potential use of ecological models

Section A. The current use of ecological models

1. Do you use, or have you used any ecological models – defined in their broadest sense - for your work?

If not please go to section B.

2. Which models do you use, and what do they do? Were they developed internally (Environment Agency) or elsewhere?

3. For what purpose do/did you use these models?

4. Could you describe the business needs for their use? These might include support for national or regulatory policy, legislation, science or operational management.

5. How frequently do you use these models?

6 Are you satisfied with their scope, performance and reliability? Please identify any particular strengths, weaknesses or risks.

7 How might the models be improved?

Section B. The business need for ecological models

8. By comparison with present approaches, could your business needs be better satisfied by the use of ecological models? Would the gains be greatest for national, regional or routine decisions? (Any examples?)

9. What are the practicalities of developing such models? Will the benefits outweigh the costs and difficulties?

10. Are you aware of any existing models – for example in the research community – that could be used by the Environment Agency?

11. Are there particular difficulties or challenges that prevent the fuller use of ecological models in your work? (lack of resources, lack of knowledge, lack of time, lack of training, poor model performance…)

12. Could expert judgement offer an alternative to the development of ecological models in satisfying national, regional or routine business needs?

Section C. Finding a model best suited to your needs

13. How precise are your needs for modelling? Do you need a coarse understanding/modelling of the problem at hand or a precise quantitative response?

14. What type of modelling methods best would best fit your needs (if more than one need, complete for each):

a. Conceptual/qualitative models (e.g. risk assessment maps)

b. Empirical-statistical models – (e.g. linear regression; classification)

c. Process-based models?

d. Stochastic or agent-based models?

e. Other types of models (please specify)

Section D Are the appropriate resources in place?

15. Do you have the time and/or capacity to develop or improve models that fit your needs?

16. Does the necessary science exist to support the development or the use of a model that would address your business needs?

17. Are the necessary data available to parameterise the model(s) you need to develop, and to apply the model(s) routinely? What would be the cost of acquiring these data?

18. Where do you think the skills to develop and/or apply ecological models should be? E.g. With specialists outside the Environment Agency? In the Environment Agency national Science Group? In the Environment Agency regions? In the Environment Agency's Areas and Operations sections or a mixture of all ?

Section E. Wider technical issues

19. Do traditional statistical models (GLM, GAM, ANOVA, ...) represent, in general, a practical approach to summarizing evidence of relationships between environmental pressures and ecological response? Should the Environment Agency be focussing on these techniques?

20. Do you take account of uncertainty and variability in the models that you use? Do you think area managers and staff need to be able to assess or quantify these aspects in the models they use?

21. Have you knowledge of Bayesian approaches? Might they make better use of ecological data, and better handle uncertainties in model structures and parameters, particularly in the context of classifications of ecological status of water bodies?

22. Do you have any further comments or questions you think should be addressed in this survey?

Prof Steve Ormerod; Dr Isabelle Durance; Dr Ian Vaughan (Catchment Research Group, Cardiff University); Dr Stephen Maberly (CEH Lancaster).

Appendix 3: Mail sent to consultees with questionnaire

Dear Colleague,

As you know following recent e-mails from Sarah Evers (EA), Cardiff University and CEH Lancaster are helping the Environment Agency to evaluate its current and potential uses of ecological modelling.

This phase of the work focuses on a questionnaire survey, and we are extremely grateful for your help in this task. The questionnaire is attached to this mail – intended for you to complete by whatever means suits you best. Our ideal is that we should speak to you by phone, and one of us (Isabelle Durance, Ian Vaughan, Stephen Maberly, Steve Ormerod) will be in contact to arrange a convenient time. If you prefer, by all means complete the questionnaire by mail. Our time is short, and any such responses would valuable.

Like all questionnaires, this one is imperfect, and we hope you'll forgive any poorly phrased questions on our part.

What do we mean by a model?

Our definition of ecological modelling for this exercise is broad. We take it to mean the numerical, conceptual or graphical representations or simplifications of real ecological systems.

In this respect, 'modelling' encompass a continuum from informal statements about ecological systems, to formalised mathematical descriptions. From the Environment Agency's perspective, models are tools to assist in the understanding and management of the ecological resources within your sphere of interest. Your main business needs will probably be to predict, understand or analyse their responses to key drivers. Applications in classification or Programmes of Measures are likely to be growing major uses.

What is our task?

Our overall task in this part of our work, as defined by the Environment Agency, is to help you identify:

i) Priority areas of Agency business need for ecological modelling, including policy and operational tools.

(b) Opportunities that exist to develop and use ecological models

(c) The role and potential value of local expertise and expert judgement.

We will also advise upon:

(d) How to discriminate between 'evidence-based approaches', ecological risk assessment, ecological outcome modelling and more formal modelling applications.

(e) How to determine the most appropriate forms of ecological model for Agency application.

(f) The availability of underlying ecological science.

(g) The data requirements for model development and application.

(h) The selection of model structures and parameterisation (best model or best models?).

(i) The validation of site-specific models and their portability/extrapolation to other sites/situations.

We look forward to hearing more of your views since, in the end, these will be among the most critical elements in our feedback.

Yours sincerely,

Isabelle Durance, Ian Vaughan, Stephen Maberly, Steve Ormerod.

Appendix 4: List of consultees

Name	Approximate job scope
Alice Hiley	Biosys
Paul Bryson	WFD
Phil Harding	Area- ditto - Midlands
Andrew Wither	Principal Scientist - Estuarine and Marine Water
Geoff Phillips	Team leader - Ecology technical team
Jim Heslop	Area- Technical Specialist - biodiversity - NE -Northumbria
John Murray-Bligh	Ecology technical team - RIVPACS
Juliette Hall	Water resources hydroecology
Mitch Perkins	South Wessex Area -Ecological Appraisal Specialist
Trevor Hardy	Area- NE - WQ modeller
Veronique Adriaenssens	Senior Scientist - Ecology
Colin Powesland/Ji Ping	Policy Manager - Air Quality
Neil Murdoch	Area- SW - WQ modeller
Samantha Fishwick	Principal Scientist – Science Ecotoxicology (Formerly Ecosystems and Human Health)
Stephen Roast	Scientist Ecotoxicology
Tony Warn	Policy Manager - Water Quality
Neil Preedy	Diffuse pollution - decision support tools
Richard Hemsworth	WFD
Amanda Veal	Ecology technical team - artificial intelligence project
David Corbelli	WFD - Flood Defence Policy
Charlotte Murray	Sussex Area Technical Specialist - Fish, Recreation and Biodiversity
Catherine Chapman	Sussex Area Team Leader, Ecological Appraisal
Kim Baldacchino	National Data Unit Manager, Twerton
Mark Diamond	Technical manager (Conservation/Ecology)
Doug Wilson	Monitoring Policy
Paul Logan	WFD
Graeme Storey	Policy Advisor Water Management -Environmental Forecasting
Stuart Allen	Senior Scientist (Water Resources). PM for CERF and RAFA
Rob Grew	Water resources - hydrology
Chris Extence	Area- Ecological Appraisal team leader (Anglian) - LIFE
Craig Elliott	Policy Manager - Flood Defence
Hugh Potter	Senior Scientist (Pollution Fate & Transport), WQ Mining issues
Jonathan Smith	Hyporheic Zone Research Fellow at Agency, Sheffield and Bham Unis.
Karen Williams	EMAP - freshwater
Kath Charles	Water resources - hydroecology
Mike Best	EMAP - marine
Tim Johns	Senior Scientist, Ecology
Catherine Wright	Head of Environmental Monitoring/ Assessment, EP Directorate
Bill Brierley	Principal Scientist - Ecology
Brian Shields	Fisheries Technical
Graeme Peirson	Fisheries Science
John Pinder	Area- Penrith - lakes partnership - Lake District lakes
Nigel Milner	Fisheries Science
Paul Raven	Head of Conservation/Ecology
Rob Wilby	Climate Change Science Manager
Robin Wyatt	Principal Statistician Salmonids
Roger Timmis	Science Manager - Air
Simon Leaf	Advisor - SUW and SEP (WR and WQ)
Susan Casper	Sediments science

Appendix 5: Workshop agenda as prepared by the Environment Agency

Workshop on Ecological Modelling in the Environment Agency
Monday 26 February 2007
at the Priory Rooms, Birmingham City Centre
http://www.theprioryrooms.co.uk/location.htm

Objectives
1. Report Environment Agency response to consultation on ecological modelling in the Environment Agency and disseminate results
2. Assure that results are representative and accurate
3. Attain consensus on top business priorities for ecological modelling in the Environment Agency
4. Identify any science gaps in meeting Environment Agency needs for ecological modelling
5. Propose, explore and agree options for developing Agency ecological modelling capacity

Facilitator: Prof Paul Whitehead, Aquatic Environments Research Centre, Reading University

Agenda

10:30	Coffee	
11:00	Welcome	Steve Fletcher
11:05	Introduction	Bob Harris
11:20	Workshop objectives of workshop	Paul Whitehead
11:30	Use of models for assessing contaminant impacts in ecological risk assessments	Stephen Roast
11:45	Results of consultation:	Steve Ormerod, Cardiff Stephen Maberley,CEH
12:15	Questions and feedback	Paul Whitehead
12: 35	Introduction to breakout group tasks	Paul Whitehead
12:45	LUNCH	
13:15	Breakout group orientation	Paul Whitehead
13:20	Breakout groups 4 groups of 8 to discuss and identify/propose and prioritise: • Key business needs for ecological modelling • Gaps in science (knowledge, models and data)	Delegates

- Options for achieving needs

14:30	Feedback to main group	Breakout group spokes-people
15:10	Discussion/clarification/assimilation of feedback	Paul Whitehead
15:50	Roundup: Summarise preferred option(s) and way forward	Steve Fletcher
16:00	CLOSE	

Project and workshop contributors

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Invited Speakers

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Appendix 6: Detailed group reports from workshops (Birmingham, 6/02/07)

1. Background and introduction

A one-day workshop, with an invited list of delegates drawn from (but not exclusive to) those initially consulted was held in Birmingham in late February 2007. The agenda is reproduced in Appendix 5, and its objectives were to:

1. Report the Environment Agency response to the consultation on ecological modelling in the Environment Agency, and to disseminate the results
2. Assure that the results were representative and accurate
3. Attain consensus on top business priorities for ecological modelling in the Environment Agency
4. Identify any science gaps in meeting Environment Agency needs for ecological modelling
5. Propose, explore and agree options for developing Environment Agency ecological modelling capacity

In addition to a morning session of presentations, each of four working groups was tasked with addressing three major questions, being:

1. What are the major business drivers for ecological modelling in the Environment Agency?
2. Are there any major science gaps that prevented development and delivery?
3. What should be the strategies for developing ecological modelling within the Environment Agency or its sphere of influence?

This brief section summaries, as far as possible, the detailed points made by the four working groups. Numbers in brackets following each point made refer to the group number offering each point. To respect confidentiality and Chatham House rules, Group membership has not been disclosed.

1 What were the major business drivers for ecological modelling in the Environment Agency?

Points made varied between new needs or drivers and existing needs as follows:

New needs and drivers

The tools formerly used for other statutory activities of the Environment Agency are often not adapted to the new tasks involved in delivering for the EU legislation, namely the Water Framework Directive and Habitats Directive (1, 2, 3, 4).

The monitoring programs in place should be revised to serve WFD and HD purposes. Revising sampling strategies, with the help of built-for-purpose modelling tools could also help save money and increase monitoring efficiency (2, 3).

The indices existing to capture ecological health are increasingly outdated, and for example BMPW scores are essentially linked to sanitary pollution. New indices are required that respond to the notion of good ecological status (2).

The links between physical/chemical attributes of the water bodies and biota need to be better understood. Currently in some areas, even coarse first tier decision making information is unavailable, leaving many decisions to be made on sole expert opinion. This is not easy to defend (1, 2, 3, 4).

There are far too few existing models in the Environment Agency linking ecological status to physico-chemical status, and new models need to be built-for-purpose, for example by linking existing hydrological, morphological and water quality models to ecological threshold targets or ecological health indices. Currently, the Environment Agency has too few tools to understand or predict the consequences of management decisions such as restoration on the ecological status of water bodies (1, 2).

Existing drivers

All the groups agreed that the range of tools used up to now by the Environment Agency for its core statutory activities are in need of scrutiny. Some need to be updated (e.g. RIVPACS), some need to be revised or even discarded (e.g. not adapted to current needs, poor documentation, poor account of uncertainty, too complicated, too demanding in data), some new ones are required to respond to challenges like climate change (1. 2. 3. 4).

The Environment Agency needs better tools to be able to perform better in its core activities. In rough priority order these were suggested to be: Licence Abstraction, Biodiversity Action Plans, resource assessment for CAMS, Drought Impact studies, Strategies for Environmental Assessment, Planning Applications, Salmon and Freshwater Water Fisheries Act, Impact Assessment, Defra-driven activities like setting standards e.g. for salmon abundance. Needs include:

- Understanding the links between ecology and physico-chemical pressures better, for example to facilitate reliable screening. In core activities of the Environment Agency, inaccurate screening decisions can have far-reaching financial consequences, and decisions not based on evidence are hard to defend (1, 2).
- More tools capable of providing rapid decision making guidance at catchment scales (2, 3).
- More tools for impact assessment studies to identify the effect of pressures on an outcome, and also to differentiate between pressures. Diagnostic tools need to be developed (1, 3, 4).
- Uncertainty analysis needs to be better developed for forecasting (3, 4).
- With new pressures like climate change or invasive species, the Environment Agency needs appropriate tools to provide prompt response, or predictive management decisions. These tools are not available currently (1, 2, 3, 4).

2. Were there any major science gaps that prevented development and delivery?

A large array of science gaps were perceived:

There is a major knowledge gap in the link between ecological processes and hydro-morpho-chemical processes in water bodies (1, 2, 3, 4).

Much needs to be done to define sets of physico-chemical thresholds for biota, an essential requirement for management (1, 2).

Staff working on ecosystem recovery need to know where recovery thresholds lie – i.e. the points of no return (1)

There is a need to identify the adequate level of taxonomy needed for the different activities of the Environment Agency, and to plan monitoring accordingly. Most data are collected at family level, and experience shows that this level is not always sufficient (2).

There is a need to make the sampling strategies more effective and better focused on ecological aspects. The design of monitoring networks could be optimised (2, 4).

Data quantity (incomplete data sets, varying frequency, mismatch of sites for different variables) and data quality (limits of detection, lack of taxonomic resolution, poor sampling techniques, lack of meta-data) need to be ameliorated to meet current needs (1, 3, 4).

Inter-relationships between water bodies and their surrounding catchments, as well as issues of connectivity, need to be better understood (1, 2).

More work is needed to understand natural or cyclical variations in data. These requires accurate, factorial comparisons between reference and impacted sites (2, 3).

More work needs to be done to identify reference conditions (1, 4).

The Environment Agency needs to develop and to protect long term-data sets which are the key to understanding/ predicting the impact of environmental pressures on biota (2).

3. What should be the strategies for developing or promoting ecological modelling within the Environment Agency or its sphere of influence?

Overarching need to integrate knowledge and management decisions across systems (air, land and water) at a range of spatial and temporal scales in order to take an holistic approach to ecosystem health (4).

The Environment Agency needs to work with more multi-functionality, and more multi-disciplinarity. This seems to have been achieved better in fisheries, in hydrology and in hydro-morphology than among ecologists (2, 3).

There is a need to increase esteem of ecologists within the Environment Agency (4).

Demonstration projects could show the value of models, in particular their financial benefits. The formation of a core ecological modelling team with regional 'model champions' to promote and provide advice on models locally could be an option (1, 2, 4).

Scientists need to think about financial savings for managers (2).

An up-to-date survey / inventorying of models and modellers needs to be produced, building on internal capacity. This should include explicit assessment of fitness-for-purpose (2, 3, 4).

Knowledge of where the expertise in modelling lies needs to be organised better and disseminated (2, 4).

The Environment Agency needs to safeguard knowledge acquired by staff; when staff leave, the corresponding expertise may be lost (4).

Communication, transparency and defensibility in decision-making need to be promoted, and modelling could help this process (3, 4).

Staff need to promote awareness that what is currently done for WFD is only part of what is needed (3).

Appendix 7: Advice on wider technical issues in ecological modelling

1. Background and introduction

The third objective of this project was 'to allow the external experts to advise upon various aspects of ecological modelling'. The project specification suggested that this included issues such as:

a) How to discriminate between 'evidence-based approaches', ecological risk assessment, ecological outcome modelling and more formal modelling applications (see Sutherland, 2006).

b) How to determine the most appropriate forms of ecological model for Environment Agency application.

c) The availability of underlying ecological science.

d) The data requirements for model development and application.

e) Outline guidance on the selection of model structures and parameterisation (best model or best models?).

f) The validation of site-specific models and their portability/extrapolation to other sites/situations.

Within the resources available during this project, we are unable to give exhaustive advice on all these points. Moreover, until ecological modelling plays a fuller part in Environment Agency business (see main report, recommendations), these aspects of technical context are more peripheral. We offer the following informal views.

2. Some general points about ecological modelling

Models have two fundamental purposes:

i. to increase the understanding of an ecological system

ii. to make predictions about a system.

Both are relevant to the Environment Agency's activities, but developing business needs will particularly emphasise the second. These two aims encompass a wide range of different tasks for which models can be used. In ecology, these include:

- Making statements of current knowledge about an ecological system, for example in the form of a conceptual, qualitative model (perhaps represented graphically). In scientific research this might represent a hypothesis that further research would attempt to falsify.
- Using simple models as a problem-solving tool, or simple way of communicating the behaviour or dynamics of ecological systems (such as illustrating potential reactions to environmental change; Starfield 1997).
- Identifying/highlighting potential environmental problems, by comparing observed ecological elements to those predicted (e.g. RIVPACS). More advanced models

could consider the nature of the observed-expected discrepancies to diagnose potential causes, although this is still an area in need of development.
- Predicting future ecological conditions: ecological responses to environmental change.
- Producing quantitative summaries of existing data: building models with existing data and then interpreting the structure of the models. In this way models could act as 'translation devices', converting empirical data into expert, quantitative knowledge.

Predicting ecological responses to environmental change is perhaps the most important (potential) role for modelling in the Environment Agency. Possible changes of interest include habitat management (e.g. designing Programmes of Measures), climate change, flood defence and other hard engineering, and river restoration. Predicting the potential outcomes of such changes can be extremely valuable in designing management strategies and selecting between alternative management prescriptions. Examples from our own work have included statistically-based predictions about the response of streams to climate change (Durance & Ormerod 2007) or the mitigation of acidification using alternative methods (Ormerod et al. 1988; 1990). Model predictions in the latter case were tested by subsequent experiments (Rundle et al. 1995; Bradley & Ormerod 2002). All these cases involved funding from, or collaboration with, the Environment Agency or its predecessors. However, applications to the current need to develop Programmes of Measures are few.

3. Model uncertainty and evaluation

Model uncertainty pertains to the confidence that can be placed in the structure of a model and in its predictions (e.g. confidence intervals), whilst testing assesses the accuracy of the predictions (i.e. agreement with reality). The two concepts are closely linked.

Uncertainty has been greatly overlooked in ecological modelling, although recent years have seen some attempts to redress the imbalance. It can be introduced by the data used to construct a model (for example through measurement error, inaccurate grid-referencing) or by uncertainty about the model(s) (such as model selection, weak underlying science). It is a serious issue because failure to consider uncertainty leads to the presentation of model predictions with an exaggerated level of confidence. Sutherland (2006) suggests that it is '…too tempting to give credence to impressively presented results based on limited biology'. Ways of incorporating uncertainty into ecological modelling are undergoing rapid development, including:

- Bayesian model averaging to address the problems of finding the 'true' or 'correct' model (e.g. Wintle *et al*. 2003).
- Error budget methods for identifying the major sources of uncertainty (e.g. Parysow *et al*. 2000).
- Sensitivity analyses to assess the potential effects of errors in model parameters, expert opinion, etc (Jager & King 2004).

Development of these methods, and acknowledging uncertainty, should greatly strengthen the case for using ecological models in environmental management.

The importance of testing the **accuracy** of predictions is more widely acknowledged than overall uncertainty. For some types of models (e.g. species distribution models), the theory and methods for testing are relatively well developed, although are not always practised (Vaughan & Ormerod 2005). Testing is a fundamental stage in developing ecological models, and vital if confidence is to be placed in their predictions. Three aspects to be tested are:

- Overfitting – whether a model not only describes the relevant ecological relationships, but also the idiosyncrasies of empirical data used to calibrate it. This limits a model's applicability
- Transportability – the accuracy of a model under novel conditions e.g. different lakes or river systems, or predictions in the past or future.
- Model fit – conditions under which a model performs poorly, such as within certain river catchments, suggest ways in which it could be improved.

The use of predictive models is more readily defensible when they have been thoroughly tested.

4. A dichotomy of empirical models

Empirical ecological models can be classified in several ways, but a broad split into correlative and mechanistic types is useful for the current advice and discussion. These can be considered the ends of a continuum, rather than there being a strict distinction.

4.1 Correlative modelling methods

Correlative models simply describe the correlations between a series of independent variables and an ecological response. Independent variables are typically selected for the ease with which they can be collected, or because they are the only variables in an existing data set. Such models need not be ecological plausible to be useful *predictive* tools, and so can be built in situations where ecological understanding is poor: clearly, extreme care and thorough testing is required in such instances (Vaughan & Ormerod 2003). More commonly, correlative models strike a compromise between ecological relevance and the ease with which variables can be recorded.

Simple statistical models, such as GLMs, are the most frequent correlative modelling methods. GLMs are *the* most common models in some areas (e.g. predicting species' occurrences). The following comments also apply to more modern methods (e.g. artificial intelligence methods such as classification trees, genetic algorithms, neural networks; GAMs; empirical Bayesian methods), as they too model the correlation structure.

Advantages of correlative models:

1. An effective, quantitative way of summarising ecological data and/or the relationships between ecological and environmental data.
2. Many techniques are simple, widely available and many people already have the required level of expertise.
3. Versatility – a wide range of data types and relationships between ecological responses and predictors can be modelled by using a range of different methods. For example, GLMs can use many types of ecological data held by the Environment Agency (e.g. binary/nominal data, ordinal, count data, continuous measurements, etc), whereas GAMs and many artificial intelligence methods can model complex, non-linear correlation structures.
4. Cost effective. Correlative models are often relatively cheap to develop and may not require much understanding of the system being modelled – simply data (Guisan & Zimmermann 2000).
5. Applicability to large spatio-temporal extents. Correlative models in some instances offer some of the only methods for capturing or parameterising ecological effects at scales beyond experiments or straightforward measurements of processes.

6. Accessibility and understanding. Basic statistical training at undergraduate and postgraduate level has provided wider understanding of basic correlative models than is the case for other methods.

Disadvantages of correlative models:

1. Major doubts about their transportability to new situations: new areas or novel environmental conditions, such as following climatic changes (Vaughan & Ormerod 2005; Sutherland 2006; Durance & Ormerod 2007).
2. Many methods are easily abused. This could range from the use of a stepwise regression analysis to identify the 'important' variables driving an ecological response, to attempting to draw firm ecological conclusions based upon an unrestricted data-mining exercise. The Environment Agencyse of automatic model development from empirical data in many pieces of software encourages these practices.
3. Models can only be as good as the data on which they are based. Developing and testing a sound model often requires more data than is often realised (Vaughan & Ormerod 2003)
4. Important variables or processes may not be appropriately represented by those available for correlation, while spurious effects are possible.

There is a wealth of opportunities for using correlative ecological models in the Environment Agency, many of which have not yet been considered. The most important roles relate to extracting ecological information from existing data holdings (e.g. BIOSYS) to help inform management and highlighting potential problems by comparing observed and predicted biology. Both of these are applications that do not require major extrapolation outside of calibration data (e.g. future predictions). However, such developments should be tempered, where necessary, by constraints associated with caveats about the underlying data quality. Such models should also be used by staff with a strong enough ecological understanding to recognise spurious results.

Mechanistic modelling methods

Mechanistic models try to capture the mechanisms that drive the ecological processes of interest, in an attempt to increase model realism. For example, if the population size of a protected species was the focus, a mechanistic model might incorporate information about rates of reproduction and survival, density dependent processes and the possible impacts of density independent, stochastic events.

Advantages of mechanistic models:

1. Considered to have greater biological realism than correlative models. This should lead to a greater understanding of the system of interest.
2. Mechanistic models based on first principles of ecology may provide the greatest capacity to predict responses to environmental change. For example, models that simulate how individuals maximise their fitness in a novel environment, and the consequent emergent properties at a population level, may be more effective at predicting population sizes in novel environments than correlative models that lock specific population densities to specific combinations of environmental variables (Sutherland 1996; Grimm & Railsback 2005).

Disadvantages of mechanistic models:

1. More expensive and difficult to produce than correlative models. Greater knowledge of the system is required – e.g. fundamental demographic parameters. Detailed behavioural and individual-based models (e.g. Stillman *et al*. 2000, 2003) require a vast body of underlying research to parameterise them.
2. Heavily data dependent for model calibration and hence extremely expensive.
3. The ecological rates/dynamics used to parameterise many mechanistic models may not be constant in the face of environmental changes (Sutherland 2006).
4. Mechanisms that affect species or populations may be context dependent, and there is no guarantee that mechanistic models will be any more transportable than simpler models. Limits of validity are poorly understood.

Mechanistic models have a range of desirable properties for predicting ecological responses to environmental change or for affording greater insights into freshwater systems. Numerous opportunities could be identified for using such models in the Environment Agency, but for most of these they would be prohibitively expensive to produce. They may be justifiable for limited numbers of species of particular concern – alien species, those of economic value, those of high conservation concern, or species found at sites of special interest.

5. The role, potential value and potential weakness of local expertise and expert judgement

Some general points are made about expert judgement in the main report (Sections 6.4 and 6.7). Other general observations about expert opinion are that:

- 'Expert opinion/judgement' relates to any way in which the opinions of practitioners, researchers or other 'experts' contribute towards management or decision making. The expertise could relate to a particular aspect of ecology (e.g. specific species, ecological processes or ecological system) or an aspect of geography (e.g. site-specific/local expertise).
- There is a sharp contrast in ecology & environmental management between the *informal* use of expert judgement/opinion, which has always happened, and *formalised* expert judgement, which is growing in importance.
- Formal expert judgement has been little explored in environmental management compared with other fields. In the scientific literature, there are very few examples pre-2002, but a rapidly-increasing number since then. Expert opinion is more widely used in freshwater ecology and management than in many terrestrial systems: a common example is the use of species traits in the interpretation of monitoring studies.
- Expert opinion can be used in several ways with respect to modelling:
  i) in place of models;
  ii) as the basis for constructing predictive models (i.e. no empirical data are used);
  iii) on a hybrid basis – combining expert judgement and empirical data.
- In empirical modelling, expert opinion can be introduced in numerous ways. Examples include: the selection of data to collect, variable selection, ranking habitat suitability for a species, or eliciting priors in a Bayesian analysis. Models are rarely developed without any form of expert opinion in contrast to data mining.
- Expert opinion encourages a more mechanistic basis for ecological models than automated statistical approaches. This may make (partially) expert-based models more transportable (but see Seoane *et al*. 2005).

5.1 Methods for using expert opinion in ecological modelling

- Expert opinion can be added to models in a very simplistic fashion. Examples include treating expert judgement about habitat characteristics in the form of an ordinal scale (e.g. from 'very poor' to 'very good' for a species), or as simple Boolean rules, either of which could then be adding into an empirical model (e.g. Pearce *et al*. 2001). Such direct methods are weak in terms of handling uncertainty.
- Most attempts to combine expert opinion and empirical data in ecological modelling do so in a Bayesian context, leading to what is sometimes called subjective Bayesian analysis. Typically, this involves eliciting expert opinion in the form of a probability distribution for model parameters. This is a quantitative description of an expert's opinion, described as their prior belief (Garthwaite *et al*. 2005). The distributions are then updated based upon empirical data to give the posterior distribution – the basis for inference and prediction (Lele & Allen 2006). In this way, expert opinion is updated in light of empirical data. Elicitation is a complex process for a non-statistician (Garthwaite *et al*. 2005). Good elicitation accurately captures an expert's knowledge, independent of how good the knowledge is. However, variation and uncertainty in experts' estimates are problematic (Garthwaite *et al*. 2005).
- Frequentist alternatives to Bayesian methods for combining expert opinion and empirical data are also being developed (e.g. Lele & Allen 2006).
- It is recommended that if expert opinion is included in a model, it is done in such a way that its contribution to the outcomes can be distinguished from that of empirical data (Cox 2006). Sensitivity analyses are one possibility (e.g. Johnson & Gillingham 2004). Methods are also being developed to try to communicate uncertainty.

Models incorporating expert judgement should be subject to the same rigorous testing that purely statistical/mathematical models are.

5.2 The value of expert opinion in ecological modelling

It is difficult to generalise about the value of expert opinion, as the degree of knowledge, in absolute terms and relative to empirical data, is likely to vary substantially between systems, as is the way in which it is employed (e.g. different stages in the modelling process or the quantity of expert judgement compared to empirical data in a model). There are ecological examples of both improvements (e.g. Al-Awadhi & Garthwaite 2006) and reductions (e.g. Pearce *et al*. 2001; Seoane *et al*. 2005) in the accuracy of empirical models when expert judgement is incorporated. The general consensus is that good expert knowledge has the potential to improve some empirical models, whereas poor knowledge or knowledge that is variable between experts may reduce model quality.

One of the problems with expert opinion is the difficulty of tracing the source of the 'knowledge'. It could come from rigorous experimentation or an effective synthesis of a range of studies, or it may simply be a best guess (Sutherland *et al.* 2004).

The Environment Agency has already reviewed the use of fuzzy-knowledge systems, and some Environment Agency staff associated with this project consider it to have unexploited value (Adriaenssens et al. 2004).

6. Discriminating between risk assessment, 'evidence-based approaches', formal modelling, ecological outcome modelling and applications (see Sutherland, 2006)

We consider that ecological risk assessment is well developed in the Environment Agency, and offer no further views here.

6.1 Evidence-based management

Evidence-based approaches are mainly discussed in relation to the effects of management interventions. This reflects the origin of the evidence-base paradigm in medicine, for assessing the efficacy of different treatments and selecting between alternatives, rather than simply relying on practitioners' best guesses (Sutherland *et al.* 2004). Evidence-based management is grounded on a body of evidence accumulated through the careful documentation of management experiences. At its best, the evidence-base comprises a series of management experiments, from which firm conclusions can be drawn. Adaptive management provides a framework within which further management 'experiments' and evidence can be gathered (Sutherland 2006).

Current weaknesses of the evidence-based approach include:

- it is restricted to management decisions that have been used before;
- outcomes, interventions and their context must be readily categorised to allow summation or replication. This precludes their use in large, complicated and relatively unique actions that sometimes characterise river-basin management.
- the strength of evidence for an intervention may be weak until it has been documented several times;
- although many interventions have been carried out by the Environment Agency and other organisations, the paucity of monitoring and documentation of effects means that many opportunities to start building an evidence-base have been squandered;

The key difference between evidence-based approaches and expert opinion is that in the former, the basis upon which management recommendations are made can be traced and the intervention proven to have been effective in other instances. The Environment Agency has recently experimented with evidence-based reviews of some aspects of stream management, for example commissioning a review from Birmingham University to assess whether in-stream structures and woody debris increase the densities of salmonids.

6.2 Formal modelling

Formal modelling – correlative, mechanistic or more conceptual – typically relates to specific elements of ecological systems. Examples include the prediction of species, assemblage or demographic responses to environmental changes. Models can provide quantitative predictions and confidence limits, whereas expert opinion and evidence-based conservation are often more qualitative: addressing the types/directions of changes, without quantifying the magnitudes or rates of change. Both expert opinion and evidence-bases can feed into modelling.

Formal modelling and expert opinion are more widely applicable than evidence-based management. They can even be applied where there is no evidence base, although clearly this has concomitant risks.

6.3 Outcome-driven modelling

Outcome-driven modelling, as defined by Sutherland (2006), describes a more holistic approach to ecological prediction and consequent decision making. It considers a range of possible ecological outcomes and calculates the likelihood that each will occur, along with the potential ramifications. Outcome-driven modelling has the potential to assist in making major, complex decisions, such as selecting between different management strategies in devising Programmes of Measures or plans for river restorations, based on the likely environmental conditions that would result and the subsequent ecological outcomes. Key features and strengths of outcome modelling include (Sutherland 2006):

- it is a framework within which different sources of information can be combined: formal modelling, evidence-based knowledge, expert opinion
- transparency – the probabilities of different outcomes are displayed, and the ways in which they are calculated are made more explicit than within many modelling methods or expert judgement
- it is readily updated as understanding improves or new data become available
- it links physical models (predicting likely environmental conditions) and ecological models in a straightforward manner
- by displaying several possible outcomes and assigning probabilities to each, outcome-driven modelling could be an effective way of conveying uncertainty

A key difference between outcome-driven modelling and evidence-based or formal modelling approaches is that it represents an holistic framework for prediction. Outcome modelling combines outputs from these other techniques, rather than being an alternative to them.

7. Some possible additional recommendations for the Environment Agency

7.1 Using expert opinion in the Environment Agency

- Expert opinion will continue to play a central role in Environment Agency decision making – at least in the short-medium term – irrespective of the role that modelling plays. This will particularly be true for low-risk decisions and in local casework. Seen in this light, it is important to consider how best to use expert opinion in modelling (both by itself and combined with empirical data). There is clearly a pressing need to consider: i) how to elicit and use expert opinions, ii) the possible biases, iii) the development of frameworks for handling expert opinion, and iv) how to provide accountability/transparency.
- It may be possible to devise a standard approach to combining expert opinion and empirical data from a range of sources: atlas data, existing data holdings (even with spatial biases), experts, models. This would represent a pragmatic use of all available resources, provided it was within a sound framework and way of handling uncertainty/error (and its propagation).
- Careful thought is required about how to validate expert opinion and/or models.

- **Our strongest suggestion is that the Environment Agency considers reviewing how (best) to use expert judgement as a question in its own right**.

7.1 Outcome-driven modelling, evidence-based approaches and formal modelling

- There is much potential to develop the Environment Agency's evidence base, by targeted monitoring of the effects of management interventions and systematically recording the results. It is particularly easy to see how this could relate to discrete habitat management or conservation measures, such as the impacts of channelisation or the addition of flow deflectors.

- An improved evidence base would further increase the Environment Agency's modelling potential. Models based upon traceable evidence would be more readily defensible.

- Outcome-driven modelling, and related decision support methods, should be explored further to see how they might meet the Environment Agency's requirements. Their capacity to combine any available sources of information – modelling, evidence or judgment – could make them valuable pragmatic tools. In the short-medium term at least, it seems likely that the Environment Agency would achieve the greatest success in predicting ecological responses by combining information from multiple sources within a suitable framework.

7.1 Environment Agency data holdings

A careful audit of Environment Agency data, with a view to their use for ecological modelling, would be valuable. This needs to take into consideration such issues as:

i) the spatial scales at which data are recorded
ii) idifferences in methods among regions (e.g. recording biological data to different taxonomic resolutions)
iii) the effect of sampling design, and in particular biases in the distribution of sampling sites, for example towards the positions located on the road network,
iv) ‘important’ variables for modelling that are not recorded;
v) the temporal extent and resolution (Kadmon *et al*. 2004; Barry & Elith 2006) and
vi) the sensitivity or appropriateness of methods for current needs.

Using existing data holdings that were collected for other purposes means that data are likely to be sub-optimal for some ecological modelling. There is little flexibility as the sampling ‘design’ is already fixed. These disadvantages are offset by the size of the data holdings, in terms of spatial and temporal extent and resolution. We suggest that the key is to understand the potential limitations and make them explicit when utilising the data.

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