A Review on the State of the Art in Scenario Modelling for Environmental Management

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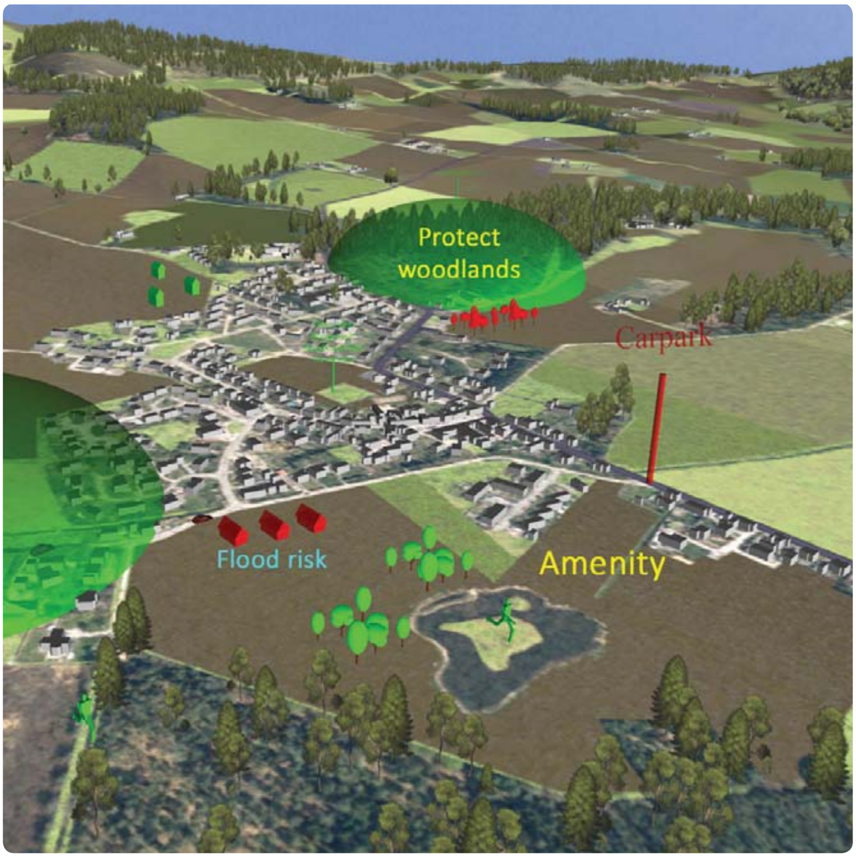

RESEARCH ENVIRONMENTAL OBJECTIVES

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A Review on the State of the Art in Scenario Modelling for Environmental Management

Potential for Application in achieving the Swedish Environmental Objectives.

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Preface

Environmental work has traditionally been focused on one theme and issue at a time; consequently one may not see the effects of decisions on other sectors or the environmental problems they cause. The sixteen Swedish Environmental Objectives are an example of this, with specific targets for the desired state for air, water, forests and oceans, etc. There has been little attention paid to integration or cross-cutting perspectives in the work of achieving the environmental objectives. The interplay between society and the environment is complex and therefore a systems perspective is needed whereby environmental targets and objectives can be transparently connected to policies and measures with interested parties and other interests involved. This means that some environmental objectives will have to be weighed against the goods involved and prioritized based on environmental, societal and economic concern. This places stronger demands on the state administration in its environmental work, and on the analyzes, methods and tools available to manage the data. This report is aimed at increasing knowledge about the methods and tools available for landscape management and points to where research and development is heading that may be useful for the authorities.

The views expressed in this report are those of the authors and cannot be cited as representing the views of the Swedish Environmental Protection Agency.

The study has been funded by the Swedish environmental Protection Agency´s Environmental Research Grant.

Swedish Environmental Protection Agency, September 2015

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Executive Summary

Context from the Call

"The increased pressure on land and water landscapes' various resources, conflicts of interests and the lack of a holistic approach are challenges that require new forms of work…

The Swedish Environmental Protection Agency and the Marine and Water Authority see a need to develop a broad-based methodology to integrate environmental issues, natural value assessments and other social issues in the form of tools and methods for scenario modeling."

Priorities of the Call

- *An international research overview of the different scenario modeling approaches and their applications.*

In addition to involving experts from SLU and attendance at the 'SeaScapes' workshop (22 May 2014, Västragötaland) and UNISCAPE "Landscape Observatories in Europe II", Turin, Italy (22-23 September 2014) the project engaged with leading experts in their respective fields from the James Hutton Institute (UK), Institute for Environmental Studies (Netherlands), University College London (UK), Delft University of Technology (Netherlands) and the Institute of Landscape Planning and Ecology at Stuttgart University (Germany).

- *The research review will critically and constructively respond to innovative international research and development of landscape modeling, both in terms of technologies and applications, modelling and visualisation of complex relationships in landscapes with different nature, scale and time horizons. The research will reflect on the utility of these methods for managing landscape from an ecosystem perspective, connectivity, landscape fragmentation and cumulative effects open for use and participation of different social actors consider the various actors uprightness, on scales from local over national to the international level.*

The landscape issues considered by this report are wide ranging in nature, scale and complexity, from landscape change simulation and visualisation for social inclusion in planning (such as optimal green structure design in urban areas for comfort and sustainability), to field level soil management, catchment scale visual landscape management, catchment scale water management, soil management and water born pollutant modelling, to national soil carbon budgeting and marine nutrient cycles at the coastal and Baltic scales and incorporation of global climate scenarios.

The various chapters and subchapters are connected by a common ecosystem perspective. This starts close to the planning and policy level, considering models of actual, perceived and cumulative impact in landscape planning (chapter 1) and how these may be communicated to stakeholders. It discusses how emergent effects from cumulative complex systems can be modelled with cellular automata and Agent Based Models (chapter 2), looks specifically at ecosystem/biosphere modelling approaches to soil modelling (chapter 3) and links in the flow of nutrients through an ecosystem via freshwater hydrology and the effectiveness of policy such as the Water Framework Directive in moderating this (Chapter 4), which in turn connects to models of the bio-geochemical flows in marine ecosystems (Chapter 5), before returning to look at models for detailed planning in an urban context with respect to urban ecosystem services (Chapter 6).

Each chapter looks at a range of modelling approaches, from older but simpler methods to the state of the art. Chapter 7 recognises that, due to limits in knowledge, funding and staff time, pragmatic approaches may be as effective as complex state of the art models. A range of data mining approaches are discussed with examples of some of the environmental applications to which they are being applied, but also the wider infrastructure support which can fully leverage their capability.

The report considers direct citizen engagement with planning (chapter1 and appendix 4) and how this is beginning to be included in broader processes for GeoDesign (Steinitz, 2012), but also how tacit behavioural knowledge and stakeholder preferences may be built into models themselves (chapter 2). All chapters consider the role of models for ensuring transparent, objective, decision making. The report highlights specifically models relating to public perception of visual landscape change, urban climate and storm water management, soil management for a range of applications, and the cumulative effect of run off pollution from land to marine environments, including the freshwater processes which link these into a complete system. However, it is the general consensus of the reviewers that “model chaining” i.e. linking multiple components of an eco-system process together, including people, is problematic. In the absence of a strong motivation for a tightly integrated model directed to a specific application, a “suite” of complementary models used in concert by a suitably diverse team of experts is a more pragmatic and robust approach.

- *Researchers who receive funding are expected to participate in the Environmental Protection Agency's annual conference after the end of the project the Environmental Protection Agency and the Marine and Water Authority wish to undertake workshops and exchange of experience between researchers and practitioners.*

The project was presented to the annual Naturvårdsverket conference in 2014 and 2015 and allocated resources for interaction with public authorities and other relevant actors. The project directly engaged with staff at Länsstyrelsen and selected municipalities, and also sought to set these discussions in a wider context through a national survey. The report will be presented at GeoInfo, Malmö, in October 2015 and further opportunities will be sought to publicise its findings thereafter.

Structure of the Review

This review cannot cover every aspect of scenario modelling in depth. Rather it focuses on four general ‘domains’, selecting models therein based on their relevance to the 16 Environmental Objectives, pragmatic utility, and predictive quality. It is in the nature of landscape processes that these four domains do not easily break down into chapters and while particular chapters, and particular models, have more or less relevance to certain objectives, and key objectives are noted in each case, these are not intended as exclusive categories.

Socio-economic modelling is a distinct skill to that of modelling in the bio-physical sciences owing to the higher degree of qualitative and theoretical inputs and the frequent use of stakeholder engagement and interactive modelling approaches (Pricea, 2012). Techniques often applied here therefore tend to focus on those methods which can handle sparse, qualitative or fuzzy data, and in particular to elicit knowledge from people and encode it, for example via Bayesian Belief Networks (McCloskey et al., 2011, Aitkenhead and Aalders, 2011), then extrapolate that knowledge, e.g. via Cellular Automata or data mining (CHAPTERS 1, 2, 7)

Marine and fresh water modelling represents a challenging environment. Mapping is often considerably less certain, timescales of change are often shorter, boundaries and zoning harder to identify and enforce planning policy upon and of course the environment often requires true 3D process modelling of complex water flow and chemistry functions (Stelzenmüllera, 2013, Ménesguena, 2007). Land based activities impact on marine models through pollution, sedimentation and so on, while water based processes impact on landscape models most dramatically in terms of flooding, but also with respect to fresh water catchment processes where water is both a vital driver of, and limitation to, landscape change. (CHAPTERS 4,5,7)

Landscape modelling by contrast may often suffice in 2 or 2.5 dimensions. However the range of factors in landscape data is very large, as is the range of techniques, scales and classification systems applied. Future landscapes are complex to predict, particularly due to the 'human' factor, which may result in quite unexpected outcomes. However, on average many decision making processes may be predicted through techniques such as cellular automata combined with GIS based knowledge of constraints such as agricultural potential and planning regulations (CHAPTERS 1,2,3,4,6,7). People's experience of the landscape and their daily interaction with it can also play a pivotal role, thus visibility modelling is a significant and complex part of scenario development and remains an important research area both in terms of computation and human perception (Sang, 2015, Ode, 2010, Tveit, 2006). Finding intuitive ways to communicate the results of complex models when producing future scenarios is also an important part of landscape modelling (Miller, 2006) (CHAPTER 1). Visualisation is clearly one aspect to this, but work on the future auditory landscape, and even it smells has been shown to be important in influencing the degree to which scenarios are perceived favorably or otherwise (Orland et al., 2001, Appleton and Lovett, 2005, Lange, 2011).

People as Stakeholders in the scenario development process is another important aspect as it provides the opportunity for conflict resolution (Andersson et al., 2008), but places significant limits on the complexity of the models which may be deployed as results must be produced and communicated in real or near real time. This requires a balance to be struck between precision, comprehensiveness and feasibility (CHAPTER 1).

Urban Modelling is a distinct area of landscape modelling due to the fine scale at which data is often available and the detail with which results need to be understood. For example, urban heat models are complex, and when incorrectly estimated can result in dangerous effects for very specific locations of just a few meters. Similarly issues of water transport and flooding are quite different in urban areas where underground drainage is a dominant issue. On the other hand terrain modelling techniques may be brought to bear in far more detail than is feasible at regional or national scales but it may be for local or regional authorities to identify and obtain the appropriate data and models for their area. (CHAPTERS 6,7).

Delimitation

Potentially this review could become as extensive and complex as the environment itself, so there are very many subjects which are not reviewed in detail here. However many of the models discussed do touch on other domains and the range of methods and techniques covered are relevant to other subjects also. The subjects selected address many of the key environmental challenges. The review is not structured by landscape type, for example coastal, forest or mountain where in different subsystem models may have their own specific interactions and significance. However many of the subsystems, such as soil properties, nutrient cycles or public perception, are addressed *across* landscape types. This, it is believed, provided the best means to achieve a comprehensive overview of the methods and models available without excessive repetition, while also addressing the skills and data required to support these. However, there is clearly a case for further individual studies of modelling within specific landscape types and regions.

Review Process

The review consists of four key components: Expert review of specific subjects, a database of models and methods resulting from the reviews, interviews and workshops with academics and government agencies and a national survey of municipalities.

Consultation

In order to ensure that the review considers both the cutting edge in modelling methodologies, and the practical implementation of models within environmental management, the review team consulted with experts at the James Hutton Institute (JHI), Aberdeen, UK (www.hutton.ac.uk).

The JHI is one of Europe's largest environmental research institutes and a leader in integrative environmental modelling and is a key advisor to local and national government agencies in the UK. The JHI specializes in projects which combine expertise in socio-economics, ecology, catchment management, agriculture, soil science and landscape modelling. These multi-disciplinary projects often use both qualitative and highly computational modelling approaches in synthesis, but maintain a practical, stakeholder guided, approach.

Based in Scotland, the JHI also has much relevant experience as regards the social and environmental challenges facing Sweden such as large scales and remote populations but also locations with intense land use pressures. As such it is considered that the JHI provides an ideal option for studying landscape scale modelling of a nature likely to be relevant to the Swedish Environmental Protection Agency (Naturvårdsverket).

Study visits were also undertaken to the 'ExCiteS' team at University College London, UK. The Department of Architecture, Delft Technical University, Netherlands. The Department of Spatial Analysis and Decision Support at the Institute for Environmental Studies, VU University Amsterdam Netherlands and IPLÖ, University of Stuttgart, Germany.

The Modelling Reference Database

The models reviewed are linked with the related publications cited and to this report within a database. This allows queries to be made based on the environmental goal of interest - three primary related objectives have been assigned to each article or computer program reference. Key words such as technique or application domain recorded within cited publications can also be searched as can author. In this way relevant models to specific challenges may be identified, as may groups and individuals with experience in their operation. Alternatively, groups of models may be extracted via a policy oriented, ecosystem perspective rather than simply by academic discipline. It is hoped that this database will be maintained and expanded as a working reference resource.

Workshop

In order to gauge the awareness of, interest in and capacity for scenario modelling within the Swedish planning system a workshop was organized on 2nd October 2015 at SLU Alnarp, for planners, GIS analysts and environmental experts. Three municipalities, Lomma, Kalmar and Malmö, were selected in order to provide a range of municipality size and because each were known to be interested in GIS modelling for the selected thematic focus of coastal flooding. Representatives from Länsstyrelsen and Naturvårdsverket also participated.

Participants were asked about the way in which flood scenarios were created, how future scenarios were assessed within their municipalities, what kind of modelling work was used and why, when consultants or external agencies were used, and what issues constrained their use such as data availability, staff training and time. In addition to flooding, participants were also asked to consider other issues such as nitrate pollution and to give their own examples on other issues, e.g. urban green space and traffic planning. Lastly, participants were also asked to comment on a draft of the national survey of municipalities. Since, from this workshop, it became clear that some Länsstyrelsen had a particularly important role to play a specific meeting was then arranged with staff at Länsstyrelsen Skåne.

These meetings were held in Swedish and professionally facilitated by Sveaplan (Sveaplan.com) a company with experience in leading workshops for spatial planners and familiar with conflict resolution in the planning process. These discussions inform the conclusions presented here as to the utility of scenario modelling at present and recommendations as to potential mechanisms to make scenario modelling more accessible.

Survey of Municipalities

All municipalities in Sweden were invited to respond to a web survey regarding the key ecosystem services that are of concern to their municipalities, the modelling presently undertaken and the technical resources available to them.

Introduction

This report presents the core findings from a review of environmental scenario modelling undertaken by the Swedish University of Agricultural Science (SLU) on behalf of Naturvårdsverket and Havs och vattenmyndigheten. It does not attempt to address all the many potential environmental issues which such a review could theoretically encompass. Rather it focuses on several categories of problems which together represent coupled systems with impact on the 16 Environmental Objectives set out by Naturvårdsverket. The subjects cover different stages in relevant natural cycles (e.g. carbon, nutrients), the role of Land Use / Land Cover change within these and the socio-economic drivers of this.

In addressing models relevant to this broad range of subjects, most mainstream modelling methodologies are discussed, however the reviewers were asked to focus on models which would be likely to be of particular relevance to an applied policy setting across a range of scales. The review should be read in this light, it is not intended to form a comprehensive collation of all models on a given subject. Where reviewers have provided recommendations or other evaluations of particular models this is their own professional opinion given within this context.

The review team was also tasked with considering the ‘utility’ of models within Sweden’s environmental management system, and in particular how they might be used to represent or facilitate stakeholder participation in planning as a means to further citizen involvement in achieving the 16 environmental objectives. This report therefore addresses the capacity of different actors within the planning system to undertake scenario modelling, including questions of where and how they source modelling expertise at present, but it does not seek to represent a compendium of this. It is hoped, however, that it can provide a resource for identifying the modelling capabilities relevant to a given issue and be a first step in building capacity for its use in environmental management.

The Scale of the Problem: Uncertainty, Complexity and Conflict in Eco-System Services.

Recent years have seen a growing recognition of the interdependence between different eco-systems and humanity’s dependence on Eco-System Services (ESS), as encoded within the Convention on Biological Diversity (CBD, 1994), Arhus Convention (UNECE, 1998) and most recently the European Landscape Convention (Council of Europe, 2000). This has focused interest on understanding systems at the landscape scale, that being the entire system over an “area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors” (Council of Europe, 2000).The Swedish government has ratified and incorporated these within its own legislative framework, setting out 16 national objectives describing the quality of the environment that Sweden wishes to achieve by 2020 (Prop. 2009/10:155)

The Millennium Ecosystem Assessment sought to provide a picture of the current state of ESS around the world as to the existing degree of environmental degradation, but also its likely resilience to future scenarios (Hassan, 2005, Carpenter, 2005). In parallel to this policy level interest, increasing knowledge of the environmental processes in combination with rapidly increasing computer power has allowed systems to be modelled in much greater detail and over much larger scales than was possible only a decade ago. These models may explore large data sets (‘data mining’) to find subtle relationships or may simulate bio-physical processes such as flooding, soil nutrient flow or crop growth to provide information on a detailed scale or to assess the strategic impact of future scenarios (Demir and Krajewski, 2013, Negm et al., 2014, Aitkenhead, 2011). It has also been increasingly recognized that people are part of these systems, are important drivers of change, and that solving complex environmental problems may be more effectively achieved by understanding people's motivations and attitudes and influencing public opinion (Peterson et al., 2003).

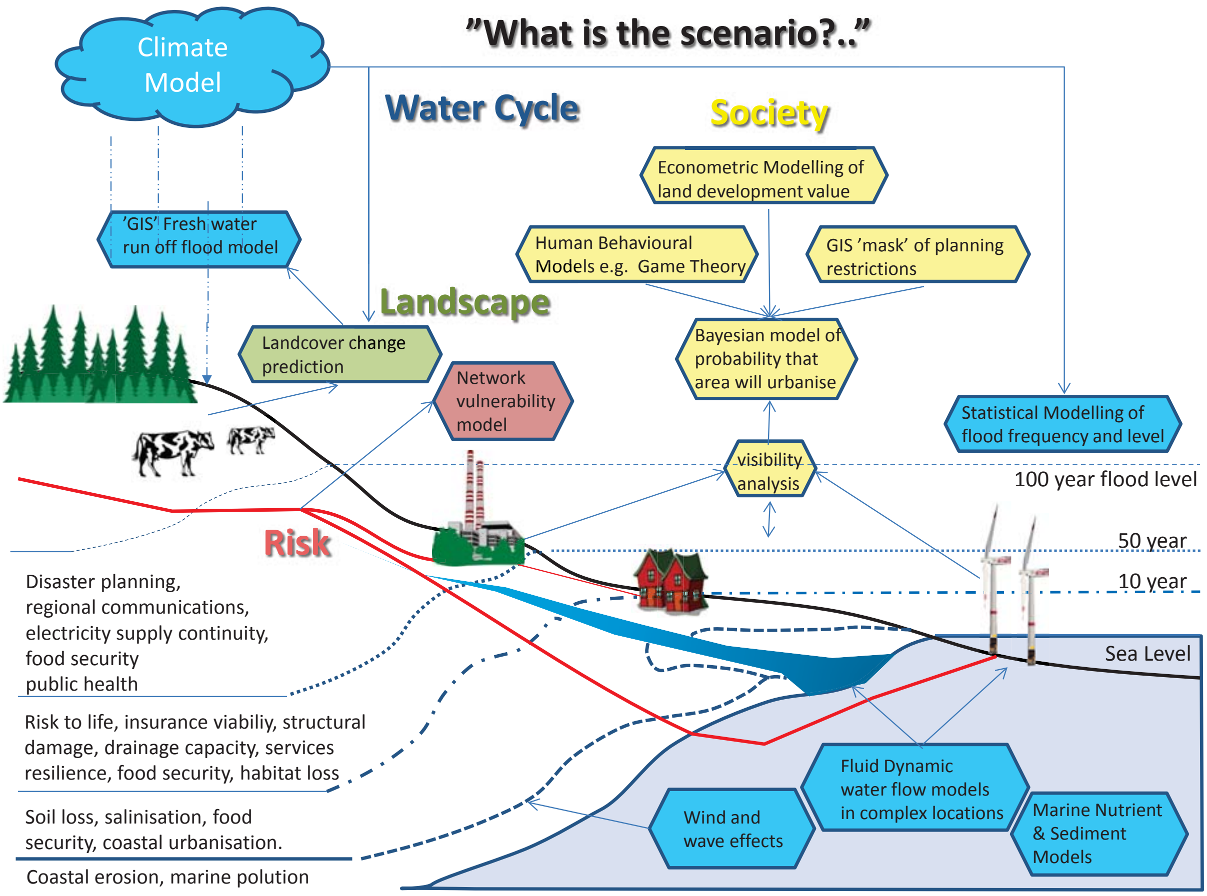

Figure I- 1 : A Coupled Socio-Environmental System

Figure I-1* Provides an illustration of how different components of a system may be addressed by different types of models, with the output of some providing inputs in terms of scenarios on which other models may run. However, even this simple situation shows how complexity quickly accrues at the landscape scale. For example climate change may be taken as an externality, with current trends providing some basic scenarios, or alternative climate scenarios may be developed based on expert knowledge being encoded into simulations. This choice influences both the fresh water and marine flood models and each has its own potential sources of error. Historical data may not hold true in future, while expertise may be incorrect, in both cases the levels of rainfall or sea level rise will also reflect some imprecision. These errors thus propagate to the flood models and the predicted impact of flooding on a range of other risks from food security and electricity supply, to soil loss and bio-diversity. Thus models need to be selected which provide effective knowledge about individual systems, but an alternative might be selected in order to minimize error propagation at an integrated landscape scale.

Attention must therefore be paid to the purpose of the model. For example, will anthropogenic effects be encoded and incorporated within the model, where one may face issues of quantifying vague data, or will the model be used to inform stakeholder opinion, where the risk is that those with less expertise may see precision as validity. Figure I-2* shows a meta-model of the system illustrated in Figure I-1, with focus on the role of the modelling stages as illustrated by the colour of the links between landscape issues.

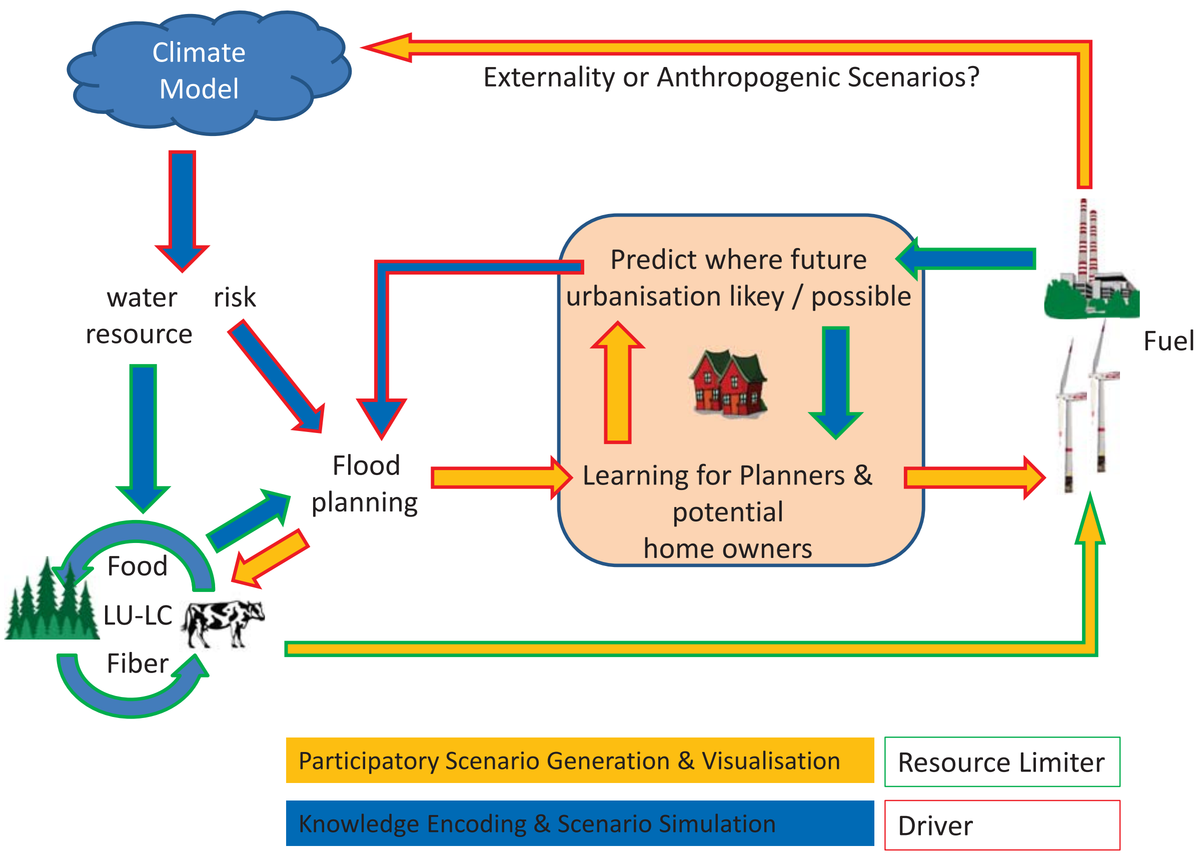

Figure I- 2 : A Meta Model of a Coupled Socio-Environmental System

A Participatory Approach

Participatory scenario generation refers to models where key decisions about how to generate a scenario are based on discussions between experts and other stakeholders as to what factors should be considered and what outputs shown (for example the worst or best case).

Knowledge encoding is where information is first gathered, e.g. from statistical databases or via expert and stakeholder consultation, and then its implications distilled (e.g. via trend analysis or a neural network) and encoded into a modelling method. The method may be simple (GIS overlay) or complex (cellular automata) but the underlying principle is to generate as objective a scenario as possible. These two approaches are often used together with one informing the other. The outline to each link arrow in Figure I-2 illustrates that a model may be providing a driving process to another system, or establishing the bounding limits to that system, for example water availability may be a driving factor in flooding, but is likely to be a limiting factor in choice of land use. Similarly, the land covers available will be a limiting factor in the choice of flood management options.

Social Science and increasingly the humanities have become integral parts of the modelling process, be that in providing methods to understand different sectors of public opinion (Peterson et al., 2003, Sang, 2008), or building expert knowledge into models (Pricea, 2012), or even simulating human and wildlife decision making through cellular automata or agent based models (ABMs) (McLanea, 2011). Combining Socio-Economic and bio-physical models has also become an important potential tool in policy and planning by allowing examples of future scenarios to be developed based on robust evidence, and communicated through intuitive visualisations (Miller, 2006). In this way stakeholders can be shown the potential impact of developments, or potential future problems if we, collectively, fail to adapt our behavior to use common pool resources sustainably (Ostrom, 1994).

A Pragmatic Approach

While the research community has responded to the demands of complex systems by providing complex models, there has also been a notable “utility gap”. Some of the most comprehensive modelling approaches, which build together socio-economic and bio-physical models into an integrated system, are simply too hard to implement or understand to be feasibly employed by most of the agencies who might need their guidance. This may be due to limits in data availability, the cost of specialist equipment or software and licensing issues. Perhaps the most difficult issue to address can be lack of the range of skills needed to implement and interpret the results, which is itself a fundamental part of the modelling process.

One reason why skills become such a critical issue is the sheer range of modelling methods and scenario contexts to be considered. Knowledge is needed both within various technical subjects such as computer science, geo-information science, visualization or internet design and socio-economic disciplines such as stakeholder engagement, governance, sociology, agro-economics and demography, aswell as bio-physical sciences from meteorology to soil science and chemistry (to name but a few). These then need to engage in teams with domain expertise such as management of mountainous regions, transport planning, marine planning and so on.

Furthermore the scale of application is critical both in terms of the data which might be available and the nature of the questions to be asked. National agencies may be most interested in methods which can be applied nationally and provide suitable statistics at that scale. Local government on the other hand may be able to provide more detailed data and use more spatially intensive modelling techniques, but they are also more likely to need precise spatial output, perhaps for visualization for stakeholder engagement as part of the scenario development process (Figure I-3).

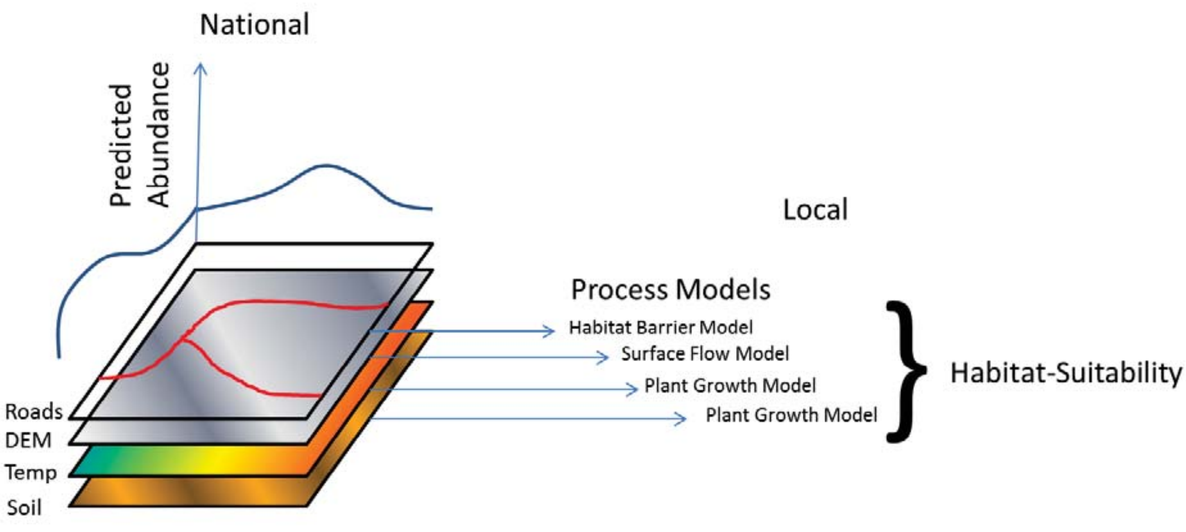

Figure I- 3 : Spatial Scale, Modelling Approach and Example Application

So is it feasible to expect each region to maintain its own scenario modelling expertise? Any review of landscape scale scenario modelling needs to take into account the organisational structure within which models may be implemented and the opportunity for them to have a realistic impact on policy. Models need to be evaluated not only in terms of their ability to accurately describe systems, or predict future scenarios, but also in terms of their feasibility and whether actors in that system such as planners and members of the public can understand and trust the scenarios generated.

While scale of application is a critical decision, it may also become necessary to employ models which extrapolate results from detailed case studies to larger areas. Thus spatial sampling methodology is a vital part of the overall scenario development process, in particular to ensure that "spatial minorities" are represented (Sang, 2008). The question must extend therefore beyond what models might be feasibly used at present to what Spatial Data Infrastructure (e.g. INSPIRE EC 2007 (EC, 2007)) is needed to enable sustained use of more sophisticated scenario models and how the modelling resources available can be organised to best effect.

Proceed with Caution

A Model is only as good as the science which underpins it and how well that science is encoded within the model. Furthermore, the best predictions will only be achieved when correctly calibrated, which also entails the operator appreciating the end goal to be not only prediction of a systems response to a given degree of confidence, but providing actionable information for decision makers. Finding the right balace between scientific accuracy and intuititive, policy relevant communication is not always easy, particularly when "processes .. happen on many different time scales, and the degree of predictability differs for each."[1] Modelling, particularly when combined with maps and other visualisation, can help provide an intuitive picture. However while *"in science being 'wrong' is often at least as important as being 'right'"*[1] in environmental management confidence in model output is critical. Yet the range of agency decision makers have to make a difference may infact be relatively crude in relation to model output, in which case simpler approaches which allow a broader range of scenarios to be considered may in some cases be more effective and provide greater confidence as to a course of action than precise but unwieldy simulations. Equally, decision makers need to recognize error margins are in many respects the most useful part of model output, and develop methods to plan for this uncertainty. In both cases, developing linguistic and conceptual common ground between scientists, technical specialists and planners is vital if models are to be effectively deployed and potentially serious misunderstandings avoided.

[1] Ball, P., *Caution should be the watchword for scientists trying to predict the future,* The Guardian, Wednesday 12 November 2014.

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* Figure I-1 and Figure I-2 contain clip art ; <http://vectors8.com/cow-drawing-logo-design/>; <http://www.aperfectworld.org/nature.html> ; <http://www.clipartlord.com/free-cartoon-house-clip-art/>

1 Landscape Modelling and Stakeholder Engagement: Participatory Approaches and Landscape Visualisation for Conflict Resolution

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1.1 Introduction

Landscapes are defined as "*an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*" (Council of Europe, 2000) Cultural Landscapes are defined by the UNESCO World Heritage Convention (1992) as distinct geographical areas or properties uniquely "... *represent[ing] the combined work of nature and of man*". It also describes cultural landscapes as a "*diversity of manifestations of the interaction between humankind and its natural environment*", and that the protection of traditional cultural landscapes can contribute to maintaining biological diversity. Indeed, Pilgrim and Pretty (2010) propose that the resilience of ecocultural systems is at its strongest when biological and cultural diversity can be considered as an interdependent whole.

Since publication of the Millennium Ecosystem Assessment (MEA, 2005), ecosystem services (ES) have been steadily incorporated into international, national and regional policies across numerous sectors and are being embedded into natural resource management and planning. ES are the benefits people obtain from ecosystems that, in the case of regulating, provisioning or cultural services, deliver goods. Goods are "*all use and non-use, material and non-material outputs from ecosystems that have value for people*" (UK-NEA, 2011), and cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (MEA, 2005).

Several ES frameworks (conceptual and decision-making) have been developed to incorporate the ecology and economics of ecosystems into natural resource policy, planning and management (De Groot, 2002, UK-NEA, 2011). Cultural services, such as the artistic, aesthetic or spiritual benefits associated with ecosystems, are included in many such frameworks and typologies currently being used and debated (Daniel, 2012). Landscapes are key elements of such services, and central to their delivery.

Future landscapes can be explored through the use of scenarios that represent different storylines of change. These can then be quantified using rule-based or other approaches to convert the storylines into spatially-explicit representations combining multiple drivers such as climate change, policy or socioeconomic factors into patterns of land use change (Brown, 2014). Representing such scenarios with landscape visualisation tools enables an exploration of alternative futures for different purposes. These include modelling of public preferences with respect to landscapes under different scenarios, dialogue with domain experts on the characteristics of change (e.g. rate, extent, interactions between features, etc.), and raising awareness of the prospects of change amongst stakeholders of differing levels of expertise.

1.2 Landscape conceptual framework

Tveit (2006) present a framework for the assessment of landscape visual character (the VisuLands framework). The framework links landscape indicators to theories of landscape aesthetics and landscape perception, providing a comprehensive approach to visual landscape assessment. The framework identifies key concepts of landscape aesthetics:

1. Stewardship (sense of order/care, human presence by active landscape management);
2. Coherence (unity of a scene, repeating patterns of colour and texture, correspondence between land use and natural conditions);
3. Disturbance (lack of contextual fit and coherence, constructions and interventions);
4. Historicity (historical continuity and historical richness, different time layers, amount and diversity of cultural elements);
5. Naturalness (closeness of landscape to perceived natural state);
6. Visual scale/openness (landscape rooms/perceptual units);
7. Complexity (diversity, richness of landscape elements and features, interspersion of pattern);
8. Imageability (qualities of a landscape present in totality or through elements; landmarks and special features, natural and cultural, making the landscape create a strong visual image in the observer, making landscapes distinguishable and memorable);
9. Ephemera (changes with season and weather).

The framework was developed further by Ode et al. (2008), identifying a range of currently used indicators for visual landscape assessment. Fry et al. (2009) explored the conceptual common ground between visual landscape character and key ecological aspects, identifying a range of landscape indicators relevant for both visual and cultural functions and ecological function. This framework provides a basis for assessing the potential impacts of drivers of change with respect to landscapes (e.g. Ode and Miller (2011); Tveit and Ode Sang (2014)). However, the identification of indicators which relate to cultural services such as sense of place, identity or spiritual qualities of landscapes, is challenging, and thus far no common and meaningful indicator system has been developed.

The OECD (2001) presented an agricultural context for defining landscapes (Figure 1-1). They classify landscapes by reference to the presence of human intervention. Agricultural landscapes are conceptually linked to landscape management through structure, function and value. Ecological indicators within landscape planning have their foundation and theoretical base in landscape ecology. This is related to three fundamental components of landscape: structure, function and change (Forman, 1995). Identifying the main structural elements in the landscape and their relation to ecological processes is essential for our understanding of how landscape change will affect species and ecological communities, and hence ecosystems (Turner et al., 1999). Understanding the relationships between structure and function also enables the prediction of ecological consequences of proposed spatial solution(s). These directly link to the groupings of ecosystems and habitat types (A to E, Figure 1-1). Value has different components, two of which can be distinguished in this framework from Unwin (1975): landscape value: the investigation and measurement of value judgments or preferences in the visual landscape; and landscape evaluation: an assessment of the quality of the objective visual landscape in terms of individual or societal preferences for different landscape types.

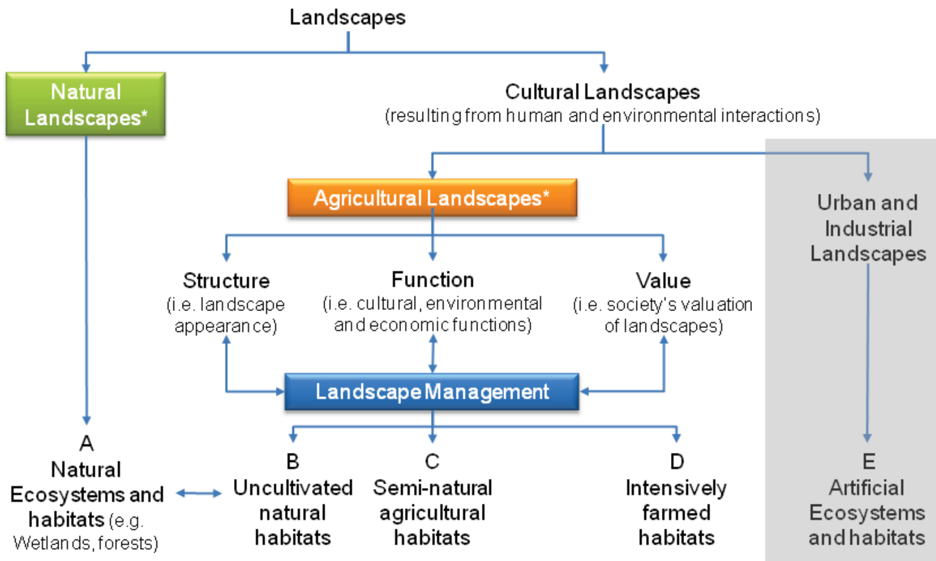


Figure 1-1 Defining cultural and natural landscapes: the agricultural context (after OECD, 2001).

This classification of landscapes provides a basis for associating landscapes and their characteristics with particular types of management practice and pressures for change. The nature of management practices may change through time, with consequences for the functions and aesthetics of landscapes.

The UK Foresight Land Use Project (2010) highlighted the importance of an integrated land systems perspective for understanding the complex relationships between society, land and landscape. Figure 1-2 shows a representation of the set of landscape concepts with respect to the OECD classification of landscapes. This combination provides a basis for analysing changes in socio-economic or biophysical changes to be translated into a landscape framework, with which scientific tests relating to landscape impacts can be planned, and representations of land uses be designed.

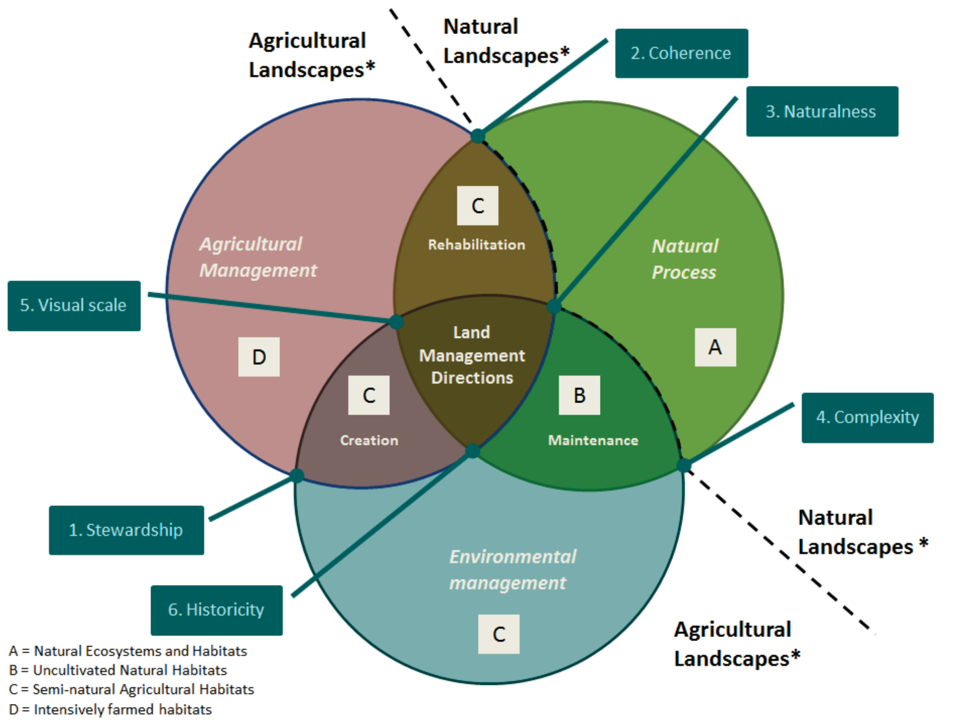


Figure 1-2 Conceptual interactions between processes of change in rural areas and selected landscape concepts (Modified after Fry et al., 2009).

1.3 Prospective changes in land use

Driving forces continuously modify the ‘state’ of a landscape, making them neither stable nor constant, but dynamic evolving features. Change has always been integral to landscapes (rural and urban) but “it now seems more intensified in terms of pace and persistence” (Halfacree, 2006). Rural landscapes experience rapid (traumatic) and slow, continuous (but cumulatively large-scale) change (Antrop, 2004) with two main trends: intensification and extensification (Vos and Klijn, 2000). Both of these processes can potentially degrade landscapes and features, as has been documented from many regions (e.g. Slovakia, Pyrenees, Norway; Green and Vos, (2001); Fjellstad and Dramstad, (1999)).

Agricultural intensification may lead to disturbance and damage of cultural heritage objects, soil erosion, flooding, pollution, and reduced quality of landscape experience. Land abandonment, followed by scrub encroachment and woodland growth, may reduce perception of landscape quality and accessibility. Precisely which processes of landscape change are dominant, and the consequences of these changes, can vary under different geographic and climatic conditions.

Antrop (2005) has stressed the importance of understanding which land uses are changing, how quickly, by how much and how this relates to historical legacies. He recognises that drivers of change have different dynamics and effects over time, and that actual and planned change may follow different pathways (Figure 1-3).

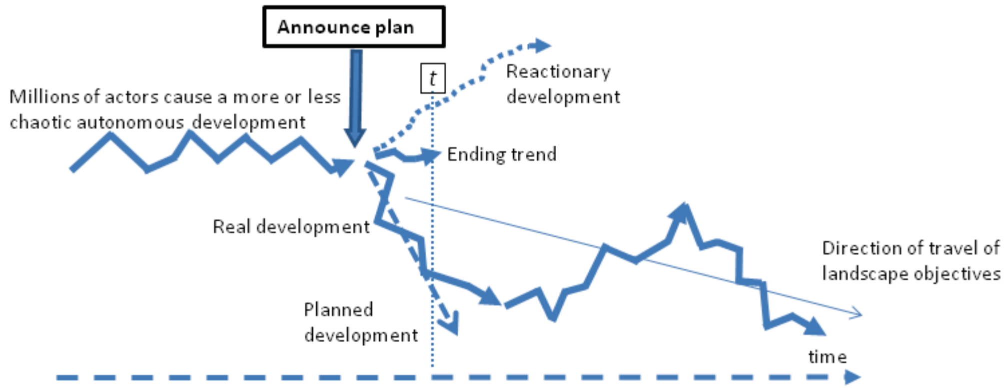


Figure 1-3 Autonomous development and process of planning (from Antrop, 2005).

Landscape is often perceived as the backdrop to events and less often as having its own history and traces of former land use, which is required to understand *landscape as space* (Nord, 2009). Tools which enable greater understanding of the time periods through which landscapes evolve include Landscape Character Assessments (LCA), which is a set of techniques and procedures used to classify, describe and understand the evolution and physical and cultural characteristics of landscape. A complementary classification system is that of the Historic Landscape Characterisation (HLC) methodology used in Scotland, England and Wales (Fairclough and McInnes, 2002 (Fairclough, 2002, Aldred, 2003) which was developed to provide a comprehensive understanding of the historic environment and establish an overall framework in which discrete heritage assets may be located (Clark, 2004).

These two groups of techniques have methodologically many things in common and are in line with international initiatives such as the Dobris Assessment (Stanners and Bourdeau, 1995) and the European Landscape Convention (ELC) (Council of Europe, 2000) which advocate protection of natural and cultural heritage at the landscape level. In particular the European Landscape Convention (ELC) states that "…*the landscape contributes to the formation of local cultures and that it is a basic component of the European natural and cultural heritage, contributing to human well-being and consolidation of the European identity*." In its National Measures, the ELC obliges signatory states to promote the "… *participation of communities and public authorities in decisions affecting the landscape of the region or locality*."

In many cases, landscape changes can significantly reduce biodiversity, cultural value, and sense of place (Naveh, 2007, UK-NEA, 2011). Knowledge about the direct and indirect impacts of environmental and human influences on landscapes will improve understanding of the roles of landscape components and wider cultural significance, and inform strategies for protection, mitigation of risks, and increased landscape resilience to change. The use of scenario development and modelling can help develop such understanding and so inform strategies for the protection and enhancement of cultural landscapes.

Understanding historical changes in landscape can inform the development of policies, strategies and monitoring frameworks for the effective management of cultural landscapes. This also requires consideration of prospective futures. Nassauer (1995) proposed working with 'possible landscapes', bringing multi-disciplinary perspectives to bear when considering human behaviour in ecological systems. The use of such multiple perspectives provides one means of developing credible scenarios of alternative futures, drawing on expertise in the biophysical and socio-economic sciences.

1.4 Scenario analysis

1.4.1 Overview

Scenarios are “plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces” (Nakicenovic, 2000). They are not forecasts, predictions, projections or plans of the future for a given time period (van der Heijden, 2002).

Scenario analysis provides one tool for considering the implications of a plan or management decision across a range of future possibilities (Steinitz et al., 2003), and therefore also a valuable analytical device for spatial planning (Couclelis, 2005), enabling practitioners to engage with the process of developing coherent storylines that are applicable at a range of scales.

The use of scenarios for strategic planning began to be formalised for the analysis of war games post World War II (van der Heijden, 1966), and used in business situations (such as Royal Dutch Shell; Wack (1985)) politics (e.g. Kahane (1998)), and environmental assessments (e.g. Gallopin et al., (1997)). A description of their use and evolution is presented in the Scenarios Working Group of the Millennium Ecosystem Assessment (www.unep.org/maweb/en/Scenarios.aspx), and the UNEP GEO-3 Scenarios (Potting and Bakkes, 2004) and a review of scenario development by Rothman (2008).

The development and use of scenarios enables evaluation of different decision choices (in policy or business) and the range of alternative outcomes and associated pathways (e.g. Ringland (1998)). These may be described in terms of destinies, because current state and development pathways set limits on possible futures, and choices, which will influence the differences between potential futures. Ringland (1998) summarises their roles as:

- (i) Consequence assessment: assessing the implications of present action, decisions, policies, etc.;
- (ii) Early warning and guidance: detecting and avoiding problems before they occur;
- (iii) Proactive strategy formulation: considering the present implications of possible future events;
- (iv) Normative scenarios: envisioning aspects of possible or desired future.

Therefore, scenarios provide a context for exploring the development of policies and plans under alternative futures, both socio-economic (e.g. economic conditions) and biophysical (e.g. climate change). Consideration of possible but extreme pathways of change enables the testing of the sensitivity of change to disruptive events (e.g. disease outbreak, civil unrest, business failure), and the timing of decision-making events (e.g. political elections, meetings of company Boards, actions of individuals). Von Reibnitz (1988) presents this as in Figure 1-4.

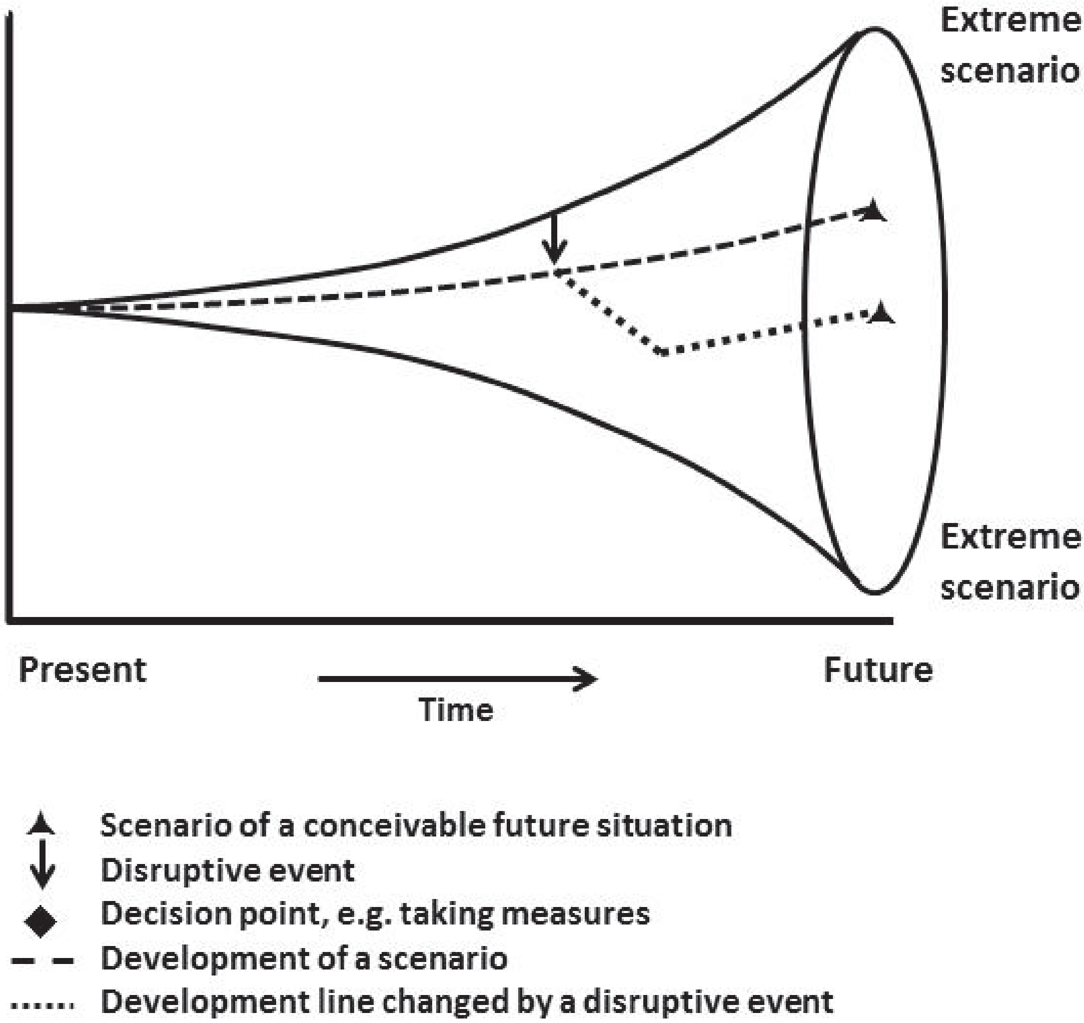


Figure 1-4 Conceptual representation of the effect of a disruptive event on a range of possible scenarios (Source: von Reibnitz, 1988)

Van Notten et al. (2003; Figure 1.4) developed a typology of scenarios, listing the characteristics of 14 types, and their alignment with identifyied overall themes of scenario development (project goal, process design, scenario content).

	Overarching themes	Scenario	Characteristics
A	Project goal: Exploration vs decision support	I	Inclusion of norms?: Descriptive vs normative
		II	Vantage point: forecasting vs backcasting
		III	Subject: issue-based, area-based, institution-based
		IV	Timescale: long term vs short term
		V	Spatial scale: global/ supranational vs national/ local
B	Process design: Intuitive vs formal	VI	Data: qualitative vs quantitative
		VII	Method of data collection: participatory vs desk research
		VIII	Resources: extensive vs limited
		IX	Institutional conditions: open vs constrained
C	Scenario content: Complex vs simple	X	Temporal nature: claim vs snapshot
		XI	Variables: heterogeneous vs homogeneous
		XII	Dynamics: peripheral vs trend
		XIII	Level of deviation: alternative vs conventional
		XIV	Level of integration: high vs low

Figure 1-5 Typology of scenarios (source: Van Notten et al., 2003).

This typology provides a basis for assessing the choice of methodology with respect to the purpose of the task to hand. The discussions of change in Figure 1-3 and Figure 1-4 above, whether relating to landscape (Antrop, 2005) or conceptually (von Reibnitz, 1988), communicate the same message of recognition of the importance of pathways of change, reflecting key trigger points which then redirect processes, such as those which affect land use and landscape. The nature of such triggers may be ones which are planned and controlled, such as decisions which represent a change in policy or in its implementation (e.g. permission for a development), or unplanned and unexpected, such as a natural disaster or extreme event (e.g. flash flood).

Climate change scenarios suggest an increasing vulnerability of cities to water scarcity, flooding, heatwaves, and increase of related costs of infrastructure, hazard management and health systems (Gupta, 2012). The EEA (2009) notes that 26 European river basins are already under permanent water stress, while another 43 experience it seasonally. According to projections, the numbers are going to increase by about 30% by 2030. Although rare in nature, ‘low-probability high-impact events’ (e.g. Alcamo et al., 2006) such as large-scale floods and disease outbreaks are usefully employed within scenario analysis to highlight the extreme outcomes of events. These ‘shock’ scenarios can be used to investigate the resilience of existing land systems and the prospective impacts on landscapes. Their impacts can be translated through theoretical effects on the landscape concepts, or based upon empirical evidence.

For example, extreme flood events may modify river channels, removing surface vegetation and damaging built infrastructure, reducing the sense of order and care, and active management, and so reduced levels of stewardship, and increased levels of disturbance. These would lead to negative impressions of landscape. However, such changes could be ephemeral in nature with repeat flooding adding to the historical imprints on the landscape (e.g. ox bow lakes), evidence contributing to the impression of naturalness, and visual complexity of landscape elements (i.e. non-geometric patterns), and effects possibly restricted to a single season. Such effects may contribute to positive impressions of landscapes, based on the theory of ecological models that landscape quality is related to naturalness or ecosystem integrity (Daniel, 1983).

1.4.2 Scenarios and landscape change

Several international, European and national initiatives or studies have developed high level socio-economic scenarios, some being combined with biophysical aspects (e.g. climate change through emissions factors). Examples include those developed for the IPCC, MEA, EEA, UK Foresight, UK NEA and ESPON. Most of these are spatially explicit, using contextual biophysical and, or, socio-economic information of the area in question.

European Union projects which have used scenario approaches in regard to land use and landscape change, either exploiting existing frameworks or developing new ones include ALARM, CLUE-S (Agarwal, 2000), Dyna-CLUE (Verburg, 2009), IMAGES (Verburg et al., 2010), LN-LCN (Schroter, 2004), ITE^{2}M Waldhardt (2010) PLUREL, VOLANTE (Paterson, 2012), MOLAND (Walsh and McNicholas, 2010), EURURALIS and VisuLands (e.g. Miller (2006)).

Examples of the use of scenarios in relation to land use and landscape follow, mapped onto the Van Notten typology in terms of the themes Project Objectives and Scenario Content.

Example 1. Multi-functional futures: Project aim – decision-support, normative scenarios

Waldhart et al. (2010) used a normative approach to develop a scenario of a multifunctional landscape of the future, in a study water catchment in the Wetterau region of Hesse, Germany. They compared the existing landscape with a scenario of a multi-functional landscape which was developed by domain experts.

The approach taken was in five main steps: 1) documentation of the current landscape structure and land use at the scale of uniformly managed land units; 2) detection of functional deficits of today´s landscape considering environmental, economic, and societal attributes; 3) compilation of a catalogue of alternative land uses suitable to minimize the detected functional deficits; 4) application of a rule based modification of current land-use patterns into a normative scenario; and 5) a comparison of the current landscape and the normative scenario using indicators modelled.

The ITE^{2}M modelling toolset (Frede, 2002) was then used to assess the level of multi-functionality in the landscape of the scenario and the current landscape, using spatially explicit modelling of land cover or land use units. The components of the ITE^{2}M toolset included accumulation of heavy metals per agricultural unit (using ATMOIS), water quality and quantity (using SWAT), plant species richness (using ProF), breeding populations of farmland indicator bird species (using GEPARD), economic returns in terms of land rent and yield (using ProLAND), and impacts on social welfare using choice experiments (CHOICE). The last of these models was used to provide an estimate of the preferences between the current and future landscape, and textual descriptions of other scenarios of landscape scenery. The combined analysis showed that the expert derived scenario of a potential future landscape would lead to a net benefit to society.

Example 2. Climate change, energy and landscape: Project aim – exploration, time-scale short

One threat to landscapes in general and cultural and historical landscapes in particular, is that of climate change, which may influence people's perceptions of an area's history and the cultural services it supports (Fyrhi, 2009). The impacts of climate change on ecosystems, and in the redefinition of biotopes, an effect already observed in geotope change, also affects those cultural landscapes with a strong environmental or agricultural component.

Young (2011) uses an inventory linked to a set of 24 indicators of climate change, derived from the US Environmental Protection Agency, and potential impacts on cultural landscapes (e.g. increases in extreme weather events increase soil erosion, accelerating deterioration and exposure of archaeological sites; temperature changes lead to changes in animal behaviour, migration to new areas and impacts on vegetation growth, land abandonment and succession on historic sites). Such impacts can be assessed in relation to landscapes using the VisuLands framework of landscape concepts, and the OECD classification represented in Figure 1-2. Within this framework, factors such as land abandonment intersect agricultural management, environmental management, and natural processes. Evidence of the processes of abandonment may imply a reduction in stewardship and increase in naturalness, and possibly residual evidence of historic patterns of land management (i.e. historicity). The changes in indicators of different concepts may not always be immediate, or simultaneous, and may represent increases in the indicator of one concept, and decreases in another. Therefore, it simportant to recognised the complexity of a systems interactions between concepts when interpreting the implications of change on a landscape (Ode, 2009).

Eventually, one would expect these changes to modify the extent or nature of elements used in a Landscape Character Assessment (LCA). Therefore, the mapping of landscape character could be expected to produce an output showing the difference in character through time, either reported by the units mapped at year 1, or by the delimitation of new map units.

Testing public reactions to alternative futures under climate change has been undertaken in several studies. One, by University of East Anglia and Rothamsted Research explored public perceptions of future landscapes in an agricultural area where land management regimes are modified to reflect alternative scenarios of mitigating and adapting to climate change. This was to support communications on local stakeholder perspectives of potential future land uses, in a time frame which was near term.

Dockerty et al. (2006) describe the development of interpreting the impacts of climate change through GIS-based visualisations, for a study area in Norfolk, SE England. Their study was based on scenarios of climate change using projections for the United Kingdom, linked to future world development pathways of National Enterprise, Local Stewardship, World Markets and Global Sustainability (Berkhout, 2002).

A GIS database was developed at the level of individual fields using national mapping from Ordnance Survey. A land use allocation model (CLUAM, Parry et al., (1999)) was then used to prepare land allocations of crops under each of four development pathways, although model support was only available for two (National Enterprise and Local Stewardship). The approach to the development of visualisation to represent each scenario was based upon the associated land cover features, vegetation and buildings which would be expected under each scenario.

No public engagement was involved in the development of the content of the Local Stewardship scenario, with reference made to the potential for including interactivity in the discussions about landscapes (e.g. Stock and Bishop (2005)).

Figure 1-6 shows a landscape from two viewpoints, at two dates (2001 and 2020), with the latter under scenarios of two land management regimes.

Figure 1-6 Shows an example of the potential impacts of climate change on rural landscapes

(Courtesy of Trudie Dockerty, Andrew Lovett, Gilla Sünnenberg, Katy Appleton, Martin Parry). (a) and (b) Summer 2001; (c) and (d) Summer 2020 with no climate mitigation

Example 3. Socio-economic drivers of change: Project aim – exploration, time-scale long; Scenario content.

The Millennium Ecosystem Assessment (MEA) sets out one exploration of alternative futures through the use of scenarios, and the IPCC SRES (Nakicenovic, 2000) provides an overarching framework to contextualise future socio-economic change for scenarios of land use. This framework categorises scenarios based upon two axes that define major uncertainties in future global development: global versus regional governance, and market-oriented versus environmental values. Figure 1-7 shows four scenarios of development pathways based upon the UK Climate Impacts Programme (UKCIP;

Berkhout et al., (2002)) version of the IPCC SRES, with the a specific emphasis on aspects of land use change (Brown, 2014).

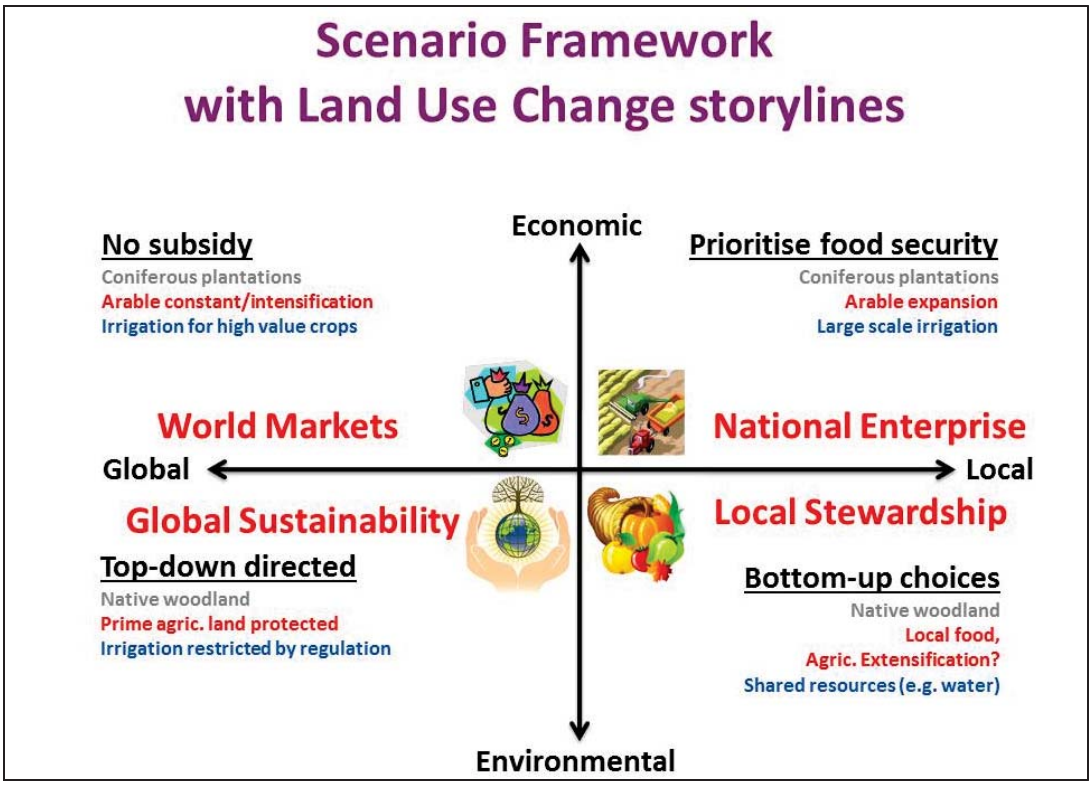


Figure 1-7 Scenarios of development pathways, based on the UK National Ecosystem Assessment (UKNEA, 2011).

Brown and Castellazzi (Brown, 2014) show how scenarios, storylines and policy objectives can be translated into spatially-explicit realisations at the level of the land parcel or field, using LandSFACTS software and the Integrated Agriculture and Control System (IACS) data in a stochastic process to create allocations of agricultural and forest land uses that meet set constraints (e.g. proportion of increased woodland across a catchment). Such an approach can be equally used with any spatial unit (e.g. land use or cover polygon, population ward, or water catchment) to explore alternative options for land uses.

Figure 1-8 shows the spatial distribution of land cover and use based on three scenarios calculated for 2050: World Markets, National Enterprise, and Global Sustainability, at two scales of the river catchment (River Dee, NE Scotland), and the sub-catchment (Tarland).

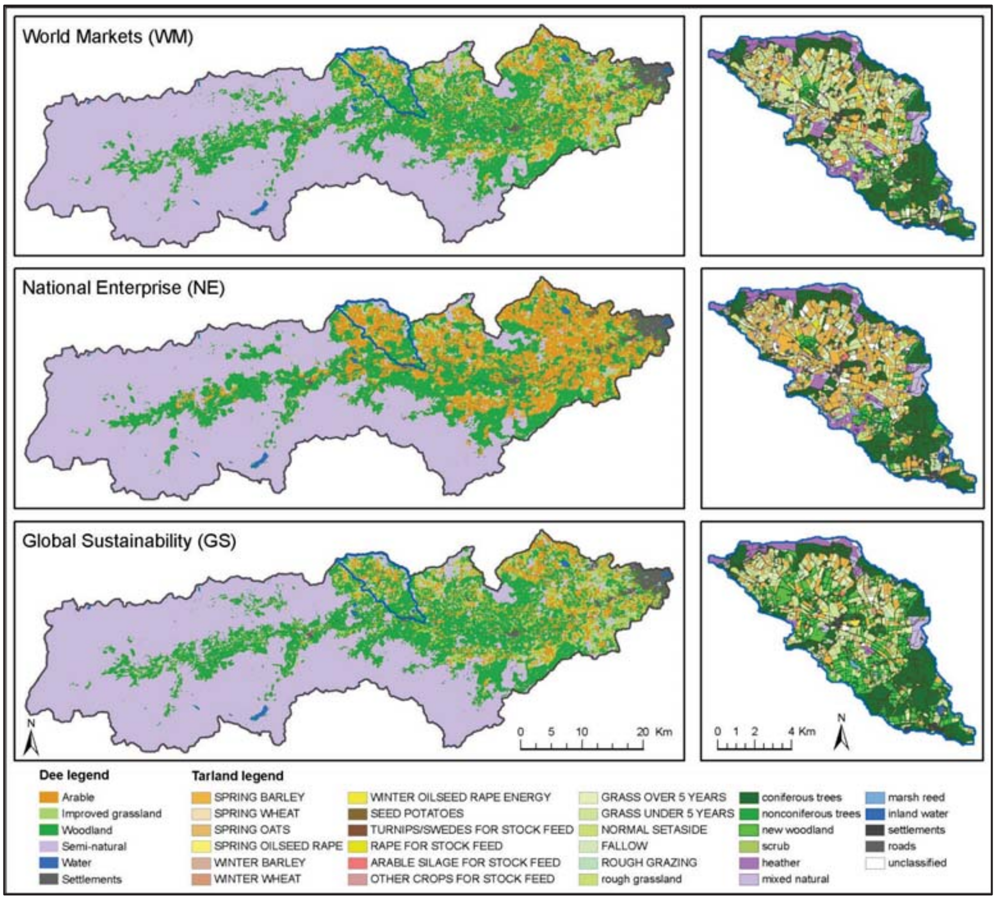


Figure 1-8 Spatial representation of scenarios for 2050 for the Dee catchment and Tarland sub-catchment, NE Scotland (Brown & Castellazzi, 2014).

The outputs from spatial rule-based models developed for sectoral strategies, such as woodland expansion, wind energy, urban development, can be used as inputs to developing scenarios in case-study areas, and outputs interpreted with respect to landscape character and special qualities to assess potential impacts on cultural landscapes, and their visual representation[2]. Stakeholder-based elaboration of scenarios enables assessments of options for managing or adapting to environmental and socio-economic change under scenario conditions. The spatial models shown in Figure 1-8 were used as the basis for visualisation of changes in the current landscape (2012), as influenced by each of the three scenarios and an additional locally-defined scenario (Local Stewardship). The 3D model was then used in a mobile virtual reality environment (Virtual Landscape Theatre, www.hutton.ac.uk/learning/exhibits/vlt). This theatre was then used in venues in different

[2] For examples in relation to streetscapes see <https://www4.rgu.ac.uk/sss/research/page.cfm?pge=2532> and CRAIG, T. C., A.; GALAN-DIAZ, C., 2012. The influences of actual and perceived familiarity on environmental preferences for the design of a proposed urban square. *Urban Studies Research, ,* Article id 767048, 9pp.

For green-space see LAING, R., DAVIES, A. M., MILLER, D., CONNIFF, A., SCOTT, S. & MORRICE, J. 2009. The application of visual environmental economics in the study of public preference and urban greenspace. *Environment and Planning B: Planning and Design,* 36**,** 355-375.

places in the United Kingdom to elicit audience preferences for the prospective landscapes (Figure 1-9), and to produce audience-prepared local stewardship scenarios in which participants selected and located features in the virtual reality model and environment (Ball et al., 2008).

Figure 1-9 Eliciting public opinions on alternative future land uses in the Virtual Landscape Theatre with audiences from: (a) Birmingham, (b) Ballater, north-east Scotland.

Findings on landscape preference were interpreted with respect to the VisuLands framework of landscape concepts. In summary, audiences were positive towards landscapes with a visible mix of land uses, sound stewardship, elements of perceived naturalness and visual diversity. Of the representations of pre-prepared scenarios, Global Sustainability was preferred. Once developed, the landscape representing the Local Stewardship scenario then ranked highest amongst local participants, which was influenced by the bottom-up nature of its development.

Comparing between the consultation events, there was commonality between audiences in a desire for amenity woodland in fields adjacent to the village, quality recreation areas in the village, conservation interests, and recognition of risks to water quality with increased agricultural activity. Audiences local and non-local to the study area were positive towards small-scale wind turbines associated with farming or communities.

However, significant differences between audiences arose with respect to the siting of medium-sized windfarms on hills in the north of the area. Those unfamiliar with the area (i.e. in Birmingham and some in Edinburgh), argued that renewable energy was a priority and highlighted open hilltops as opportunities for maximising energy return. Those familiar with the area, even if not residents, were conscious of its local significance and previous rejections of proposals for such developments.

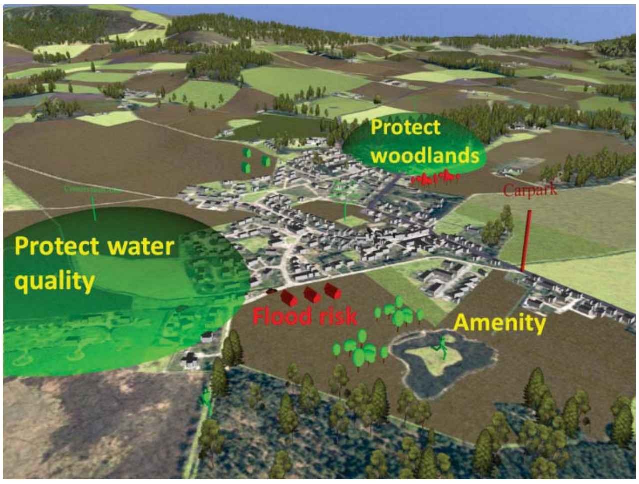


Figure 1-10 Overview of land use and landscape features developed from an audience local to the case study area.

Figure 1-10 shows a refined local stewardship scenario produced from one of the workshop sessions using the virtual reality environment with audiences local to the case study area. This highlights the recognition of risks to the existing community (e.g. flooding), mitigation measures, increased provision of local energy and amenities, and a desire to protect local resources (e.g. water quality and woodlands). The same approach to developing a 'local stewardship' scenario but by audiences which are not local to the site did not identify the importance of mitigation of risk, nor to the protection of certain local resources. The non-local audience focused on the provision of new resources (e.g. housing and renewable energy), but in different places in the local landscape.

The differences between the scenarios of Local Stewardship can be interpreted with respect to the recognition and experience of threats to landscapes and resources, and attitudes and identification of opportunities. It also raises an overall question of governance in terms of who has the right of decision-making, and therefore the legitimacy of the development of scenarios, both top-down, and bottom-up to different parts of the community. It may lead to distinctions to be made between the content of scenarios developed by communities of place and community of interest.

1.5 Discussion

The evolution in use of methods for developing and using scenario tools has contributed to their uptake in relation to assessing consequences of drivers of change at different geographic scales. However, there are certain requirements for the operationalisation of such tools. These include their role in the process of scenario development (e.g. participatory approaches), or assessment of implications (e.g. assessments of landscapes).

The engagement of stakeholders in the development of scenarios of alternative futures, and associated evolution of landscapes, contributes to the aspirations, and requirements, of the Aarhus Declaration on access to information and public participation in decision-making (UNECE, 1998). The General Provisions of the Declaration note that governments should take legislative and regulatory steps to "… promote environmental education and environmental awareness among the public, especially on how to obtain access to information, to participate in decision-making and to obtain access to justice in environmental matters." The importance of engaging the public in environmental issues is included in a Specific Provision of the European Landscape Convention.

The delegation of responsibility for developing these scenarios, and the authority they then carry, can be considered with respect to Arnstein's ladder of participation (Arnstein (1969); Figure 1-11). Arnstein's seminal work defined a multi-level participatory classification, comprising eight levels of involvement, clustered under three main categories: non-participation; tokenism; and citizen power. Non-participation embraces levels where citizens' involvement is at largely at an educational level, meaning they are informed and educated on a subject, but where only one-way communication exists (i.e. Mode 1). Tokenism involves active participation from citizens, but with their opinions not significantly influencing final decisions. Under 'citizen power', there is, to different degrees, direct influence of citizens on the decision-making process.

In circumstances where the governance structure of the engagement confers authority to the process such that the scenarios evolve into plans, the position on Arnstein's ladder is one of the higher 'degrees of citizen power'.

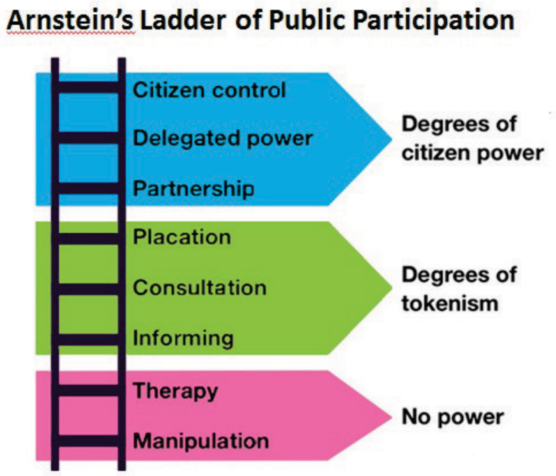


Figure 1-11 Arnstein's ladder of participation (Arnstein, 1969).

The degree of impact of public participation on decision making processes is dependent upon the degree of involvement of the public which, in practice, falls into three main levels: 1) *information*, dissemination or directive participation (where information is communicated primarily in one direction to the public); 2) *consultation*, where public opinions are sought and considered in expert or managerial decision- making; 3) *collaboration*, where representatives of the public are involved actively in developing solutions and directly influencing decisions to a greater or lesser degree (Sheppard, 2005).

In addressing environmental issues with long term consequences, decisions extend beyond the scientific context and interact with their social and political contexts. Decisions about how to deal with the inherent uncertainties, what risks to take and what contingencies to plan for, can be informed by science but in the end, they are an expression of human ethics and preferences, and of the socio-political context in which they are made (Kay et al., 1999).

These type of problems are designated by several authors as social decision problems (see, for example, (Papamichail and Robertson, 2003, Healy, 1999, Cortner, 2000) and represent situations where scientists cannot provide any useful input without interacting with the rest of the society, and where the it is difficult for the rest of the society to perform sound decision making without interacting with scientists (Munda, 2004). Authors such as (Kay et al., 1999, Mayumi and Giampietro, 2005, Luks, 1999, Haag and Kaupenjohann, 2001, Ravetz, 2004, Funtowicz and Ravetz, 1994) argue that public opinion is a crucial aspect in legitimising policy-making for science and technology, requiring effective two-way communication pathways, trust building, citizen participation and learning processes.

As discussed earlier, scenarios provide means of considering options, and assessing a range of alternative outcomes. The development of scenarios and their assessment can be considered with respect to questions of governance and authority. High level, global scenarios, can be used to provide an overall context for considering continental, national and large area regional change. Such scenarios are likely to have been developed with expert panels supported by analysis of trends (e.g. MEA). Such high level scenarios provide a context, or bounds, for the development of those used at regional and local levels. These are most likely to be considered to be 'informing' or 'consultation', particularly in the development of scenarios of 'local stewardship' as per the UKNEA.

Landscapes can withstand disturbance and change. However, Ahern (1999) notes that they are vulnerable to irrevocable disturbance, or permanent change. To support discussion and assessment of actions and development pathways within the context of alternative futures there is a requirement for comparisons to be made of the impacts and implications on natural and cultural heritage features, such as water quality, habitats and their connectivity, and landscapes. These should be of a form which can be readily interpreted and meaningful for the task in hand, and designed with the target audience in mind, whether domain expert, policy officer, land manager, or member of the public.

ICT tools, and visualisation in particular, have been used increasingly as part of information, consultation, and collaboration in relation to issues of global significance. For example, the representation of landscapes of the future including 3D imagery (e.g. Dockerty et al., (2006); Donaldson-Selby et al., (2012)), sketches, or imagery (e.g. Palomo, 2011) enable the interpretation of change in relation to landscapes. Visualisation tools have been used for helping communities to plan for adaptation against impacts and effects of climate change as demonstrated by the research team at the Collaborative for Advanced Landscape Planning, at University British Columbia, Canada (Sheppard et al., 2013). They have developed the use of virtual and augmented reality and Geographic Information Systems, with tools such as Community Viz (Placeways, 2013), and provide a video game which they describe as empowering lifelong learners to creatively construct their own futures.

Stock et al. (2005) describe the use of visualisation tools linked to GIS to support discussion with land managers with respect to future land uses and indicators of change in landscape features (e.g. water). The system developed is 'Spatial Information Exploration and Visualisation Environment' (SIEVE). Chen et al. (2008) describe the development of this tool which uses a gaming engine and a GIS, with visualisation tools to help communities envisage scenarios of landscape change. The translation of such change into impacts on the character of landscapes is described by Ode et al. (2009), and Ode and Miller (2011).

Sets of indicators can also be used through the application of models to representations of outputs under different scenarios. For example, Waldhart et al. (2010) use the model network ITE^{2}M which comprises other models such as ATOMIS, SWAT, ProF, GEPARD, ProLand, and CHOICE for the provision of indicators. The outputs provided for stakeholders are combinations of numerical summaries, charts and maps. Such outputs enable discussions by stakeholder on trade-offs through multiple scenarios (Palomo et al., 2011).

Steinitz et al. (2003) presents summaries of impacts of ten alternative futures, by percentage change relative to a baseline condition, and by percent ranking within the range of futures. Brown and Castellazzi (2014) use assessments by ecosystem service, presenting the results in the form of spider diagrams and maps, both by scenario, and by geographic scale.

The geographic area defined of interest requires to be consistent with the nature and content of the scenarios (e.g. relevance of the drivers of change; constraints on change). The work presented in the examples above are both geographically defined by water catchments (Wetter, Germany, Waldhart et al.; Dee, Scotland, Brown and Castellazzi). These provide discrete geographic units for assessing and comparing the implications on the provision of ecosystem services, between scenarios.

The increasing popularity of citizen science offers the prospect of greater levels of data capture, with online tools providing mechanisms for such data to be geospecific. The uptake of mobile technologies provides new opportunities for the capture and presentation of information about the environment. This includes the representation of landscapes augmented with information on attributes which may not be visible, such as soil erosion risk, or pollutant flows.

1.6 Future development

Further development of tools should include certain factors which are of increasing importance:

i) **Geographic area and scale.** The application of scenarios and the calculation or interpretation of potential impacts on the landscape, are generally within a defined spatial unit (e.g. water catchment), with representations using eye-level imagery from set viewpoints. This enables a structured approach to the design of the implementation of scenarios, and the assessment of landscape impacts, and analysis which takes account of boundary issues (e.g. including views of landscapes outwith the area defined but visible from within it). However, this is somewhat inflexible.

   There may be no clear biophysically or politically defined boundary of an area of interest. Stakeholders may not always restrict the assessment of impacts to within an area, perhaps wishing to include the approaches to an area when considering its setting, potential cumulative impacts of developments, or the experiences of travel to and from an area.

   Therefore, when designing a scenario development exercise, and the evaluation of potential impacts on landscapes, greater account should be taken of the availability and usability of data in areas surrounding that of primary interest. This will enable consideration of flows of ecosystem services across what may have been considered to be a boundary, a geographic context for evaluating impacts on landscapes, and flexibility for participants to evaluate impacts.

   Similarly, the stakeholder or participant should be able to view the landscapes from locations of their choice, and not restricted to eye-level views. To support this, information associated with spatial data should enable changeable ‘levels of detail’, to generate a model of the landscape with generalisation and simplification of representation.

ii) **Pathways of change.** Scenarios of alternative futures, with impacts on landscapes, rarely present a sequence of change for each scenario (i.e. a *transient scenario*), such as progressive changes in vegetation cover, or in the timing of events (e.g. earlier crop harvests, year on year). The narratives or storylines of a scenario could include information on the pathways of change. For example, a long term goal of improved habitat quality could include thinning or removal of commercial woodland with a short term adverse impact on the visual landscape, such as increase in visual disturbance, with a longer term increase in perceived naturalness and reduced incoherence in a landscape view.

Communicating the impacts of a scenario should include information about the interim stages through which a landscape may go, including the adverse impacts. This will aid :

a. credibility of the exercise and others which may follow.
b. understanding of the potential complexity of the issues being discussed.
c. relevance to participants, with steps along each pathway of change over meaningful timescales rather than only over the long term..

This creates challenges for the modelling and representation of landscape change, with likely increases in the temporal resolution of information (e.g. annual rather than decadal or more), indicators which are sensitive to the nature of changes, and technical demands on the creation of the spatial representation of scenarios of change, and the evaluation of change through time. These data should support the development and evaluation of the narratives of each scenario, with the capability for the stakeholders or participants to query the state of an area at any point in time. In the case of landscapes, such queries should be reported with respect to the landscape concepts to enable explanations of the assessments as landscapes evolve, and used together with quantitative indicators to interpret changes in benefits through time.

The types of tools currently available and envisaged, for scenario development or evaluation, can be made available for use by the communities of interest, practice and place which have a stake in the nature of change in landscapes. The mechanisms of access may be online for use on a desktop computer, or for use in the field via devices such as tablet PC or Google Glasses which enable the augmentation of a scene with visual representation of features, and associated graphical or numerical information.

Such tools would require to support the capture and sharing of information not just receiving and viewing, and be within an understood system of governance. Therefore, the authority with which participants could contribute (i.e. place on the Arnstein ladder of participation) should be clear to all parties. Such an evolution of the social structures, tools and data would be in line with the aspirations of both the Aarhus Convention, and the European Landscape Convention, which underpin many current public policies.

1.7 Summary

Specific approaches are summarized with respect to their most relevant environmental objectives in Table 1-1. Wider conclusions to draw from the review might be summarized as follows :

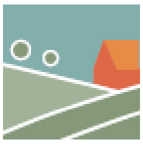
- Engaging stakeholders in developing scenarios of alternative futures and landscape change contributes to public policies linked to the Aarhus Declaration on access to information and public participation in decision-making.

- The use of scenarios enables consideration of options, and assessing alternative outcomes and futures. However, narratives and storylines should consider the pathways of change which could include adverse short term impacts on landscapes before realising longer term benefits.

- 3D visualization tools, linked to spatially expressed scenarios and modelling, provide effective means of communicating, but need to be easily interpreted and designed with the target audience in mind, whether domain expert, policy officer, land manager, or member of the public.

- The increasing popularity of citizen science has the potential for capturing data on stakeholder's opinions on landscapes and potential impacts of pressures for change, using 3D tools which enable geospecific representations of alternative futures.

Table 1-1 Chapter 1 Summary for Key Environmental Objectives

Environmental goal	Pros	Cons
 **A Varied Agricultural Landscape**		
Normative scenario	Allows comparison of current and normative scenarios using indicators for assessing changes in agricultural landscape (e.g. Fry et al 2009). European funded research into landscape modelling has often focused on agricultural landscape and hence a broad suite of models is available.	Complex process of building normative scenarios depending on an integrative framework of models (such as ITE^{2}M)
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines	Depends on integrative framework of models obtained from qualitative scenarios to spatial scenarios as shown by Brown & Castellazzi (2014).
	Allows for public participatory process in the development of story lines with stakeholders engaged in agricultural landscapes.	Potentially many stakeholders.
	Spatial scale independent	
Visualisation – ICT tools	Allows for public engagement and could be developed using land use allocation models such as CLUAM (Parry et al.,1999) as used by Dockerty et al. (2006) .	Ability to communicate requires artistic aswell as technical ability.
 **A Magnificent Mountain Landscape**		
Normative scenario	The approach allows comparison of current and normative scenarios using indicators for assessing changes. Some of the issues, including agricultural landscape modelling, deal with those relevant to mountain landscapes (e.g. Brown & Castellazzi, 2014 in relation to extensification). Analysing these changes with regards to change in LCA and/or aspects of naturalness/remoteness (e.g. Ode et al. 2009) also provides possibilities.	Complex process of building normative scenarios depending on an integrative framework of models. Few of the reviewed models deal specifically with mountainous landscapes. Mountainous landscapes are, by definition, large scale, which may be challenging for data collection and processing.
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines Allows for public participatory process in the development of story lines as carried out by the Swiss partner in the VisuLands project (Miller & Morrice, 2006). Spatial scale independent.	Depends on integrative framework of models to get from qualitative scenarios to spatial scenarios. Non-local stakeholders (tourists) with a large interest and impact

Environmental goal	Pros	Cons
Visualisation – ICT tools	Allows for public engagement and hence an evaluation by the public of changes in this environmental goal (e.g. Brown & Castellazzi, 2014)	Ability to communicate requires artistic aswell as technical ability.
Sustainable forests		
Normative scenario	Allows comparison between current and normative scenarios using indicators for changes in landscapes with forest or woodland elements, e.g. visual stewardship.	Complex process of building normative scenario depending on an integrative framework of models (as exemplified by ITE^{2}’M). The reviewed models deal with forest regrowth and regeneration but the data generated has limitations with regards to drawing conclusion on changes in the wider goal of sustainable forests.
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines. The reviewed modelling approaches did not address forests per-se, but the general approach could still be valid to analyse changes in this environmental goal.	Depends on integrative framework of models to get from qualitative scenarios to spatial scenarios as shown by Brown & Castellazzi, 2014).
	Allows for public participatory process in the development of story lines.	
	Spatial scale independent	
Visualisation – ICT tools	Visualisation can be used to communicate and assess public response to other models of forest function and ecology.	Ability to communicate requires artistic aswell as technical ability.
A Good Built Environment		
Normative scenario	The reviewed approaches include urban expansion (e.g. VOLANTE, Paterson et al. 2012; Dyna-CLUE, Verburg, 2009).	Complex process of building normative scenarios depending on an integrative framework of models where there has been limited research. While some of the land allocation models deals with built up land, the detail and scale of those models gives limited information for how “Good” that build environment may be. However, it does provide a means to begin to assess stakeholder response.
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines. Models set in an urban context include public preferences	Depends on integrative framework of models to get from qualitative scenarios

Environmental goal	Pros	Cons
	and greenspaces, e.g. Laing et al., (2009). Allows for public participatory process in the development of story lines. Spatial scale independent	to spatial scenarios.
Visualisation – ICT tools	Allows for public engagement and assessment of design impact – e.g.visual impact, intuitive communication of design alternatives in varying weather conditions, day, night etc.	Ability to communicate requires artistic aswell as technical ability.

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2 Agent-based models of coupled social and natural systems

Jiaqi Ge and Gary Polhill

2.1 Introduction

Agent-based models (ABM) are dynamic computer simulations that explicitly represent the interactions of heterogeneous individuals. Interest in such models stems from a number of disciplines. Some economists see agent-based models as enabling them to escape the restrictive assumptions of human rationality needed for tractable mathematical analysis under the classical paradigm, among other reasons (Axtell, 2000). Indeed, the broad affiliation of disciplines interested in a 'complex systems' perspective, in which systems of multiple interacting heterogeneous elements generate 'emergent' structure and order at the aggregate scale, offers a new metaphor for understanding economic systems. Arthur, Durlauf and Lane's (Arthur et al., 1997) introduction to *The Economy as a Complex Evolving System*, for example, cites various features of real economic systems that are challenging to classical analysis, but entirely natural from a complex systems perspective: e.g. out-of-equilibrium dynamics, dispersed interaction and the lack of a global mediator. Agent-based models are closely aligned conceptually to a complex systems view of the world. Broader interest in agent-based modelling in the social sciences is derived from its perceived potential as a 'third way' between the quantitative and qualitative camps (Moss, 1999). The conceptual chasm between these two is often over-emphasised, with most pragmatic social scientists willing to adopt mixed-methods approaches to case studies, but if seen as a formal environment in which to explore the dynamic outcomes of more assumptions than the human mind can reason with logically, agent-based models offer qualitative social scientists new tools to explore their findings, which can potentially be fitted to data gathered and analysed by quantitative social scientists. Geographers are interested in agent-based models because they can be used to represent space explicitly.

Agent-based models are used to study coupled human and natural systems (CHANS) because of their capability to represent spatially-embedded complex adaptive systems, and their ability to model interactions within and between the natural and human sub-systems. Hare and Deadman (2004) see ABM as a suitable tool for modelling coupled social and environmental systems for several reasons. First, ABM is capable of spatially-explicit representation of the environment, which enables capturing the effects of spatially-mediated interactions that would otherwise be ignored despite having a potentially significant effect on the dynamics of the system (Filatova et al., 2013). Second, ABMs can represent the feedback loops within and between human-natural systems (Parker et al., 2008, Filatova et al., 2013). Finally, ABMs allow multiple complex sub-systems to co-evolve. In particular, they allow individual agents to react to a dynamic and responsive environment and to learn according to some decision models. Decision models in ABMs are not restricted to assumptions of rationality or bounded rationality as in most standard economics models. Other behavioural models such as rule-based, heuristic or adaptive algorithms can also be used.

2.2 Practical issues

Boero and Squazzoni (Boero and Squazzoni, 2005) offer one perspective on the spectrum of approaches to agent-based modelling, ranging from abstract, conceptual models, to fitted case-studies. Agent-based modelling’s transition from more stylised models to empirically calibrated models is documented in Janssen and Ostrom (2006)’s introduction to a special issue of *Ecology and Society* on the subject.

Except for the purely theoretical papers, most studies included in this review have used empirical evidence to initialize and calibrate their agent-based models. Model initialization and calibration draw on various sources of data: primary data collected by the researcher through interviews, surveys and/or social network analysis, secondary data sets (especially census and cadastral data), as well as information in the form of theories and conclusions drawn from observations in previous research. The data can be qualitative or quantitative data as discussed above, and in models of CHANS, ecological/geographic data may complement social, psychological and demographic data. Smajgl et al. (2011) review the various ways empirical can be and have been used in the agent-based model development cycle. Model calibration using available data and other empirical evidence have become common practice in the development of agent-based models, especially when the research goal is to study real-world systems and concrete policy implications. Indeed, the data demands of empirical agent-based models can be significant, and rely on the integration of diverse sources (see, e.g. Gotts et al. (2014)).

Perhaps as a consequence of the data demands, the area of out-of-sample model validation remains largely open. Not many agent-based modellers of coupled human and natural systems use out-of-sample data to validate their models, though some do. The ones that do out-of-sample validation do it in a less rigorous way (e.g. at an aggregate level, or using a small sample size), partly due to data limitations. Adding to the difficulty is that ABM of CHANS often has a high-dimensional parameter space and a large output set, due to the complexity of the model (as understood by the number of phenomena and entities it represents). Agent-based models may require different data and techniques to do model validation than equation-based models, not least because fitting the data well is only part of the story – agent-based modellers are also concerned with the representation or ontology by which the fit has been achieved (Polhill and Gotts, 2009).

Increased computational cost is another issue in the use ABM to model CHANS. Including multiple coupled systems in the model has significantly increased the degree of complexity and thus the computational cost of the model. Bithell and Brasington (2009) modelled land use change in a 4.1 km^2 catchment area with three coupled systems: hydrology, ecology and human. The authors have encountered challenges from the significant increase in complexities and nonlinearity in the coupling of multiple systems even in a small confined area. They concluded that modelling coupled complex systems is very different from modelling each complex system individually. The degree of complexity would increase exponentially by including multiple systems in the model, which requires larger computational capacity to accommodate the model.

There is a long tradition of stakeholder participation in the research community in modelling CHANS, using agent-based approaches and otherwise. Voinov and Bousquet (2010) reviewed different types of stakeholder modelling exercises, how they are carried out and any issues with them. Involving local stakeholders in the modelling process can be beneficial in many ways: it will encourage mutual learning and facilitate better decision making; it will also help avoid potential conflicts between stakeholders and researchers, and among different types of stakeholders, especially when the stakeholders from different groups compete for scarce resources and have conflicting interests. It is especially important if policy recommendation as a result of research will eventually be implemented in the local community. Researchers developing agent-based models of coupled social and natural systems have included stakeholders in model development and validation process (see summary table Appendix 2.2.1).

Though numbers of research teams have been using participatory model development exercises for some time, they have yet to become a widespread practice in developing agent-based models, partly because such exercises can be resource intensive, and in any case need a community of stakeholders willing to engage with the process and can see a benefit from doing so. The ‘companion modelling’ community (referred to as the ‘French school’ by Moss (2008) because the membership of the community is chiefly from French research establishments) typically undertakes work in situations of conflict over environmental resources among the stakeholders, Bommel et al. (2014) developed visualization tools such as using UML diagrams to assist stakeholder participation. They did a case study of rangeland management and drought phenomena in Uruguay with local livestock farmers being heavily involved in the model development process. For example, several participatory workshops were held where ABM models were presented and explained to local livestock farmers using various visualization tools. The feedback from local farmers was then incorporated in redesigning the model.

2.3 Theoretical issues

One of the earliest questions in the agent-based modelling community was, “What is an agent?” Much of the debate focuses on what are necessary and sufficient conditions for an entity to be considered as an agent, but consideration is also given as to whether an implementation of in a model of an agent meets these criteria. The diverse disciplinary backgrounds of the researchers engaged in agent-based modelling means that there is not a consensus. In the Artificial Intelligence/Sociology literature, an agent is often an autonomous entity with rich cognitive models implementing decision-making and behaviour (Arifovic, 1994, Chen and Yeh, 2001); in the economics literature, an agent is often an individual human or organization with objectives and goals (Janssen et al., 2000, Zellner et al., 2009). Among geographers and in the GIS literature an agent may simply be a patch of land (Torrens and Nara, 2007, Torrens and O'Sullivan, 2001), particularly where there are links with the cellular automata community. In the complex systems/econophysics literature there tends to be greater interest in generating complex emergent behaviour from simple interacting agents, and behavioural models can be (metaphorically) based on such things as fields of magnetic particles, or more generally, simple heuristic algorithms (Flentge et al., 2001, Farmer et al., 2005).

One way to draw these viewpoints together is to see agency as a narrative concept in much the same way as Dennett treats intentionality in his famous Intentional Stance (Dennett, 1989). Just as Dennett argues that an entity may be seen as intentional if its behaviour can be explained by reasoning about beliefs, desires and intentions ascribed to it by a third party, agency can be seen as something ascribed to an entity by an observer. To some extent, agency can be seen as a narrative concept – i.e. real-world entities are not objectively agents (at least from a modelling perspective), but the model is being used to tell a story, and in the manifestation of that story it may make sense to represent as agents things (such as patches of land) that might not be seen as having agency under traditional conceptualisations of the term.

In CHANS literature, an agent can be an environmental entity such as a patch of land or a social entity such as a household. Agents in the CHANS studies in this review include individuals and households (farmers, households, managers and policy makers), formal and informal social organizations (juridical regions, irrigation and canal systems, and social networks) as well natural entities (crops, land patches, forests and rivers).

Although the stated goals of agent-based models are to model individual decision-making and interactions explicitly, it should not be assumed that methods and algorithms for either are settled or standardised. In the case of decision-making, this issue is derived from the various disciplinary backgrounds of those applying agent-based models, discussed earlier. An (2012) categorized decision models used by agent-based models on coupled human and natural systems into nine groups based on the approach and the underpinning theory: (1) microeconomic models, (2) space theory based models, (3) psychosocial and cognitive models, (4) institution-based models, (5) experience or preference-based decision models, (6) participatory agent-based modelling, (7) empirical or heuristic rules, (8) evolutionary programming, and finally (9) assumption and/or calibration-based rules. We will briefly talk about each decision models in the following paragraph.

Microeconomic models refer to agents making decisions to maximize certain profit, revenue or profit. Space theory based models assume agents' decision making is a function of its distance to the closest physical and social features. Psychosocial and cognitive models believe that agents make decisions based on their beliefs or intentions, aspirations, reputation of other agents and social norms. Institution-based models postulate that agents in the same environment will copy each other. Experience or preference-based decision models are simple, straightforward and often self-evident real-world strategies based on observations or ethnographic histories. Participatory agent-based modelling involves real people directly telling the modeller what they would do under certain conditions. Empirical or heuristic rules are assigned decision rules derived from empirical data or observations without a strong theoretical basis or other guidelines. In evolutionary programming literature, decision rules emerge from processes similar to those in natural selection theory with the ability to copy, cross-breed and mutate. Finally, assumption and/or calibration-based rules are used in places where inadequate data or theory exists such as daily activity routines and social contact structure in public health or epidemiology field.

One dimension of decision models is the degree to which individual agents optimize. Heuristic decision rules such as rule of thumb, imitation, following and flocking have a low degree of optimization. Heuristic decision rules are more in line with the early guideline (often based on a more complex systems theory perspective) that decision rules in agent-based models should be simple, the so called "keep it simple, stupid (KISS)" principle (Axelrod, 1997). By contrast, individuals with optimization decision algorithms do have objectives or goals in mind when they are making decisions. They attempt to achieve certain goals or to maximize certain objective function, under possible constraints of information and mental/computing power available to them. A mixture of heuristics and optimization rules can also be used. For example, individuals can use heuristics rules until a certain threshold has been reached, after which they switch to optimization rules. Another dimension of decision models is how consistent they are with major psychological theory. Here, the emphasis is on attempting to represent in the simulation the ways in which real people make decisions. An example is Aamodt and Plaza (1994) Case-Based Reasoning algorithm, which is intended as a model of the way in which real-world experts make decisions by looking for similarities between the case in hand and their earlier experiences of similar situations.

Research has shown that different decision models implemented at an individual level will lead to different aggregate results. Jager et al. (2000) compare an artificial ecological-economic system in which agents have to choose between working in a fishery, which acts as a common pool resource, or in a mine, one implementation dominated by *Homo economicus* agents using optimization rules, the other by *Homo psychologicus* agents using heuristics. They found that in the latter case, the transition from fishing to mining society is more complete than in the former case. Moreover, when individuals are heterogeneous in working ability, *Homo economicus* on average decrease their time spent working, whereas *Homo psychologicus* increase their time spent working. They also showed that macro-level indicators of sustainability are strongly affected by behavioural assumptions at individual level; for example, fish stocks are depleted less in the *Homo psychologicus* implementation. In related work, Boschetti (2007) compared results when individuals act on selfish, unselfish (social) and collective intelligence goals. He found that when individuals act on collective intelligence, meaning they consider the impact of their behaviour on the community and maximize their profit, each individual and the community as a whole can achieve optimal results altogether.

In the graph below (Figure 2-1) we summarize the nine decision rules in An (2012) along the two dimensions: degree of optimization and psychological basis.

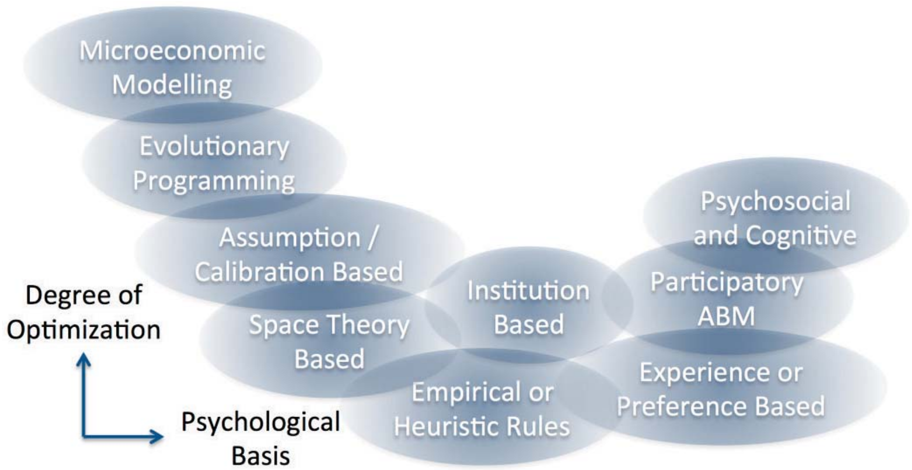

Figure 2-1 Rough ordering of various approaches to modelling decision making in agent-based models with respect to the degree to which they attempt to optimize the outcome and their basis in psychology

Voinov and Shugart (2013) discussed issues associated with coupling social and physical system models together. Lack of consistency and compatibility problems arise when individual models developed under different domains for different purpose with different spatial and temporal scales are coupled as sub-models in a larger model – especially where the outputs of one model are fed in to the inputs of another.

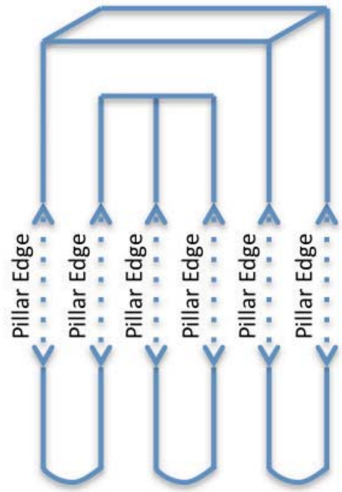

Figure 2-2 The 'blivet' optical illusion as a metaphor for issues with connecting sub-models with semantically labelled inputs and outputs together. Image taken from (Polhill et al., 2012).

Using metaphors such as the 'blivet' optical illusion (Figure2-2), the authors warned that 'integronsters' (statistically valid, but ugly and useless models) may be produced as a result of connecting sub-models together. These problems can be seen in more general terms as arising from issues of semantic heterogeneity. Bellatreche et al. (2006) list common problems that come under the heading of semantic heterogeneity: *naming conflicts* (where the same name is used for different entities, or different names for the same entity), *scaling conflicts* (where concepts are represented at different spatial or temporal scales), *confounding conflicts* (where concepts appear to have the same meaning, but don't), and *representation concepts* (where concepts are represented in different ways). Though typically applied to data integration across multiple heterogeneous databases, integration of models is no less susceptible. Indeed, (Polhill and Gotts, 2011) have argued that model integration has additional challenges for semantic heterogeneity through *algorithmic conflicts*, where submodels may represent the same subprocess using different algorithms to model the dynamics.

2.4 Case studies of application

Applications of agent-based modelling have been made in areas of land use change, urban development and management of natural resources such as farm land, forestry and water resources. There have been a number of recent reviews on the subject. Filatova et al. (2013) reviewed and identified four key challenges ABM faces when modelling CHANS, including (1) design and parameterizing of agent decision models (2) verification, validation and sensitivity analysis, (3) integration of socio-demographic, ecological, and (4) biophysical models and issue of spatial representation. Heckbert et al. (2010) reviewed contributions of ABM in ecological economics in areas such as natural resource management and land-use change, urban systems modelling, market dynamics, changes in consumer attitudes, innovation, and diffusion of technology and management practices, commons dilemmas and self-governance, and psychological aspects to human decision making and behaviour change. Matthews et al. (2007) reviewed applications of agent-based land use models and discussed the models' usefulness as research tools to provide new insights into complex natural resource systems Parker et al. (2008) did cross-site comparisons of four important case studies of agent-based land use models and proposed a general framework for model comparisons and generalization. Finally, as previously stated, An (2012) reviewed various decision models used in ABM of CHANS dynamics, and discussed their strengths and weaknesses.

2.4.1 National scale

Caillault et al. (2013) implemented a simple theoretical model to look at multi-scale incentive networks and how they affect farmer decision and landscape changes. The three incentive scales being modelled are: a global 'policy' network promoting specific land uses, an intermediate 'social' network with shared knowledge and collective promotion of land use practices and a local 'neighbourhood' network where neighbours influence each other's land use practices. The model is abstract and has not been implemented in a real-world setting.

The fact that we can hardly find any ABMs of CHANS implemented at national or international scale in a real-world context reveals the difficulty of the task. The level of complexity and data requirements make it extremely challenging for ABMS of CHANS to go beyond regional/local scale. A further issue is computational capacity. As previously stated, as we include multiple systems and interactions between the systems, complexity in the model increases exponentially even considering a small area (Bithell and Brasington, 2009). Current computational capacity may not be able to support models at national or international scale. The other problem is data availability. Empirical ABM models usually require individual level data and detailed geographic and ecological data to be calibrated and validated. Such data at national or international level is hard to acquire. Finally, there is the problem of model accessibility. A model too complex and at too large a scale could potentially become hard to understand and thus less useful. For these reasons, researchers so far have chosen to apply ABM of CHANS in a regional/local context.

2.4.2 Regional/local scale

Most agent-based models are done at the regional or local scale, perhaps due to limitation on available data and computing capacity as previously stated. An issue with developing ABMs of CHANS at local or region scale for specific purposes is that it makes the models hard to generalize. Parker et al. (2008) noted that these models are developed to specific research questions as they apply in a particular research site. They also require datasets tailored to the study site in order to be calibrated. As a result, the models cannot be easily applied to other research sites or be generalized to answer higher-level research questions, thus running the risk of being relegated to the status of a scientific curiosity. The authors then proposed that all land change models take certain processes in a general framework. The question of generalization from one case study to another, however, runs deeper in the social sciences than in the application of modelling. Indeed, to some extent, it is a reflection of the ability of ABM to bridge the gap between the qualitative and quantitative social sciences that it offers a context in which to discuss the issue. The following are examples of ABM applied in regional or local CHANS.

Gaube and Remesch (2013) modelled land-use and energy consumption in the urban setting of Vienna. Modelling around 770,000 households living in 59 neighbourhoods within 23 administrative districts in Vienna, the authors analyse the effect of residential location decisions of households on the spatial pattern of energy consumption. The model is carefully calibrated using both demographic data and data on spatial landscape. For example, model initialization is drawn from a dataset of 1,651 Vienna households (3,402 persons). The categorization of households is based on an empirical study, which uses data from interview of 8,300 persons in Vienna. Population growth, rental income and landscape features in the simulation are derived from data and empirical study as well.

Valbuena et al. (2010) developed an agent-based model and did a case study in the Eastern part of the Netherlands of the size about 600 km^2 with around 2,700 agricultural holdings. They use a detailed survey of 333 farmers to build agent typology and to initialize individual farmer characteristics. Five agent types are defined by their likelihood to participate in certain processes such as stop farming, increase/decrease production and diversification.

Another example is that of Smajgl and Bohensky (2013), in which the authors develops an agent-based model to study the effect of poverty-alleviation policies such as fuel subsidies on poverty and deforestation patterns in East Kalimantan, Indonesia. The research features deep involvement and two-way communications with local communities and stakeholders. For example, to derive household typologies for the local households, a survey was carried out by a local research team of around 3,000 households. After the survey, a three day workshop with local experts was held to validate and put into context the survey results, and the process went on for several rounds.

2.5 Use of agent-based models in policy-relevant and decision-making scenarios

ABM is often used in policy-relevant and decision-making scenarios. It is strength of ABM to simulate scenarios of major policy changes, to look at out-of-equilibrium dynamics the policy changes bring about, and the adaptation and evolving of the systems in the long run triggered by policy changes. The following are examples of ABM of CHANS applied in policy-relevant scenarios.

One of the earliest examples of agent-based modelling being used in a policy-relevant scenario is the work of Lansing and Kremer (1993) on Balinese water temple networks in the context of the Green Revolution program in Bali, Indonesia. In this case study, rice farming households (*subaks*) in Balinese river basins had to co-ordinate over irrigation and rice planting synchrony to manage supply of water and control pests. Water temples featured in the landscape, and their role in the co-ordination of rice planting was not immediately apparent because the practices were embedded in a religion with a history of several hundred years. Using a simulation model calibrated with observations and data from field studies, the authors found that the structure of water temple networks could have developed through a process of spontaneous self-organization, rather than deliberate planning by royal engineers or other planners. Moreover, contrary to international development agencies' assessment that an end to the productive role of water temples was an almost inevitable result of technical progress, the authors found that self-organizing temple networks are intrinsically capable of a better job of water management than either individual autonomous *subaks* or centralized hierarchical control.

Becu et al. (2003) modelled a catchment area in northern Thailand to analyse local conflicts over the use of water and other natural resources. In particular, they developed simulation models to analyse local conflict between upstream irrigation management and downstream agricultural viability, which has both biophysical and social origins. Their model features an interface called 'viewpoint', which allows stakeholders to interactively select their chosen behaviour in the model. By showing people these 'viewpoints' explicitly, the stakeholders are able to see choices made by others, and hence to come to understand each other's point of view. They argued that, as multiple rural stakeholders are involved, appropriate solutions should only emerge from negotiation. This is an example of Companion Modelling, a branch of ABM typically applied in situations of conflict over environmental resources. Companion modelling adopts a radically constructivist perspective in order to engage the stakeholders in the modelling activity. This means the model attempts to match the way the stakeholders *say* the system works rather than necessarily the way scientists say it works. (Though some companion modelling exercises do draw on scientific models.) This is important in allowing the stakeholders to trust the model. In these exercises, the model acts as a tool to facilitate negotiation and mutual understanding; as such it is an output of the process, and to some extent is secondary to the desired outcome of facilitating peaceful interactions among diverse stakeholders in managing environmental resources.

Happe et al. (2008) describe an agent-based spatial model to simulate the impact of agricultural policy change on different farm structure. They look at the policy impact on two very different farm business types: one characterized by small-scale, family-operated farms, the other by large-scale agribusiness farms. They then carry out a serious of policy experiments with different payment structures, such as guaranteed prices and decoupled payments proposed in the 2003 reform of the EU's Common

Agricultural Policy. The results show that the two different farm business types respond differently to policy regimes, which should be taken into account when designing policies.

Janssen et al. (2000) built an agent-based model to capture the interactions between grass, shrubs, sheep, pastoralists and the policy environment. In particular, they studied the co-evolution of pastoralists' management styles and governmental policies. They found that each policy has different and often unexpected economic and ecological consequences.

Polhill et al. (2013) studied the relationship between agri-environmental incentive schemes and environmental benefit using a coupled agent-based model of land use change and species meta-community model. They tested four kinds of policy and found non-linearity in the relationships between the amount of incentive and environmental benefit resulting from them. The study highlighted importance of context in determining the success of agri-environmental incentive schemes and suggested that policies have a localised component.

Zellner et al. (2009) looked at the impact of zoning restrictions on land-use patterns, and the emergence of a variety of zoning policy games played between neighbouring jurisdictions. Smajgl et al. (2009) assess impacts of fuel subsidy on poverty and fish catch in central Java, Indonesia.

Cellular automata as models of socio-ecosystems are spatially-explicit models in which behaviour is located in cells (discrete spatial regions). Each cell can exist in a defined set of states, which depend on its own state and those of its spatial neighbours. The transition rules, the set of states, and the rules defining which cells are neighbours of which other cells, are the same for all cells. The long-run (macro) behaviour of cellular automata can sometimes be analysed mathematically. There is an intersection between agent-based models and cellular automata models where behaviour is located in spatial cells, and the state of those cells is of significant interest. In cellular agent-based models, however, the strict rules of cellular automata are often relaxed – e.g. cells may have different neighbourhoods, or different transition rules. In some cases, agents may interact with a cellular biophysical model; the state of the biophysical cell depending on the behaviour of the spatially-embedded agents as well as the state of its neighbouring cells.

Millington et al. (2009) developed a cellular automata (CA) model of forest fire spread. A spatially explicit Landscape Fire-Succession Model (LFSM) was developed to represent Mediterranean Basin landscapes and human activity. Perry and Millington (2008) reviewed and discussed wildfire models including ABM models such as LFSM. The authors consider the two motivations of wildfire models: prediction and exploration, to be complementary rather than competing. Hu and Sun (2007) developed an agent-based model of wildfire suppression on a discrete cellular space. They then used the experiment results to demonstrate strategies used by firefighting agents in different fire suppression scenarios. Bousquet et al. (2002) developed a ABM model of virtual forest and used role game to study forest management with two groups of agents, forest and herdsmen, who have potential conflicts but are subject to the same fire hazards. Walsh et al. (2008) developed a CA model of CHANS in the Northern Ecuadorian Amazon to understand linkage between people and the forestry environment, and the evolving nature of human-environment interactions over time and space in response to exogenous shocks such as changes in policy and regulation.

Table 2-1 Chapter 1 Summary for Key Environmental Objectives

Environmental goal	Pros	Cons
A Varied Agricultural Landscape		
Normative scenario	Allows comparison of current and normative scenarios using indicators for assessing changes in agricultural landscape (e.g. Fry et al 2009). European funded research into landscape modelling has often focused on agricultural landscape and hence a broad suite of models is available.	Complex process of building normative scenarios depending on an integrative framework of models (such as ITE^{2}M)
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines	Depends on integrative framework of models obtained from qualitative scenarios to spatial scenarios as shown by Brown & Castellazzi (2014).
	Allows for public participatory process in the development of story lines with stakeholders engaged in agricultural landscapes.	Potentially many stakeholders.
	Spatial scale independent	
Visualisation – ICT tools	Allows for public engagement and could be developed using land use allocation models such as CLUAM (Parry et al.,1999) as used by Dockerty et al. (2006) .	Ability to communicate requires artistic aswell as technical ability.
A Magnificent Mountain Landscape		
Normative scenario	The approach allows comparison of current and normative scenarios using indicators for assessing changes. Some of the issues, including agricultural landscape modelling, deal with those relevant to mountain landscapes (e.g. Brown & Castellazzi, 2014 in relation to extensification). Analysing these changes with regards to change in LCA and/or aspects of naturalness/remoteness (e.g. Ode et al. 2009) also provides possibilities.	Complex process of building normative scenarios depending on an integrative framework of models. Few of the reviewed models deal specifically with mountainous landscapes. Mountainous landscapes are, by definition, large scale, which may be challenging for data collection and processing.
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines Allows for public participatory process in the development of story lines as carried out by the Swiss partner in the VisuLands project (Miller & Morrice, 2006).	Depends on integrative framework of models to get from qualitative scenarios to spatial scenarios. Non-local stakeholders (tourists) with a

Environmental goal	Pros	Cons
	Spatial scale independent.	large interest and impact
Visualisation – ICT tools	Allows for public engagement and hence an evaluation by the public of changes in this environmental goal (e.g. Brown & Castellazzi, 2014)	Ability to communicate requires artistic aswell as technical ability.
Sustainable forests		
Normative scenario	Allows comparison between current and normative scenarios using indicators for changes in landscapes with forest or woodland elements, e.g. visual stewardship.	Complex process of building normative scenario depending on an integrative framework of models (as exemplified by ITE^{2}'M). The reviewed models deal with forest regrowth and regeneration but the data generated has limitations with regards to drawing conclusion on changes in the wider goal of sustainable forests.
	Expert driven	Expert driven
Scenario derived on socio-economic drivers of change	Based on story lines. The reviewed modelling approaches did not address forests per-se, but the general approach could still be valid to analyse changes in this environmental goal.	Depends on integrative framework of models to get from qualitative scenarios to spatial scenarios as shown by Brown & Castellazzi, 2014).
	Allows for public participatory process in the development of story lines.	
	Spatial scale independent	
Visualisation – ICT tools	Visualisation can be used to communicate and assess public response to other models of forest function and ecology.	Ability to communicate requires artistic aswell as technical ability.
A Good Built Environment		
Normative scenario	The reviewed approaches include urban expansion (e.g. VOLANTE, Paterson et al. 2012; Dyna-CLUE, Verburg, 2009).	Complex process of building normative scenarios depending on an integrative framework of models where there has been limited research. While some of the land allocation models deals with built up land, the detail and scale of those models gives limited information for how "Good" that build environment may be. However, it does provide a means to begin to assess stakeholder response.
	Expert driven	Expert driven

Environmental goal	Pros	Cons
Scenario derived on socio-economic drivers of change	Based on story lines. Models set in an urban context include public preferences and greenspaces, e.g. Laing et al., (2009). Allows for public participatory process in the development of story lines. Spatial scale independent	Depends on integrative framework of models to get from qualitative scenarios to spatial scenarios.
Visualisation – ICT tools	Allows for public engagement and assessment of design impact – e.g.visual impact, intuitive communication of design alternatives in varying weather conditions, day, night etc.	Ability to communicate requires artistic aswell as technical ability.

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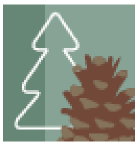
Table 2-2 Chapter 2 Summary for Key Environmental Objectives

Goal	Benefits of using ABM of CHANS	Difficulties in using ABM of CHANS
 **A Varied Agricultural Landscape**	Individual farmer behaviour and interactions can be modelled explicitly Agricultural landscape can be modelled in a spatially explicit way. Landscape planning can be simulated and tested spatially. Interactions between neighbouring land patches are modelled explicitly. Spatial correlation and network effects can be studied.	Farm level information required Spatial information required Could be computationally expensive
 **A Good Built Environment**	Transport can be modelled in a spatially explicit way. Planned construction in the future can be simulated and tested explicitly. Individual route choosing behaviour can be modelled explicitly. Impact of culture or policy on behaviour can be included. The entire regional transport system can be included. Systemic effect can be studied. For example, the level of congestion and pollution can emerge from individual route-choosing behaviour.	Microsimulation of transport has been shown to be very computationally expensive Detailed spatial data of transport required Information on individual driving behaviour required Detailed information on vehicle movement required
 **Environmental Management system**	Human decision making can be explicitly modelled. Various decision making rules can be applied and tested. The whole environmental system can be included to study the systemic effect of management practice. Any side effects and unintended consequences may emerge and be prevented. Hypothetical scenario analysis can be conducted for different management system and policy.	Individual data of each element in the system required Detailed Expert knowledge regarding the system required Could be computationally expensive Might encounter problems with integrated modelling approach

Because of the interconnected nature of these systems, each environmental objective should not be treated as separate and independent: policy promoting one of the environmental objectives might end up affecting other systems as well. Without a holistic approach to the coupled human and natural systems, there is a risk of missing important 'water-bed' effects arising from the interactions among different parts of the coupled systems.

The cited examples of ABM of CHANS covered a wide range of issues in rural and urban land use as well as water management. Systems modelled include water networks, farmland, rangeland, watershed and forestry with consideration to social systems such as irrigation management, urban systems, social and management structure, labour and commodity market. Various decision rules have being used to replicate human behaviour from simple heuristics to utility maximisation. ABM of CHANS therefore provides a promising way to model multiple connected systems and examine the system-wide impact of environmental policies.

Due to the complex and dynamic nature of CHANS, ABM could be a suitable research tool for policy analysis in CHANS. For example, ABMs can be used to test policy sustainability, to screen out unintended consequences, to test system resilience under extreme circumstances like a natural disaster and social unrest, and to analyse the comprehensive, long-run impact of a policy. Moreover, due to its flexibility, agent-based models can be developed in such a general way that they serve as templates or test beds to be used by different research teams as policy analysis tools. Templates such as AgriPoliS and SimPaSi have already been developed to assess agricultural policies.

However, modelling CHANS (with or without agents) is no easy task. Even a confined area with relatively simple natural and social structures could pose modelling challenges when multiple coupled systems are included. Empirical modelling with agents is data-intensive, and requires effort to integrate the diverse data sources and prepare them for use in the model.

One thing we can learn from the examples is the inter-connectedness of ecological and social systems. Policy makers should not only consider the impact of a policy on the system directly affected by the policy. They should also consider the indirect effect of the policy on other related systems. A locally implemented policy can trigger strategic responses from neighbouring areas and led to unintended consequences in the neighbouring areas and the area itself (Zellner et al., 2009).

Another thing we can learn is the relevance of local context in policy making. The same policy tools may create different and sometimes even have opposite effects on local systems with different institutional and cultural contexts (Happe et al., 2008, Polhill et al., 2013, Caillault et al., 2013). A further complication is that local institutional structures and cultural factors could also adapt to and evolve with policy changes (Janssen et al., 2000). The relevance of local context calls for more local stakeholder involvement both during model development and later during model validation.

Interest in agent-based modelling of coupled human and natural systems has been growing exponentially since the turn of the millennium, at least in terms of crude metrics such as number of publications (Polhill et al., 2011). Though there are unsettled questions pertaining to the representation of human behaviour and interactions in these models, and when applied in empirical contexts, to their calibration and validation, they are useful for exploring the logical consequences of concatenations of assumptions with dynamic implications that are beyond the capacity for human reasoning or tractable mathematical analysis.

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3 Modelling Soil Ecosystem Services

Mathew Aitkenhead

3.1 Introduction

In this chapter, a review of soil models is carried out. The number of models within the literature is too high to cover every example in depth, so a selection has been made based on age, stage of development and specificity to soil modelling. In addition, a number of existing soil model reviews have been investigated, to determine the depth of information already available. The best examples for further reading that have been found are those by Molina and Smith (1998), Manzoni and Porporato (2009), Kinnell (2010) and Sheng (2011).

In addition to the large number of soil model reviews that have been published in the literature, there are a number of internet fora that are relevant. The one considered most prominent and likely to provide useful information is at https://soil-modeling.org/, however there are others at https://wiki.csiro.au/display/SoilModelling/Home, http://www.soilerosion.net/, and http://opensees.berkeley.edu/community/viewforum.php?f=8. Another site with useful information relevant for the subject is at http://eusoils.jrc.ec.europa.eu/.

3.2 Methods

A total of over 200 soil-related models were identified from the literature. A brief examination of each was carried out to determine whether or not it should be included in this report. Criteria for selection included the following:

- Age: how old was the model, and therefore how likely to have been made redundant by advances since its development? Some models have been incorporated into other, more sophisticated ones over time and so their effectiveness is reduced, while others may have been developed over twenty years ago and are still relevant. Whether or not a model was discarded based on age was not simply dependent on a threshold of years, but also on relevance within the subject area.
- Development: some models have been described in the literature, but either not formally coded or if coded, have never been seen since their first, preliminary implementation. As such, it would either be necessary to develop their computer code from a sole, often opaque literature source or track down the original authors and ask if their code was still available. If the effort required to actually have an executable soil model was considered greater than the benefit of having it, then the model was not included at this stage.
- Specificity: a number of models were discovered that included a soil component but that had a much stronger leaning towards ecological, hydrological or atmospheric processes. In cases where the soil component was sufficiently sophisticated to be considered as a model in its own right, then it was included at this stage. If the soil component of the model was overly simplistic or considered unlikely to add any new information, then it was discarded.

A total of 51 soil or soil-related models were retained. A structure by which to evaluate them was required, and it was decided to use a similar one to that of Manzoni and Porporato (2009). In this work, the focus was on soil models that included carbon and nitrogen cycling, which is a narrower scope than required for a review of all soil models. However, there was useful information about a number of the models included here, and a set of criteria that allowed comparison to be made between the models. These criteria have been added to, and each soil model is now described in a single table with common characteristics as described in Table 3-1 and Table 3-2.

Table 3-1 Model classification code legend

Model class	
M	Soil microbiology, soil aggregate and rhizosphere models
L	Litter decomposition model
S	Soil model with no dynamic vegetation components
E	Coupled soil-plant dynamic model
G	Coupled soil-plant-atmosphere model for global applications
H	Soil hydrology/catchment dynamics model
I	Model integration framework
Spatial scale	
1	$<10^{-2}$ m
2	$10^{-2} – 10^{0}$ m
3	$10^{0} – 10^{2}$ m
4	$10^{2} – 10^{4}$ m
5	$>10^{4}$ m
Temporal scale	
1	$<10^{0}$ days
2	$10^{0} – 10^{1}$ days
3	$10^{1} – 10^{2}$ days
4	$10^{2} – 10^{3}$ days
5	$>10^{3}$ days

Table 3-2 Model formulation code legend

Respiration model	
GRW	Growth respiration
MNT	Maintenance respiration
G&M	Both growth and maintenance respiration
CO	Respiration defined to compensate stoichiometric imbalances
Decomposition model	
CONS	Constant rate
LIN	Linear model with respect to C_S
LINB	Linear model with respect to C_B
MULT	Multiplicative model
MM	Michaelis-Menten model
NL	Other nonlinear or mixed formulations
Mineralisation scheme	
DIR	Direct hypothesis
MIT	Mineralisation-Immobilisation Turnover
PAR	Parallel hypothesis
MIX	Other schemes with simultaneous mineralisation and immobilisation
SIMP	Simplified model or regression equation (no microbial stoichiometry)
N-limitation model	
CM	C-only (or dry weight-only) models neglecting N dynamics
IND	No N-limitation
INH	Inhibition factors
CO	Carbon overflow
CN	N-limitation effects on microbial or substrate C/N
MIX	Multiple N-limitation effects are considered

3.3 Discussion

This discussion focuses on those models considered most relevant, representative of their topics and most likely to be of use in future work. The intention here is not to discard the rest of the 51 models that have been considered, but to highlight the ones that are most easily available and implemented, commonly and successfully used and that cover the range of topics within soil modelling. The models evaluated in this review fall into five main types, as listed below. A subset of the 51 models has been identified that satisfy criteria of availability, accuracy, flexibility and sophistication for each of the five types. Each of these models is briefly discussed.

3.3.1 Soil erosion and catchment dynamics

CREAMS (Silburn and Loch (1989)) – this model provided the basis for several later versions of relevance within the subject, each of which is available for download. The general nature of the model framework has made it relevant for a wide range of catchment-based research in agricultural land, particularly looking at the impacts of land management options on erosion and nutrient runoff. The number of processes and input data types required mean that this is not an easy model to run in the first instance, but it does provide a level of sophistication and integration that is high in comparison to other models in this area.

EUROSEM (Morgan et al. (1998)) – more relevant for the modelling of extreme rainfall events and their impact on soil erosion under different land management types, this model is freely available but comes with health warnings – no support is available in order to implement the model so if difficulties are encountered, a programming solution will have to be sought.

INCA (Wade et al. (2002b)) – this model focusses on transport and fate of nutrients and pollutants within soil and catchments, and is available as an executable file. There are a number of different versions that look at different chemicals and nutrients, but the underlying model integrates soil, hydrology and vegetative processes. As such it requires a fair amount of input data to run, and produces output data of high complexity. It does not include erosion as a process, and so is less relevant for extreme weather event scenarios.

SWAT (Arnold et al. (1993)) – designed to facilitate decision-making in large, managed catchments, recent versions of this model can be used to simulate aspects of hydrology, erosion and sediment transport, nutrient and pollutant transport and fate. It is relatively complex and sophisticated, but comes with a user interface to make implementation easier. SWAT can be used to simulate a wide range of management options and climate/weather scenarios, and so is capable of being very useful if used by someone with sufficient expertise.

WATEM (Van Oost et al. (2000)) – this now exists as WaTEM/SEDEM, an integration of two models of sediment transport and erosion under different land management options. The model is designed to operate within a GIS environment and is freely downloadable. It uses a version of the RUSLE soil loss equation to calculate erosion rates and links this to runoff patterns calculated from topography and land cover parameters.

3.3.2 Soil carbon and nitrogen cycling

CarboSOIL (Munoz-Rojas et al. (2013); Munoz-Rojas et al. (2015)) – this model operates as an application within ArcGIS 10.0, and is particularly appropriate for exploring the impacts of land use on soil carbon in Europe as it incorporates characterisations of the land cover classes within CORINE. It does require a lot of input data in order to run, however.

CENTURY (Parton et al. (1988)) – the first version of this model has now been superseded and expanded into multiple versions appropriate for different land cover types. It can be used to explore relationships between land management, climate, soil carbon, nitrogen, phosphorus and sulphur. Requires a lot of information to set up and run, but is considered ‘industry standard’ amongst some researchers in this subject area. As such, it is commonly used and results can be compared with those of other researchers quite readily.

DAYCENT (Del Grosso et al. (2002)) – this is the version of CENTURY that runs on a daily time step, and as such incorporates more detailed and sophisticated submodels of soil water and temperature, and of a number of rapid processes taking place within the soil. It is therefore more relevant than CENTURY for modelling the effects of specific, time-dependent land management and crop growth activities on soil carbon and nitrogen dynamics.

DNDC (Li et al. (1992)) – another commonly-used model of carbon and nitrogen dynamics in agricultural systems, this can be used to simulate crop yield, carbon sequestration, nitrogen leaching and a number of other processes of social, environmental and political importance within agriculture. It does not incorporate the effects of short-term extreme weather events, so soil erosion and runoff are not included.

Roth-C (Farina et al. (2013)) – a soil carbon turnover model with a long and distinguished pedigree, this relatively simple model of carbon dynamics in mineral soils has been incorporated into a number of other soil models and has been refined and adapted over the years into its current version. There are currently other models that are more sophisticated and accurate in describing carbon dynamics, but Roth-C is very useful for initiating carbon pool sizes in soil process models, something that is often challenging and that has large impacts on eventual model accuracy.

3.3.3 Crop productivity

MONICA (Nendel et al. (2011)) – this relatively new model could also be included under the ‘carbon and nitrogen cycling’ heading, but has much more of a focus than those models on crop management, yield and condition, while still retaining useful submodels on C and N cycling and hydrological processes. It is relevant across a very wide range of environmental conditions and is relatively simple to set up and run.

DSSAT (Jones et al. (2003); Dzotsi et al. (2010)) – this is less of a model than a system for implementing crop simulation models, and for integrating soil databases, climate data, experimental results and other data into these models. It is commonly used for land management decision support under different climatic conditions, and can be used to explore the impacts of different management options on crop yield and condition.

3.3.4 Ecosystem/biosphere modelling

DRAINMOD-DSSAT (Negm et al. (2014)) – developed as a model for describing hydrology of poorly drained soils, DRAINMOD incorporates climate, soil and vegetation characteristics into its implementation. DRAINMOD has been integrated into the framework of DSSAT (above) to provide a model that includes not just the hydrology of the soils considered but also water quality and crop yield.

It is considered still 'under development' in some areas that will improve its flexibility for different crop types and environmental conditions, but another version (DRAINMOD-FOREST) also exists for forestry. Additionally, calibration is required against existing site data for the model to run accurately.

IBIS (Kucharik et al. (2000)) – the latest version of this model, IBIS-2, does what its acronym suggests – it is an Integrated Biosphere Simulator. As such it is used for linking soil and vegetation processes within a single framework, and modelling the dynamics of water, carbon and vegetation growth all together. It is relatively complex as would be expected, and includes a very large number of processes and parameters. The input data required to run it is also quite demanding, but the model is very flexible and can be used for a number of different scenario modelling questions.

MBL-GEM (Rastetter et al. (1991); Le Dizes et al. (2003)) – simulates plant growth and development, allocation of C and N throughout the plant/soil system, soil C decomposition and sequestration. As it operates on a point-by-point basis, it does not incorporate matter or energy flow between grid cells and so cannot be used for hydrological dynamics. This model very much considers the plants and soil as a single system, and has been designed with this concept in mind.

3.3.5 Energy balance

SCOPE (van der Tol et al. (2009)) – this model links vegetation photosynthesis with incoming spectral radiance and fluxes of water, heat and carbon dioxide in the plant/soil system. The main bias of the model is towards vegetation radiative transfer but it also incorporates soil and atmosphere components, and so can be considered as fully integrative. The model is not fully available to download, but may be available from the authors upon request.

3.4 Summary

A number of models have been evaluated that have relevance for land management decision making. The spatial and temporal scales over which these models operate vary considerably, as do the parameters that are output. For soil erosion and nutrient loss modelling, the models commonly operate at the catchment scale or smaller and over a relatively short time step. Producing regional scale, long-term scenario predictions would require a lot of computational and data resources. For models of soil carbon and nitrogen cycling, the spatial and temporal scales vary considerably, as does the complexity of the models applied, meaning that scenarios can be explored at scales from local to national, and daily to multi-annual. The data complexity of the models also varies, with those that are applicable at larger scales being less complex and easier to implement. It is therefore easier to identify a model that is more relevant for the scale in question for soil carbon/nitrogen models than it is for soil erosion models. This is due in part to the fact that soil erosion models incorporate hydrological processes that operate over a range of spatial scales.

Crop productivity models can generally be applied at the scales desired, but require significant data resources to implement and operate on short time steps. They also often require specific information about the crops of interest. More generally applicable ecosystem/biosphere models have similarities to crop productivity models in that they incorporate information on soils, vegetation, climate and topography/hydrology, but these often take the form of frameworks rather than specific locked models, and can accommodate different types of submodels within their operation. They are complex and require a lot of data to initialise, often in the form of field measurements of the ecosystem being simulated. They are therefore less relevant to decision making over regional scales than crop productivity models. Table 3-3 sumarises the implications of this with respect to the spatial and temporal scale to which models may inform key Environmental Objectives in Sweden.

Table 3-3 Chapter 3 Summary for Key Environmental Objectives

Environmental Goal	Pros	Cons
Reduced climate impact	Good choice of soil carbon & nitrogen models available; existing frameworks for integration of soil models within global circulation models.	Models appropriate for climate modelling are at the simple end of the scale, and do not incorporate some important processes very well (soil hydrology in particular).
Good-quality groundwater	Catchment-scale soil models incorporate multiple processes relating to erosion and chemical transport; the models are flexible and relatively accurate, and operate at small spatial and temporal resolution.	Models relevant for this objective do not include all possible chemicals of concern (although they do cover a wide range); soil hydrology models generally lack implementations of snow and ice.
Thriving wetlands	Soil models designed to simulate peat soils specifically have been developed.	Peatland condition is difficult to assess for baseline data of these models, which has a strong bearing on the accuracy of the results.
A varied agricultural landscape	Crop growth models exist that can be used for scenario modelling and multiple crop types.	These models often require a great deal of parameterisation, are complex and the results require careful interpretation.

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4 Modelling Fresh Water Ecosystem Services

Sarah Dunn

4.1 Introduction

The origins of most present day approaches to hydrological modelling have evolved from the 1970s when theories such as the variable contributing area (Beven and Kirkby, 1979) led the way in conceptualizing hydrological thinking and the development of simple modelling tools such as TOPMODEL (Beven et al., 1984). Improved computing capability in the 1980s paved the way for more complex modelling and the Systeme Hydrologique Europeen (SHE) model (Abbott et al., 1986) emerged as the first physically-based spatially distributed hydrological model. Since then many hundreds of hydrological models have been developed for application to different geographic regions, and at different spatial and temporal scales. Concurrently, recognition of some of the problems in model parameter identification (Beven, 1989) and the equifinality of model predictions (Beven and Binley, 1992) have shaped the direction of modelling methodologies to encapsulate uncertainty analysis as a necessary modelling activity and lead to the development of more formalised frameworks for model application and testing (Refsgaard et al., 2007a). There is still continued debate (Refsgaard et al., 2010, Ewen et al., 2012) over the relative merits of different modelling approaches and a very broad set of model options are now available for the end-user.

The development and application of hydrochemical models (for simulating losses of pollutants from the land to water bodies, chemical modification within surface and ground waters, and export to the estuarine and marine environment) has necessarily lagged behind hydrological modelling with a recognition that adequate representation of hydrology is a necessary first step in simulating hydrochemistry. Beyond this, understanding of biogeochemical, solute and particulate transport processes are all prerequisites to the development of conceptual or physically-based hydrochemical models. Paradoxes have been raised in relation to how the chemistry of runoff can be temporally highly variable and yet apparently associated with old water (Bishop et al., 2004). Additionally, the very small scale at which biogeochemical cycling occurs makes interactions with hydrological processes difficult to represent (Weiler and McDonnell, 2006, Tague et al., 2010) and transport of materials, especially those associated with sediment is highly heterogeneous in both space and time. Consequently, early approaches to hydrochemical modelling were primarily based around empirical relationships between land use and nutrient export (Reckhow and Simpson, 1980, Beaulac and Reckhow, 1982), which led to the development of so-called export coefficient models (Johnes, 1996a). Many process-based and conceptual models for pollutants such as N, P, sediment, dissolved oxygen (DO) and dissolved organic carbon (DOC) have been developed more recently, but their capabilities for simulation of hydrochemical responses in rivers and lakes are still being shown to have limitations in some cases (Vellidis et al., 2006, Dean et al., 2009, Zessner et al., 2011, Glavan et al., 2011). Opinions are still divided in relation to the merits of simplicity versus complexity of model structures and in practice this depends primarily on the context in which the modelling is being undertaken and the purpose for which it is required.

The following review aims first to summarise the different approaches to hydrological and hydrochemical modelling of freshwater, and then to provide an overview of how models have been used in practice to address typical policy and environmental issues. For a broader overview of hydrologic and water quality models the reader is referred to review articles such as Singh and Woolhiser (2002), Borah and Bera (2003), Cox (2003), Kampf and Burges (2007), Schoumans Schoumans et al. (2009a), Schoumans et al. (2009b), Arthington et al. (2010), Ampadu et al. (2013), Kelly et al. (2013a), Li and Heap (2014).

4.2 Modelling approaches

4.2.1 Model types

Milad et al. (2012) undertook a review of different model classifications that are commonly applied within hydrological and water quality studies. Although the precise terminology has differed there are 3 main model typologies that can be defined as empirical, conceptual and physically-based (also sometimes termed deterministic or mechanistic). There are a further two additional approaches that have been receiving increased interest and attention in recent years: data-based mechanistic modelling (Young and Beven, 1994), which exploits the power of recursive estimation to help identify relevant model structures to characterise linear and non-linear processes, and Bayesian network approaches (Reckhow, 1999, Borsuk et al., 2004) that attempt to structure complex behaviour into a probabilistic explanatory network. The latter have proven to be of particular benefit for application to address complex inter-disciplinary problems and to aid communication with stakeholders and end-users. An overview of these five modelling approaches is given in table 4-1 below, together with a simple summary of some of the pros and cons of each.

Table 4-1 Pros and Cons of 5 Different Modelling Approaches to Hydrology and Water Quality Issues

Pros	**Cons**
Physically-based models	
Capture key processes and inter-relationships and feedbacks between them	Commonly a mis-match between scales of implementation and scale of heterogeneity in properties
Represent heterogeneity in systems	Many parameters and, in practice, most still require calibration
Parameters should be related to measureable properties	Equifinality issues (Beven, 1993)
More robust for extrapolation to different conditions (e.g. climate / land use change)	Under-pinning physical representations are not always appropriate at relevant scales of application (Christiaens and Feyen, 2001)
	Long processing times
Examples SHE - (Abbott et al., 1986); MIKE SHE - Refsgaard and Storm (Refshaard and Storm, 1995); HYDRUS –(Simunek et al., 2008); PSYCHIC –(Davison et al., 2008); (Stroemqvist et al., 2008).	
Conceptual models	
Usually less computationally demanding than physically-based approaches	Likely to be restricted in suitable range of applications depending on processes included
Fewer parameters to calibrate (especially if spatially lumped)	Can still have many parameters
Uncertainty analysis easier with fewer parameters	Parameters need calibration
	Equifinality is still an issue
	Extrapolation to changed conditions is only

	appropriate where relevant affected processes are included in the model structure
Examples TOPMODEL –(Beven et al., 1984), (Quinn et al., 1991); MAGIC –(Wright et al., 1986), (Cosby et al., 2001); SWAT –(Arnold et al., 1998); (Arnold and Fohrer, 2005); (Gassman et al., 2007); HSPF – (*Bicknell*, 1997); AGNPS –(Young et al., 1989); (Bosch et al., 1998); INCA – Wade (Wade et al., 2002c, Wade et al., 2002a, Wade et al., 2002b); SWIM –(Krysanova et al., 1998);.	
Empirical models	
Simple to apply and short simulation times	Restricted in geographic range of applicability
Transparent and easy to interpret outputs	Not applicable to simulate responses to changed conditions
Suitable for application at large scales	Non dynamic (temporally lumped)
Input data based on measurable system properties (e.g. area of land use, topography etc.)	
Examples Export coefficient –(Johnes, 1996b); Phosphorus Index – (Gburek et al., 2000); Phosphorus indicators tool –(Heathwaite, 2003); SCIMAP –(Reaney et al., 2011); Artificial Neural Network models – Maier (Maier and Dandy, 2000, Maier and Dandy, 2001); (Zhang and Govindaraju, 2000).	
Data-based mechanistic models	
No prior assumptions about key processes in catchment	Dependent on good quality observational data
Efficient simulation avoiding over-parameterisation	May be limited in transferability to changed conditions if relevant processes not characterised by initial model structure
Less data intensive than physically-based models	
Examples Young, 1992 (Young, 1992, Young and Beven, 1994, Chappell et al., 1999, Romanowicz et al., 2008).	
Bayesian network models	
Allows a complex causal chain to be articulated	Generally non-spatial and non-temporal
Incorporates uncertainty directly using probability distribution functions	Model assessment of structural uncertainty is often neglected
Can integrate different types and sources of information	Often requires discretisation of continuous variables
Suitable for communication of model results to end-users	
Examples (Reckhow, 1999, Borsuk et al., 2004, Castelletti and Soncini-Sessa, 2007, Dorner et al., 2006, McDowell et al., 2009, Stewart-Koster et al., 2010);	

4.2.2 Spatial and temporal scale

Many models have a degree of flexibility with regard to the spatial and temporal scales at which they can be implemented, but identification of relevant scales is important in selecting the most appropriate modelling approach. The purpose of the modelling may be a key factor in this decision; Kelly et al.

(2013b) identified types of purpose as prediction, forecasting, management and decision-making under uncertainty, social learning and developing system understanding / experimentation.

Within the broad typologies of models there may be further sub-division according to the degree of spatial delineation that the models attempt to capture, and models are commonly classified either as lumped, semi-distributed or distributed. A lumped model represents the catchment or study area as a single unit with homogenous properties whereas a distributed model attempts to characterise the full range of heterogeneity in physical, topographic and climatic properties across the study area, using some form of gridded network e.g. Abbott et al. (1986). A semi-distributed model lies somewhere between, representing the study area as a set of some form of hydrological or chemical response units (Kouwen et al., 1993, Bende, 1997) defined on the basis of a range of common characteristics. Kampf and Burges (2007) undertook a review of spatially distributed hydrologic models and developed a framework to compare different models on the basis of a suite of characteristics that included process representation, the nature of equations (physical, analytical, empirical, or conceptual), coupling, solution technique, and spatial and temporal resolution.

In broad terms, due to their high data demands, physically-based distributed approaches are most likely to be applied at the smallest scales and simpler more empirical approaches at the largest. Conceptual modelling is commonly used in catchment and river-basin scale studies. Different data sources will be more suited to different spatial scales of application and different modelling objectives will requires assessment at different scales. For example, in order to consider how citing of manure stores might impact on losses of pollutants from fields to water courses, a model that can be applied at the scale of a field or farm is likely to be considered appropriate (Davison et al., 2008), whereas a model aimed at identification of regional hotspots of pollution would likely involve different data sources and scale of application (Dunn et al., 2004a, Dunn et al., 2004b). One common issue in modelling studies is that a mis-match between measurement and modelling scales can lead to a need for estimation of ”effective” parameters (Pachepsky et al., 2004). The adoption of a nested hierarchical approach of scale appropriate modelling (Quinn, 2004) has become increasingly popular (Volk et al., 2010).

The temporal scale of a model needs to be linked to the temporal scale of the processes that require interpretation. In some cases this can be challenging where linked sub-systems may operate at different spatial and temporal scales. A good example of this is where groundwater is an important component of the water balance but its response times (which may be years to decades) are very different from surface waters. Some models are non-temporal, for example where key attributes of a system, such as hydrological connectivity, might be modelled under different land use or management scenarios and others refer to a lumped output, for example aggregated over an annual time-scale. In other situations the temporal dynamics of weather patterns and biogeochemical cycling are important influences on responses and in these cases models are commonly run at daily resolution. For responses strongly influenced by extreme events, such as high flows, it may be necessary to run models at sub-hourly resolution. Temporal scale is also linked to spatial scale in the sense that smaller systems will generally respond more rapidly and therefore may need a shorter model time-step to capture the dynamics of the system.

4.2.3 Model evaluation

Model evaluation is a critical step in any model application and includes procedures such as model sensitivity analysis, calibration, validation, and uncertainty analysis. Protocols for implementing suitable procedures have been proposed (Beven and Freer, 2001, Jakeman et al., 2006, Refsgaard et al., 2007b) and some variations on these approaches form the basis of current accepted modelling practice. An important phase in the development of modelling protocols came about as a result of the recognition of uncertainty in hydrological model simulations (Binley et al., 1991). This led on to the development of tools such as the Generalised Likelihood Uncertainty Estimator (Beven and Binley (Beven and Binley, 1992, Freer et al., 1996) applied first in the context of hydrological simulation but subsequently also to water quality (Schulz et al., 1999, Dean et al., 2009), and used to quantify the uncertainty in model predictions resulting from equifinality of different model parameterisations. Other similar tools have also been developed to assist with parameter calibration and uncertainty estimation (Doherty and Johnston, 2003, Abbaspour et al., 2007, Yang et al., 2008).

Sensitivity analysis is also considered important for better understanding model behaviour and key model parameters. From the early methods proposed by Spear and Hornberger (1980) many numerically efficient tools are now available to facilitate implementation of sensitivity analyses (van Griensven et al., 2006, Matott et al., 2009).

Another key aspect of model evaluation is the metrics that are used to assess model performance. In hydrology, the Nash-Sutcliffe efficiency (NSE) has traditionally been used as a measure of goodness of fit (Nash, 1970), but studies have highlighted the limitations of this as a single objective function, especially in terms of biasing towards correct simulation of high flows (Schaefli and Gupta, 2007) and there has been a move towards the use of multiple objective functions including statistics such as percent bias, and root mean square error as well as the NSE (Moriasi et al., 2007, Ritter and Munoz-Carpena, 2013). Others have proposed using alternative, multiple, observations of system behaviour as a means of reducing parameter uncertainty through better constraining of the model. In a hydrological context, measures derived from variables such as saturated area (Franks et al., 1998), recession analysis and hydrograph separation (Guntner et al., 1999) and tracer data (Uhlenbrook and Leibundgut, 2002) have all been explored as alternative objective functions. In a water quality context, simulation of different chemical species is sometimes used together with spatially-distributed sub-catchment scale observations (Dunn et al., 2013).

Issues of error and uncertainty in model structures are harder to assess, compared with parameter uncertainty. Some studies have undertaken model inter-comparisons (Reed et al., 2004, Smith et al., 2004, Smith et al., 2013) which have generally shown that no single model performs best in all cases. Clark et al., (2008) developed a methodology to diagnose differences in hydrological model structures by combining different components from a set of models to see which combinations performed best. This experiment showed that the choice of model structures is equally as important as the model parameterisation. Clark et al., (2011) subsequently advocated testing multiple working hypotheses for systematic and stringent testing of model alternatives.

4.3 Participatory approaches

For a number of reasons the application of hydrology and water quality models to aid practical river basin management and decision support has lagged behind their use in research contexts (Borowski and Hare, 2007). The implementation needs of the EU Water Framework Directive (WFD) have proven to be a key turning point in making models more accessible and relevant to end-user needs. Saloranta et al., (2003) developed a set of benchmark criteria to help water managers and other users in selecting appropriate models to address their needs. Many decision support tools have been developed to facilitate practical implementation of models, but it has been found in practice that these are not always adopted as widely as expected (Junier and Mostert, 2014). An alternative in the form of participatory modelling has emerged as a powerful tool that can (a) enhance the stakeholders' knowledge and understanding of a system and (b) identify and clarify the impacts of solutions to a given problem, usually related to supporting decision making, policy, regulation or management. Voinov and Bousquet (2010) discuss the various different approaches to stakeholder involvement and the situations in which each may be appropriate. In conclusion they found that stakeholder participation helps to relate models with real needs, and can be beneficial in terms of providing new data and ideas. Kelly (2013a) also examines suitable approaches for facilitating stakeholder engagement in the modelling process using models that can accommodate multiple issues, values, scales and uncertainty considerations.

4.3.1 Typical applications

Collins and McGonigle (2008) outlined a number of common and important issues related to diffuse pollution that required to be addressed in order to meet the requirements of the EU WFD. This included: coupling of pollutant loadings to ecological impacts; multiple pollutants and the risk of pollution swapping; appropriate spatial targeting of mitigation methods; the important role of sediment; and delays in water quality responses resulting from mitigation of diffuse pollution. Modelling tools have the potential to address many of these issues, but there has been mixed success in terms of how well this has been achieved. Other aspects of hydrology and water quality are associated with different sets of issues such as: reliability of water supply quantity and quality; flood risk assessment; and future proofing of water resources against potential changes in climate and land use. The following sections of this review consider some typical practical situations in which hydrological and water quality models could and have proven to be of value, and examine how and which tools have been used. It is important to note, however, that literature citations relating to model applications do not necessarily reflect how successfully the models have been practically taken up by relevant end-users. Where possible this has been evaluated and highlighted, but in many cases the information is hard to glean from available literature.

4.4 Integrated river basin management

In Europe, the WFD has introduced a number of mandatory river basin management procedures that regulatory authorities are required to undertake. Many of these processes can be assisted by model applications.

In the early task of river basin characterisation, modelling was found to be of value as a means of extrapolation to support gaps in evidence from monitoring data. The Scottish Environment Protection Agency commissioned the development of a screening method using a suite of models to assess the risks from diffuse pollution based on pollutant inputs to the land surface and outputs to water bodies - SNIFFER (2006). Outputs from the screening tool included a spreadsheet characterising averaged estimated pollutant loadings for a range of determinands at a 1km^2 resolution across Scotland. Hojberg et al (2007) also outlined how modelling approaches could be used to support monitoring programmes to help meet the objectives of the WFD. Another task that leant itself to assistance from modelling in the early stages of the WFD was the delineation of groundwater bodies (Cools et al., 2006).

One important aspect of the river basin management process is targeting of management activities to high risk areas. Modelling tools can assist with the prioritisation process through carrying out source apportionment to help identify pollution hot-spots. Panagopoulos et al. (2011) applied the SWAT model (Arnold et al., 1998) to help identify high risk areas of pollution from sediment, N and P, in a typical Greek catchment with limited available monitoring data (provided by national level monitoring). The study found that even in data limited situations the model could be usefully applied to target diffuse pollution abatement actions. In the UK the SAGIS (source apportionment GIS) model UKWIR (2012), which builds on the earlier SIMCAT (simulation catchment) model, has been adopted by both the Environment Agency of England and Wales (EA) and SEPA. Models commonly used by the EA such as SIMCAT rarely appear in the literature because they are not generally used for regulation outside of the UK. This is probably due to their stochastic component as well as a lack of commercial exposure (Cox, 2003), but their wide usage by the regulatory authorities highlights the benefits of simplicity in models for practical decision-making.

Parry (1999) outlines the regulatory and non-regulatory programs developed by the U.S. Environmental Protection Agency (USEPA) to implement its legal mandate to control water pollution in the US. Following implementation of the basic laws, states are required to identify and list waters that are not meeting standards, to prioritize them, and to develop Total Maximum Daily Loads (TMDLs) for the pollutants of concern. Models are used to support the development of TMDLs and a review of the various options has been undertaken by Borah et al. (2006). Radcliffe et al. (2009) compared modelling procedures for P in the US, which are mostly based around the TMDL concept, with those more commonly applied in Europe to address similar issues. They found that the European approaches were more likely to take into account leaching of P and the identification of critical source areas, but that scaling up of these models to the watershed scale was an issue, as a result of over-parameterisation. A need for more parsimonious models and better monitoring data (to take advantage of the technological improvements that allow nearly continuous sampling for P and sediment) was identified. One model that has been used regularly for estimation of TMDLs is SWAT (e.g. Santhi et al., (2001); Jha et al., (2010)). Some of the reasons for the popularity of the SWAT model are its accessibility and user support which have led to wide-scale international application (Gassman et al., 2007).

Klauer et al. (2012) presents a decision support tool (BASINFORM) for river basin planning. The tool comprises (i) a procedure for framing the specific problems in the water bodies, including quantification of the need for action, (ii) modelling tools for quantifying the impacts of management measures, and (iii) a method for selecting cost-effective combinations of measures. One innovative feature of BASINFORM is that it structures the complex decision problems appropriately for practical use and provides a framework for integrating scientific and practical knowledge. BASINFORM has been used for practical implementation of the WFD in the German Federal State of Thuringia. A similar set of objectives was addressed by Barton et al. (2008) through developing a Bayesian network approach to manage a river basin in Norway. This tool was used to evaluate eutrophication mitigation costs relative to benefits, as part of the economic analysis under the WFD.

A Bayesian network approach was also proposed as a suitable tool for water resource management by Castelletti and Soncini-Sessa (2007). The pros and cons of such an approach were discussed by framing their use within the context of a participatory and integrated planning procedure, and exploring how they could be integrated with other types of models.

Stithou et al. (2012) describes the implementation of an alternative participatory modelling approach to support integrated catchment management planning in Ireland. This involved a Choice Experiment method of valuation to capture a number of different components of ecological status beyond chemical and biological determinands to include the value that the targeted population of the catchment place on the non-market economic benefits of ecology. The value of participatory modelling approaches was also examined in a study in south-eastern Sweden (Jonsson et al., 2011). This compared three approaches to formulating objectives to address eutrophication via model assisted dialogue and found that local stakeholder participation was a valuable approach for formulating goals at the local level.

4.5 Water supply and drinking water quality

Understanding of the resilience of water supplies and drinking water quality is of great importance and is a topic that can be improved and supported by the use of models. Several countries have developed national water resources models to support planning. Denmark established a national model in 2003 in order to assess their exploitable groundwater resources (Henriksen et al., 2003). The model is setup in the MIKE SHE/MIKE 11 modelling system (Abbott et al., 1986, Graham and Butts, 2006), to generate a physically based and fully distributed description of the entire land phase of the hydrologic cycle. The DK model has been widely utilised for national and regional scale assessments. For example, Henriksen et al. (2008) presents an application to examine the use of different resource indicators relating abstraction limits to groundwater recharge and their implications for exploitable resources. The reliability and uncertainty within the original version of the model has been subject to on-going debate and, consequently, it has recently been enhanced and updated (Hojberg et al., 2013).

In the Netherlands, a national hydrological model, the National Hydrological Instrument (NHI) (http://www.nhi.nu), has also been developed (De Lange et al., 2014), which is an integral water management model focused on water shortage and on the very detailed surface water distribution system in the country. The NHI consists of various physical models at appropriate temporal and spatial scales for all parts of the water system.

4.5.1 Pathogenic Contamination Models

On a global scale, pathogenic contamination of drinking water poses the most significant health risk to humans, although significant risks to human health may also result from exposure to nonpathogenic, toxic contaminants that are often globally ubiquitous in waters from which drinking water is derived (Ritter et al., 2002). Modelling of pathogen contamination has proved notoriously difficult due to difficulties in forecasting the highly variable sources of pathogens both in time and space and understanding of the precise mechanisms of pathogen transport (Ferguson et al., 2003). Bradford et al., (2013) summarises the many challenges in understanding and modelling these processes and summarizes current conceptual and quantitative models for pathogen transport and fate in agricultural settings over a wide range of spatial and temporal scales. Greatest success in this area has been where pathogenic monitoring data have been combined with modelled discharge, for example from Combined Sewer Overflows (Mahajan et al., 2013). The SWAT model although coded to model bacteria fate and transport has rarely been used in this context and a review of the model processes is considered necessary to enhance its capability (Baffaut and Sadeghi, 2010). In a novel approach focused on identification of source hot-spots, Sokolova et al. (2012) applied a microbial source tracking methodology linked to fate and transport modelling to provide information on the contribution from different contamination sources to the pathogen concentrations at the intake of a drinking water treatment plant.

4.5.2 Pesticide Contamination Models

Pesticides are another key contaminant of concern in relation to drinking water quality. Modelling of pesticides has also proved somewhat problematic but gradual progress has been made in this regard. One of the earlier tools applied to model pesticide fate and transport was the Root Zone Water Quality Model (RZWQM). A review of applications of RZWQM found that 3 key processes in achieving good pesticide simulation were: accurate parameterisation of soil permeability at different depths; simulation of pesticide sorption kinetics; and calibration of the pesticide half-life (Malone et al., 2004). Koehne et al. (2009) reviewed progress in pesticide models incorporating preferential flow and found that the principal difficulty relates to appropriate parameterization of the preferential flow and pesticide processes. Various experimental and model development strategies were proposed to help with further enhancement of the models. Payraudeau and Gregoire (2012) also reviewed a large number of pesticide modelling studies and identified a number of key points in pesticide evaluation: indicators inferred from conceptual or physically-based models are useful as operational tools; only physically-based models are capable of capturing all the processes and feedbacks that may be important; few models are capable of assessing pesticide loads; and at the catchment scale understanding of hydrological connectivity is vital.

4.5.3 Nitrate Contamination Models

Nitrate may cause health problems if present in high concentrations in public or private water supplies. The US EPA applies a maximum contaminant level goal of 10mg/l nitrate-N whilst in Europe the EC Nitrates Directive (EC, 1991) sets a maximum concentration of 50mg/l nitrate (equivalent to 11.3mg/l nitrate-N) for all groundwaters and surface waters used for drinking water abstraction. In Europe this has led to the designation of Nitrate Vulnerable Zones (NVZs) where action programmes must be implemented to reduce losses of N from agricultural land. Modelling approaches have been used to support both the designation of NVZs and also to assess the effectiveness of measures to reduce nitrate pollution. Lake et al. (2003) used a GIS modelling approach to collate data on root zone leaching, soil and geological attributes to make recommendations for an enhanced set of groundwater NVZs in England and Wales. Sample and Dunn (Sample, 2014) undertook a national scale modelling exercise to predict average concentrations of nitrate leaching from agricultural land. This was linked to national monitoring data and groundwater body definitions in order to support decisions for the 2013 review of NVZ boundaries. Many modelling studies have also been undertaken to examine the effectiveness of NVZ action programmes on reducing nitrate concentrations in drinking water. These are discussed in the section on effectiveness of measures below.

4.5.4 Sediment Models

Sediment is another important water quality determinand in the context of drinking water quality. Modelling of sediment at catchment scales has proved quite problematic due to the high heterogeneity in sources and transport processes, and the importance of deposition and remobilisation. de Vente et al. (2013) undertook a critical evaluation of a range of models. They identified that modelling of soil erosion and sediment yield strongly depends on the spatial and temporal scales considered. In large catchments, non-linear regression models were found to be the most useful whereas in medium-sized catchments, best results were obtained by factorial scoring models like PSIAC, FSM and SSY Index (de Vente et al., 2005). Most of the conceptual and process-based models were found to represent only a selection of erosion and sediment transport processes and therefore can only provide reliable results where the considered processes are indeed dominant.

4.6 In-stream chemistry, eutrophication and ecology

Eutrophication of rivers and lakes arises from an oversupply of nutrients which can lead to detrimental impacts such as an increase in the biomass of algae and especially increases in cyanobacterial dominance of phytoplankton (Smith, 2003). The EU WFD has recognised the importance of the ecological integrity of freshwaters through setting targets for surface water status in terms of ecological quality. This has altered the emphasis of water quality studies from previous hydrochemical based assessment. However, modelling of freshwater ecology has proved extremely challenging, not least because of the apparently large variability in the importance of different factors in different geographic and climatic settings. Consequently, implementation of the EU WFD has continued to rely heavily on monitoring and prediction of chemical status (especially N and P) as key factors in determining overall ecological quality. In the UK, environmental standards have been identified by the UK Technical Advisory Group on the Water Framework Directive (UKTAG) and include threshold values for a range of different pollutants. Standards for phosphorus in rivers have recently been revised as a result of improved understanding of the relationship between phosphorus and river plant communities (UKTAG, 2013). Although there are no surface water standards for nitrogen included in the UKTAG list, the threshold for drinking water concentrations defined through the EC Nitrates Directive is still applicable.

Many models have been developed and applied to simulate surface water N and P concentrations, and to explore the relationships between climate, land use, management and water quality. As outlined earlier these range in complexity from simple export coefficient type approaches to complex physically-based models. Whereas the simpler models tend to be more tailored to specific conditions and purposes, several of the more complex catchment scale conceptual models have received widespread use.

The SWAT model (Arnold et al., 1998) is one such example which has been extensively applied internationally and is referred to by more than 1700 literature citations. This does not necessarily mean the model structure and performance is any better than many other models, but its accessibility is a key factor. SWAT includes equations to simulate hydrology, N, P, pesticides, bacteria, carbon, sediment, biological oxygen demand and dissolved oxygen in rivers (Neitsch et al., 2011). It also includes an extremely comprehensive set of management options for exploration of varying agricultural practices. The results of this is that there are a vast number of parameters that need to be identified and very often, where local information is lacking, default values for these would be selected. The danger in this is that the end-user has a belief that the model can do more than is genuinely true as the underpinning data and information are inadequate (Daggupati et al., 2011, Silgram et al., 2009). Conan et al., (2003) coupled the SWAT model with a groundwater model, MODFLOW, and its companion contaminant and solute transport model, MT3DMS (Prommer et al., 2003), to assess the benefits of decreasing manure application from 210 to 170 kg N ha^{-1} as required by the EC Nitrates Directive.

The AnnAGNPS (Annualized Agricultural Nonpoint-Source Pollution) model (Bosch et al., 1998) is another model that has received widespread use to predict non-point source pollutant loadings from agricultural watersheds especially to compare the effects of implementing various conservation alternatives within a watershed. It has been most commonly used in studies of runoff and sediment losses and their relationship to land use planning (Sarangi et al., 2007).

In Europe, the Integrated Nitrogen in Catchments model (INCA) (Whitehead et al., 1998, Wade et al., 2002c) has also been widely used. INCA simulates nitrogen export from different land-use types within a river system, together with the resulting in-stream nitrate and ammonium concentrations at catchment scales. The primary objective of the model is to provide a tool which aids the understanding of nitrogen dynamics and which thereby can be used to help support river-basin management and policy-making (Wade et al., 2002c). The structure of the INCA nitrogen model has also been used to develop separate models for sediment and phosphorus (Wade et al., 2002c, Wade et al., 2002b, Wade et al., 2002a), dissolved organic carbon (Futter et al., 2007), and mercury (Futter et al., 2012). Examples of recent applications of INCA models include: better understanding of controls on inorganic nitrogen leaching in Finland (Rankinen et al., 2013); to determine the key factors controlling run-off, sediment and phosphorus losses in Norway (Farkas, 2013) and to improve understanding of dissolved organic carbon dynamics in the context of drinking water supply in Sweden (Ledesma et al., 2012). Although INCA has been found to give good simulations of many aspects of the relevant biogeochemical cycles it also suffers from issues of difficulties in parameter identification (McIntyre et al., 2005b, McIntyre et al., 2005a, Dean et al., 2009) and some questions remain regarding the representation of certain processes of the phosphorus cycle (Farkas, 2013).

Problems in modelling phosphorus at catchment scales are quite widespread and are underpinned by a poor knowledge base regarding the extrapolation of understanding from small scale mechanistic studies on the sources and mobilisation of P (Haygarth et al., 2005). In general, models have been found to give an acceptable estimate of P loadings at annual time-scales but simulations of daily, or even monthly, variability in concentrations and loads are much poorer (Chu et al., 2004, Silgram et al., 2009). It is notable that the majority of performance metrics cited for P simulation are in relation to estimates of loads rather than concentrations; with a good hydrological simulation being a key factor in determining the former.

In the context of predicting the ecological impacts of N and P on primary production in surface waters Keck and Lepori (2012) used data from a large number of experiments to develop regression models to examine the relationships between N, P and microphytobenthos biomass but found that without information on factors such as light and disturbance, the predictive ability of the models was limited. This highlighted the importance of considering factors beyond nutrient concentrations in developing models of ecological response. Zhang and Rao (2012) applied the Water Analysis Simulation Program (WASP –James et al. (1997)) to simulate eutrophication of lake water. As well as including two nutrient cycles (N and P) and three functional phytoplankton groups this lake model also considers distinct features of the morphological, hydrological, and climate conditions. Inputs of N and P for lake models of this type could potentially be generated by catchment models such as SWAT or INCA to enable the effects of different N:P loading ratios on the lake ecosystem to be assessed in terms of simulated phytoplankton biomass.

4.7 Effectiveness of pollution mitigation measures

The EU WFD requires member states to adopt cost-effective mitigation measures to achieve good status for all waters and with agriculture considered as a primary source of rural diffuse pollution, many of the potential mitigation methods are targeted at management of agricultural systems. The difficulty in monitoring sources of diffuse pollution has raised important questions about how to evaluate the effectiveness of individual actions and there is a clear role for numerical models to assist with this. Shepherd et al. (2011) evaluated a range of published models for their capability to simulate agricultural production systems and their associated environmental system losses under a changing climate, as well as the ability of the models to handle adaptation and mitigation methods. This study identified three models, DAYCENT (Del Grosso et al., 2002), PASIM ((Riedo et al., 1998), and SPACSYS (Wu et al., 2007) which accommodate most of the features required to assess the effects of farm mitigation and adaptation on environmental losses under a changing climate. These three models all include process-based representation of agricultural systems including full C and N cycles, water and energy. While models such as these enable improved understanding of effectiveness at a field scale they do not address the challenge of integration to the spatial scales at which WFD objectives require to be met (Iho, 2005); although measures are implemented at farm level, the ecological targets are set at the sub-catchment or catchment scales (Bouraoui and Grizzetti, 2014). Temporal issues also need taking into account, as achievement of good ecological status over short time-scales appears problematic due to lags in water quality responses (Meals et al., 2010, Kronvang et al., 2009).

Various approaches (Cherry et al., 2008, Collins et al., 2014) have been used to assess the effectiveness of a broad suite of potential mitigation options (Newell Price et al., 2011, Schoumans et al., 2014) at other scales. These approaches have included the use of literature data and expert judgement (Newell Price et al., 2011), application of generalised farm-scale models (Gooday et al., 2014) and the application of catchment models ranging in complexity from simple empirical loss coefficient approaches to complex process-based models (Bouraoui and Grizzetti, 2014). The capabilities of models depend essentially on the purpose for which they were developed (Schoumans et al., 2009). The FARMSCOPER tool (Gooday et al., 2014) has been designed in collaboration with the UK Department for Environment Food and Rural Affairs (Defra) as a decision support tool to assess diffuse agricultural pollutant loads on a farm and quantify the impacts of farm mitigation methods on these pollutants. The farm systems within the tool can be customised to reflect management and environmental conditions representative of farming across England and Wales and over 100 mitigation methods are incorporated, including many of those in the latest Defra Mitigation Method User Guide. Models such as FARMSCOPER provide invaluable management tools to support farm advisors, but their application at catchment scales (Zhang and Rao, 2012) has been found to have some limitations. This is likely to be due in part to the fact that additional processes such as de-nitrification, sediment sorption or plant and microbial uptake (Hejzlar et al., 2009) also affect the efficacy of mitigation measures when assessed at the point of impact in a stream. In addition such tools are generally not dynamic, and therefore cannot reproduce time lags in water quality responses.

Conversely, complex catchment scale process-based models operate at the scale used to assess effectiveness and can incorporate important temporal and spatial aspects. However, they suffer from other issues including difficulties in data provision and model parameterisation, leading to high uncertainty in model predictions. Also many catchment models lack characterisation of key farm-scale management activities that can have a strong influence on simulated diffuse pollution (Dunn et al., 2013). The INCA suite of models is very good at combining both point and diffuse sources of pollution together with in-stream processing, but is very limited in the range of agricultural management options that it can represent. (Whitehead et al., 2013) demonstrated how the model could be used to examine the effectiveness of measures for phosphorus mitigation in the Thames catchment in England, where point sources from sewage effluent are a major source. As a result of the broad range of management options integrated in the SWAT model it has been widely used to assess the effectiveness of measures (see e.g. Holvoet et al. (2007); Panagopoulos et al. (2011); Lescot et al. (2013)). Barlund et al. (2007) assessed the utility of the model in this context for a catchment in Finland and found that the SWAT descriptions of the management options required some modifications in order to describe correctly the reduction efficiency for local conditions. This highlights the significant uncertainty that can be associated with modelling approaches of this type and it is important that this aspect is not neglected. Vagstad et al. (2009) compared results from different models and found big differences in the predicted effect of the management scenarios, leading to different management practices being identified as being most effective for reducing nutrient losses.

The results of some modelling assessments have highlighted that delivery of WFD water quality objectives for some systems could be extremely challenging. Volk (Volk et al., 2008, Volk et al., 2009) used a spatial decision support system to integrate ecological and socio-economic assessment methods, scale-specific and GIS-based data and knowledge modelling and visualization techniques. They explored various land use and management strategies by applying the SWAT model to a river basin in north-western Germany and found that substantial, expensive water and land management changes at different scales would be necessary to achieve the WFD water quality targets. Similarly, Glavan et al. (2012) undertook a study of the Axe catchment in south-west England and examined the effect of three different mitigation scenarios by applying the SWAT model. The results of the model analysis suggested that there may be a fundamental incompatibility between the delivery of WFD targets and the maintenance of viable agricultural systems in this region.

Another important issue in the context of the effectiveness of mitigation measures is the expected time-scales of recovery. Meals et al. (2010) summarised the important processes influencing lag time as hydrology, vegetation growth, transport rate and path, hydraulic residence time, pollutant sorption properties, and ecosystem linkages. The magnitude of lag time is highly site and pollutant specific, and may range from years to decades for excessive P levels in agricultural soils, and decades or more for sediment accumulated in river systems. Groundwater travel time is also all important contributor to lag time and may introduce a lag of decades between changes in agricultural practices and improvement in water quality. Thus, evaluation of effectiveness through monitoring alone is very challenging and process-based modelling can be a valuable tool to aid understanding. Some studies have used atmospheric tracers to support inverse modelling of groundwater residence times, particularly in the context of predicting recovery from nitrate pollution (Dunn et al., 2012a, Dunn et al., 2012b). Recovery from P pollution is less well understood and MacDonald et al. (2012) highlighted a need for an improved ability to predict the dynamics of recovery after termination of agricultural use.

4.8 Scenario assessment

Future climate and land use changes will have implications for water quantity and quality and could make attainment of targets, such as those set by the EU Water Framework Directive, harder to achieve. High uncertainty in how climate and land use will change, coupled with the extreme complexities of modelling multi pollutant water quality on larger scales, means that it is difficult to factor future changes into policy decisions. Scenario based planning is commonly adopted as a means of articulating mental models about the future and can help support managers in making better decisions Dong et al. (2013)). Hydrology and water quality models can play an extremely valuable role in demonstrating how future scenarios might be expected to impact on surface and groundwater systems. Stakeholder interaction is an important aspect of scenario based assessments and Jessel and Jacobs (2005) described the benefits of stakeholder input at two different stages of the process; both as a means of establishing relevant scenarios prior to model application and then subsequently in interpreting the results of hydrological and water quality modelling to establish management priorities. A similar participatory approach was adopted by Andersson et al. (2008) who used model outputs to guide stakeholders in reaching agreement on environmental objectives and then to develop suitable mitigation plans for achieving these.

Wilby et al. (2006) explored an integrated approach to climate change impact assessment by linking established models of regional climate (SDSM), water resources (CATCHMOD) and water quality (INCA) within a single framework. The results confirmed large uncertainty in the impacts on freshwater resulting from climate change uncertainty, as characterised here by the choice of general circulation model, but showed that delivery of EU WFD objectives under climate change could be evaluated using the same framework. In the UK, the 2009 UK Climate Projections (UKCP09) delivered a more robust base for climate change assessments than previous scenarios because they provided future data based upon a more systematic characterisation of uncertainty across several climate models (Murphy et al., 2009, Street et al., 2009).

As well as the hydrological drivers of climate change on pollutant losses changes in the bioavailability of pollutants may also be important, with changes in biogeochemical cycling triggered by changes in temperature and soil moisture. Whilst increases in temperature from climate change might be expected to increase the rates of some chemical processes, such as mineralization of soil organic matter, this may be offset against the effects of modified water availability. A detailed study of the effect of wetting and drying cycles on nitrogen mineralization concluded that increasing summer droughts would most likely reduce the mineralization and fluxes of N (Beier et al., 2008, Borken and Matzner, 2009). Other processes such as plant uptake or gaseous emissions could also be enhanced by temperature increases and would tend to counteract any increases in mineralization. Increased denitrification in aquatic systems may also be offset by increased N fixation (Jarvie et al., 2012). Projections made at the European level for winter wheat for the 2071–2100 time-slice showed large spatial variations in N-leaching due to the many interactions between changes in crop uptake, fertilization, nitrogen mineralisation and soil water balance (Olesen et al., 2007). Current models may be quite limited in how well all of these key processes are characterised and this should be an important consideration in their selection and application to climate change studies.

Many recent watershed modelling studies have examined the impacts of climate change and land use change on a range of hydrological and water quality determinands including: stream temperature (e.g. (Luo et al., 2013), sediment (e.g. Zabaleta et al. (2014)), nitrogen (e.g Salmon-Monviola et al. (2013)), and phosphorus (Woodbury and Shoemaker, 2013). Steffens et al. (2014) summarised the relative importance of parameter uncertainty in modelling pesticide leaching versus the uncertainty in future climate scenarios. While the SWAT model is most commonly cited in relation to these types of scenario assessment, other models have also been found useful. Yang and Wang (2010) evaluated the utility of the HSPF model (Bicknell, 1997) for predicting responses to climate and land use change scenarios in the context of river basin planning and the future delivery of WFD targets. Novotna et al. (2014) applied the WaSim model to an agricultural catchment in Quebec to assess the impacts of climate change on suspended sediment and nutrient loadings. Couture et al. (2014) applied the INCA model chained with the MyLake model to examine the potential impacts of climate and land use change on lake phosphorus loadings and chlorophyll concentrations.

At larger (e.g. national) scales, there is also a demand for outputs from large-scale models to inform implementation of the EU WFD and other policies. Dunn et al. (2012a) examined the relative importance of potential changes in climate versus potential changes in land use in terms of runoff and nitrate leaching, by applying a conceptual national scale water balance and nitrogen budgeting model. van Roosmalen et al. (2007) undertook a regional impact study of the effects of climate change on groundwater recharge in Denmark using a physically-based modelling approach.

In some cases, implementation of complex multi-pollutant modelling tools may be an impractical option, and different approaches may be considered more appropriate for development of horizon scanning policy. Heathwaite (2003) identified a need to develop generic models of pollutant export based on expert knowledge that are simple to use and easy to apply. This concept has been taken forward by some alternative modelling approaches which are more suitable for broad-scale assessment. For example, the use of fuzzy logic linked to simple export coefficient models (Islam et al., 2013) or the use of literature reviews and expert opinion as a means of developing rule-based models (Zhang et al., 2013). A key attribute of simpler modelling approaches is that their objectives need to be quite tightly defined and limitations in model structures can be problematic when they are extrapolated to differing environmental conditions (Refsgaard et al., 2006). It is the scale and direction of change in water quality that is of primary interest in relation to horizon scanning policy, and a simple qualitative methodology focused on this was found to provide SEPA with appropriate understanding to inform their future evaluation of Significant Water Management Issues for the WFD (Towers et al., 2012). Macleod et al. (2012) also found expert knowledge on the key drivers of pollutant loss to be helpful for rapid evaluation of the direction and sensitivity of water quality responses to future climate and land use scenarios. An important aspect of an approach presented by Volk et al. (2008) was found to be a visualisation tool that enabled simple explanation of complex system inter-relationships in communicating with stakeholders. Integration of this type of relative risk modelling approach with spatial data on environmental characteristics can create a powerful tool, whilst retaining advantages of simplicity in terms of tracking of errors and immediate visualisation of results (Pistocchi et al., 2010).

4.9 Summary

The preceding review has outlined the current state of the art with regard to modelling of hydrology and fresh water quality and illustrated its applicability in relation to several key water management issues. Limitations of the current suite of modelling tools and methods have also been highlighted where relevant, but in summarising it is worth reiterating some of these issues. As is clear from this review, the choice of model depends to a large degree on the scale of application and whether the aim is to take into account many driving factors in a complex system, perhaps one as yet unobserved or to consider specific responses to a particular change in a spatially limited context. Most of the models discussed here would be relevant to the environmental objectives relating to acidification, ground water, eutrophication and the ultimate aim of ensuring flourishing lakes and streams. Generally, conceptual and empirical models might be expected to be more pragmatically useful in a dynamic planning context, particularly if swift responses for use with participatory methods was required, but are less able to give a definitive answer as to the “best” course of action due to equifinality and reliance on previously observed circumstances. Bayesian and mechanistic approaches can handle more complex situations where the physical relationships are not all known, but their output is highly dependent on relevant data and models require considerable expertise to set up, thus might be of most use for more strategic impact assessment. For specific, local, impact assessment, physically based models can give spatially precise output and capture key inter-relationships including predicting future unobserved cases, but in practice still require calibration to specific circumstances.

4.9.1 Key gaps

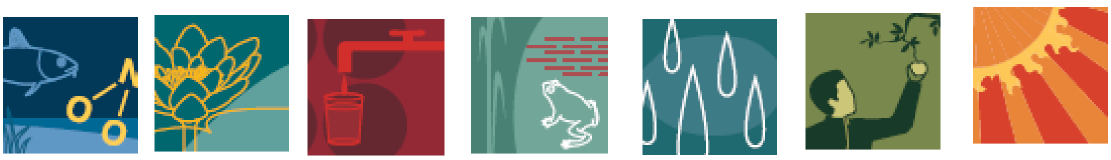
There are still fundamental gaps in scientific understanding that limit the capability of models to address important questions. This is especially true of the relationships between chemical composition and ecological status. Noges et al. (2009) outlined some of the remaining challenges in assessing ecological status and despite scientific progress since then, many of these remain true today. Another challenge that is only starting to be considered is that of multi-pollutant impacts and pollutant swapping (Collins and McGonigle, 2008). van Groenigen et al. (2008) developed a national scale model, and used it to quantify the effects on GHG emissions of environmental policies aimed at reducing NO_3^- leaching and NH3 volatilisation in Europe, but there appear to be few other modelling studies that have considered management in the context of multiple pollutants.

Although modelling tools are available to simulate a broad range of water quality variables, there are still many uncertainties not just in relation to model parameterisation but also the model structures and their inherent assumptions. Models developed in specific regions are likely to have limitations when applied in different geographic and climatic zones due to the importance of different processes that may be inadequately characterised by the model structure. Another key limitation is the availability of data at appropriate spatial and temporal resolutions to parameterise and calibrate / validate models.

4.9.2 Future approaches

Ensemble modelling is increasingly recognised as a suitable approach to address issues of structural uncertainty in models (Refsgaard et al., 2006). This procedure involves the application of multiple models to simulate the same determinand followed by inter-comparison of the results to derive uncertainty bounds. Kronvang et al. (2009) applied eight models for N and five models for P and found coefficients of variation between the model simulations of 67% for gross P loss and 40% for gross N loss. Exbrayat et al. (2013) explored the utility of the approach for simulating N responses to simple fertiliser management changes. The results showed that although each of four models gave good calibration statistics, one of the models simulated a very different response to management changes. The authors proposed an adaptation of the reliability ensemble averaging philosophy to weight the outputs in a situation of this type.

The increasing interest in participatory modelling approaches (Voinov and Bousquet, 2010) reflects a growing recognition that models can serve as extremely valuable platforms for assisting stakeholders in understanding current conditions and the causes behind these conditions (Andersson et al., 2008). Kelly et al. (2013a) have developed a framework to assist modellers and model users select an appropriate participatory modelling approach according to the purpose of the model application. Approaches of this type are considered likely to increase in popularity in the future.



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5 Modelling Marine Ecosystem Services

Akoumianaki, I

This review aims to help identify appropriate models to validate or predict the impact of drivers with the potential to influence the Swedish marine environment. The scope of the review was laid out in a start-up meeting with the project team and is in line with the environmental quality objectives of the Swedish Environmental Protection Agency related to the marine environment, hereafter reported as the 'marine objectives' (Table 5-1). In particular, we examine models describing how global drivers of change (e.g. rise in temperature and CO_2) and regional stressors operating in the Baltic Sea and its drainage basin (e.g. precipitation, farming practices) may alter marine physical, biogeochemical and ecosystem processes. Emphasis is on indicators that help develop scenarios to assess the effectiveness of policies towards achieving the marine objectives.

Table 5-1 Types of models and indicators aligning with the environmental quality objectives of the Swedish Environmental Protection Agency related to the marine environment (NATURVARDSVERKET, 2012), reported here as the 'marine objectives'. N, P, C: nitrogen, phosphorus, carbon, respectively. *Coupled to physical (including Atmospheric-Ocean General Circulation and coastal) models.

Scenario development		Marine objectives (NATURVARDSVER-KET, 2012)	Indicator for determining compliance with the marine objectives	Type of model*
Major global drivers of change affecting marine ecosystems (Assessment, 2005)	**Regional stressors to the Baltic Sea environment (Backer et al., 2010)**			
Climate variability and change Plant nutrient use (fertilisers) Fishing / Coastal use Biological invasions and disease	Eutrophication Acidification Climate impacts on physio-chemistry, morphology Toxic pollution Fishing –cod etc. fishmeal production Biodiversity declines Use/management of coastal/marine space-legislation drivers	Zero eutrophication	• Nutrient (N, P, C, sediments etc.) and pollutant export to sea • dO_2 • Pelagic and benthic biogeochemical cycling	Export of nutrients from land to sea Marine biogeochemical/ecosystem processes
		A balanced marine environment, flourishing coastal areas and Archipelagos	• Dynamics of lower or higher trophic levels • Pelagic and benthic biogeochemical cycling • Ecosystem structure	Export of nutrients from land to sea Marine biogeochemical/ecosystem processes
		Natural acidification only	• Carbon cycle • Carbonate system • pH	Marine biogeochemical/ecosystem

				processes
		A rich diversity of plant and animal life	• Diversity (species/trophic/ functional)	Marine biogeochemical/ecosystem processes

In short, eutrophication and the continuing pollutant (nutrients and toxic chemicals) inputs are the most serious environmental issues in the Baltic Sea. These have led to algal blooms; spread of dead zones, with subsequent biodiversity declines; fisheries depletion, and the accumulation of toxins through the food chain (Kong et al., 2014). In addition, climate change has already increased the Baltic Sea's temperature by 0.08^{o}C per decade, which is higher than the global average of 0.04 to 0.05^{o}C per decade (cited in Kong et al., 2014).

Meanwhile, eutrophication, pollutant emissions, and climate change drive perturbations in many regions of the world. Models have been developed to address the impacts of these stressors, separately or in combination, on indicators of change. Scenario-driven modelling is increasingly used to help evaluate and project the effectiveness of mitigation policies at local, regional and global scales. In this regard, the indicators used to determine compliance with the marine objectives (Table 5-1) have either been identified either by Naturvårdsverket or relevant legislation (e.g. WFD, Marine Strategy, Biodiversity convention), or by the model itself.

Here we review models that simulate scenarios on changes in the atmosphere-sea interaction and the climate system, land use, nutrient use, coastal use, water quality, fishing and ecosystem structure. In the context of the earth system these scenarios are intertwined (e.g. climate change interacting with changes in water quality) and thus better explored by coupled models to provide a realistic representation. However, for the needs of this review we can distinguish three general model categories:

- physical models, and in particular atmosphere-ocean general circulation models (AOGCMs) and coastal models;
- nutrient export (from land to sea) models; and
- marine biogeochemical cycling and ecosystem models (including lower trophic levels of ecosystems and ecosystem models).

In this review we briefly account for the scenarios examined and processes described in the models; scale of response to drivers (global versus regional); datasets and, if possible software, required; case studies; and drawbacks. Given the interdisciplinary nature of problems and impacts on the marine environment, the focus is on: model approaches of the river-sea continuum and the nutrient to fish linkages; fluxes and processes at system interfaces, i.e. land-to-coast, air-to-sea, benthic-pelagic; and biogeochemical or ecosystem models coupled with physical models.

5.1 Overview of models

An indicative list of data sources to validate marine models is provided in Table 5-2. In general data can be gathered by remote sensing techniques to provide boundary conditions in regional climate and hydrodynamic models in global and regional physical and biogeochemical/ecosystem models. Data can also be derived from *in situ* measurements, historical databases and field experiments. In the case of general ocean or coastal circulation models, observational data readily available at regularly spaced grid points are the most useful. *In situ* observations are usually not representative of conditions covering an area the size of an average model grid box, thus a comprehensive analysis is required to match model simulations and observations.

Table 5-2 Observational data sets used for model validation in marine models. In general, data can originate from remotely sensed and in situ data, historical data and field experiments for the globe and regions. Specific examples or detailed information are provided, where possible.

Parameter	Observational	Spatial	Temporal
Atmospheric circulation data	remotely sensed and *in situ* data, historical data and field experiments for the globe and regions e.g. http://www.nodc.noaa.gov/General/current.html	varies	varies
Ocean Circulation data			
Coastal physical models			
pCO_2 and CO_2 flux	(Takahashi et al., 2009, Sabine et al., 2012)	4 □×5□	Annual
Alkalinity	GLODAP, GLobal Ocean Data Analysis Project data http://cdiac.ornl.gov/oceans/glodap	1 □×1□ (40 levels)	Annual
Dissolved inorganic carbon		1 □×1□ (40 levels)	Annual
O_2 and Macronutrients (NO3, PO4, SiO3)	(Levitus et al., 2013)	1 □×1□ (40 levels)	Monthly
Primary Productivity	(Buitenhuis et al., 2013) (satellite algorithms)	1 □×1	Monthly
Chlorophyll	Seawifs, MODIS databases (Sayer et al., 2013)	1 □×1□	Monthly
Process cruises	e.g. JGOFS study sites		
Ocean time series stations	e.g., HOTS, BATS, Station Papa (Sarmiento, 2013)		
Baltic Sea databases	e.g. bathymetry http://data.bshc.pro/#2/58.5/14; Baltic Sea Monitoring Data (HELCOM stations) http://ocean.ices.dk/helcom/Helco		

5.2 Physical modelling

Air-sea interactions and sea level rise are perceived as drivers rather than indicators of change in achieving the marine objectives. Therefore, it is considered that physical models should only briefly be described to account for the backdrop of the processes involved in marine eutrophication, acidification, ecosystem balance, and conservation. These include coupled atmospheric-ocean general (or coastal) circulation models, hydrodynamic, and wind-wave models. Key features and operational skills required to run physical models used in marine eutrophication, pollution, biogeochemical and ecosystem scenarios are given in table A2.5.3.

A complete analysis of all the many applications of physical models is beyond the scope of this review. With this in mind, this section draws content on atmosphere-ocean general circulation models from (Bader et al., 2008) (Donner et al., 2011, Stock et al., 2011) (Griffies et al., 2000); and on coastal models, including hydrodynamic and wind wave models from (Dyke, 2001), unless otherwise stated. References for each model are given in table A2.5.3. The term “coastal” signifies waters from the upper continental slope to the coast (depth<200 m), although the most intense human activity and ocean productivity occur in inshore waters (depth< 30 m).

AOGCMs are widely acknowledged as the most sophisticated tool available for global climate simulations, and particularly for projecting future climate states and understanding the ocean’s role in the global heat and carbon balance. Most importantly, marine ecosystems and biogeochemical processes are controlled by water circulation and mixing and, up to a certain extent, by their drivers. For example, the interaction of ocean / coastal biology with physical processes is important for air-sea gas exchange, including key processes related to Greenhouse Gas (GhG) mitigation (i.e. bi-carbonate chemistry and marine biological pumps) and cloud formation (i.e. dimethyl sulfide exchange). In addition, these models help understand or predict coastal impacts of ocean dynamics (e.g. impacts of coastal erosion, sea level rise on coastal uses and coastal ecosystems).

AOGCMs are key to construction of climate change scenarios, more so in combination with dynamic or statistical downscaling methods. This is because they have the potential to provide spatially and physically consistent estimates of regional climate change due to increased atmospheric greenhouse gas emissions (GhG) levels. In addition, projections are available for a large number of climate variables, at a variety of temporal scales, and for regular grid points all over the world, which should be sufficient for many impact assessments (e.g.Table 5-2). AOGCMs can be used to provide a physically plausible range of climate changes in regional scenarios especially when using an ensemble of different models with the potential to decrease uncertainty of AOGCM-based scenarios.

AOGCMs are made up of component models interactively coupled via exchange of data across the interfaces between the atmosphere, ocean, cryosphere, and earth surface. The ocean component is commonly driven by the atmospheric fluxes of heat, momentum (Navier-Stokes equations), and precipitation (freshwater) simulated by the atmospheric component. These fluxes are functions of the sea surface temperatures (SST) simulated by the ocean model. Other driving fluxes of the ocean component include sea-ice formation, freshwater inputs from sea-ice melt, and freshwater river discharge at the continental boundaries. The state of the ocean can usually be defined by the temperature, salinity and three components of velocity. Temperature is commonly stored as potential temperature (relative to a pressure of 1 Atm) because this remains constant under adiabatic changes in pressure. Then the evolution of the ocean can be specified using a momentum equation to give the time change in velocity and an advection-diffusion equation for the changes of temperature and salinity (using density as a proxy). The system also needs a continuity equation, an equation of state and boundary conditions to be specified.

Using a latitude-longitude grid means that spacing between grid points of the meridians near the North Pole becomes very small. This requires the model to use a small time-step which results in high computational cost. To overcome this, models such as OCCAM (Coward and De Cuevas, 2005) are split into two parts, the first using a standard latitude-longitude grid (Pacific, Indian and South Atlantic Oceans) and the second using a rotated grid oriented to match the first model in the Equator at the Atlantic.

In general, three important approximations (known as 'primitive equations') are often made to reduce the computational load, e.g. models MOM and OCCAM . The first assumes that the state of the ocean is incompressible; the second that the vertical velocity is small, i.e. vertical momentum can be neglected; and the third that small changes in density (horizontal momentum) can be neglected except where they affect the horizontal pressure gradient.

Most ocean models use Arakawa grids either of type B (e.g. MOM, OCCAM, and HadAM3H) or C (e.g. NEMO ocean engine). A preference for B grid at coarse (greater than the Rossby radius of the ocean which is 25 km) resolution and C grid at fine resolution is based on the superior representation of poorly resolved inertia ± gravity waves by the B grid whereas the C grid is superior for well resolved waves. B grids are better at representing oceanic fronts and currents with small vertical extent and velocity boundary conditions near coastlines.

5.3 The challenge of regionalisation and downscaling

In the context of modelling biophysical interactions, there are specific scale requirements for meaningful simulations. For example, although SST can successfully simulate atmospheric forcing of ocean circulation (vertically and horizontally) in mesoscale, it gives uncertain representation of the dynamics of phytoplankton functional types in the vertical mixed layer in the smaller spatial scales of biogeochemical processes (Sinha et al., 2010 (Sinha et al., 2010)). Given it is still insufficient to capture the fine-scale structure of climatic variables in many regions of the world a number of techniques (e.g. interpolation, statistical downscaling methods that are based on empirically derived relations between observed large-scale climate variables and local variables or high-resolution regional climate models restricted to a domain with simple lateral boundaries driven by outputs from global or larger scale regional models) exist to enhance the resolution of AOGCM outputs that is necessary for impact assessment studies.

Another scale-related problem is the implementation of AOGCMs in simulating coastal dynamics. Early ocean models assume that ocean temperature responds directly to changes in atmospheric heat fluxes at seasonal time-scales and longer, failing to account for the large thermal inertia of the deep oceans that slow down the rate of temperature variability. State of the art AOGCMs have full dynamic deep-ocean components with long timescales (multi-century to millennia) accounting for the response of the abyssal ocean to greenhouse gas emissions. These models describe the full dynamics and thermodynamics of the global ocean basins and allow simulation of the full three-dimensional (3-D) current, temperature, and salinity structure of the ocean and its evolution. However, their resolution is too coarse (~ 1 degree for seasonal or longer time scales; 0.1 degree at daily timescales) for coastal or regional implementation in climate scenarios. Therefore, the challenge is to use approximations of global models or different codes to suit coastal and local dynamics, e.g. regional model RCAO, its ocean component adjusted from OCCAM, which includes a river routing scheme connecting river flow with river mouths in the Baltic area proper (Meier and Doscher, 2002).

Ocean and coastal models solve, numerically, momentum equations, transport equations for heat and salinity fluxes, an equation of state, and an equation for the ocean surface. They both contain significant approximations of sub-grid-scale processes. For example, they both include turbulence and molecular diffusion (at the scale of centimeters) that are not resolved by the model but are critical in that they represent processes by which energy is removed from the ocean. However, global and coastal models tend to differ primarily in their representation of turbulence (i.e. mixing): global models must keep the temperature and salinity structure of the low energy deep ocean; coastal models must incorporate complicated algorithms to describe the vertical turbulence over the full water depth in seas with high (or higher that the ocean) hydrodynamic regime.

Global and coastal models also differ in their need to represent the pressure and density relationship, which is an essential feature of global ocean models. In contrast to global models, coastal models need to consider tidal or wave-associated movements across a shoreline slope. Further, coastal models must define the limit of the modelled area. In doing so they frequently include open-boundary conditions making assumptions about ocean conditions beyond the modelled area (e.g. the end of the continental shelf is a typical open boundary, such as the Kattegat or Skagerrak in the case of Baltic Sea regional models). The open boundary is dealt with as a streamline: no flow passes through it, although no net flow is what is actually required. Another way of defining the modelled area is by nesting models so that a fine grid model is embedded inside a coarser (often global) grid model. However, high energy phenomena such as tides and waves are difficult to represent accurately at low resolution.

Hydrodynamics models allow for accurate and robust representation of processes in both near- and far-field regions of the discharge outfalls. Hydrodynamic models can be 2-D (depth-averaged) for well-mixed conditions or 3-D where vertical mixing is limited in the vicinity of the outfall due to density variation or absent. Hydrodynamic models (e.g. 3-D TELEMAC), can be used to simulate tracers such as the water flow fields and distributions of temperature, salinity, E. coli and harmful algal blooms. In the case of sewage outfalls, for example, due to the higher temperature of the effluents, 3-D models are more suitable to represent the density-driven flow processes (Bedri et al., 2013) and literature cited therein).

Ocean wave models are designed to capture swell from distant storms and forecast the state of the seas. They aim at representing the growth, dissipation and transport of wind energy conveyed to the sea-surface to provide quantitative information to ocean users, mainly in the coastal zone, where the majority of uses are based. So-called 2nd generation models (such as SLIM) use an unstructured mesh to enable an accurate representation of coastlines and islands and reduce singularities associated with the poles in geographic coordinates (Gourgue et al., 2013, Elskens et al., 2014). Their main advantage is their ability to adjust the resolution when and where it is actually needed to increase the range of resolved scales. They can be refined in the areas of interest, or where the more demanding dynamics requires a finer resolution (e.g. heterogeneous coastal landscapes).

In this regard, among the methods based upon unstructured grids, the discontinuous Galerkin (DG) method (which is used in SLIM model) offers high-order accuracy, excellent parallel scaling and an efficient treatment of convective terms. These favourable features have been exemplified by SLIM application in predicting pollutant transport on suspended material from river to estuary to sea (Gourgue et al., 2013, Elskens et al., 2014); and in realistically simulating hydrodynamic impacts on ecology in complex bottom topographies (e.g. (Legrand et al., 2006). On the other hand, 3rd generation models (such as WAM) parameterize explicitly each of the wave built-up processes, nonlinear transfer of energy, and dissipation ((Group, 1988).

To sum up, global and coastal ocean models tend to be run separately, either with one-way, or coupled nesting. With more powerful computers, and smart grids (including, in the future, unstructured grids), it is likely that single model runs will produce not only global conditions, but also high (< 1 km) resolution of dynamics into the shore, for immediate uptake by the coastal community, including managers and maritime industry.

5.4 Biogeochemical models describing export of nutrients from land to sea

5.4.1 Background

Fluxes of materials generated on land to the atmosphere and the aquatic systems determine the budgets of carbon (C), nitrogen (N, phosphorus (P), silica (Si) as well as toxic substances in the ocean, and therefore impact marine biogeochemical and ecosystem processes. Several pathways and complex, interacting processes are involved in the transfer of water, nutrients, sediments and toxic substances from land to air and the sea, acting at different spatial and temporal scales. Firstly, solid and dissolved particles exported to sea come from a variety of sources across the catchment-sea continuum, including soils (i.e. weathering), precipitation, groundwater, riparian zones, floodplains, rivers, lakes, estuaries and, fertilisers, and wastewater. Secondly, different processes are responsible for the retention of water (e.g. damming, infiltration), nutrients (e.g. denitrification, uptake and release by vegetation, periphyton and microorganisms, and), sediments (e.g. sedimentation and entrainment), and toxic substances (e.g. sorption and exchange reactions with soils and sediments, chemical precipitation in the water column). Hydrological pathways and many factors including temperature and land cover affect these processes controlling the absolute amount of water and mass discharged to the ocean (Ensign and Doyle, 2006, Alexander et al., 2009). C, N and P loading of rivers can lead to coastal eutrophication, which is associated with fundamental changes in marine food webs, toxic algal blooms, decreased oxygen levels (hypoxia or even anoxia), and fish kills. Such phenomena are increasingly common in many coastal seas, including the Baltic Sea (Pyhälä, 2012). This underscores the role robust nutrient export models can play in linking land-based sources of nutrients with marine eutrophication under different climate scenarios to formulate abatement policies.

5.4.2 Types of models

In the context of this review we examine models representing nutrient export from catchments to rivers and, by extension, from catchments to sea. These models describe sources and sinks of nutrients such as N, P, C and Si and their transport pathways to the outlet of the catchment, i.e. the river mouth, and have been used to estimate nutrient export to the coastal zone (Table A2.5.4). They combine hydrological and biogeochemical components and have been found to predict satisfactorily nutrient loads at river mouth from a variety of land use management practices in a variety of river basins. In their majority, they are open source or freely available (Table A2.5.5).

Models describing nutrient export to sea differ in the system boundaries, spatial and temporal resolution, and the complexity of their representation of catchment processes. As regards system boundaries, encompassing whole river basins, including groundwater, soil and landscape components, or river networks has important implications for the way the model defines diffuse sources of nutrients. It also affects the way soil-plant interactions control nutrient sinks and sources (e.g. plant uptake, mineralisation, immobilisation, denitrification, leaching). For example, the Soil and Water Assessment Tool (SWAT), which works with whole basins, defines diffuse sources as the inputs to soil from atmospheric deposition, N fixation in the soil, and fertiliser and manure application at a daily time step using a computationally intensive process-modelling approach for integration (Rollo and Robin, 2010). Other river basin models, such as SPARROW (Schwarz, 2008, Brakebill et al., 2010) and MOdeling Nutrient Emissions in River Systems (MONERIS) (Behrendt et al., 2007a, Fuchs et al., 2010, Venohr, 2010, Hirt et al., 2013), define diffuse sources as the soil surplus, i.e. the difference between total inputs to soil and output as crop yield, which is assumed to be transferred to the aquatic component of the catchment. On the other hand, RIVERSTRAHLER /SENEQUE (Garnier et al., 2002, Sferratore et al., 2005, Ruelland et al., 2007, Lancelot et al., 2011, de Brauwere et al., 2014a) and AQUATOX (Park et al., 2008), which use the drainage network or monitoring site as boundaries, define diffuse inputs of nutrients to surface flow and base flow by empirically associating annual fluxes of nutrients to each land use/soil class in the catchment. This approach does not take into account specific soil processes.

As regards spatial resolution, models used in estimating nutrient export to the sea vary from lumped to semi-distributed approaches. Because of underlying computational and structural complexity, the application of distributed deterministic models is limited in small sites or single stream reaches. In general, lumped approaches, although computationally efficient, do not consider spatial distribution of sources and sinks within a river basin. This may compromise the prediction of changes to nutrient inputs to the sea from catchments with a range of soil types, hydrological and geographical conditions, land uses, and, in the case of transboundary seas, national water policies (Kroeze et al., 2012). In this regard, popular catchment models such as MIKE SHE, TOPMODEL, CREAMS, and ANSWERS (Adams, 2007, Tsakiris and Alexakis, 2012), are out with the remit of this review. However, the NANI/NAPI budget approach, which allows the user to calculate NANI (Net Anthropogenic Nitrogen/Phosphorus Inputs) from commonly available databases downloadable from the internet, deserves special reference. Its virtue is its simplicity (e.g. fast computing, few parameters incorporated into a mass balance approach) and its applicability in management and policy making (e.g. use of detailed data on crops, animals, and people at regional and national scales). Description of the NANI/NAPI tool can be found in: http://www.eeb.cornell.edu/biogeo/nanc/nani/nani.htm. Examples of its application in the Baltic Sea are examined by Wulf et al. (2014) and Hong et al. (2011, 2012).

The advantages of lumped models are exemplified by the numerous applications and validation of the Nutrient Export from WaterShed (NEWS) models (Harrison et al., 2010, Mayorga et al., 2010, Seitzinger et al., 2010) and MOdeling Nutrient Emissions in River Systems (MONERIS) (Palmeri et al., 2005, Artioli et al., 2005, Nikolaidis et al., 2009, Fuchs et al., 2010, Hirt et al., 2014). These models use a 0.5 degree gridded (i.e. ~50 km x 50 km resolution) N and P fertilizer application and runoff generation to predict various water-quality characteristics from statistically significant whole-basin characteristics. This resolution, albeit coarse, has allowed broad application in a variety of catchments and enabled us to see distinct patterns of how the coastal zone responds to land use at the regional and global scale.

However, a finer-scale approach would greatly enhance the ability of such models to support water management decisions at regional scales. A way of doing this is by applying semi-distributed models which account for spatial distribution of land use practices and catchment characteristics by dividing the catchment into uniform (in terms of land use or land cover) sub-catchments, e.g. NEWS2 (Mayorga et al., 2010), SPARROW (Roberts et al., 2009, Brakebill et al., 2010), SWAT (Park et al., 2008, Rollo and Robin, 2010, Samaras and Koutitas, 2014), HSPF (Hunter and Walton, 2008), and AVGWLF (Evans et al., 2008; Strobl et al., 2009; Volf et al., 2013). Alternatively, the drainage network can be segregated into a regular scheme of tributaries with averaged characteristics by stream-order, e.g. RIVERSTRAHLER/SENEQUE approach (Garnier et al., 2002, Sferratore et al., 2005, Ruelland et al., 2007).

The models used to estimate nutrient export to the sea also differ in the way and degree of representation of the biogeochemical and hydrological processes and transport pathways described. Statistical regression models, such as SPARROW, provide empirical estimates of nutrient transport by simply fitting stream monitoring data with sources (e.g. a variety of farming practices) and landscape properties using a few predictor variables (Preston et al., 2009); recent empirical Bayesian approaches have managed to reduce SPARROW's computational uncertainties (Qian et al., 2005). In this context, models using regression approaches to explain nutrient sources and sinks and load at the river mouth (e.g. NEWS, MONERIS) are popular in that they have low data and time (annual averages) requirements while providing statistically robust global or regional outputs (Mayorga et al., 2010). However, this may be confounded by the use of variables that are surrogates of nutrient sources, thus perplexing the quantification of cause and effect relationship between nutrient sources from land and loads in surface waters.

Describing and predicting the time dependency of nutrient export to the sea necessitates the use of deterministic approaches, as in SWAT, RIVESTAHLER/AQUATOX/SENEQUE. These models use daily time steps and can provide inter-annually and seasonally variable flux and concentration results, which are key to understanding coastal and marine ecosystem dynamics. Nevertheless, owing to their computational complexity, process-based models, such as SWAT and HSPF, have only been used to model land runoff from small catchments to small coastal bays (Park et al., 2008, Samaras and Koutitas, 2014).

5.5 Marine biogeochemical / ecosystem models

5.5.1 Background

Predicting the state of the ocean as an ecological - biogeochemical system responding to climate and anthropogenic activity is one of the most pressing challenges facing scientific community. This is because ocean biogeochemical (OBGC) cycles are driven by complex interactions among physical, chemical and biological processes that link living and non-living components of the ocean-atmosphere and land-ocean systems. As a result OBGC cycles are at the heart of a series of environmental issues with important socio-economic implications. For example, the spread of dead zones and near-bottom hypoxia in coastal areas caused by eutrophication, the latter directly linked to anthropogenic imbalances in the nutrient ratios along the aquatic continuum, threatens marine living resources. Similarly, changes in the marine acid-base (pH) balance caused by the increasing atmospheric carbon dioxide (CO_2) fluxes into the sea, a phenomenon known as ocean acidification, pose a risk on marine biodiversity, especially calcareous plankton at the bottom of the pelagic food chain and rocky reef species. Yet, the combined effect of climate change and fishing on OBGC cycles and ecosystems remains largely unexplored.

It is fair to say that it is impossible for a model to ever fully describe the complexity of ocean ecosystems and biogeochemical processes. This is because OBGC modelling is data driven, with only site- or time-specific processes playing an important role in predicting ecosystem function and response to external forcing. Interestingly, a great amount of observations has been gathered so far from large scale field and satellite programs. Data availability along with the improvement of computational skills, have led to the development of conceptual and statistical models as well as sophisticated numerical modelling approaches. Nowadays, OBGC modelling is largely considered as a tool of exploring scientific hypotheses, understanding complex physical, chemical, species specific and multispecies interactions, and predicting the outcome of scenarios (see for example (Assessment, 2005) at a global or regional scale. Most importantly, the development of downscaling methods allows global models to be validated by comparison with local interdisciplinary measurements. Thereby, such models can be used in national studies for the formulation of marine resource management strategies at a local level.

Even so, a review of current models shows that in many cases key OBGC processes are still simplistically represented, frequently lacking clear mechanistic basis with questionable assumptions and respect to the mass conservation principle (*the verification problem*). In addition, both regional and global model descriptions are compromised by poor consistency between modelled output and observations (*the validation problem*). This is because of our limited understanding of the key OBGC processes, such as mineralisation, functional role of groups of species (e.g. marine microbes, zooplankton grazing behaviour), or ecosystem compartments (benthic recycling). In addition, fitting the small spatio-temporal scales of biogeochemical processes to the large scale of whole ecosystem and physical processes, i.e. from hours to decades and from kilometers to global, creates the so –called ‘multi-scale problem’ in ecosystem modelling.

The key problem in marine modelling emerges from our limited ability to evaluate complex parameterisations of functional groups and processes with real observations in space and time. In fact, only the simplest simulations with only a few state variables can be validated and therefore used in data-assimilation and ensemble applications. Simulating interdisciplinary, detailed data and rates, such as primary production, grazing, growth, mineralisation, detritus sinking, nutrient uptake, is a demanding task, difficult to implement, even in regional models, more so in global. Challenges are both analytical (e.g. number of samples and analyses), computational (e.g. development of algorithms, required simulations), and financial (e.g. evaluation cost). Care must be taken in defining which variables are necessary to reveal patterns in OBGC processes and ecosystem response while increasing the predictive power of simulations. Uncertainty can be generated by cumulative measurement errors when large numbers of variables are accounted in the model. Errors in model structure (i.e. how variables are represented in processes) and output (i.e. goodness of fit of modelled with real data), are also significant sources of model uncertainty. In general, the optimal size of predictive models can be achieved using a small number of variables (‘simple as necessary’ approach). Not surprisingly, IPCC has used one of the simplest, but testable, models, i.e. HadOCC.

5.5.2 Types of models

There are strengths and weaknesses in all types of OBGC-ecosystem models. Empirical OBGC models apply only under restricted conditions set by the range of model variables. Dynamic mass-balance models, on the other hand, are difficult and costly to calibrate, validate and run, and tend to accumulate uncertainty in the prediction. Complex modelling approaches include representations of fluxes of both nitrogen and carbon, the discretization of plankton boxes into size-based classes (Moloney and Field, 1991), the incorporation of a spatial dimension along with depth (e.g. (Dadou et al., 2001), and the coupling of biogeochemical models with hydrodynamic models (e.g., (Koné et al., 2005)) to work in three dimensions. That said, biogeochemical processes may be integrated directly into models as in the case of the Baltic long-term large-scale models SANBALTS (Savchuk and Wulff, 2009) and BALTSEM (Savchuk et al., 2012a, Savchuk and Wulff, 2009), 2002), which focus on rapid estimates of eutrophication for decision support. The model BALTCOST addresses nutrient load reductions at a Baltic-wide scale (http://www.balticnest.org/balticnest/thenestsystem/). The model uses detailed land use data in combination with retention capacity estimates to assess abatement costs and effectiveness of measures, such as reductions in fertiliser use and livestock numbers, wetland restoration on agricultural land, and improving waste water treatment. Such models include INCA-N (Integrated Nutrients in Catchments - Nitrogen), and CoastMab. In addition, OBGC cycles may also be developed as separate modules in coupled-biogeochemical models. The term coupling is used to describe the link between either biological and physical models (e.g. (Dippner, 2006)) or lower and higher (i.e. fish) trophic levels (Fennel et al., 2001). In the former case, coupling is actually a one-way forcing, either offline or online, from the hydrodynamic/physical to the biological model; in the latter case it is a two-way approach with information transfer both up (bottom-up) and down (top-down) the food web. In coupled physical-biogeochemical models, the physical model solvers give the advantage of upgrading the physical modelling as calculation capacity increases and new physical model solvers are developed. The physical part of these models is supplied by a GCM and it defines the impact of temperature, salinity and currents, and the delivery of limiting nutrients (advection, upwelling etc.). The BGC component is supplied by a variety of models of varying complexity, known collectively as ‘ecosystem models’. These cover a variety of topics and scales but generally simulate phytoplankton growth in response to light (carbon fixation) and nutrients, then redistribute carbon and nutrients throughout the water column and the food web[3].

The simplest form of ecosystem models describes cycling from nutrients (N) to lower trophic levels, most notably phytoplankton (P) and zooplankton (Z), and detritus (D), also known as NPZD models. In these models trophic interaction between phytoplankton and high trophic levels is implicitly represented by a fixed zooplankton mortality (natural mortality and predation by fish) term. This serves mainly as a closure term (Edwards and Yool, 2000) and is a source of great uncertainty in zooplankton simulations that needs to be adjusted during the calibration of NPZD models (Arhonditsis and Brett, 2004).

More sophisticated ecosystem models include in their representation of the oceanic mixed layer fluxes of nitrogen between nitrate and ammonium pools, phytoplankton, zooplankton, bacteria, a dissolved organic nitrogen compartment and detritus (Fasham et al., 1990). Processes like uptake, grazing, death, sinking, decomposition and mineralization are explicitly modelled with differential equations and allow the simulation of plankton dynamics (Franks, 2009)).

Examples of this category include are the ecological regional ocean model ERGOM, and the Rossby Centre ocean model (RCO) coupled to Swedish coastal and ocean biogeochemical model SCOBI Both ERGOM and SCOBI currently have three-dimensional set-ups, such as the RCO-SCOBI (Eilola et al., 2009) or ERGOM coupled to the modular ocean model (MOM) circulation model (Pacanowski and Griffies, 1999). As regards global models, there currently several models available such as MEDUSA, which is coupled with, and PISCES which is coupled with.

More recently, and as a result of the need to understand the long-term effects of climate change on marine ecosystem services, there has been emphasis on predicting the combined effects of climate change and fishing. This led to the development of the end-to-end approach (Fulton, 2010), which accounts for the dynamic forcing effect of climate and human impacts at multiple trophic levels. In this context, end-to-end models represent the entire food web and the associated abiotic environment from nutrient to fish. In doing so, they require the integration of physical and biological processes at different scales and the representation of a two-way interaction between lower and higher trophic levels. This type of models is the most complicated as it accounts for multi-species or multifunctional groups and their direct and indirect interactions in a variety of spatio-temporal scales. Therefore the

[3] A list and description of models that are developed to address eutrophication drivers and mitigation strategies in the Baltic context is available in the web site of the Baltic Sea Experiment-BALTEX (http://www.baltex-research.eu/projects/survey_bgcm.html).

end-to-end approach, although it is encompasses all the components of marine ecosystems, is subject to verification, validation and multi-scale problems. A notable example of this approach is the Ecopath with Ecosim (EwE) model, a food web model representing an ecosystem at a steady state by a network of quantified flows between ecosystem compartments (Christensen et al., 2005). Likewise, the BaltProWeb - Baltic Proper Food-web model is an end-to-end ecosystem model which can facilitate ecosystem-based management of the Baltic Proper (http://www.balticnest.org/balticnest/thenestsystem/).

5.5.2.1 SUMMARIES OF SELECTED MODELS

This section gives a critical analysis of the key features of selected coupled biogeochemical / ecosystem models. A comparative presentation of the state variables is given in Table 5-3.

HadOCC - *Hadley Centre Ocean Carbon Cycle model* (Palmer and Totterdell, 2001). The model was the ocean biogeochemistry component of the Met Office's HadCM3 climate model (Table 5-2) used for the first ever coupled carbon-climate study.

Model structure: The model is a simple NPZD representation with low number of variables/processes and the ability to resolve bulk patterns such as latitudinal patterns in chlorophyll and primary production. The model accounts for (i) spectral dependency in light penetration (ii) parameterisation of spectral absorption by phytoplankton. However, there are several limitations: (i) dependence of remineralisation rates on temperature and C/N ratios are fixed, thus making it impossible to simulate impacts of climate change on OM lability; (ii) no representation of the benthic compartment, bacteria or dissolved detritus, iron and silicates; (iii) no representation of biological parameters such as prey selectivity and phytoplankton functional types; (iv) poor representation of shallow seas and oligotrophic systems; and (v) poor representation of zooplankton mortality.

Table 5-3 Comparative presentation of key variables in popular biogeochemical / ecosystem models . * information taken from(Kwiatkowski et al., 2014)

Parameter	HadOCC	Diat-HadOCC	MEDUSA2	PlankTOM10	ERSEM	ERGOM	SANBALTS	BALTSEM
Web site / Download site	http://gcmd.nasa.gov/records/HadOCC.html	http://gcmd.nasa.gov/records/HadOCC.html		http://lgmacweb.env.uea.ac.uk/green_ocean/model/model.shtml	http://www.meece.eu/library/ersem.html	http://www.ergom.net/index.php/home.html	http://www.baltex-research.eu/projects/survey_bgcm.html	http://www.baltex-research.eu/projects/survey_bgcm.html
O_2			√	√	√	√	√	√
N	√	√	√	√	√	√	√	√
P				√	√	√	√	√
Si		√	√	√	√			√
Fe		√	√	√	√			
C	√	√	√	√	√			
ALK	√	√	√	√	√			
Detritus			√		√	√	√	√
Sediment diagenesis					√	√	√	√
Generic Phytoplankton	√	√		√				
Diatoms		√	√	√	√	√		√
“Large					√			

Phytoplankton”								
Picophytoplankton			√	√	√			√
Coccolithophora				√	√			
N_2-fixers				√		√		√
Flagellates					√	√		
Phaeocystis				√				
Generic Zooplankton	√	√				√		√
Microzooplankton			√	√	√			
Mesozooplankton			√	√	√			
Macrozooplankton				√				
Heterotrophs					√			
Bacteria				√	√			
Tracers*	7	13	15	39	57			

Diat-HadOCC (Halloran et al., 2010). This model is a development of the HadOCC model (i.e. NPZD model) and has been used to run simulations for the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5). Due to its simplicity it has low uncertainty. The model is already coupled to the HadGEM2 framework for evaluation.
Model structure: This model includes two phytoplankton classes (diatoms and 'other phytoplankton') and representations of the silicate cycles, as well as a DMS sub-model (for cloud feedbacks). However, and gas phase fluxes (e.g. OC) are poorly represented while the weaknesses pointed out for HadOCC remain in Diat-HadOCC. There are several verification problems (e.g. dissolved iron cycle is not properly closed; questionable definitions of phytoplankton functional types; zooplankton mortality).

MEDUSA *Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification* (Yool (Yool et al., 2010, Yool et al., 2011, Yool et al., 2013, Anderson et al., 2013)**.** A cost-effective and well-performing model as regards horizontal and vertical trends in nitrogen, oxygen, alkalinity and inorganic carbon distributions. It is an "intermediate complexity" plankton ecosystem model separately representing the microbial loop and the large, slow-growing phytoplankton grazed by slow-growing zooplankton. The model is good for testing explicit parameterisations. It has been simulated within online instances of the NEMO physical model at resolutions 2^o, 1^o (Yool et al., 2011)) and 1/4^o (Popova et al., 2012).
Model structure; Resolves to a size-structured ecosystem of small (nanophytoplankton and microzooplankton) and large (microphytoplankton and mesozooplankton) components. MEDUSA2.0, unlike HadOCC and Diat-HadOCC, includes spatially explicit parameterisations for cycles of nitrogen, silicon and iron, C to chlorophyll ratios, ballasted fast-sinking detritus, and for nutrient recycling in the benthic compartment. MEDUSA 2.0 also includes the BGC cycles of carbon, alkanity and oxygen. However, the model offers poor representations of: denitrification, although it contains an oxygen cycle; larger phytoplankton species (e.g. coccolithophorids, flagellates); temperature dependence of zooplankton growth; bacteria; DOM; and chlorophyll in oligotrophic gyres.

ERSEM *European Regional Seas Ecosystem Model* (Baretta-Bekker et al., 1997) (Blackford et al., 2004). ERSEM is used for shelf seas water quality monitoring and climate impact assessment and is run operationally by the UKMO. It has been coupled to fisheries models (Christensen et al., 2012 (Christensen et al., 2012)) and applied in 18 locations (Fulton et al., 2004). ERSEM may be coupled to a range of hydrodynamic models in 1D (e.g. GOTM) or 3D (NEMO) which provide information on temperature and salinity or run alone in aquarium model. It has been found to be one of the computationally expensive and underperforming models, due to its using a large number of state variables (>40) (Kwiatkowski et al., 2014)It consists of an interlinked set of boxes representing lower and higher trophic levels and the cycling of carbon and macronutrients (nitrogen, phosphorus, silicon and also oxygen) in the water column, stratified or mixed, and the benthic system. The biological components are organized into functional groups, both in the pelagic sub-model and in the benthic sub-model.
Model structure: ERSEM represents many key BGC processes of temperate shelf systems such as a detailed description of the carbon cycle (including carbonate chemistry and air-sea exchange); explicit resolution of nutrient uptake by phytoplankton and cycling of labile/semi-labile organic matter in the pelagic and benthic compartments; temperature dependence of mineralisation and physiological rates; the microbial loop; and plankton functional types (four for phytoplankton, three for zooplankton and one for bacteria). The model simulates multiple ecosystem states and is probably the most appropriate

to link to fisheries. Many variables and processes are represented allowing the model to answer many questions, although this increases uncertainty. For example, the validation of plankton functional types, and especially bacteria, as well as other processes is problematic due to the lack of evidence. Originally designed for shelf seas, it lacks a ballast parameterization scheme.

PlankTOM6 & PlankTOM10 (Quere et al., 2005). The PlankTOM series of models are being developed from the PISCES-T ocean BGC model (based on PISCES model of (Aumont et al., 2003). The series includes global 3D model with local and regional applications representing lower-trophic marine ecosystems based on plankton functional types (PFTs). Parameterisation is empirically-driven, increasing validation certainty. Depending on version there are 22 to 39 variables describing the cycles of carbon and macronutrients and chlorophyll. PlankTOM is embedded in the NEMO and other GCMs.
<u>Model structure:</u> The model represents the BGC cycles of C, N, O2, P, Si, a simplified Fe cycle, and three types of detrital organic pools including their ballasting properties; representations of the air-sea fluxes of CO2, O2, DMS, and N2O are also available. PlankTOM6 is maintained with six functional types (diatoms, coccolithophorids, bacteria, picophytoplankton, protozooplankton and mesozooplankton); the latest version PlanTOM10 has in addition N2 fixers, Phaeocystis, mixed-phytoplankton and macrozooplankton (Le Quéré et al. 2005 (Quere et al., 2005)). However, the models contain fixed stoichiometry, bacteria metabolism and a minimum phytoplankton biomass, questioning the reliability of model output.

PISCES (Pelagic Interaction Scheme for Carbon and Ecosystem) (Aumont et al., 2003). It is a 3D ecosystem and carbon-cycle model intended to be used in global, regional and local applications. The model includes 24 variables describing the cycles of carbon and macro-nutrients run all together at the same time. PISCES is embedded within NEMO.
<u>Model structure:</u> The model contains four living compartments (two phytoplankton and two zooplankton size classes) and uses fixed Redfield ratios. Non-living compartments include semi-labile dissolved OM, small particles and fast sinking particles. Iron, silicon, and calcite pools are explicitly modelled, therefore are allowed to vary. Inorganic carbon is also modelled. However, the bacterial pool is not yet explicitly modelled.

ERGOM ((Meier et al., 2012, Eilola et al., Eilola et al., 2011, Meier and Eilola, 2011, Meier et al., 2011). This is a 3D biogeochemical model with regional applications. The model has nine variables and describes the cycles of phosphorus and nitrogen, diatoms, flagellates and cyanobacteria, zooplankton, oxygen and two types of detritus. ERGOM needs a host model; it can be used in a simple MATLAB model, or embedded in physical models, e.g. MOM5. As the model was originally developed for the Baltic Sea it gives robust representations of processes involved in hypoxic – anoxic cycles.
<u>Model structure:</u> The model provides a full mathematical description of photsynthesis, grazing, respiration, mortality, mineralisation, nitrification, denitrification. ERGOM is nitrogen-based and uses fixed Redfield ratios. Detritus in the sediment is either buried, mineralised or resuspended into the water column. The model uses marine ecology, hydrographic and climatological (i.e. to configure boundary conditions) data from ICES data centre. Nutrient forcing is from riverine nutrient loadings (e.g. in the case of Baltic Sea model runs loadings are derived from the daily operational output of the hydrological HBV model run at SMHI for 43 Baltic catchments.

BALTSEM – Baltic sea Long-Term large Scale Eutrophication Model (Savchuk et al., 2012a, Rolff and Agren, 1999). This is a regional, Baltic-specific model aiming at capturing the main features of the Baltic Sea eutrophication. Biogeochemical models previously developed for several sub-basins of the Baltic Sea were combined with a new physical model and extended over the entire Baltic Sea. BALTSEM divides the Baltic Sea into 13 interconnected marine basins, homogeneous in horizontal scales but accounting for vertical gradients. The interactions among state variables within and between these basins are simulated by two modules, with hydrodynamic and biogeochemical state variables expressed as annual averages. The model uses data provided by HELCOM to reconstruct nutrient loads from land sources (Wulff et al., 2009, Savchuk et al., 2012b). The full list of the data contributors can be found at http://nest.su.se/bed/acknowle.shtml.

Model structure: A detailed description of the model can be found at **http://www.ergom.net/index.php/home.html**. In short, the hydrodynamic module describes water exchange between the 13 basins: parameterizations of flows between basins and through open boundary in the northern Kattegat differ due to different dynamic characteristics; vertical stratification is resolved by having a variable number of layers created by inflows of waters with differing density; and the sea-ice model has been adapted to the dynamics of the Baltic Sea (Nohr *et al.*, 2009 (Nohr et al., 2009)). Dynamic flow is forced by varying wind (originating from a dynamic downscaling of the ERA40 reanalysis with the Rossby Centre Atmospheric model (RCA) at a 3h resolution, sea level, and density differences (e.g. caused by freshwater runoff) between the basins. Vertical mixing is represented by a mixed layer model for the Baltic Sea. At the open boundary in the Kattegat the boundary condition are modelled as concentration profiles.

The biogeochemical module accounts for benthic pelagic coupling in each of the thirteen basins. The pelagic system is represented by diatoms, cyanobacteria, and others, heterotrophs (both micro- and mesozooplankton constrained by density-dependent mortality).

Overall BALSTSEM captures well the seasonal dynamics of the hydrodynamic and biogeochemical variables. BALTSEM is one of the few models attempting to represent processes responsible for internal nutrient regeneration in marine environments (i.e. zooplankton excretion, pelagic detritus mineralization, and release of re-mineralized nutrients from the sediments). However, a pronounced mismatch between modelled and observed nitrate and phosphate values indicates a weakness of BALTSEM to represent the stoichiometry and intensity of summer nutrient recycling in certain sub-basins (e.g. Bothnian Bay). The model systematically underestimates silica consumption during the spring bloom and, most importantly, primary production in general. The latter, however, is caused by poor calibration due to the great between and within variability of observed levels of nutrient depletion during and after the spring bloom in the Baltic Sea. The model also fails to represent deep-water renewals following inflows to the system, as shown in hindcast simulations. Last but not least, validation of internal nutrient feedbacks is limited by the scarcity of evidence on benthic remineralisation. This is a major challenge for the performance of the model and its future use in scenario analysis. This is because measured rates of internal nutrient regeneration appear to be so large as to confound the response of the Baltic Sea and its sub-basin ecosystems to external nutrient inputs and perturbations induced by climate changes.

SANBaLTS - Simple As Necessary Long-Term large-Scale (Savchuk, 2006). Coupled physical-biogeochemical model describing the effects of changing nutrient loads on environmental state in the seven major marine basins of the Baltic Sea. This steady-state regional Baltic Sea model draws on the concept of simplicity: a few first-order aggregated biogeochemical and physical processes drive the large-scale dynamics of nutrients in the Baltic Sea(Wulff et al., 2001).

Model structure: The model includes six pelagic (dissolved inorganic nitrogen and phosphorus, labile organic nitrogen and phosphorus, and refractory organic nitrogen and phosphorus), and two benthic (remineralised nitrogen and phosphorus) state variables (concentrations). Oxygen is also simulated as a regulator of nutrient cycles. The model defines primary production, nitrogen fixation, pelagic recycling, sedimentation, output from the sediments, denitrification in the sediments and in the water column, and burial rates. The model uses external nutrient inputs (annual terrestrial loads, atmospheric depositions and nutrient inputs from the Skagerrak) and water flows linking pelagic and processes as constant values to satisfy mass balance assumptions. In SANBaLTS primary production depends to N and P concentration, the latter according Michaelis-Menten kinetic. Nitrogen fixation depends on N:P ratio and stoichiometric phosphorus surplus. Sedimentation of organic nutrients is proportional to concentration and inversely depends on the average basin's depth. Regeneration of nutrients in the water column and by the sediments is simulated as a first order (linear) reaction with a basin-specific mineralization rates (yr^{-1}): inorganic nitrogen mineralization flux is denitrified (lost from the system) while the rest is released into the water column; sediment phosphorus mineralization flux is retained in the sediments. Sinking velocities, pelagic and benthic mineralization rates are represented as a function of temperature. All benthic nutrients are buried with the basin-specific burial rates, determined using the ratio of river discharge to river basin volume (i.e. a reciprocal to the freshwater residence time) as a proxy for all sediment sources.
Overall, largely due to its simple configuration, SANBaLTS captures well the averages of large scale processes. Notable strengths of this model include its robust representation of sediment denitrification, nitrogen fixation, and of the benthic fluxes into the water column.

Ecopath with Ecosim (EwE) (Heymans et al., 2012, Okey and Pugliese, Niiranen et al., 2013, Plaganyi and Butterworth, 2004, Christensen et al., 2005, Pauly et al., 2000, Falk-Petersen, 2004, Essington, 2007, del Monte-Luna et al., 2007, Zeller and Reinert, 2004, Espinosa-Romero et al., 2011) et al., 2006). A free ecological/ecosystem modelling software suite (http://www.ecopath.org/) with widespread use -about 130 EwE models have been published from all over the world including the Baltic Sea - due to its practical advantages. The most notable of them is that it deals with all trophic levels of the food web. It is used in determining trophic interactions in ecosystems with commercial fisheries (e.g. stock assessment) and in evaluating ecosystem effects of different fishing policies.

Model structure: It has three main components: a mass-balance, food web model representing an ecosystem at a steady state by a network of quantified flows between ecosystem compartments principally designed to answer ecological questions and evaluate fishing impacts (*Ecopath)* -; a time dynamic simulation module for policy exploration *(Ecosim*)-; and a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas *(Ecospace)*. It has relatively simple data requirements, mostly already available from stock assessment, ecological studies, or the literature (e.g. biomass estimates, total mortality estimates, consumption estimates, diet compositions, and fishery catches).

In the Ecopath module pelagic and benthic compartments are based on various levels of taxonomic and functional aggregation, from detritus and phytoplankton to zooplankton and top predators. Ecopath parameterizes models combining two master equations, one to describe the production term and one for the energy balance of each group (see equation 1 in Table 5-4). In Ecosim, changes in the biomass of each functional group are described by coupled differential equations that express biomass flux rates among pools as a function of time varying biomass and harvest rates (Eqn 2 in Table 5-4). Predator-prey interactions are moderated by prey behaviour to limit exposure to predation (foraging arena concept), such that biomass flux patterns can show either bottom-up or top down control. By doing repeated simulations Ecosim allows for the fitting of predicted biomasses to time series data. The rate at which the prey can move between these two components determines the predation pressure on a particular prey population and is determined by a vulnerability constant (*v*, Eqn 3 in Table 5-4). 'Vulnerabilities' represent the degree to which a large increase in predator biomass will cause in predation mortality for a given prey. Ecosim also contains a routine to allow a 'forcing function', which may represent physical or other environmental parameters, to influence these trophic interactions.

Overall, the EwE representation of the food web allows species and even finer groupings such as age classes within species to be assessed, but also allows species to be represented as members of functional groups (e.g. other large pelagic species). This flexible and simple discretization of functional groups in the EwE approach is the closest and more practical attempt towards end-to-end modelling.

Table 5-4 The core formula of the Ecopath with Ecosim food web model

Equation no.	Equation	Variables
Eqn. 1	$$\frac{P_i}{B_i} = \frac{Y_i + E_i + BA_i + \sum_j Q_j \cdot DC_{ji}}{B_i \cdot EE_i}$$ Where, $$M2_i = \sum_{j=1}^{n} Q_j \cdot DC_{ji}$$	$(P/B)_i$ the annual production per biomass ratio, B_i is the biomass, BA_i is the biomass accumulation rate for each group, Y_i the mortality caused by fishing and $M2_i$ the predation mortality rate of group *i*. Other mortality equals in which EE_i is the ecotrophic efficiency of group *i* (i.e., the proportion of group *i* production that is consumed by predators included in the model and extracted by the fishery)
Eqn. 2	$$dB_i/dt = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (MO_i + F_i + e_i)B_i$$	$\sum_j Q_{ji}$ is the total annual consumption per biomass, g_i is the net growth efficiency and MO_i other mortality rate of group *i*. Term $\sum_j Q_{ij}$ is the biomass of group *i* eaten by predators *j*.
Eqn. 3	$$Q_{ij} = \frac{a_{ij} v_{ij} B_i B_j}{(2v_{ij} + a_{ij} B_j)}$$	Q_{ij} is the total consumption of *i* by *j*, a_{ij} the effective search rate of *i* and v_{ij} vulnerability of *i* to predation by *j*. B_i and B_j as in the Eqn 1.

5.6 Summary

To sum up, a plethora of experimental data and sophisticated model tools and scenario simulations are available. These can be used to support decision-makers and stakeholders while model outputs could help raise awareness of climate change, eutrophication, and possible abatement strategies among the general public. Figure 5-1 summarises the pros and cons of the types of models examined in this review in the context of the 'marine objective' and with an eye to their applicability in nutrient mitigation, marine resources management, and transboundary policy making. However, it must be stressed that there is still a lack of process understanding, and proper process parametrizations. Model verification and validation are among the major challenges of the HELCOM Baltic Sea Action Plan (BSAP) for the near future.

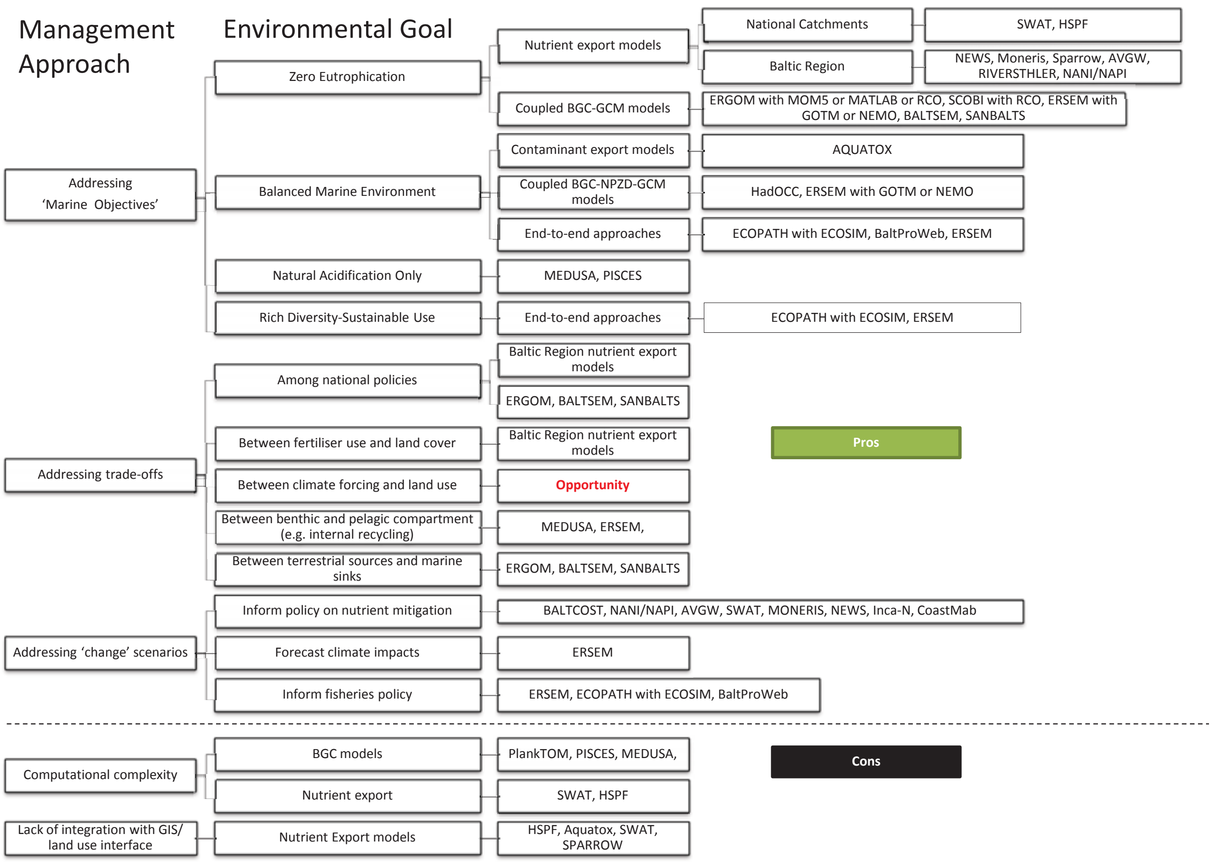

Figure 5-1 Decision Tree for Connecting Management Approach, Environmental Objectives and Relevant Models

5.7 References

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6 Flood and Climate Modelling for Urban Ecosystem Services

Johanna Deak Sjöman and Neil Sang.

6.1 Introduction

With a growing urban population and concern for future sustainability, adaptation and mitigation to climate change is of significant concern to current urban development planning. However, the foundation of how to plan and design for such future conditions lies in an understanding of how today's urban landscapes interact with current situations of climate and weather. How the spatial layout and quality of materials will affect storm water regulation, energy use in buildings, peoples' health and recreational patterns etc., are all parameters directly linked to sustainable development and influenced by weather and microclimate conditions.

This review aims to discuss some of the key models available today with regards to the regulation of urban ecosystem services, in particular storm water and temperature regulation. Different models exist in order to help analyze how the quality of materials and vegetation contribute to the mitigation and adaptation to climate and weather. Some of these models also help assess how the beneficial effects will vary depending on different development scenarios – for example changes in land cover and land use set within a specific time frame, geographic location and meteorological condition. Whilst certain models are chiefly concerned with site level situations and even pinpointing the individual characteristics of e.g. a specific tree species, other models deal with larger scale contexts incorporating a whole catchment or urban conurbation.

Although the economic gain of green infrastructure (e.g. reducing energy use in buildings due to shade from trees and wind regulation) is of much interest the review will not address how various methods explicitly quantify financial profit because the concept of 'normalising' environmental parameters in economic terms is a complex and controversial approach which requires more nuanced discussion than space allows here. Pollution dispersal and nutrition overload will not be explicitly covered in any detai,l though some of the models referred to do provide functions in relation to this. However the principles (and some of the models) set out in chapter 3 and chapter 4 are relevant to an urban context also with the principle difference being how the flow of water is managed, which is the main focus of the flood models in this chapter. The flow of water itself is an import first step in understanding how pollutants move and accumulate, but there are many other factors specific to each pollutant which require domain expertise in each case, readers interested in this are directed as a first step to the review of Fallahshorani et al. (2012) of coupled urban traffic, air and water quality models.

6.2 Sea Inundation, Storm water and Sustainable Urban Drainage

Models of water flow may, for the purpose of this review, be divided along four key lines:

- Whether the model is truly 3D (i.e. it considers subterranean conduits)
- Whether the model is fluid dynamic or simply moves water downhill regardless of the real capacity of that space.
- Whether the model assumes impermeable surfaces or considers absorption and /or saturation.
- Whether the model refers to sea inundation, rainfall or both.

6.2.1 Sea Inundation

A prior point of information here is to note that coastal flooding estimates are commonly referred to in terms of the level expected during a given interval of years, e.g. a 10 year event, or a 50 year event, as measured from a stated baseline year. For example a 50 year event from today, is the highest sea level expected every 50 years given the current climate, i.e. it may occur tomorrow or in 30 years, but it is expected to occur within 50 years. That is not necessarily the maximum sea level which is to be expected given the climate which might pertain in 50 years from today. This review will deal primarily with how to model the sea inundation spatially once the maximum sea level rise has been calculated, rather than delve into the complexities of how those sea level scenarios may be generated.

The simplest model for sea inundation is the so called “bath tub” approach, where by the predicted sea level is measured against a Digital Elevation Model (DEM) of the area. The chief advantage is that it is trivial to implement in a standard GIS and thus using high resolution DEM is feasible. It also does not imply any sophistication so limitations are easily described and intuitive to understand. The principle limitation is that this model will flood areas which are below the projected sea level but isolated from the sea by higher land (Figure 6-1).

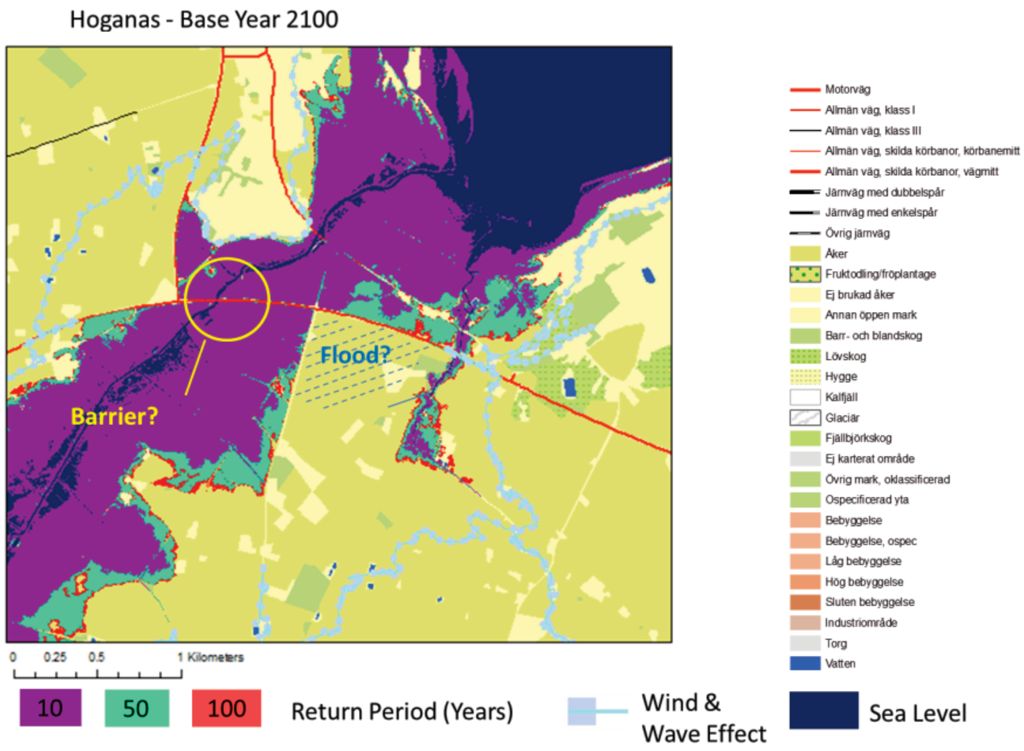

Figure 6-1 Flood predictions and the significance of barrier representation

(Image from the 'Rising Sea Levels' project, fuded by the Swedish Civil Contingencies Agency, MSB)

Depending on the terrain and the size of the area of interest, flooded ground not connected to the sea might be removed on a case by case basis or by using a mask layer if desired, but for larger or more complex terrain the decision may not be obvious.

A relatively simple approach to resolve the issue of flood connectivity is to use a series of cost-path analyses to establish whether a sufficiently low cost path to the sea is obtainable i.e. a route which does not pass over higher ground than the predicted sea level. This approach was used in Figure 6-1 to exclude the area marked "Flood?" in figure 6-1, where low lieing land was protected by a raised road. Alternatively so called "Simple Dynamic Inundation Models" (McLeod et al., 2010) achieve the same effect by simulating inundation one grid cell at a time, they may require some programming skills to implement but thus also provide the potential to include other heuristics such effects of land cover type.

Either approach raises a more difficult question however with respect to data accuracy which is particularly exacting in urban areas. Elevation models are usually only available as 2.5D surfaces seen from above so, for example, a bridge would appear to form a dyke wall. Some adjustment must be made to this DEM to allow for water to pass under objects, which may require field work to verify when such an adjustment should be applied. In figure 6-1 a small channel was introduced to the DEM in the area circled in yellow as the bridge did not create a barrier to the river. Had this channel not been created most of the river valley would have been apparently isolated from the sea. Since field work did not reveal any connecting channels for the area highlighted in dashed lines, the road here does indeed form a dyke and is not modelled as flooded. Note however that adding a such a channel to the DEM would directly disrupt the connectivity in a model of the transport system and misdirect the flow of rain storm water over the terrain, which is one simple example of how integrating several models may not be as simple as just "chaining" them together.

In an urban area the problem is particularly exacting not only due to the number of complex 3D terrain features, but because some buildings will act as barriers to water flow while others will allow water to pass through them. So even assuming an accurate DEM of high precision which includes buildings, this is not a simple issue to model. Inaccuracies in the DEM, or interpolations of DEM to DTM may also create barriers which do not exist or remove those which do, though this is now rare with high resolution datasets.

A further issue is that of the rate of the volume of water which any given aperture may allow. This issue is acute in urban areas where connectivity may be by small drain pipes and culverts. Even in modelling of sea inundation where the total volume of water is very large, this may be relevant as it can determine whether an object is to be treated as a barrier or not. After the need to calculate flow pressures on buildings in the path of floods, it is perhaps the principle reason why urban models of flooding might demand a fluid dynamic approach.

6.2.2 Mathematical Models

Mcleod et al. (McLeod et al., 2010) provide a helpful overview of coastal inundation models. Their opinion is that 3D mathematical models such as MIKE 3D and TELEMAC 3D are as yet unproven, though they were not specifically looking at urban areas in which the 3rd dimension is very important, and no doubt the respective development teams would counter this conclusion. What is clear is that regardless of the model used high resolution models may introduce problems in addition to computation time:

- Data error becomes more significant as minor terrain features may have large influences on the results.
- The relative importance of different variables may change with resolution, for example friction[4].

MIKE FLOOD

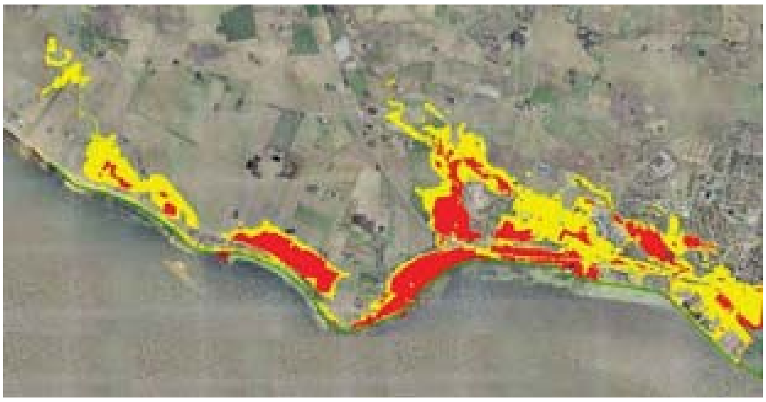

Figure 6-2 Example output of MIKE flood map, Municipality of Trelleborg, Sweden. ©DHI

MIKE Flood has a long history of development and is widely used. It permits a flexible spatial resolution (via raster quad-tree and TIN). Flow is modelled as an uncompressible liquid, using dynamic drivers and as such it is relevant to complex terrain with funnel effects. It further provides:

[4] http://hig.diva-portal.org/smash/record.jsf?pid=diva2:119152

- Built in storm surge model
- Inland flooding and overland flow modelling.
- Momentum dispersion.
- Tidal Potential

MIKE thus provides some indication of not only where land will flood, but how quickly and with what force. Parameterising this however is a skilled process requiring DEM, Wind data (MIKE FLOOD has its own wind generator if needed and has data links to NCEP ad NOAA), bathymetry and tides. The model itself must then be calibrated to consider sea bed resistance, momentum dispersion coefficients of landcovers, wind friction factors, ground water level, discharge rates from streams and whether to treat the catchment as a closed or open system. Not all functionality is free, down loads are available from http://www.dhisoftware.com/Download/DocumentsAndTools/ShortDescriptions.aspx or as a Cloud option at https://saas.dhigroup.com/.

TELEMAC

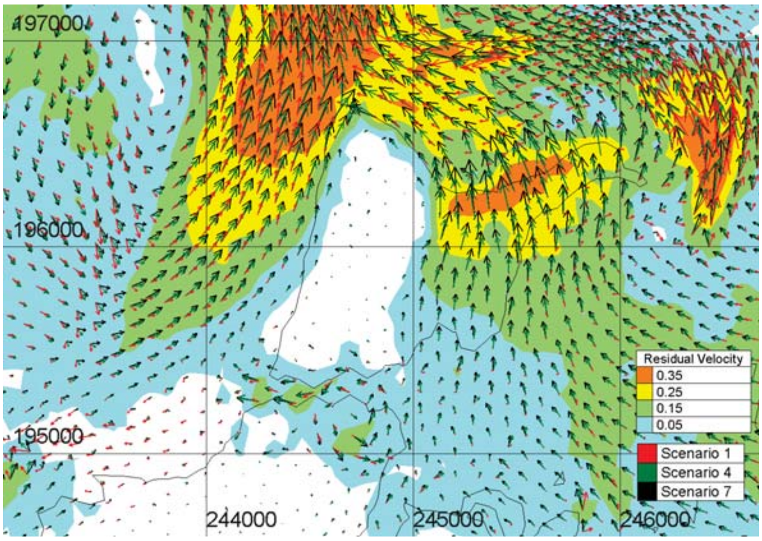

Figure 6-3 Example of flow model output in TELEMAC 2D

(http://www.cams.bangor.ac.uk/Divisions/project_details.php?project=25)

A comprehensive overview of the hydrological processes simulated in TELEMAC is available from http://www.opentelemac.org/index.php/publications . It is a powerful system used by many state agencies in Europe, but also highly complex requiring up to 14 separate datasets[5] including CHAN options to other impact models. From the point of view of distributing simulated data, the fact that the software is freely available and open source is positive, but training is charged for and would certainly be requisite.

6.2.3 Integrated Ecological/Economic Coastal Inundation Impact Models

Although not suited to urban areas themselves, it is worth noting for this review more widely that integrated assessment packages have also been developed which include built in methods for localising models in relation to global drivers. These may serve to provide the larger scale driving

[5] http://www.opentelemac.org/downloads/MANUALS/TELEMAC-D/telemac2d_user_manual_v6p0.pdf

scenarios to which more detailed local flood models can respond. In particular the surrounding catchment management is critical to what scenarios of rainstorm water urban areas may face.

DIVA

DIVA is an integrated assessment model which has gained some popularity (Athanasios T. Vafeidis, 2008, Brown et al., 2013, Hinkel and Klein, 2009, Hinkel et al., 2013, Hinkel et al., 2010). It was not clear, from the review, precisely how the inundation model is created, rather the flood model seems to be a prior stage to further scenario modelling. The coast line is segmented with regards to how it responds to the inundation model according to a range of parameters (flooding, erosion etc.) This is then saved into a database to allow end users to combine different scenarios of high water and additional data such as population to estimate potential vulnerability. The spatial resolution is coarse but the data structure is divided at break points in relation to the response variables thus may be quite prescise for some locations, but its utility for any given location may only be determined by testing the model output. None the less, DIVA may provide an example of how models can be structured for participatory planning because new scenarios can be entered easily and most of the complex parameterisation is hidden and pre-calculated. Since all data is contained within the model, the user need only select scenarios. DIVA is Open Source but the model does not seem to be currently available[6].

SIMCLIM

SIMClim is a modelling framework which is designed to run at a range of spatial scales. It provides built in data for some scales but users can add detailed local data. It thus provides one general global climate model, with many sectoral sub-models on impact, e.g. water, agriculture, ecology in relation to those pre-calculated climate models.

SIMClim provides an inbuilt estimator for Extreme Events Analysis. Coastal flooding does not seem to be its main use however. Inland flooding, drought and agricultural models are more commonly reported uses. Like DIVA, the inundation model is not clearly documented, rather it focuses on ease of use[7] through providing inbuilt models and data to select from, including local sea level rise models. The choice of in-built models is backed by a global scientific advisory board[8] but verification for a specific location would be advisable.

SIMClim is a modelling framework rather than a model itself. So the inputs depend on the application. In this context it appears to use shoreline response time (in years), closure distance from the shoreline (m) and DEM. It can also respond to depth of material exchange or closure depth (m), dune height (m) and residual shoreline movement (m/year) and is MAGICC and IPCC data compatible.

Mcleod et al. (2010) argue that the more complex ‘Ecological Landscape Spatial Simulation Models’ “may create over-confidence among users who may assume that the increased data and feedbacks incorporated in the model provide more robust outputs. These models can be difficult to validate and calibrate due to the high level of aggregation, the dynamic long term nature of the model, and the

[6] http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5358.php

[7] http://coastclim.com/simclim/downloads.php

[8]http://www.climsystems.com/about/staffprofiles.php ; http://www.climsystems.com/products/

complexity of the subsystems and their interactions, thus their primary application is for research." (McLeod et al., 2010). This might be also be stated with regards to the 'mathematical models' where they incorporate additional dynamic 'impact' assessments for different sectors (Andersen, 2003). Individual models may be amenable to confidence intervals or monte-carlo scenarios, but it is hard to factor out all the sources of error in multiple models chained together.

6.2.4 Rain Storm Water Modelling

Early catchment scale models represented the catchments and sub catchments as a single "curve number", with water flow at specific locations referring to a distribution curve representing the flow rate out of that catchment to be expected a given time-interval after a given amount of rainfall (Boughton, 1989). In some respects this is a pragmatic and effective approach, since each location is calibrated against historical data for this location. It therefore takes into account the landcovers and soil types which pertain to that case. While the concept may have been overused (Moore, 2005) within the constraints of its intended purpose it remains an effective approach used in models such as MIKE 11. Calibration of this approach requires a skilled hydrologist but attempts have been made at automatic calibration (Madsen, 2002) thus catchments may easily be represented in such a model provided the relevant field data is available. However, it can only represent how the catchment is likely to respond again to a similar rain storm, assuming the same landcover pertains thus it cannot respond to changes in these parameters. Since curve-number models can only provide predictions within within the observed parameter space, it is to be expected that data mining approaches should prove useful in calibration (Madsen, 2002) and are starting to supersede the method as more complex questions are considered such as urban water quality (May and Sivakumar, 2009). Additional information, such as ground water recharge levels and over ground flow are deduced from the equation rather than mechanistically estimated. The impact of landcover change is therefore not incorporated, nor do curve numbers offer a firm basis to extrapolate to more extreme climatic events, for this a spatial simulation is required.

In the simplest 2D model water accumulation may be estimated by assuming a completely impervious surface with no friction, thus all water which falls on one location at the first time step, will flow into the adjacent downhill unit. One may then consider either "total accumulation" if there is no outlet to the catchment, or "peak flow" where by a steady state is reached at which the total water in any one location is that accumulated from all the upstream area, plus its own rainfall. Most GIS packages will provide the basic functionality to calculate either of these two scenarios for a given precipitation rate. Once issues of DEM resolution and modelling of buildings as solid objects are taken into account, this would provide a reasonable "worst case" scenario in an urban area once all permeable surfaces are saturated and all storm drains have exceeded their capacity. It is not, however, a particularly realistic guide to less than the worst case scenario given that urban areas contain sinks for water both via the drainage network and via urban green space.

A further option available within standard GIS packages (e.g. within the Spatial Analyst extension of ArcGIS) is to provide absorption rates based on landcover as a layer representing the proportion of the water entering a cell which flows downstream and the proportion which remains. Various absorption standard rates have been suggested for different land covers, but ultimately such a model requires calibration with local data or via comparison with the conceptual models of the whole catchment. For a high resolution DEM processing times can be lengthy on a standard desktop machine, so calibration is hard to achieve in practice. Mark et al. (2004) review several 1D models incorporating urban drainage networks, and set out their own attempt to simplify the issue by focusing on flow along the road network in order to provide spatially explicit coverage from a 1D model, but they also recommend a 1x1m DEM, which presents a challenge in itself.

MIKE Urban is a professional modelling package focused on urban water. They integrate 1D and 2D model approaches and provide 2D models with the ability to operate on a multi-resolution grid, allowing more detailed simulation around buildings, for example, but saving on time in more open or simple regions. 2D fluid dynamic equations can be solved, such as dispersion, and a specific package deals with ground water. MIKE is a large package with many sub modules and as such cannot be comprehensively reviewed here. Other open source alternatives of more limited scope are available, e.g. LISEM[9] , while Artificial Neural Fuzzy Interface (ANFI) methods may perform more effectively under imperfect data[10].

Simply establishing the baseline criterion for what constitute the "best" hydrological model is not straightforward (see Kalantari et al. (Kalantari, 2015)) but none of the models considered so far place much emphasis on the active role of vegetation in water management. Elliot and Trowsdale (Elliott and Trowsdale, 2007) review 10 models with respect to their ability to model "low impact" drainage such as wetlands, ponds and filter strips, over a range of scale and applications thus :

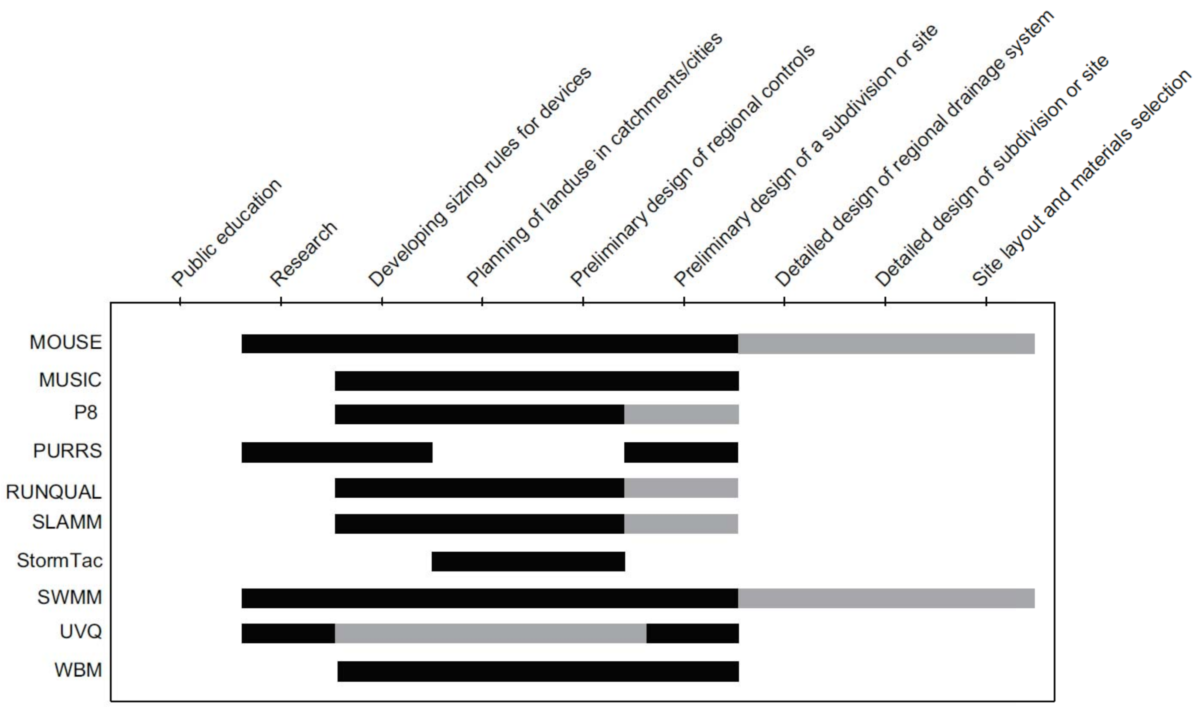

Figure 6-4 Potential uses for selected LID models (Elliott and Trowsdale, 2007 - figure 1)

Elliot and Trowsdale (*ibid*) conclude *that "None of the ten models ... reviewed are intended for the full spectrum of uses that could be demanded of a model in relation to LID. The models most commonly address the middle ground of planning and preliminary design levels of use"* However while "…the *models differ in the types of LID device that are included explicitly… all the models can represent the effects of reducing imperviousness or improving soil infiltration properties, all but one can model ponds, all the contaminant models can represent reduction of contaminant generation, most*

[9] http://blogs.itc.nl/lisem/2013/05/17/migrating-to-this-website/

[10] http://engineerspress.com/pdf/WSJ/2013-03-Special%20Issue/a6%20_WSJ-1313s06_.pdf

of the models can be used for infiltration devices, and the majority of the models can represent on-site detention tanks… In many cases, a device which is not represented explicitly in the model can still be modeled indirectly by altering the parameters of other devices or combining other devices." (Elliott and Trowsdale, 2007)

While Low Impact Drainage models are not as yet matured to an industry standard, given the multiple benefits for LID this might be expected to rapidly develop, but as the above quote states, in many cases the simple 'absorption' option in most GIS flow models can be used to approximate LID provided it is calibrated to local conditions. Indeed, due to the complexity and variety of urban environments, whichever approach is used considerable effort is likely to be required to calibrate the model to each specific case.

6.3 Microclimate

Understanding the microclimate in a given site influences the preconditions of sustainable development in many ways. Cold and strong winds in the winter will, for example, intensify the energy use in buildings depending on the air tightness of the building enclosure (Bagge et al., 2011), and in areas close to the seafront strong salty winds may also increase the wear and tear on building materials. High wind speed during winter also affects outdoor recreation, and the likelihood of people to walk or cycle to local commerce and social activities subside if the area is subject to highly uncomfortable wind speed (Glaumann et al., 1993). Thermal comfort during winter time is thus integrated in how people will access and use facilities in their local communities. Wind turbulence and funnel effects between buildings and along streets are also occurring to a greater extent in cities compared to rural settlements although wind speed, in general, is stronger in the countryside (Oke, 1987), illustrating the importance of scale in modellig the urban environment. In Sweden, especially during winter time, strong winds help lower the air temperature with several degrees and thus contribute to uncomfortable physical conditions (Glaumann, 1988).

In the summer, high temperatures and lack of shade will on the other hand increase the need for cooling – in buildings as well as in outdoor public areas where people visit. In contrast to winter time, moderate wind speed might be necessary in order to increase thermal comfort. The need to address thermal comfort in the future is accentuated in a report issued by the Swedish Government in 2007 (Sou, 2007). With predictions of increased heat waves and warmer weather conditions due to climate change, the report summaries a total expenditure of approx. 500 to 600 billion (SEK) to cover healthcare costs with regards to heat exhaustion (illness and mortality) (Klimat och sårbarhetsutredningen (Sou, 2007).

Although contemporary urban planning is well abreast with the necessity to build sustainably and to plan the urban environment with regards to climate adaptation and mitigation, it is still surprising how little climate knowledge is actually incorporated into contemporary urban development. For instance, the spatial layout of buildings and infrastructure will strongly affect the urban climate. A grid plan (the most reoccurring spatial layout in current urban development) will increase wind speed throughout an area. In terms of pollution and particle removal, this is beneficial. In terms of energy use in buildings and encouraging people to spend time outdoors, this plan is problematic – especially in development schemes next to the sea front. Tall and box shaped buildings with protruding corners and sharp angles will accentuate wind turbulence whilst a more aerodynamic contour will reduce the likelihood of turbulence to occur. Also the thermal properties and albedo values (the whiteness of surfaces and subsequent reflection of incoming solar radiation) of building materials have a great effect on the urban climate. With predominantly dark surfaces and materials absorbing incoming solar radiation during the day, night time temperatures in towns and cities increase compared to the surrounding countryside – a process known as the urban heat island effect. In turn, lower humidity in the air and soil (from e.g. soil sealing) further contributes to a warmer urban environment, as do high rise buildings and narrow streets which lessen the 'sky view factor' and thereby prevent absorbed heat radiating back into space (Eliasson et al., 2011).

Green infrastructure – and specifically trees – can be used strategically in order to ameliorate different climate conditions. In comparison to other building materials trees are flexible and dynamic with qualities which change over season and throughout the entire life cycle. These are useful qualities that can advance thermal comfort and reduce building energy use if appropriate species, conditions and strategic location is taken into account. Different species also have different architectural make up of branches and foliage – traits to consider in design for shade in summer and wind regulation in winter.

In summary, many aspects and complex combinations will influence the urban microclimate. In new development schemes but also within existing built up areas, it may almost be impossible to intuitively comprehend the pattern and movement of different climate conditions over a given time frame. This is why the use of microclimate models plays an important role, as they can help the urban planner and architect to better assess future scenarios and reflect this in more sustainable design, spatial layout, use of building materials and vegetation for a site.

6.3.1 Models

The review concentrates on three microclimate models, ENVI-met (Huttner et al., 2008), SOLWEIG (Lindberg, 2008) et al., 2008), and RayMan (Matzarakis et al., 2007). All models are designed to simulate the microclimate in complex urban settings, i.e. areas with a complex geometrical layout of buildings, streets and vegetation. The makeup of each model varies and so does the level of complexity, i.e. type of input data, temporal and spatial resolutions, length of time to run simulations and the characteristics of the output data. All models are used daily in practice and research in Sweden as well as internationally. It is possible to download an run the ENVI-met, SOLWEIG, and RayMan software program on an ordinary PC as long as they are compatible to WINDOWS NT/2000/XP/Vista/7 and 64-bit platforms (Bruse, 2009, Urban_Climate_Group, 2013)

Although the reviewed models comprehensively involve simulations on the urban microclimate, the individual models represent three completely different model designs and constitute different focus specialties (discussed in the following sections). Nonetheless, the key output parameter for all models is mean radiant temperature (Tmrt) – the combined and total sum of shortwave and longwave radiation fluxes to which the human body is exposed. As such, mean radiant temperature has the strongest influence on thermal comfort and by retrieving the mean radiant temperature from a given site it is possible to calculate the exact physiologically equivalent temperature (PET) i.e. how the human body physiologically perceives heat or cold depending on surrounding radiation, wind, etc.

ENVI-met

The most complex model of the three is ENVI-met. Besides simulating microclimate conditions, the ENVI-met programs also simulate air pollution dispersal (gas and particles). ENVI-met is a CFD model (Computational Fluid Dynamics) allowing better representation of fluid flow, but as such it also taking somewhat longer to run compared to RayMan and SOLWEIG. The ENVI-met model is composed of a relatively simple and one dimensional soil model, a vegetation model and a radiative transfer model (Bruse et al., 1998). Jointly these comprise a three dimensional model (in both input and output) with a special focus on the surface-plant-air interaction. In order to process the simulation the user first needs to map the case study area on to a grid cell interface (Figure 6-5). Buildings, type of vegetation, surface cover and soil type is thus assembled as input data on the interface. The grid cells, or mesh, contains 300x300x 35 cells and each cell can obtain a horizontal extension between 0.5-10m and vertical height of 1-5m (depending on case study area and objectives) (Huttner et al., 2008). This limitation means it is not possible to run simulations of extensive areas, such as entire cities, at a suitable resolution. Instead the simulations need to be broken down into smaller fragments of individual areas and neighbourhoods. The time frame for simulations for models in ENVI-met usually range from 24 to 48 hours covering diurnal and nocturnal conditions. Simulations have a temporal resolution of 10 seconds (Ozkeresteci et al., 2003).

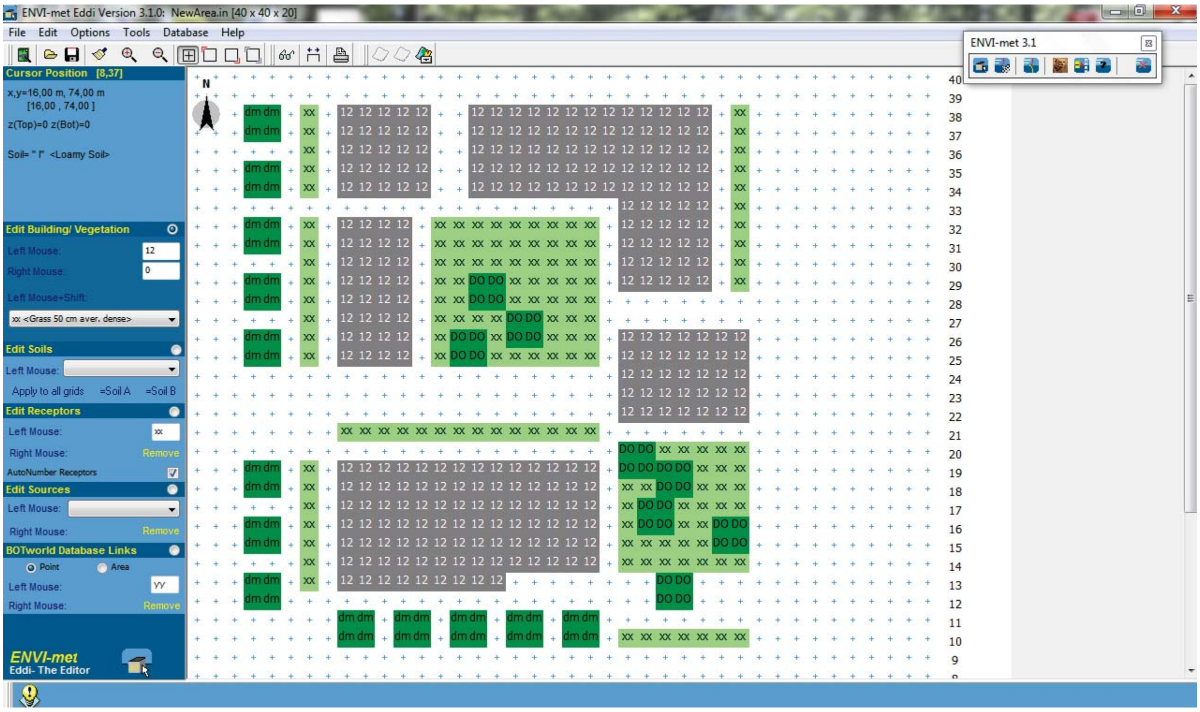

Figure 6-5 Screenshot of Envimet input data

SOLWEIG

Besides mean radiant temperature, SOLWEIG simulates shadow patterns and three dimensional radiation fluxes (Lindberg, 2011). SOLWEIG is initially a two dimensional model which takes into consideration a three dimensional approach when height data is added via a text file. As such it considers x and y coordinates with height attributes (Lindberg, 2011). All data imported to the SOLWEIG model needs to be in a raster format. Although vector GIS data can be used it has to be converted from vector to raster data before processing. The final output data is also represented in two dimensions. Similar to ENVI-met, whole towns and cities cannot be simulated in one simulation but smaller district areas need to be simulated separately (Lindberg and Grimmond, 2014). Each simulation will consider grid cells from 2500x2500 to 4000x4000 where each cell may represent 1m, 2m etc. For SOLWEIG, the time resolution of the model is one hour (although in the more recent version this has changed to 10 minutes, which is important when calculating shadow patterns (Lindberg, 2011).

RayMan

Compared to ENVI-met and SOLWEIG, RayMan is the one model requiring fairly simple and straight forward data input, usually in the form of a text file containing raster data or the RayMan obstacle file which will require a manual input onto the RayMan interface (Fröhlich, 2013). The model is two dimensional, though limited 3D data can be included to the model by adding fish eye photographs, drawings of solid elements in a hemispherical perspective, and the geometrical dimensions of e.g. buildings and trees (Matzarakis, 2009). This data is added as reference points (x, y and z) on to a grid. RayMan is developed primarily to calculate the radiation fluxes and the effects from clouds and how this in turn affects the human body. The time frame in RayMan can cover hours to days, months and even years (as used in the study by Fröhlich and Matzarakis, 2013), and the time resolution when running the model is one hour. The model can be used for very small scale calculations to estimations on a regional level (Matzarakis et al., 2007).

Today, researchers and practitioners worldwide use the three reviewed models – see e.g. Roshediat et al., (2008), Elnabawi et al., (2013), Puliafito et al., (2013), Morabito et al., (2014). In Sweden, ENVI-met was applied for microclimate studies of the Norra Sorgenfri project in Malmö (Kronvall, 2011), and the SOLWEIG program has been used for projects in Djurgårdshamnen, Stockholm (Lindberg and Grimmond, 2014). In the following sections, both input and output data will be compared in detail.

6.3.2 Data

The basic input data in all models covers geographical location (usually coordinates), time of year, local meteorological data such as air temperature, air humidity, wind speed and wind direction, and cloud cover (Huttner et al., 2008, Lindberg, 2008, Matzarakis et al., 2007). Also required is spatial layout of buildings, building height and width, and surface materials. In the SOLWEIG software materials and objects are divided into buildings and vegetation with set mean values (Urban_Climate_Group, 2013). In ENVI-met, on the other hand, buildings are defined by the inside temperature (in the building), heat transmission of the walls and roof, and albedo values for walls and roof (Bruse, 2009). Surface covers can be defined from asphalt, to concrete and brick with a range of different underlying soil types (Bruse, 2009).

The required and additional input data can thus vary between the models although all of them will incorporate a data input which calculates mean radiant temperature, radiation fluxes (short and long wave radiation), solar direction, sunshine duration, shade, sky view factor, and predicted mean vote (Huttner et al., 2008, Lindberg, 2008, Matzarakis et al., 2010). A more detailed description of all input and output parameters is presented in appendix A2.6.1. There are, however, some key differences in both the initial and additional output data when comparing the three models as will be discussed in the following sections.

6.3.3 Mean radiant temperature (Tmrt) and physiologically equivalent temperature (PET)

As already mentioned, mean radiant temperature constitutes the key output for all models and is an important parameter for estimating thermal comfort (or discomfort) to the human body. Although most weather reports will provide information on air temperatures and wind speed, the heat radiation from the materials in our surrounding environment plays a decisive role to whether the human body will experience thermal stress or not. In the ENVI-met model, radiation fluxes are calculated from the sky and buildings (‘upper hemisphere’) and from ground level (‘lower hemisphere’) (Lindberg, 2008). In SOLWEIG, calculations of radiant fluxes incorporate six angles of six longwave and shortwave radiation fluxes (upward, downward and from the four cardinal points) (Lindberg, 2008).

Due to the technological improvement in ameliorating indoor climate in the 1950´s and 60´s with air conditioning, the following decades contributed to research deriving various calculations into the thermal energy balance of human bodies from which the ‘predicted mean vote’ (PMV) developed by Fanger (2009) still forms a sound foundation in contemporary assessments. However, compared to indoor space, thermal stress in outdoor environments is the result of several additional attributes and climate conditions. As such, Physiologically Equivalent Temperature was derived to better assess thermal stress in complex outdoor urban environments (Honjo et al., 2009).

Physiologically Equivalent Temperature helps define the heat budget of the human body in a way that is easily interpretable by both professionals and laypeople (Höppe, 1999). It provides a basis for how the thermal conditions in a particular environment could be adjusted to mitigate physical discomfort taking into account attributes such as clothing and activity (Mayer, 1987). Several factors contribute to how the human body physiologically will experience climate and weather conditions. For example, the surrounding materials in a compact urban setting will store energy and re-radiate heat that will increase the perception of how warm or cold the actual air temperature is. In a street canyon surrounded by brick buildings and surfaces covered with asphalt, the likelihood of thermal stress will be greater compared to a planted area with mature trees. Strong wind will have a cooling effect on experienced air temperatures (wind chill effect) and this could be problematic during winter time in areas subject to very low air temperatures or beneficial during summer when cool breezes will help ameliorate thermal qualities in very hot areas (Oke, 1987).

However, physiologically equivalent temperature also considers personal attributes such as physical activity and conditions; metabolic rate, physical work outpu; net radiation of the body; imperceptible perspiration; convective heat flow; the heat flow due to evaporation of sweat; the sum of heat flows for heating and humidifying the respired air; the storage heat flow for heating or cooling the body mass; age and clothing (Büttner, 1938.).

RayMan is the only model enabled to calculate physiologically equivalent temperature. The input data complies with the attributes discussed above and makes it possible to retrieve estimates independent of geographical location. As such, RayMan is often used in combination to the other models, where the mean radiant temperature retrieved from either SOLWEIG or ENVI-met can be converted fairly easily in the RayMan spreadsheet (Fröhlich, 2013, Johansson, 2014. , Lindberg and Grimmond, 2014). By modelling the mean radiant temperature and subsequent physiologically equivalent temperature, planners and architects may, beforehand, understand which urban areas may be subject to severe heat stress or intensely cold situations. Such information may also be retrieved for future scenarios involving measures of climate change adaptation.

6.3.4 Sunshine duration, shade and sky view factor

Sunshine duration is a parameter which all three models consider (Lindberg, 2008, Matzarakis, 2009, Huttner et al., 2008). This can be simulated for any day throughout the year independent of geographical location and sky view factor. Access to sunlight and how this will vary depending on time of year is a significant factor with regards to sustainable development. In winter time, passive solar gain in buildings is important to lessen the energy use and heating bills (Littlefair, 2001). However, shade from structures or adjacent buildings is often not considered for new development plans nor its effect on subsequent building energy use (Sawka et al., 2013). By simulating the solar direction and sunshine duration in microclimate models it is therefore possible to assess how existing and new developments impact on sunlight and shading patterns. Access to sunlight during wintertime is also beneficial for the public good in terms of wellbeing and recreation – in indoor as well as in outdoor environments (Ne'Eman, 1974).

Tall buildings and narrow streets help create so called urban canyons. Here, the visual access to the upper hemisphere – sky view factor – is limited. With irregular geometry of horizontal and vertical surfaces the high rise buildings and deep streetscape help contribute to trapped heat and to the night time phenomenon of the urban heat island (Eliasson et al., 2011). The sky view factor thus provides an estimation of which areas within the urban fabric of buildings, streets and open space may increase certain climate conditions such as re-radiation of short and longwave radiation, wind turbulence, heavy shading and so on. However, the calculation of sky view factor is mostly linked to estimations of mean radiant temperatures and correlations to the urban heat island effect (Gál, 2009).

The ENVI-met model will calculate the sky view factor from the three dimensional model built on to the grid interface. It does not incorporate image data such as fish eye photographs or GIS vector data files to the model. Both RayMan and SOLWEIG can use GIS based sky-view silhouette files (as long as the vector files are converted to raster files for the SOLWEIG model) (Lindberg and Grimmond, 2014). Raster data files (e.g. photographs and other pixelated imagery) will not project sharp and clear objects when zoomed into a more detailed scale, this is less of a problem for vector files (Matzarakis and Matuschek, 2011) and the difference may be significant for very local shading effects. The possibility to integrate municipal GIS or digital models of construction plans is highly beneficial as it provides a fairly quick assessment of how existing and future development will affect the sky view factor (Matzarakis and Matuschek, 2011). In this respect, SOLWEIG and RayMan have an advantage over ENVI-met.

6.3.5 Wind

Although all models incorporate wind speed as a key input parameter for various microclimate calculations, it is only ENVI-met that calculates an output of air flow and wind speed. As such, it is possible to use the ENVI-met program to assess how existing or future development will contribute to stronger or lesser wind speed and how the wind flow pattern will move throughout the area, as illustrated by Figure 6-6, the small green squares in the lower image (b) represent green structure which is reducing wind speed.

Fluid dynamic air flow simulation are, however, very complex processes for a model to calculate. Simulations in ENVI-met can take a long time and the accuracy much depends on the resolution of the nesting grids in the model. Nesting grids are like a “buffer zone” on the border of the built up model area or “buffer cells/grid points” within the built up model. Without nesting grids, calculations are compromised and it is generally held that the more nesting grids used the fewer problems with the accuracy of the simulation will occur (Bruse, 2009). In ENVI-met, nesting grids exist outside the boundaries of the digital model – but not within the make-up of cells on the grid interface. This has brought some criticism to the output results of ENVI-met when it comes to wind speed and movement patterns of air flow (Johansson, 2014. , Lindberg and Grimmond, 2014) . With no nesting grids within the modelled area, turbulent effects on the back of buildings and protruding objects will for instance not show. There are, however, more complicated CDF models where such effects can be simulated and where interlaced nesting grids exist throughout the modelled area. Examples of such models are the commercially developed FLUENT (Ansys, 2014), and OpenFOAM (Lohmeyer, 2014). These models are complicated to process and also take a long time to run, they are thus relevant to model impact around specific buildings but less use for planning over larger areas and iterative, GeoDesign, type processes. Due to its ability to replicate and process wind speed and air flow, ENVI-met simulations take longer time when compared to RayMan and SOLWEIG. Simulations of radiation fluxes are possible to run on a much shorter time in frame in the RayMan and SOLWEIG programs than in ENVI-met (Lindberg and Grimmond, 2014) and thus are more easily incorporated into iterative design methods.

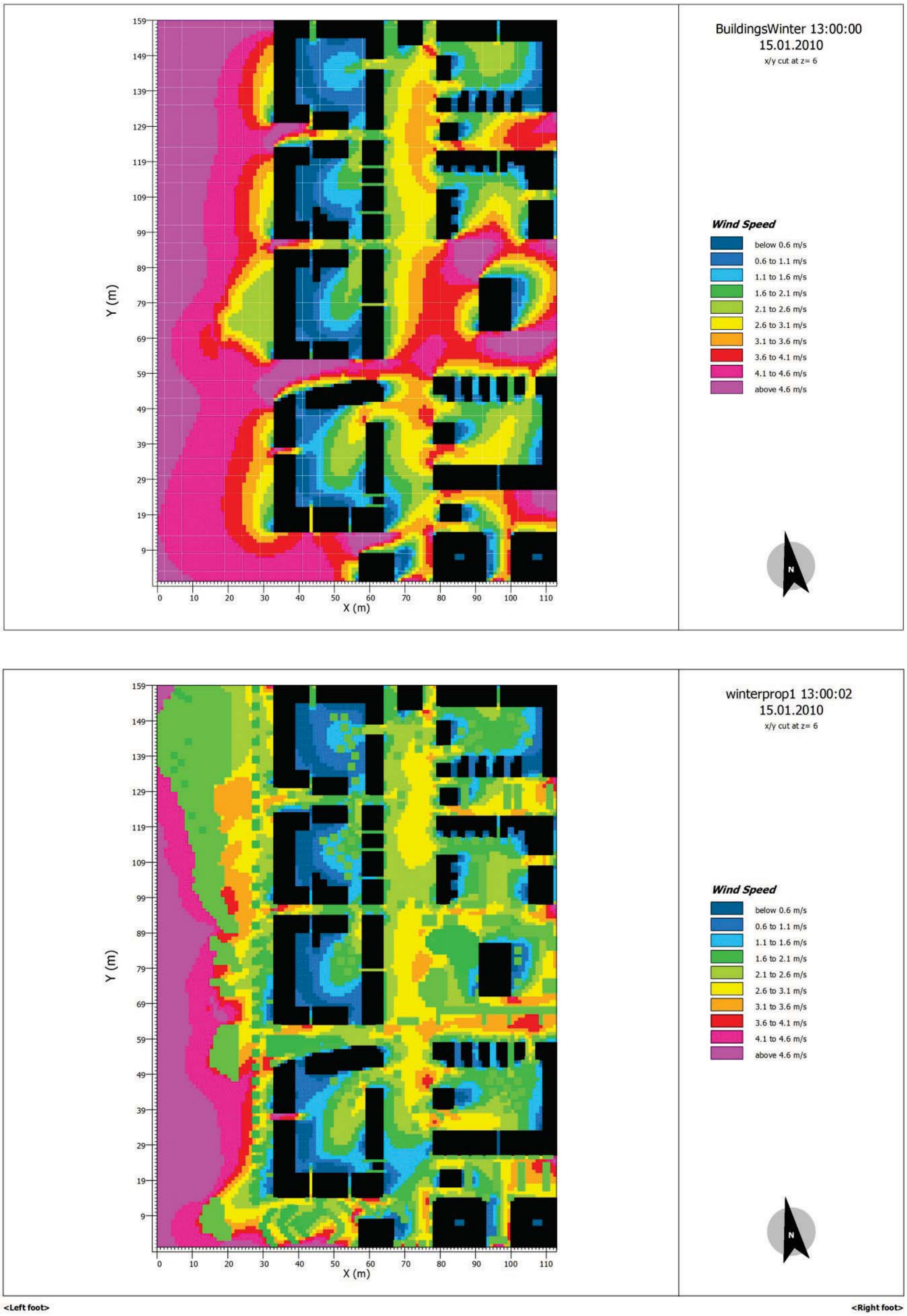

Figure 6-6 Windspeed output from ENVI-met without trees (a - Upper) and with trees (b - Lower)

6.3.6 Vegetation

Vegetation, and particularly trees, constitute a valuable asset in the urban landscape in terms of ameliorating climate conditions and the mitigation and adaptation to climate change. As mentioned previously, trees provide for multifunctional benefits when it comes to a wide range of ecosystem services – i.e. benefits to human health, recreational values, storm water control, lower energy use in buildings, etc. (Akbari et al., 2001, Xiao and Wedd, 2002, Borja et al., 2008, Grahn et al., 2003, Katzschner and In, 2011). In terms of mean radiant temperature and surface temperatures, trees can lower the temperature with approximately 18°C compared to an unshaded asphalt surface (Deak Sjöman, 2014). Evapotranspiration contributes less to this effect than the shading from the tree canopy (Lindberg, 2011). However, different trees will provide different qualities depending on species and time of year. Shading depends on the foliage and architectural make up of branches – features that may have a very different make up depending on species. How to take advantage of these qualities in terms of shade and wind regulating effects is thus an important design issue (Deak Sjöman, 2014). Simulations of how trees affect mean radiant temperatures (but also additional microclimate conditions) thus require a sound understanding of the different qualities of different species throughout the year.

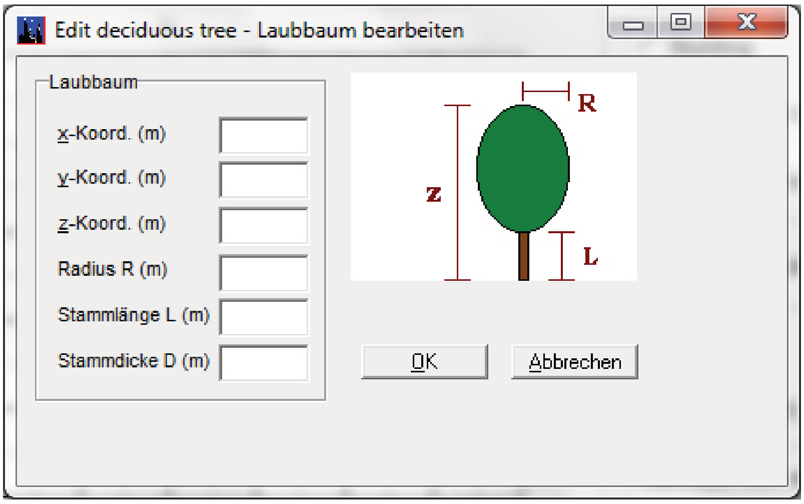

Figure 6-7 Designing the tree model in RayMan

With regards to the input data required on vegetation, all models – ENVI-met, SOLWEIG and RayMan – require different information. The most simple information input is that of RayMan, where two types of trees are distinguished – coniferous and deciduous. Tree input data consists of the basic information on tree height, stem height (from ground level to lowest branch), and radius of canopy (Figure 6-7). The deciduous tree has full leaf cover even during wintertime simulations, the alterative being to run the model without trees, so also losing trunk and branch structure (Matzarakis, 2014). The input data on vegetation in the RayMan model contains no porosity in the canopy and neither leaf area index (m² of projected leaf cover) nor leaf area density (three dimensional break up of leaf area index) are included when creating the tree elements.

In SOLWEIG the input data for trees is based on the transmissivity of solar radiation coming through the tree canopy. The measurements of canopy transmissivity consider both coniferous and deciduous trees (Media et al., 2013). Trees are then simulated in a division of a) canopy, and b) trunk, and represent visually conical or domed shapes (Lindberg, 2011). Additional input data on vegetation in the model is the surface temperature of vegetation (equal to air temperature), a constant value of 20%

shortwave and 0% longwave radiation transmission through the foliage, and an albedo value of 0.2 and an emissivity of 90%. Similarly to the input data of buildings and hard surface cover, a mean value of deciduous trees and a mean value of coniferous trees is subsequently used as tree input parameters in the SOLWEIG model (Lindberg and Grimmond, 2014).

ENVI-met allows a more detailed input database of vegetation compared to the RayMan and SOLWEIG models. All vegetation data, from turf and grasses to shrubs and trees, is based on a leaf area density value – an index value of the three dimensional layering of the otherwise two dimensional projection of leaf area index. As such, each tree (or vegetation species) can be given individual leaf density values and as such reflect both shape and specific species, with or without full leaf cover. Additional input on vegetation data considers stomata resistance and background CO2 concentration (Bruse, 2009). ENVI-met could therefore be regarded as the most advance microclimate model of the reviewed models when it comes to the interaction of vegetation and urban microclimate. By including vegetation in the models it is possible to evaluate the influence of vegetation on mean radiant temperature. In the ENVI-met model it is also possible to retrieve output data on how e.g. trees affect relative humidity, wind speed, surface temperatures etc. (Bruse, 2009).

6.3.7 Comparative critique and future development

The microclimate models ENVI-met, SOLWEIG and RayMan present three highly compatible models for estimating microclimate conditions in a complex urban environment, albeit comprising of different levels of input data and simulation mechanisms. As such the models also represent different levels of user friendliness where the model building and input data for RayMan could be regarded as the most user-friendly of the three. This said, it is still important to consider what kind of output data emerge in the end and how readily readable this data will be ((Lindberg and Grimmond, 2014). The output data of RayMan constitutes a text file, which in turn needs to be transcribed into a more visually accessible format – especially if the results are to be presented to lay persons or decision makers without expertise in microclimate simulations. Although ENVI-met is a more complex software program which requires detailed input data, manual input of building cells onto the model interface and takes longer time to simulate, the output data can be very easily depicted and visualized to lay people or to other professional groups. Other advantages are the advantage of CDF models incorporated to ENVI-met and the LEONARDO software program which helps visualize the output results into either sections or two or three dimensional illustrations. That functionality needs to be set against the scale of applications however. All three provide a fixed total grid size, the more complex the model the smaller the grid. It is possible to run whole cities in the RayMan model but large areas need to be broken down into smaller districts or quarters in SOLWEIG and ENVI-met.

As already mentioned, wind simulations in ENVI-met have been criticized due to the lack of nesting grids within the model interface (Johansson, 2014. , Lindberg and Grimmond, 2014). Thorsson et al., (2007) also question both RayMan and ENVI-met when it comes to the input parameters for the calculation of mean radiant temperature. For example, RayMan only considers three-dimensional radiation flux densities and surface temperatures and ENVI-met divides the hemisphere in upper and lower divisions for radiant fluxes – parameters which according to Thorsson et al. (2007) will not project accurately when it comes to longwave radiation, a criticism which was further validated in a study by Ali-Toudert (Ali-Toudert, 2005).

The input parameters of vegetation also present substantial variation in the functionality which can be incorporated. According to Lindberg (2014), the studies undertaken by the Urban Climate Group at the

Physical Geography, Earth Sciences Centre at Gothenburg University show little differences between species performance when it comes to affecting mean radiant temperatures. On the other hand, the different architectural and vertical make up of branches between species in winter do have an impact on e.g. wind speed depending on strategic placement (Deak Sjöman, 2013). This in turn influences mean radiant temperature, physiologically equivalent temperature, and building energy use (Höppe, 1999, Matzarakis, 2009, Nikoofard and Fazli, 2011). The default input data for vegetation in ENVI-met could be questioned however, as it provides set values for a range of trees which present relatively high (in some circumstances unrealistically high) leaf area index. As such it is important for any user to understand that it may be relevant to customize leaf area index and leaf area density to a more species specific index corresponding to the situation (growth shape and time of year). This requires retrieving the leaf area index and dividing it into ten layers of leaf area density, then replacing each value in the edit plant data base with a known value for the species.

Further questions could be raised with regards to the input data on buildings and other horizontal and vertical surfaces. For example, in SOLWEIG a mean value for all buildings and surface covers is used regardless of its actual colour and other thermal properties (Lindberg, 2014). However, RayMan, SOLWEIG, and ENVI-met are all models in a constant process of improvement and of validation (e.g. (Ozkeresteci et al., 2003, Matzarakis et al., 2010, Gulyás, 2006, Unger et al., 2011, Ali-Toudert, 2005, Lindberg, 2011). The next SOLWEIG software aims for instance to incorporate the calculation of physiologically equivalent temperature which also means an estimate of wind speed (Urban_Climate_Group, 2013) as well as individual indices for building materials.

6.4 Summary

The relevance or otherwise of particular models to achieving Sweden's environmental objectives for an urban context is highly dependent on the spatial and temporal scale of application, as well as whether the results are to be used to inform specific planning decisions, for strategic regional planning or in the most abstract form for guiding policy development nationally.

Urban areas often require greater spatial accuracy, and the trade off between accuracy, simplicity, speed and cost is reflected in Table 6-1. Not all the models described here are easily applied at the scale of a city, but it is important to recognise when modelling a smaller area that it sits within a wider context – cooler air or storm water from nearby mountains for example. Simple, large scale models, such as heuristics for the water or heat absorption of different land covers may provide the starting parameters for more detailed models. Fast models may be used during the GeoDesign stage and precise models deployed to look at the implications of the outcome of that design process.

Simplifications and generalisations which one model requires may be incompatible with another but models may be used in combination without necessarily being computationally "chained together". For example, the output of a stormwater model and sea inundation model may be combined in a GIS to consider implications for the transport network, while each model relies on different DEM; but there needs to be an appreciation of the cumulative error this entails, particularly with large differences in resolution, or conceptual differences in the representation of underground channels. Urban heat island effects may be modeled at different scales, e.g. city wide to consider health implications and at street level to consider tree planting design; but the parameters such as building material thermal capacity should be comparable if possible.

While computational issues place limits on the scale at which physical simulation models can be applied, it does not necessarily follow that "simpler" model approaches are only relevant at large scales. 'GIS' is often assumed to relate to methods easily implemented within common software packages, e.g. cost-distance or "bath tub' flooding models. It is important to recognise that more complex models, particularly the integrated models discussed, often build upon these simpler approaches. The choice is not, therefore, one between being restricted to 'GIS' or buying more advanced models developed specifically for urban areas. There is a continuum of complexity in model development, parameterization, computation time and training required. Elements such as solar radiation or soil water absorption in more advanced models can be also incorporated as heuristic estimates to refine simpler models. When to move up that continuum, and when ultimately to invest in using more advanced modelling packages depends on the degree to which the planning system needs (and is able) to respond to the additional accuracy in prediction.

Table 6-1 Chapter 6 Summary for Key Environmental Objectives

Environmental Goal	Pros	Cons
Good Quality Ground Water 		
GIS sea inundation models	Simple to implement and relatively fast to run, GIS based flow aggregation can give a first indication of how pollutants travel with water. Absorption indices can assess how much water is absorbed where.	Programming required to included soluble and particulate pollutants which do not all move in the same manner as water. Most models only work in 2.5D so do not include underground channels
	Easy to comprehend and use in a GeoDesign context with stakeholders	No fluid dynamic effects to determine aspects important to ground water such as length of submergence.
Low Impact Drainage Models	Can help design drainage which cleans the water in situ rather than concentrating pollutants downstream.	Vegetation and soil type is critical in the LID context but the models do not yet sufficiently account for this.
Mathematical (fluid dynamic) flood models	Able to consider three dimensional flow, flow force, which might carry pollutants over, or through barriers in detailed terrain.	Complex to parametarise, slow to run and limited as to areal extent which is feasible to include. Useful for urban areas, but need simpler models to give wider spatial context.
Integrated Ecological/Economic Coastal Inundation Impact Models	Provide much pre-calculated data such as future sea levels and environmental datasets which can include varying scenarios on source (e.g. urban areas, agricultural crops). Pre-calculation allows integrative scenarios to be quickly investigated with a range of drivers so useful in GeoDesign.	Coarse resolution How relevant are the example datasets provided? Very difficult to validate.
A Good Built Environment 		
Urban Micro-climate models	All three urban heat models discussed in this chapter are currently used in practice for different scales and types of application, and all deliver quantitative estimates of the cooling effect which may be achieved from different green structure and street layouts.	Parameterisation can be time-consuming, for example in relation to defining leaf area index. Run times are not always conducive to a design process, With detailed applications such as an individual street or square the spatial model may be a limiting factor in accuracy and field work may be required to gather the necessary data.
Flood Models	'GIS' based models are fast and relatively simple to implement	In an urban context simple models are only able to provide a very crude worst case estimate for flooding. Depending on the urban fabric, this may need to be implausibly conservative and says little about the likely damage.

	Physical flood models can represent complex flood topology, wind and wave pressure effects in urban canyons, and so simulate physical damage, duration of flood etc.	Obtaining the data may be very difficult – particularly estimates of the flood proof or otherwise nature of individual buildings. 3D models are slow to run for large, high resolution, areas. Modelling whole cities may not be possible. Green structure is often not well represented by models derived from engineering backgrounds,
	Low Impact Drainage models allow the water flow requirements for greener approaches to urban design to be modelled. This could provide methods to slow and capture flood water, and could (in theory) be linked to urban greening and heat models to turn a problem into a resource.	LID models are low velocity models which assume percolation of water, they do not at present integrate with the engineering models designed to deal with high velocity storm events.
Reduced Climate Impact 	..	
Urban Micro-climate models	The micro climate models provide quantitative values for the urban cooling effect from vegetation and building layout. This can be translated into reduced atmospheric carbon dioxide from reduced mechanical cooling and heating.	None of the microclimate models consider valorization directly in terms of money or carbon saved so must be linked to other models in order to allow optimization of climate, economic, and other design goals.
Flood Models	The coastal flood models and urban drainage models presented may be combined with visualisations to 'bring home' to citizens a key potential consequence of climate change.	All the flood models depend on how credible the downscaling of other complex models on climate change is for a given location, and how reliable local historical trends are considered to be. Both require specialist expertise.
	Even many commercial physical models operate on an free license, (though training can be expensive)	Physical models are processor intensive so restricted to local examples and these require expert parameterisation.
Integrated Ecological/Economic Coastal Inundation Impact Models	The Integrated Assessment Models contain downscaling algorithms, which could provide a "prima facie" risk estimate for future climate scenarios. Built in datasets allow for quick set up times. Multiple, cross-compliant, policy objectives can be investigated.	The down scaling approaches entail many assumptions the validity of which to a given locality would require expert assessment. Built in data may have important local limitations or be out dated Multiple assumptions mean error margins are hard to estimate.

6.5 Glossary

Albedo	The whiteness of a surface (measure for reflectivity)
CAD	Computer Aided Design (or Drafting)
CFD (Computational Fluid Dynamics)	Models which use numerical methods and algorithms to solve and analyze problems that involve fluid flows.
ENVI-met	A microclimate model developed by Prof. Dr. Michael Bruse Environmental Modelling Group Inst. of Geography University of Mainz.
GIS	Geographical Information Systems.
Global radiation	The temperature from a globe thermometer which measures both short and long wave radiation
Long wave radiation	The outgoing radiation from surfaces to the hemisphere/space (occurring predominantly during the nighttime)
Mean radiant temperature (Tmrt)	The mean radiant temperature, Tmrt, which sums up all shortwave and longwave radiation fluxes (both direct and reflected) to which the human body is exposed (Lindberg et al., 2008)
Nesting grid	Additional cells within or on the border of model area allowing for complex numerical calculations.
Physiologically Equivalent Temperature (PET)	The thermal conditions of the human body (the physiologically perceived temperature)
Predicted Mean Vote (PMV)	Initial value for thermal stress of the human body, mostly for indoor measurement
Raster data	Graphics composed of pixels, e.g. jpg, gif, in any colour. The image clarity may fail as image is zoomed in.
RayMan	RayMan stands of Radiation on the human body. The microclimate model is developed by Dr. Andreas Matzarakis at the University of Freiburg, Germany.
Short wave radiation	The incoming radiation from the sun during the day
Sky View Factor	A value of the amount of sky visible from obtruding objects such as buildings, trees etc.
SOLWEIG	SOLWEIG stands for Solar and longwave environmental irradiance geometry and is a microclimate model from the Urban Climate Group Department of Earth Sciences University of Gothenburg, Sweden
Vector data	Graphics composed of lines or paths (linear or curved). The vector data file contains information on the points where line starts and ends, what colours, and whether the line curves or not. Vector data contain its image clarity independent of the zoom extent.

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7 Data Mining, Machine Learning and Spatial Data Infrastructures for Scenario Modelling

Neil Sang and Mathew Aitkenhead

7.1 Introduction

The approaches discussed in sections 2-6 relate (generally) to some form of simulation or representation in a formal modelling language. The range of computational or technological complexity involved is variable, but in most cases a very high degree of domain knowledge is also required with respect to the system under investigation. This presupposes that such expertise is available, and indeed that it is sufficient to understand and represent a particular system. For large coupled systems with a wide range of socio-economic, ecological and bio-physical systems interacting this may not be feasible. For simpler systems in specific cases it may not be necessary. This chapter explores data mining as a pragmatic alternative or complementary approach. Methods and papers are summarized in Appendix 2.7.1.

A key distinction in modelling approaches is between inductive and deductive approaches. In scenario models that might be considered the primary distinction between the simulation component where by a response is derived from scientifically understood principles, and components which rely on 'externalities' – parameters provided a-priori such as a future climate scenario that has been inferred from historical trends. Where simulation is impractical (perhaps because the system is not sufficiently well understood) a pragmatic scenario may still be inferred.

Externalities are often used to maintain simplicity by focusing modelling time only on the response of the phenomena of interest rather contextual factors. It may be appreciated that these "external" parameters and trends do, in fact, respond to the model phenomena over some other spatial or temporal scale, but simulating that reciprocal response is deemed impossible or unnecessary. In situations where a sophisticated Integrated Assessment Model (Refsgaard et al., 2006) is desired, feedback loops can be incorporated between different environmental systems and human behavior by chaining together several models, however the output can quickly become impossible to verify. Various strategies have been suggested to try to assess their utility such as multiple competing models (Refsgaard et al., 2006) but given that every additional model used adds another layer of complexity to be computed and assessed it is hard to see such an approach being feasible in an applied setting. Emulating (rather than mechanistically simulating) some of these models (those of lesser interest or which are less well understood) with a statistical approximation established from observed relationships between coupled systems can be one means to limit the spread of error and so keep subsequent modelling stages operating on realistic input scenarios. For example "mechanistic fire modelling across large landscapes may be inherently intractable" (Cushman, 2006), so it may not be possible to simulate precisely where a fire will spread to but it is possible to predict the total burnt area (Safi, 2013) and then use GIS to identify likely spatial scenarios for input to further models.

Traditionally, inference of a relationship between two or more parameters would be achieved from statistical analysis of observed data. Machine Learning broadens the range of techniques available such that one need not assume an underlying theoretical statistical distribution but can instead leverage iterative optimization algorithms to explore the entire parameter space for relationships and so predict patterns which are too complex to be represented by analytical equations.

Data Mining, the practice of seeking patterns without a prior hypothesis as to what kind of relationship one is expecting to find, has grown in popularity due to the advent of Big Data, a fashionable term referring to the development of datasets which are so large even very finely nuanced effects reflecting a small proportion of the dataset can be identified with statistical significance. Data fishing refers to the problem that, given enough data, entirely spurious relationships are likely to be found simply through random chance, particularly if one does not begin the enquiry with a specific null hypothesis (Webb, 2007). Statistically sound association discovery (Webb, 2007), reduces the danger of finding spurious relationships, but does not abrogate the user from responsibility to consider whether a causal connection is realistic.

'Data mining derives its name from the similarities between searching for valuable business information in a large database... and mining a mountain for a vein of valuable ore. Both processes require either sifting through an immense amount of material, or intelligently probing it to find exactly where the value resides.'
http://www.thearling.com/text/dmwhite/dmwhite.htm

7.2 Seven common classes of data mining task

Anomaly detection (outlier/change/deviation detection) – The identification of unusual data records, that might be interesting or data errors that require further investigation. For example analysing satellite imagery of forest disturbance due to disease or pests (Ellenwood, 2009), aiding planning for both short term responses and long term probable disturbance scenarios.

Association rule learning (dependency modelling) – Searches for relationships between variables based on establishing that if several conditions are met, a certain further outcome is statistically likely to occur, e.g. tourists are likely to visit site X and Y if they stayed at hotel of type Z (Versichele et al., 2014) aiding planning for public transport and tourism promotion.

Clustering – is the task of discovering groups and structures in the data that are in some way or another "similar", without using known structures in the data. Useful for identifying subsystems at work (e.g. air pollution response to traffic levels in different seasons) and for identifying comparison scenarios (e.g. to validate if a model predicts all observed circumstances equally well (Fung, 2010).

Classification – is the task of generalizing known structure in data in order to use it for a new application. IT Communications can be classified in real time to monitor perceived environmental issues (e.g. eutrophication (TWC, 2012)). Land cover can be classified to represent actual land use (e.g. for forestry in Sweden see (Reese, 2011)) or land capability for a particular purpose such as agriculture (Bibby, 1991).

Regression – determines a function which models a trend in the data with the least error. Regression methods include quantitative (linear, multi-linear, non-linear, geographically weighted) or frequentist (logistic) which assume an underlying analytical distribution, or Bayesian which seek to estimate an underlying distribution through monte-carlo simulation (Zurr, 2007).

Interpolation – Estimating the implications of known parameters in one place or time for those of another place or time based on believed common explanatory variables.

Summarization – providing a more compact representation of the data set, including visualization and report generation. Temporal e.g. total, mean and variance over a given time period – allows easy comparison over time for the same source or between sources for same time period, and the generation of functionally relevant metrics such as frequency. Spatial summaries establish the same over a spatial unit including functionally relevant metrics such as density.

7.3 Seven Common Data Mining Techniques

Artificial neural networks: Map inputs to output through a series of weightings that are altered through repeated exposure to data points to reduce error rates or achieve a particular outcome. A generalisable approach which can predict highly non-linear outcomes, but that can be hard to interpret in order to understand the relationships between input and output parameters.

"The main advantages of using ANNs are their flexibility and ability to model non-linear relationships. The neural network is an alternative to the parameter-intensive physically based models in applications that do not rely on the subjacent physics of the system dynamics" (Kankal and Yüksek, 2012)

The examples found tended to use ANNs to address problems where a mechanistic model was either too time consuming or too hard to calibrate. Common applications include predicting the response of populations (e.g. algae) to environmental and anthropogenic drivers and, perhaps due to the tempting but limited parallel with the human brain, in modelling human perception and cognition both individually and as a collective e.g. in relation to environmental Common Pool Resource Problems (Frey, 2013). Since they operate by weighting a decision surface using 'Case Based Reasoning' about whether the predicted outcome is 'correct' or not, ANN present one method of eliciting expert knowledge from which to emulate decisions even when the experts themselves may not have a clear view of what drives their decisions (so called 'tacit' knowledge) (Nemati, 2003). It is arguable that their use has been something of a 'catch all' solution where more informative models have failed:

"There is little doubt that ANNs have the potential to be a useful tool for the prediction and forecasting of water resources variables ... ANNs need to be viewed as alternatives to more traditional approaches in certain situations and not as '…a remedy for all existing computational failings'(Flood and Kartam, 1994)." (Maier and Dandy, 2000)

For applied purposes Maier and Dandy's concern for theoretical rigor is perhaps less compelling - provided the predictions can be demonstrated to be accurate and the input parameters are both logical and amenable to policy changes. On the other hand, ANNs do rely on translating between inputs and outputs using continuous functions, which means that they cannot model discrete relationships as effectively as other approaches. There is also often a stated concern about the risk of 'over fitting' such that the responses within the known parameter space may no longer apply to future scenarios for which there is not yet training data available. However, ANNs do not over-fit any more than other methods described here if used correctly, and this concern can be obviated using appropriate dataset splitting and training approaches (e.g. k-fold cross-validation). Non-the-less ANN are probably better suited to predicting responses to limited changes in current scenarios rather than longer term future scenarios.

Decision Trees: Structures that represent sets of decisions where each 'branch' shows a different decision path history, thus creating a 'tree'. Helpful for seeing the possible outcomes of different decisions and grouping decisions at different scales (for example when classifying an image – Grass/Tree > Deciduous/Coniferous > Species of Coniferous) or clustering together net predicted outcomes of different policy decisions.

Decision Trees can be applied to a wide range of applications across all the domains of interest here. Examples were commonly found where discrete differentiation is required between a hierarchy of circumstances leading to likely outcome. It is unsurprising therefore to see the use of Decision Trees for rule induction, trying to 'step back' through the decisions which have been made in determining a given land use and thus hope to infer future decision making strategies of land owners (Pal and Mather, 2003, Aalders and Aitkenhead, 2006).

Genetic algorithms: Optimization techniques that start with many possible algorithms and combine or slightly alter them a random, maintaining only those that are most successful, thus mimicking natural selection.

The main applications of GAs are to situations where multiple parameters exist and the parameter space is complex and nonlinear. They are suitable for finding local ‘good’ solutions within the parameter space (or for finding a slightly better solution than the existing one) and less so when the best ‘global’ solution needs to be found. Examples in environmental modelling include calibration of process models, identification of sample point distribution patterns, or resource distribution planning for management decisions (Aitkenhead and Aalders, 2009).

Fuzzy classification method: A technique that classifies each record in a dataset based on a combination of the classes of those records most similar to it in a historical dataset. So likely outcomes might be inferred by looking at previous outcomes from similar, but not identical, circumstances.

This approach allows an ‘unknown’ record to be related to a number of known records using metrics of distance within the phase-space of the parameters used. The fuzzy membership allocates a measure of similarity to each record or cluster of records, and can be used to give a measure of membership of each cluster/class or to provide a ‘crisp’ classification to a single cluster. A number of comparison approaches exist, ranging from the most simple (nearest neighbor), to more sophisticated methods taking into account the distribution of values within each parameter (fuzzy k-means with expectation-maximization algorithm).

Dimensional Analysis : Structuring data so that it can be queried or visualised as a dimension of change.

The purpose of Dimensional Analysis is to simplify the relationships between variables by reducing the range of units, thus is a somewhat similar idea to factoring of fractions. It is a more general case of normalization, and is important to allow display of key relationships between variables via Principle Component Analysis (PCA) and Redundancy Analysis (RDA), which in turn provide methods to ‘exclude’ less important dimensions of variance from the analysis.

Bayesian Belief Networks: Incorporating expressed beliefs as to how components of a systems interact within a quantitative model.

Not strictly a data mining approach but included here as a means of structuring the data mining process (Aitkenhead and Aalders, 2009), and including stakeholder or expert beliefs within that structure. Bayesian Mathematics is a branch of statistics which aims to avoid assuming a given distribution model, such as the Gaussian or Poisson distribution. Instead a general form of an equation is developed with a given number of parameters and “prior beliefs” (operators) as to the possible relations between them. The shape of the distribution is estimated based on these beliefs and compared with empirical evidence (Troldborg et al., 2013). In many cases the empirical evidence is only available for parts of a complex system but experts or other stakeholders with experience of that system are able to indicate other relevant factors and estimate the strength of relationships between these factors and those which can be empirically measured. By comparing the outcome of the overall system with that predicted given the experts beliefs, one can then begin to objectively consider whether those beliefs are correct. BBN are thus a means to represent beliefs within a model, but also a technique for qualitative rule induction (Marcot, 2006).

Geographically Weighted Regression: A regression analysis which allows the operators to vary over space. GWR is a powerful tool for analyzing and visualizing the spatially dependent relationship between two or more variables (Fotheringham et al., 2002). This helps to take into account spatial autocorrelation (Borrough, 1998) which may confound standard regression because two apparently independent variables may appear to be statistically correlated (e.g. vegetation type and house price) when they are infact only co-dependent on an unidentified third variable (e.g. terrain aspect).

GWR can also help to understand how regionality affects relationships between variables, for example the relationship between changes in farm ownership structure and rates of farm abandonment may be altered by other factors such as landscape type or the presence of a significant urban area, GWR helps to separate out the different regional systems at work (Sang et al., 2014). Geographically Weighted versions of PCA have also been developed (Lloyd, 2010) [11].

7.4 Supporting Data Mining with Spatial Data Infrastructures

Data Mining, as with all forms of scientific enquiry, benefits greatly from straightforward access to data. Accessing a greater range of data can, assuming a statistically sound approach to association, improve a model by providing explanatory factors to confounding issues. For example information on anthropogenic pressure across a woodland may not exist in an ecology database, but data collected for an entirely separate purposes such as car park maintenance planning, might serve as a proxy to explain spatial variance in the ecological observations due to anthropogenic disturbance.

For complex integrative models, one of the largest costs may be sourcing the necessary data for each component model. This is particularly so when components demand data produced and held by institutions and people out with the personal networks of the modeler. In these circumstances it is often difficult to even know what information is available out with one's field of expertise; let alone where to source it.

The primary purpose of a Spatial Data Infrastructure (SDI) is to simplify the identification and locating of data via provision of meta-data in a standardized form. Meta data provides a summary of what information a database contains such as subject, the location and time period, producer and owner. Ideally some indication will also be given as to the provenance of the data, quality of the observations, spatial scale and so forth.

In order for data mining to make best use of the available data resources, it is necessary for this meta-data system to operate to common standards to allow a computer algorithm to find the relevant data. It must also be connected to a system of automated access to the data resources so that algorithms may draw on all the available data as required. This, however, then entails some system of access control to ensure only those entitled to access may do so, and possibly some form of payment mechanism where data has commercial value. The development of data distribution mechanisms is thus an organizational challenge as much as and ITC one. In principle, however, automated access should both save money directly as this need no longer be manually undertaken, and leverage greater use from the investment that generating the data represents.

Access to data alone is not sufficient to leverage the benefits of data mining. The data itself must bear some degree of compatibility. Where two different sources are being used to compile a larger data set (e.g. soil data in adjacent regions) classification may appear to be similar, but do the terms used refer to the same thing, and is this also what the end user understands it to mean? To some degree interpolation methods and classification look up tables may be used to make data comparable (Feiden et al., 2013) but it can also introduce errors and artefacts such that false relationships are found and real relationships hidden (Briant et al., 2010, Houston, 2014, Mitra and Buliung, 2012, Sabel et al., 2013, Su et al., 2011, Swift et al., 2008, Sang et al., 2005b). Mining 'big data' is thus not an alternative to employing statistical skills, but rather requires careful and knowledgeable scrutiny.

[11] This list of techniques is adapted from the techniques selected in http://www.thearling.com/text/dmwhite/dmwhite.htm

Ultimately, comparable data requires co-ordination at the collection stage, and that entails collaboration and co-operation between collecting agencies which they may not support (Sang et al., 2005a). For example ensuring the representation of "spatial minorities" - rare populations or unusual geographical contexts - is in some respects contradictory to the drivers of commercial funding models of data collection.

A key choice when considering how to develop an SDI is the balance between 'products' and 'processes' (Williamson et al., 2003, Rajabifard, 2003,). Products are specific services, such as common databases. They are usually managed by a 'Single Coordinating Body' (Sang et al., 2005b) able to control the upload of data and thus ensure both its quality and manage access rights. While such an approach provides for a product which can be tailored to particular end users requirements, it requires funding for staff time and equipment to support the process as well as the ability to persuade data collection agencies to participate. For this reason, product SDI are usually limited to state managed data, the TIGER dataset run by the US Geological Service being one of the oldest and best known examples (https://www.census.gov/geo/maps-data/data/tiger.html). The Swedish Geodata Portal represents the beginning of such a product approach (http://www.geodata.se/). It does not, as yet, include a commitment to data interoperability, API access to the datasets, or a common statistical base all of which would be necessary to fully utilise data mining.

'Process' SDIs do not seek to create single databases. Rather they are a managerial approach where by interested parties begin to negotiate common standards which allow their data to be more easily identified, accessed and ultimately become more compatible and intraoperative. How far down that road the process reaches, and what kinds of data become available, is thus dependent on the interest of participants. Some coordinating body is still required to manage that process, and perhaps provide some core architecture to host meta-data but they do not direct the process. Rather agencies which collect data as part of their own operational purpose see a mutual benefit to contributing to the system either to gain access to other's data or create a wider user base for their own. Realistically, unless the parties are interested to fund this work, success depends on achieving some mutual benefit without impeding each participant's core activities. For example compliance with the INSPIRE (http://inspire.ec.europa.eu/) legislation when collecting and storing data should result in less additional work when providing environmental data to the European Union. The specific reference to INSPIRE within GeoData.se suggests that implementation is well progressed among national level institutions within Sweden. The question is whether local authorities and local offices of national authorities are aware of its potential and requirements?

GEOSS is a global project providing one example of how a process may be implemented for gradually improving co-ordination, which ultimately can produce products such as a portal with API access (http://www.geoportal.org/web/guest/geo_home_stp) but it is worth noting coordinating efforts have received direct institutional and financial support from national governments, European and United Nations sources.

The same principles which determine data availability apply to models themselves. In theory decisions could be made more effectively and models developed more cheaply if some means existed to allow their use to be shared (Nativi et al., 2013). Models As A Service (MaaS) approaches which deliver the modelling capability via web portals offer one means to improve access to modelling resources at local level. In particular it could allow sourcing several competing models for comparison (http://www.uncertweb.org/). However it requires central resourcing both in terms of IT infrastructure, and support to end users. In the case of both data and software, the issue with their wider distribution is three fold: How to identify their existence and capabilities; how to manage intellectual property rights; How to provide end user support services.

7.4.1 Semantic Analysis and Spatial Indexing

A key difference between SDI for environmental modelling in general and SDI for participatory planning in particular is that much of the data relating to planning proposals is not quantitative and is not held within databases. The planning system tends to generate written reports where in qualitative information on stakeholder responses is quoted directly, or statistically summarized to tables within these documents. Other information such as proposed development areas may be symbolic and presented only within pictorial maps – i.e. the information has never been formally digitized as a geographical object.

Semantic analysis methodologies can go some way to extracting relevant information from traditional planning documentation held online (Brasethvik and Atle Gulla, 2001, Punitha and Punithavalli, 2012) and adoption of semantic web standards for information generation can help in collating operational data such as Building Information Modelling (Abanda et al., 2013) to help drive for example, agent based modelling for evaluating design (Aschwanden et al., 2011).

Less ambitious technologically, but requiring some organizational and procedural standardization, is to spatially index this information such that all relevant information pertaining to a particular location may be retrieved (Hill, 2006).

7.5 Summary

Data-mining techniques can be useful in addressing all 16 Environmental Objectives. Key methods and applications ca be found in Table A2.7.1. The most important distinction to note is that of the *organsiational* scale at which they might be used; these techniques require expert knowledge to calibrate but some can be made self-calibrating, while output from some calibrated models may be understood with domain expertise in the relevant environmental or planning field. Since these techniques rely on identifying trends and relationships in historical data, they are of limited used for future scenarios where new circumstances are expected (e.g. climate change) but are very useful for impact analysis in complex integrated scenarios; for example downscaling the effects of a potential future climate to a given area.

Investment in a comprehensive and accessible Spatial Data Infrastructure allows all modelling techniques to consider the widest range of factors possible by saving staff time in project design, data gathering, calibration and maintaining data currency. Resolving the related Intellectual Property issues also allows more organisations and individuals to contribute to and benefit from modelling efforts.

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8 Collective Challenges, Cooperative Solutions?

The modelling techniques set out in this review provide a powerful array of methods to help understand what the state of our environment is, what may be driving changes in that state, and how future scenarios may look given current trends or possible future policies. They also, however, present a significant challenge in terms of deciding what approach to apply where, resourcing that approach with data and skills and educating others in how to engage with such modelling methods and understand the results.

8.1 Collective Challenges

The impression gained from the workshop with agencies involvement in the Swedish planning system (2nd October 2015, SLU Alnarp) is that the utility of scenario modelling is generally recognised, however the resources to undertake even 'basic GIS' modelling methods are lacking in many municipalities. This impression is supported by the results from the municipality survey. Responses to Q11-13, for example, illustrate that while around 70% of respondents were in favour of introducing more scenario modelling work to their planning processes, most did not believe sufficient resources were available, of those who did not envisage using scenario modelling, with a few exceptions, this seemed primarily motivated by the same concern over resourcing, rather than any objection in principle to the approach:

"There is generally a need for a simple way to get a good basis for decisions. The demands are constantly increasing for risk analysis of various kinds while demands for fast processes and simplicity increases elsewhere. Good tools are important to meet these different types of expectations. "

(translated from Swedish, see Q13, Appendix 3 for original survey response)

As regards providing modelling resources, a distinction should perhaps be drawn between models which can be entirely implemented with standard GIS software and those which require more specialist modelling or statistical software and related skills. With respect to GIS based scenario development, such as some of the methods referred to in chapter 1 and chapter 6, there is considerable potential for adoption at the municipality level, and a general impression was gained that those operating GIS software often have analytical skills they would like to deploy more frequently if tasked to do so and workload permitted.

Again drawing from the local workshop and survey results, it is clear that there is considerable variance in the software skills available to each municipality (Appendix 3 Q15). This is partly a matter of municipality size and total resources, whereby a large municipality can both employ more staff and thus a broader range of skills, but also a matter of relative efficiency. For smaller municipalities some forms of modelling were seen as less necessary because staff can gain a detailed knowledge of each area and case considered while investment in software and data is expensive for the number of cases undertaken. In particular the requirement to pay a flat annual fee to access national datasets was seen as a barrier in some cases.

Modelling which goes beyond that of standard GIS software was much less frequently undertaken, but where considered necessary was almost always outsourced to either higher state agencies (e.g. mydigheter and Länsstyrelsen) or to private consultancies. While the general impression was that participants were satisfied with the work of consultants, 14% (Q14, Appendix 3) found them prohibitively expensive and a substantial minority (31% Q14, Appendix 3) stated that they did not always receive what they wanted from consultants. Workshop participants were in general agreement that the key issue was the inability to work in an iterative manner with consultants as an integral part of the planning process, meaning that work had to be specified correctly first time which is difficult for staff lacking sufficient expertise in the methods concerned (or indeed even for modelling experts). Partly the issue of lack of integration was because of the expense involved in repeatedly commissioning a consultant but also because of legal issues relating to how work could be commissioned and because results were usually reported as documents not data.

Data cost was again an important factor for smaller municipalities in this respect since they could not supply either consultants or other government agencies with the necessary data licenses to carry out work on their behalf.

8.2 Cooperative Solutions

It does not appear to be easy for individuals working in detailed planning or environmental protection to take into account the cumulative or long term implications of their decisions. Even if online Decision Support Systems were provided, it is unclear how implications in 20-50 years can be weighed against the many immediate legal requirements and pragmatic compromises that are inherent in this process. If longer term impacts are to be weighted more explicitly within each decision then some form of conversion of model results into scenario maps is likely to be required, though this might be more subtle than simple polygonal zones. Länsstyrelsen has, for example, developed heat maps of ecological value (Länsstyrelsen, 2014) which may prove a technique which fits more comfortably within existing planning practice, and would serve as a good first step to introducing systematic decision making processes that consider uncertainty and encourage planning for resilience against an uncertain future.

Where a model cannot be simplified to a map format, consultancy (be that private or to other government agencies) will remain a necessary part of the planners resources. However it would appear that guidance on how to commission this work would be welcome. Some thought is also warranted as to how modelling services from external agencies may be made more iterative in nature, perhaps for example by requiring certain types of model output to be supplied as query-able GIS layers rather than images. This is not a simple question however, as those undertaking this work must protect their business, the integrity of their output and the Intellectual Property of their data sources so some trusted intermediary web service might be required to ensure ‘buy in’ from all parties.

Strategic level planning holds more potential for inclusion of downscaling and optimisation models both on a per-case basis and when drawing up planning zones, rules and regulations. However, individual municipalities have little experience in the type of modelling required. Few consultancies offer scenario modelling support beyond fairly concise ‘engineering’ issues such as flooding or urban heat modelling. The type of expertise necessary to run the more complex models reviewed here lies mainly within research organisations, universities and government agencies. It is an open question as to what extent these people would or could take on applied modelling work at the municipality or regional scale.

At present it would appear that many municipalities look to Länsstryelsen to supply more advanced scenario models, but it is not clear how formal this arrangement is, nor that it can be feasibly scaled up. There is considerable variance in both the physical size and the population of Län (counties), and so also variance in the administrative resources available to the planning system. The existing practice whereby particular expertise may be shared across Länsstyrelsen, with certain Län having particular responsibility for given topics is one possible route to improving access to modelling skills or at least to model output. If a centralized modelling resource were to be developed this would have obvious benefits as regards integrative models, and a common IT support would be recommended since modelling work often requires somewhat specialist equipment, software, access rights and skills. On the other hand domain specific modelling skills might best be distributed within those organisations having the respective remits in order to ensure models reflect cutting edge science and policy priorities. Given these competing demands on the modelling resources at different spatial scales, consideration might be given to when complex simulation modelling can be substituted with one of the data mining techniques discussed in chapter 7. These techniques still require highly skilled operation to be effectively deployed, but they are more generic as to subject of application so investment in these skills might support a broader range of topics.

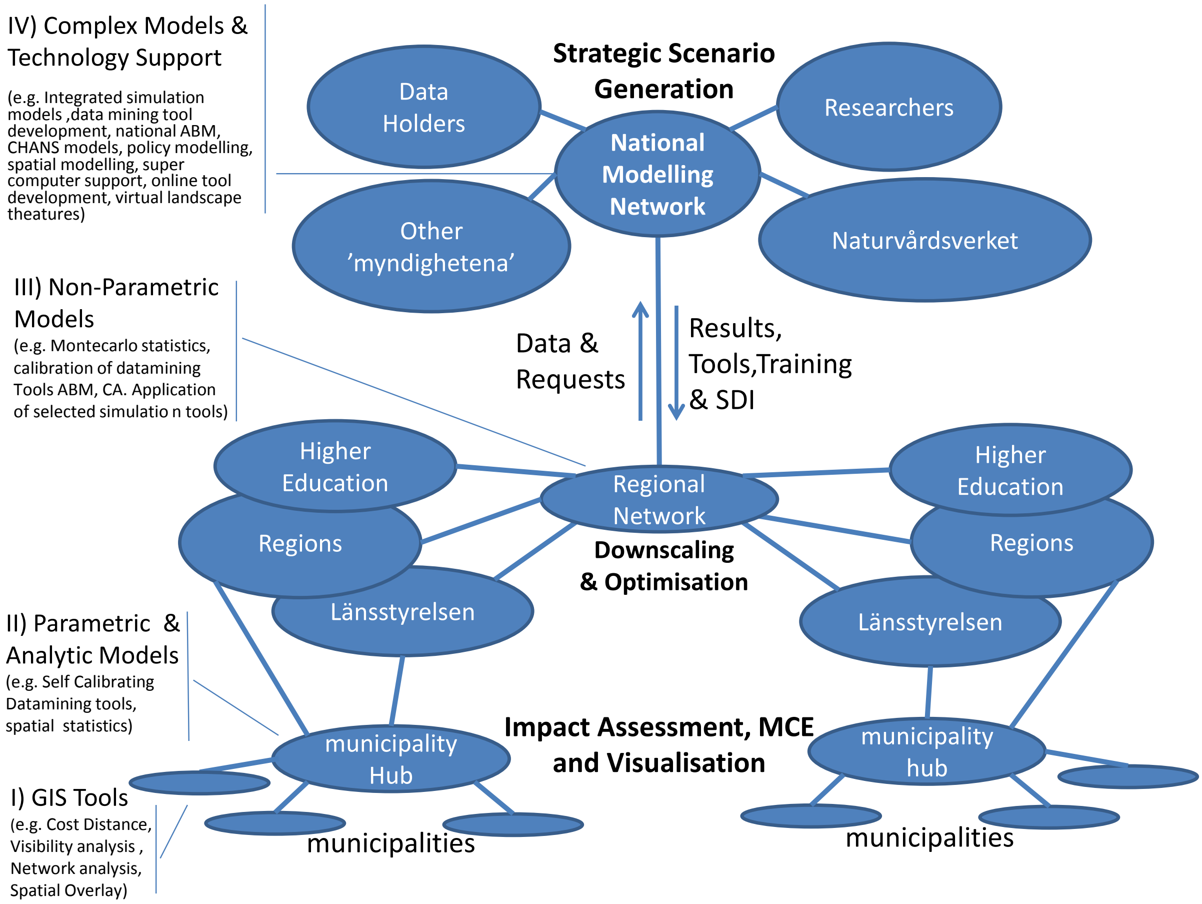

Figure 8-1 A potential network for sharing modelling capacity

Figure 8-1 illustrates one possible organisational structure by which existing skills in Sweden might be coordinated to encourage greater use of modelling approaches:

I. ‘On the ground’ at some individual municipalities, it is clear that there is a practical issue as to the time currently used by GIS staff on simple data collation and map production which might be undertaken by other staff if appropriate training, organisational SDI, and simplified mapping tools are in place. However, a deeper reason is perhaps uncertainty as to the value of GIS based analytical methods compared with expert judgement, and their appropriate use. As one respondent to the survey commented :

"We are very understaffed, so we would have the most benefit from simple models (easy to handle). However, this would be a great help when needing to relatively quickly produce a forecast, and we do not want to deliver all data to the consultant, then wait for an answer, and then still have to revise. As to more extensive investigations we must probably continue to hire a consultant, but it is still a great advantage in having one’s own knowledge of the models, so that you know what to order and can view result."
(Translated from Swedish, see Q13. Appendix 3 for original)

At this level there two related but distinct issues therefore; how to support the use of simple models for fast, iterative (and thus likely in house) impact assessment; and how to commission and/or interpret the implications of more complex scenario models. The issue is perpetuated by lack of time between ongoing work to learn and evaluate the methods as a team. Higher Education also has a role to play here in ensuring that graduates from programmes in landscape architecture, planning and related fields have a sound understanding of basic GIS analyses.

II. Some larger municipalities have the capacity to use GIS for Impact Assessment and simple Multi-Criterion Analysis (MCA) types of model, for example basic flood models, statistical trend analysis, accessibility models, site selection, spatial “hotspot” identification, and remote sensing classification in various applications. If an appropriate agreement could be established between neighbouring municipalities, supported by regional agency funding, this capacity could be expanded both spatially and to include more sophisticated modelling tools, to the mutual benefit of all the municipalities involved. An alternative to locating such facilities within one municipality could be a third party organisation such as an appropriately constituted Landscape Observatory. Some municipalities reported using such a strategy already:

“As a single municipality, it is difficult and expensive to develop your own data and models. We draw today from things that have been undertaken in a framework of regional and local authorities in cooperation. Examples are flood scenarios for the river ..."
(Translated from Swedish, see Q13. Appendix 3 for original)

As the quotation shows, many environmental management and planning problems are not limited to the spatial boundaries of one municipality, so regional cooperation is logical.

III. No municipality identified themselves as having significant capacity for predictive scenario modelling (rather than responding to a presented future scenario) nor for down scaling larger scale scenarios. If this work was undertaken at all it was outsourced to agencies such as Länsstryelsen or to private consultancies. The appropriate knowledge to commission this work is also limited, particularly for smaller municipalities. Thus it is unrealistic, at present, to expect planning processes at this scale to undertake modelling of possible future response to complex systems. But even simple outputs of such models would be useful e.g. :

"Flood mapping (data) based on 10, 20, 50 and 100 year rain would be good. How secondary drainage is working would be good to know, and what happens if a greater degree of surface sealing occurs."
(Translated from Swedish, see Q13. Appendix 3 for original)

While some respondents mentioned working with Universities on specific problems, it is also, perhaps, unrealistic to expect those who develop modelling tools for their own research to play a large role in repeatedly applying these models in various municipalities and regions. One solution may be to build on the existing specialist network system of Länsstyrelsen to support alliances with Higher Education institutions at a regional scale. Such a network could draw together the skills needed to apply (if not necessarily develop) models for downscaling the implications of scenarios generated at national scale. These down scaled scenarios may take the form of maps and statistics (e.g. 50 year flood risk), for direct use by municipalities, or calibrated tools for those regional hubs able to use them (e.g. on the spatial effect of soil sealing).

IV. The most sophisticated models, particularly those which define broad future scenarios from integrated subsystems, require for the most part expertise, data or facilities which are only available in limited numbers nationally or even internationally. These resources are generally within academia, in government agencies or specialist consultancies. There is no single, tried and tested, approach for bringing such diverse resources to bear in the planning system. Indeed, different modelling disciplines and individuals within each discipline, do not all agree as to how complex and integrated a model it is useful or wise to create. However, a coordinated call agreed between relevant national agencies for a national network addressing applied environmental modelling could potentially be very effective and it would seem all municipalities would be receptive to the results if they were delivered in clear terms :

"It is always good to have a broad basis to prepare for (partly) unpredictable future issues."
(Translated from Swedish, see Q13. Appendix 3 for original)

There is a need for a platform for experts to discuss research agendas with the key state agencies (myndigheter) and to cooperate on common protocols in data management, software development and working practices which systematically support scenario modelling within planning and environmental monitoring. Naturvårdsverket in particular could play an important role in helping communicate the most pressing needs from the planning system to those able to respond with broad scenarios, in promoting the resulting maps or tools, in encouraging regional modelling resources able to down scale implications for their regions, and in helping municipalities find the relevant organisations with the skills or equipment they require.

Another open question is where modelling of integrated processes might sit within the Swedish planning and political system. How land is to be used or protected in the long term is not a politically neutral question, as one survey respondent pointed out the civil service requires a political mandate as regards what issues to consider (Appendix 3, Q16). Models may indicate some objective trends, but in other respects face "equi-finality', that is two or more different outcomes are equally likely or equally optimal in different ways. Swedish governing agencies both promote active drivers of landscape change and place constraints on development. When integrated models are being developed which address the long term impact of investment policies, regulatory policies, and natural system responses, who manages the modelling process may be important for acceptance that output is objective. This is true whether scenarios are being modelled as a single 'CHAN' system, or via a suite of models giving output to common questions. Thus it may be that a modelling 'eco-system' needs to be developed to co-ordinate priorities, data and methods amongst various institutions from national to local.

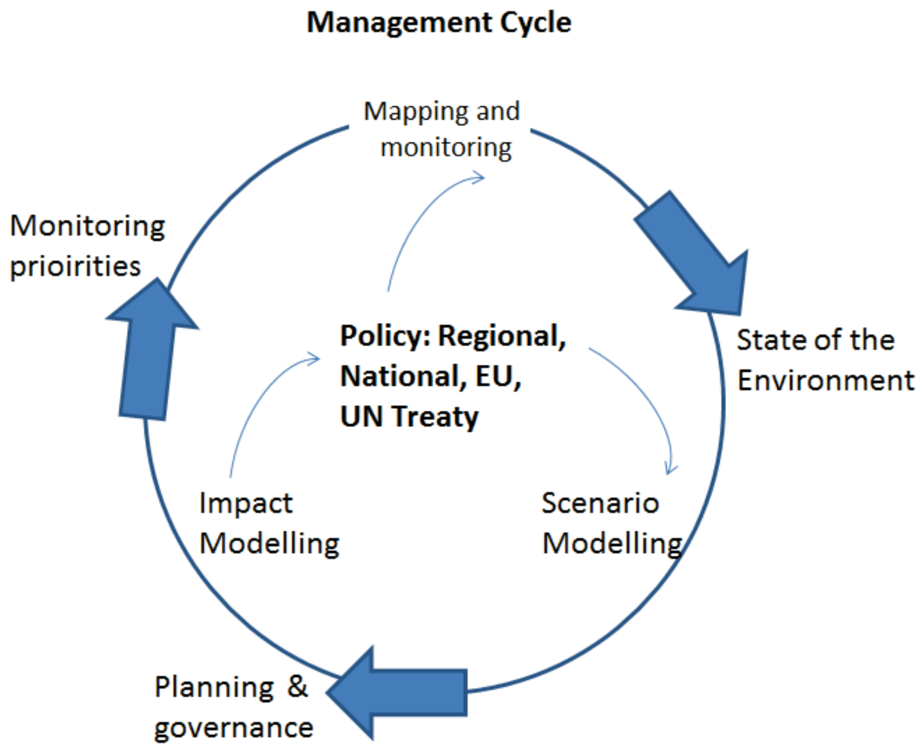

Figure 8-2 The role of modelling in connecting policy priorities to evidence based policy

Figure 8-2 illustrates a highly simplified version of the management cycle where by evidence as to trends in the state of the environment are converted into possible different management scenarios given societal variables such as the legislative context, scenarios which are then used in turn to assess the potential impact of these changes, informing policy and setting further monitoring priorities. Reality is, of course, more complex, with interwoven cycles from local to international scales including other feedback loops. For example scenario models may be used strategically as part of impact assessment, or within a GeoDesign process (Schwarz-v.Raumer, 2014, Steinitz, 2012, Wilson), however it is reasonable to suggest that the more computationally and theoretically complex models (levels III and IV) are better suited to the Impact Modelling stage in figure 8-2, at higher organisational levels (figure 8-1), where there is the time and skills to build, run and interpret them. This may, for pragmatic reasons, also restrict their use to larger spatial scales or particularly important cases. Level II and III type models (figure 8-1) might be used for policy level impact assessment, but also (if well parameterised) could provide more specific impact predictions for strategic planning targeting particular regions. With respect to GeoDesign, models at level II and I are, for the present, the most feasible and much can be achieved with these to improve the transparency, objectivity and effectiveness of strategic and detailed planning and environmental management. Developing capacity at levels II and I will prepare for adoption of more complex models as the need for them is identified and as technology progresses.

Looking ahead, the iterative nature of GeoDesign bears comparison to that advocated by the ExCites approach to Citizen Science, indeed modelled scenarios could well provide public agencies with that "something to offer" - in the form of local implications of future scenarios – which the ExCites team have found important for engagement (see Appendix 4). Yet it is also clear that the level of support required to place scenario models, or their output, into the hands of citizens is likely to be substantial, perhaps requiring intuitive visualisation and interactive 3D models such as those discussed in Chapter 1. So there is a discussion to be had as to where in the management cycle in figure 8-2 Citizen Science can best contribute and how to efficiently achieve the potential benefits at feasible cost given that, as the ExCites team's experience also suggests, templates hinder the engagement process by pre-supposing what issues the citizens wish to address and how they may be willing to engage. Learning to design templates which avoid this problem will take time and practical experience. While advancing computational power is likely to make more and more models accessible from personal devices for use within a participatory design processes, low tech approaches (paper maps, pens and post it notes), are still the foundation for a process of engagement with people who are not literate in the technology. The very role of being a participant in such an approach will be a learning process for society as a whole, and care must be taken to avoid losing the interest of key individuals and organisations by inadvertently promising more than the science or the technology can deliver.

8.3 References

LÄNSSTYRELSEN 2014. *Här fins höga naturvärden i Skåne - Artpools-och traktanalys med hjäjlp av rödlistde arter*.

SCHWARZ-V.RAUMER, H.-G., STOCKMAN, A. 2014. GeoDesign – Approximations of a Catchphrase *Digital Landscape Architecture.* Zurich, Switzerland.

STEINITZ, C. 2012. *A Framework for Geodesign: Changing Geography by Design,* Redlands, California, USA, ESRI Press.

WILSON, M. W. On the criticality of mapping practices: Geodesign as critical GIS? *Landscape and Urban Planning*.

9 Conclusion

Over all it is clear that a great deal of expertise has been encoded within models of complex environmental systems. Some of these models may be chained together to form even more complex models which, in some circumstances, are helpful to narrow down the range of possibilities from an uncertain future.

Complex integrated models are not, however, generally those of most use to decision makers. While decision makers welcome deeper knowledge, they do not welcome further complexity. Planning does need to develop approaches to handle uncertainty and to consider possible future branches from the development path, but modelling is only useful if it recognises the limitations on how decision makers can take output into account. It is important to be clear whether the model is being used to predict future scenarios out with the parameter space of the empirical evidence or within it. In the latter case, simpler models may suffice which leave more effort for exploratory approaches and iterative GeoDesign.

Participatory methods are useful in reducing conflict, and as such should help Sweden achieve its environmental objectives by helping direct attention to alternative options which conflict less with public opinion or balance resources across priorities. Participation need not involve technology but the process of formalizing qualitative evidence can help understand the system and help predict non-linear responses due to human behaviour, while visualisations can help objectively explain the scientific issues. As with all modelling the complexity of the method must be balanced against benefit and ultimately it is for the planning system to decide how the knowledge gained should influence democratic decision making. However there is a risk of “tokenism” if participant’s opinions do not significantly influence outcomes, thus care must be taken not to use up the social capital and good will of citizens on consultations that lack a clear response mechanism.

Participatory modelling, by definition, needs to be deeply integrated within the community and planning context to which it is applied. There is a strong case however for the provision of standardized tools and methods at some higher organizational level to provide some economy of scale and quality assurance to the process, particularly if less populous regions – which may be responsible for ecosystem services of national importance - are to benefit.

Online provision of modelling tools provides one route but has substantial training implications for the use of all but very basic methods. A network of modelling specialisms between regional and national organisations is another option but ownership of this process needs careful consideration so that model development considers wider input than the remit of their host organisations. Ultimately, however, the cumulative, long term, systemic impacts of many small decisions needs to be delivered and understood locally. Social media, internet applications and citizen science mean that there are options emerging for more interactive, query based, communication of model output which sit between static maps in reports and direct operation of modelling software. A conversation is needed as to how these options can help balance longer term strategic goals against more immediate legal requirements and development objectives.

Rather than build a centralised system based around technology and services, it is perhaps better to introduce scenario models in response to particular challenges, alongside consideration of the planning implications. Addressing each challenge will help build networks, data access, social capital, analytical capacity and experience allowing wider, more integrated questions to be addressed over time. In particular Naturvårdsverket could foster greater adoption of scenario modelling within Swedish environmental planning and governance by:

- Fostering a national network for applied environmental modelling, connecting research, and practice and government agencies.
- Fostering regional networks, including Higher Education bodies, regional government and Länsstryelsen, to share skills, tools and experience in model downscaling and optimisation methods.
- Development of local “hubs” to support ‘level II’ type modelling for priority processes.
- Calling for the removal of financial and intellectual property barriers between public agencies and public data.
- Identifying priority processes in strategic and local planning where modelling is needed and issuing a call to develop specific workflows, guidance, tools and data for this.
- Supporting national standards and tools to help municipalities spatially index all their planning related documents and data.
- Initiating a program of education and support to encourage municipalities and regional authorities to prioritise training *entire teams* on how models may be built into their decision making (i.e. planners and environmental officers not only the GIS specialists) and looking at workflows to facilitate use of modelled scenarios.

Using a ‘process’ approach to infrastructure development, protocols and standards may be applied to encourage compatibility and comparability between models as more interconnected ecosystem services are addressed. In this way modelling capability may be built in parallel with the capacity of the planning system to use that information and as stakeholders gain an understanding of both what environmental modelling is for and how they may have a role to play.

10 Acknowledgements

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11 About the Authors

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12 Appendix 1 – Model/Reference Database

Please contact Naturvårdsverket for enquiries

13 Appendix 2 – Model Tables

A2.2 Agent Based Modelling for Stakeholder Representation In Coupled Socio-Ecological Scenarios

A2.2.1 SUMMARY TABLE OF SELECTED PAPERS AND AGENT BASED MODELS WITH KEY ENVIRONMENTAL OBJECTIVES

Author(s) year	Env. Obj. *	Research Topic	Target Systems	Target Area, Country	Usage Scale	Simulation Time Span	Target Policy/ Phenomenon	Model Calibration	Model Validation	Stakeholder Participation	Template Used
An, Liu et al. 2001	12, 13, 14, 16	rural land-use	human, ecology	2000 km^2 Wolong Nature Reserve, China	Regional	4-6 years	Fuel wood consumption, panda habitat degradation	interview data from local households	yes, simulation predictions (such as fuel wood consumption) tested against out of sample data	interview local households about social attitudes	n/a
Becu, Perez et al. 2003	8, 13, 14, 15	rural land-use	ecological, hydrological and social	43.6 km2area in Northern Thailand, Thailand	Local	10 years	local conflicts caused by use of water and other natural resources	data provided by Thai government, major household survey data, climate data	yes, simulation data checked against actual land use pattern	none	CATCHSCAPE
Bithell and Brasington 2009	8, 9, 12, 13	rural land-use	ecological, hydrological and social	4.1 km^2 catchment area, n/a	Local	6000 years	n/a	hourly rainfall and discharge data, 1:10,000 topographic mapping of the catchment	no	none	n/a

Author(s) year	Env. Obj. *	Research Topic	Target Systems	Target Area, Country	Usage Scale	Simulation Time Span	Target Policy/ Phenomenon	Model Calibration	Model Validation	Stakeholder Participation	Template Used
Caillault, Mialhe et al. 2013	13	rural land-use	farm land, human	n/a	Global, Regional, Local	250 time steps	global, social and local incentive network	n/a	no	n/a	n/a
Gaube and Remesch 2013	1, 15	urban land-use	urban land, residential location choice	Vienna, Austria	Local	50 years (2001-2050)	four urban planning policy scenarios	behavioural survey data, geographical, demographic and economic data	no	none	n/a
Happe, Balmann et al. 2008	13	rural land-use	farm land, human	East Germany (Saxony), West Germany (Baden-Wurttemberg), Germany	Regional	25 years	farm subsidy structure: guaranteed price, compensatory and decoupled payments	data on 12-30 individual local farm such as production capacities, and general data on prices, technical coefficients and costs	no	none	AgriPoliS
Huigen, Overmars et al. 2006	8, 13	rural land-use	farm land, watershed	San Mariano Watershed, the Philippines	Local	100 years (1990-1999)	n/a	Census, historical data and life stories (oral history), geographic	yes, simulation results against actual ethnic proportions	oral histories from elders to gain insight into migration history, reasons for migration	n/a

Author(s) year	Env. Obj. *	Research Topic	Target Systems	Target Area, Country	Usage Scale	Simulation Time Span	Target Policy/ Phenomenon	Model Calibration	Model Validation	Stakeholder Participation	Template Used
										etc.	
Janssen, Walker et al. 2000	13	rural land-use	range land, human	n/a	Local	200 years	conservation, free market, stability, drought relief policy	Historical rainfall and wool price data from 1896 to 1997. The stocking rate, grass biomass and income from 1890	no	n/a	n/a
Lansing and Kremer 1993	8, 13	water management, land use	water networks, human	Bali, Indonesia	Local	25 years	Green Revolution in Bali	geographic, demographic and behavioural data collected on field study	yes, simulation predictions (such as harvest) tested against two years of historical data	local expert knowledge	n/a
Polhill, Gimona et al. 2013	13, 16	rural land-use	farm land, human	n/a	Regional	80 time steps	incentive payment for biodiversity	n/a	no	n/a	n/a
Schlüter and Pahl-Wostl	8, 13, 16	water management	social, irrigation, aquatic	Amudarya River delta in Central Asia, n/a	Local	200 years	centralized and decentralized	geographic	no	none	n/a

Author(s) year	Env. Obj. *	Research Topic	Target Systems	Target Area, Country	Usage Scale	Simulation Time Span	Target Policy/ Phenomenon	Model Calibration	Model Validation	Stakeholder Participation	Template Used
2007							management regimes				
Smajgl and Bohensky 2013	8, 12, 13, 15	rural land-use	farm land, forest, water network, labor market and migration	East Kalimantan, Indonesia	Local	9 years	poverty-alleviation policies such as fuel subsidies and poverty cash payments	household survey, geographic data	no	Iterative: local expert knowledge, sequential validation workshops with local stakeholders	SimPaSi
Torrens and Nara 2007	15	urban land-use	urban land, property market, residential location choice	2.78 km^2 Salt Lake City's Gateway district, The United States	Local	500 months (about 40 years)	gentrification	demographic (census) data such as ethnicity, property data such as property value, size, type and location geographic	no	none	n/a
Valbuena, Verburg et al. 2010	13	rural land-use	farm land, human	600 km^2 rural region in Eastern Netherlands, The Netherland	Regional	20 years	policy protecting small farms	detailed farmer survey, geographic	no	none	n/a

Author(s) year	Env. Obj. *	Research Topic	Target Systems	Target Area, Country	Usage Scale	Simulation Time Span	Target Policy/ Phenomenon	Model Calibration	Model Validation	Stakeholder Participation	Template Used
				s							
Walsh, Messina et al. 2008	8, 12, 13, 15	rural land-use	forest land, non-forest land, urban land, human	20,000 km^2 Northern Ecuadorian Amazon, Brazil	Regional	34 years (1986-2010)	deforestation, urbanization, social transition	demographic (census) data, community survey, GIS geographic input, maps, satellite image	no	none	n/a
Zellner, Page et al. 2009	12, 15	exurban land-use	exurban land, residential location choice	n/a	Local	not say	property tax, lot-size restriction, zoning policy	descriptive data for Southeast Michigan	no	n/a	n/a

* Sweden's Environmental Objectives

1. Reduced climate impact 2. Clean air 3. Natural acidification only 4. A non-toxic environment 5. A protective ozone layer 6. A safe radiation environment 7. Zero eutrophication 8. Flourishing lakes and streams 9. Good-quality groundwater 10. A balanced marine environment, flourishing coastal areas and archipelagos 11. Thriving wetlands 12. Sustainable forests 13. A varied agricultural landscape 14. A magnificent mountain landscape 15. A good built environment 16. A rich diversity of plant and animal life

4	**$10^2 – 10^4$ m**
5	$>10^4$ m
Temporal scale	
1	$<10^0$ days
2	$10^0 – 10^1$ days
3	$10^1 – 10^2$ days
4	$10^2 – 10^3$ days
5	$>10^3$ days

A2.3 Land Use Land Cover Change and Soil Ecosystem Services

A2.3.1 SOIL MODEL DESCRIPTIONS

Model name	AGNPS
Primary publication(s)	Young, R.A., Onstad, C.A., Bosch, D.D., Anderson, W.P., 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. Journal of Soil and Water Conservation 44(2), 168-173. Geter, W.F., Smith, P., Drungil, C., et al., 1995. Hydrologic unit water quality model GIS interface to four ARS water quality models for use by soil conservation service. Edited by: Heatwole, C. Conference: International Symposium on Water Quality Modeling, Orlando, Florida, April 1995 – Proceedings of the International Symposium. ASAE 95(5), 341-347.
Weblink	http://go.usa.gov/KFO
Model class	H
Spatial scale	3, 4
Temporal scale	1, 2
Data demands	Detailed topography, crop & livestock details, nutrient source information and pesticides used. Also soil classes (US system) and specific soil information, and stream cross-section data.
Processing demands	Moderate/high – modern desktop PC should handle it. Written in Fortran 90.
Parameter complexity	High
Output complexity	Program ‘STEAD’ designed as a utility tool for extraction and summarisation of output data file. Difficult to handle directly otherwise.
Availability and cost	Free to download following registration
Input data assumptions	Agricultural land only
Relevance to extreme events	Good relevance, incorporates climate data files and can be made to incorporate extreme weather events.
Degree of empiricism	High, based on observed relationships and pedotransfer functions.
Parallelisation & ‘cloudability’	Difficult to evaluate, probably low. Appears designed to run on a single box, could work just as well on a virtual machine as a desktop. Runs on any system that supports Fortran 90.
Policy/management specificity	Relevant only for investigating impacts of specific management strategies on agricultural land. High relevance for non-point source pollution particularly with pesticides and fertilisers.
Research priority relevance	Good for catchment dynamics, investigating impacts of land use/land cover change and climate change impacts.
Flexibility to environmental conditions	Works in all climatic zones, but does not incorporate snow/ice conditions within model.
Predictive accuracy	Good for runoff rates, sediment transport
Model formulation codes	Respiration rates are user-defined, no decomposition or mineralisation
Other comments	Used for erosion and pollutant transport within watersheds, and runoff rates.
Model name	Agro-C
Primary publication(s)	Huang, Y., Yu, Y., Zhang, W., et al., 2009. Agro-C: A biogeophysical model for simulating the carbon budget of agroecosystems. Agricultural and Forest Metereorology 149(1), 106-129.
Weblink	http://www.sciencedirect.com/science/article/pii/S0168192308002062
Model class	E
Spatial scale	1 (models soil at a specific point)
Temporal scale	1, 2
Data demands	Needs soil C, N, pH, texture for setup, daily temperature & rainfall for running. Requires detailed information for crop submodel, although a lookup table with calibrated values for selected crop types is available. Also requires farm management - planting days, timing and rates of fertilisation, manure inputs and crop residue management.
Processing demands	Moderate, runs quickly on desktop PC.
Parameter complexity	Moderate
Output complexity	Relatively simple, gives distribution of dry mass, carbon and a few other parameters between carbon pools in the soil/crop system.

Availability and cost	Model has not been developed as a software package.
Input data assumptions	Appears to assume flat ground, no lateral flow, atmospheric conditions at sea level. Soil hydrology not considered, and rooting depth appears to be ignored.
Relevance to extreme events	Processes do not consider extreme events and appear limited to standard range of climate conditions.
Degree of empiricism	A large proportion of the model uses rate equations that are based on literature, relatively simple equations that are calibrated from observations.
Parallelisation & 'cloudability'	Potentially very parallelisable, but does not exist as a software package so would need to be coded for such.
Policy/management specificity	Specific to exploring effects of fertilisation and related management on agricultural land.
Research priority relevance	Limited in scope to agriculture, but allows rapid exploration of possible scenarios and could be adapted for different calibrations. Relatively easy to add additional rate equations and process descriptions.
Flexibility to environmental conditions	Relatively flexible, appears applicable within temperate/equatorial climatic conditions.
Predictive accuracy	Good, for the restricted range of parameters given as outputs.
Model formulation codes	G&M, MULT, SIMP, CO
Other comments	
Model name	AMG
Primary publication(s)	Saffih-Hdadi, K., Mary, B., 2008. Modeling consequences of straw residues export on soil organic carbon. Soil Biology & Biochemistry 40(3), 594-607.
Weblink	http://www.uni-giessen.de/cms/fbz/fb09/institute/pflbz2/olb/aktuelles/veranstaltungen/SOMpaticfolder/duparque
Model class	S
Spatial scale	3
Temporal scale	4
Data demands	2
Processing demands	Minimal – fairly simple model.
Parameter complexity	Relatively simple
Output complexity	Relatively simple, SOC split into two compartments only.
Availability and cost	Simeos-AMG decision support tool available upon request, no cost.
Input data assumptions	Agricultural land with field cropping and organic inputs. Stubble always incorporated.
Relevance to extreme events	Not flexible enough to incorporate extreme events.
Degree of empiricism	Model calibration against observations and analyses required, or using a lookup table for specific organic wastes that have been calibrated.
Parallelisation & 'cloudability'	Could be carried out relatively easily, but is not really necessary due to the simplicity and rapidity of the system.
Policy/management specificity	Useful for decision support for land management.
Research priority relevance	Moderate/low
Flexibility to environmental conditions	Moderate. Restricted to subtropical/temperate climates.
Predictive accuracy	Moderate accuracy in calculating soil carbon stocks.
Model formulation codes	GRW, LIN, N/A, CM
Other comments	
Model name	ANIMO
Primary publication(s)	Rijtema, P.E., Kroes, J.G., 1990. Some results of nitrogen simulations with the model ANIMO. Fertilizer Research 27(2-3), 189-198.
Weblink	http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facilities-Products/Software-and-models/ANIMO.htm
Model class	S
Spatial scale	3

Temporal scale	2
Data demands	Moderate – accesses existing maps and time series data, but does require user input to set up the processes. This includes soil moisture, fertiliser management, soil physical and chemical properties and boundary/initial conditions (approximately 80 parameters).
Processing demands	High
Parameter complexity	High
Output complexity	High, over 1000 parameters output relating to soil physical and chemical properties.
Availability and cost	Free for non-commercial use in an academic environment.
Input data assumptions	Mineral soil, agricultural land. A version of the model (SWAP-ANIMO) does work with peat soils.
Relevance to extreme events	Moderate – does not incorporate a number of processes associated with extreme rainfall events (e.g. overland flow) and does not incorporate freeze/thaw.
Degree of empiricism	Calibrated to specific soil units,
Parallelisation & ‘cloudability’	Source code not normally available, although Alterra may make exceptions. Would require significant coding effort.
Policy/management specificity	Highly relevant for scenarios exploring soil and groundwater nitrate, N and P losses from farmland.
Research priority relevance	Relevant for nitrification, nutrient availability and scenario modelling in agricultural land.
Flexibility to environmental conditions	Good, appears able to accommodate all soil types and a wide range of vegetation characteristics.
Predictive accuracy	Accurate for a wide range of parameters, appears to lose accuracy at the ‘high end’ range for nutrient dynamics.
Model formulation codes	N/A, LIN, DIR, IND
Other comments	
Model name	BACWAVE
Primary publication(s)	Zelenev, V.V., van Bruggen, A.H.C., Semenov, A.M., 2000. "BACWAVE," a spatial-temporal model for traveling waves of bacterial populations in response to a moving carbon source in soil. Microbial Ecology 40(3), 260-272.
Weblink	http://download.springer.com/static/pdf/82/art%253A10.1007%252Fs002480000029.pdf?auth66=1406112071_321c6257a33ba9c0d0a60a7570c8f822&ext=.pdf
Model class	M
Spatial scale	1
Temporal scale	1
Data demands	Low
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Not a coded model.
Input data assumptions	Very few assumptions, but the model is very specific
Relevance to extreme events	Unknown
Degree of empiricism	High
Parallelisation & ‘cloudability’	High, but would require coding.
Policy/management specificity	Only relevant to wheat growth, and limited to an exploration of conditions in the soil. This is more a theoretical work exploring root-bacterial interactions.
Research priority relevance	Moderate
Flexibility to environmental conditions	Unknown
Predictive accuracy	Accurate for predicting growth cycle dynamics of bacteria on wheat roots.
Model formulation codes	GRW, MM, N/A, CM
Other comments	

Model name	BATS
Primary publication(s)	Yang, Z.L., Dickinson, R.E., 1996. Description of the biosphere-atmosphere transfer scheme (BATS) for the soil moisture workshop and evaluation of its performance. Global and Planetary Change 13(1-4), 117-134.
Weblink	http://regclim.coas.oregonstate.edu/dynamical-downscaling/model-description/index.html
Model class	G
Spatial scale	1-5
Temporal scale	1
Data demands	High, requires multiple parameters for many different land surfaces. However, there is a lookup table of standardised values for main land cover types.
Processing demands	High
Parameter complexity	High, incorporates a large number of parameters and processes
Output complexity	High
Availability and cost	Model code not available, but outputs available for download. This model is used as part of the RegCM3 Regional Climate Model of the USGS.
Input data assumptions	Soil composed of three layers and only one vegetation layer, so multi-canopy simulations not possible.
Relevance to extreme events	High, although it is not known if it incorporates land cover change over time within a simulation (i.e. the effects of fire, flood or storm damage).
Degree of empiricism	Multiple derived relationships, calibrated through observations.
Parallelisation & ‘cloudability’	High, in fact already achieved as part of climate modelling work.
Policy/management specificity	Highly specific for climate change scenario modelling.
Research priority relevance	High.
Flexibility to environmental conditions	High. Designed to facilitate climate change simulation.
Predictive accuracy	Good to moderate for predicting soil water content in three-layer soil system.
Model formulation codes	G&M, N/A, N/A, N/A
Other comments	
Model name	**CANDY**
Primary publication(s)	Franko, U., Crocker, G.J., Grace, P.R., et al., 1997. Simulating trends in soil organic carbon in long-term experiments using the CANDY model. Geoderma 81(1-2), 109-120.
Weblink	http://ecobas.org/www-server/rem/mdb/candy.html
Model class	S
Spatial scale	1-5
Temporal scale	1
Data demands	Moderate, description of soil physical and organic matter conditions required for setting up. Also requires crop rotation, irrigation and fertilisation information.
Processing demands	Low
Parameter complexity	Low/moderate
Output complexity	Low
Availability and cost	Assumed freely available upon contacting the author.
Input data assumptions	No slope or effects of erosion, cation exchange or other nutrient effects upon organic matter decomposition.
Relevance to extreme events	Low
Degree of empiricism	Fitted to incubation experiment, but only one carbon pool used.
Parallelisation & ‘cloudability’	Would need to be coded.
Policy/management specificity	Low

Research priority relevance	Low
Flexibility to environmental conditions	Unknown
Predictive accuracy	Low/moderate (only one soil C pool and not calibrated to other conditions).
Model formulation codes	N/A, CONS, DIR, IND
Other comments	
Model name	CANTIS
Primary publication(s)	Neel, C., 1996. Modélisation couplée du transfert et des transformations de l'azote: paramétrisation et évaluation d'un modèle en sol nu. Ph.D. Thesis, Université Pierre et Marie Curie, Paris, 276pp. Rodrigo, A., Recous, S., Neel, C., et al., 1997. Modelling temperature and moisture effects on C-N transformations in soils: comparison of nine models. Ecological Modelling 102(2-3), 325-339.
Weblink	http://research.eeescience.utoledo.edu/lees/papers_pdf/Rodrigo_1997_EcolModell.pdf
Model class	S
Spatial scale	3
Temporal scale	2
Data demands	Moderate – requires: initial nitrate, water, carbon, C:N; rainfall, temperature throughout profile.
Processing demands	Moderate – will operate on a standard PC.
Parameter complexity	Low/moderate
Output complexity	Low
Availability and cost	Model description published, but coding required.
Input data assumptions	Uniform texture, no effects of texture on matric potential.
Relevance to extreme events	Uncertainty about accuracy of model under drought conditions.
Degree of empiricism	Low – based on transport & decomposition relationships in the literature.
Parallelisation & 'cloudability'	Potentially high, but not coded.
Policy/management specificity	Relevant for calculations of mineralised nitrate in the soil.
Research priority relevance	Low
Flexibility to environmental conditions	Low
Predictive accuracy	Moderate, comparable with other models.
Model formulation codes	GRW, MM, PAR, INH
Other comments	
Model name	CarboSOIL
Primary publication(s)	Anaya-Romero, M., Muñoz-Rojas, M., Pino, R., Jordán, A., Zavala, L. M., and De la Rosa, D., 2012. Carbosoil, a land evaluation model for soil carbon accounting, EGU General Assembly, Vienna, Austria, 22–27 April, EGU2012-7227, 2012. Muñoz-Rojas, M., 2012. Modelling carbon sequestration capacity in Mediterranean soils, Ph.D. thesis, University of Seville, Spain, 169pp.
Weblink	http://www.biogeosciences.net/10/8253/2013/bg-10-8253-2013.pdf
Model class	E
Spatial scale	Dependent upon input spatial data
Temporal scale	4
Data demands	High: annual temperature/rainfall; topography/erosion parameters; soil (pH, N, texture, BD etc.); land use and carbon.
Processing demands	Moderate (desktop PC)

Parameter complexity	Low
Output complexity	Low (soil carbon at different depths)
Availability and cost	Not obviously available for download, but the authors have produced an application to run within ArcGIS 10.0.
Input data assumptions	Will only work with specified land cover classes (although these are the CORINE classes, so it can be applied across Europe).
Relevance to extreme events	Based on regression equations – if the conditions go outside those previously experienced, the model will not be valid.
Degree of empiricism	High, based on regression equations.
Parallelisation & 'cloudability'	Runs on ArcGIS, so can be operated on a virtual machine. No information about ease of running in parallel.
Policy/management specificity	Highly relevant for exploring the impacts of land use/land cover on soil carbon at a local, regional or international scale.
Research priority relevance	High
Flexibility to environmental conditions	High
Predictive accuracy	High
Model formulation codes	Based on regression equations
Other comments	
Model name	CASA
Primary publication(s)	Potter, C.S., Randerson, J.T., Field, C.B., et al., 1993. Terrestrial ecosystem production – a process model-based on global satellite and surface data. Global Biogeochemical Cycles 7(4), 811-841.
Weblink	https://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5323.php
Model class	G
Spatial scale	5
Temporal scale	3
Data demands	Moderate
Processing demands	Moderate
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Unknown
Input data assumptions	Assumes monthly satellite imagery (AVHRR) is available and consistent.
Relevance to extreme events	Uses monitoring data, so if an extreme event happens it will be recorded and modelled.
Degree of empiricism	High, uses observed relationships between satellite imagery and NPP.
Parallelisation & 'cloudability'	High
Policy/management specificity	Relevant for monitoring global net primary production and other relevant processes such as desertification.
Research priority relevance	Can provide data for a wide range of research purposes.
Flexibility to environmental conditions	High
Predictive accuracy	Model not fully validated but appears reasonable.
Model formulation codes	GRW, LIN, DIR, IND
Other comments	
Model name	CEM
Primary publication(s)	d'Annunzio, R., Zeller, B., Nicolas, M. et al., 2008. Decomposition of European beech (Fagus sylvatica) litter: Combining quality theory and N-15 labelling experiments. Soil Biology & Biochemistry 40(2), 322-333.

	Ågren, G., Bosatta, E., 1998. Theoretical Ecosystem Ecology. Understanding Element Cycles, second ed. Cambridge University Press, Cambridge.
Weblink	https://www.researchgate.net/publication/256853962_Decomposition_of_European_beech_%28Fagus_sylvatica%29_litter_Combining_quality_theory_and_15N_labelling_experiments
Model class	L
Spatial scale	3
Temporal scale	4
Data demands	Litter quality needs to be defined.
Processing demands	Low
Parameter complexity	Low
Output complexity	Low
Availability and cost	Not coded.
Input data assumptions	Assumes forestry leaf litter.
Relevance to extreme events	Effects of extreme temperature, particularly freezing, will not be simulated.
Degree of empiricism	Model parameters adjusted to fit experimental measurements, need to fit model to local data.
Parallelisation & 'cloudability'	Unknown
Policy/management specificity	Useful for estimating carbon sequestration and nutrient turnover in forests.
Research priority relevance	Model of decomposition, carbon and nitrogen incorporation and release
Flexibility to environmental conditions	Low
Predictive accuracy	Good levels of accuracy with closely calibrated models.
Model formulation codes	GRW, LIN, DIR, IND
Other comments	This model will not operate well if site-specific measurements are not available.
Model name	CENTURY
Primary publication(s)	Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils – a model. Biogeochemistry 5, 109–131. Parton,W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic-matter levels in Great-Plains grasslands. Soil Science Society of America Journal 51, 1173–1179.
Weblink	http://nrel.colostate.edu/projects/century5/reference/html/Century/overview.htm
Model class	E
Spatial scale	3
Temporal scale	3
Data demands	Moderate – quite a lot of site description required for model initiation. Detailed management information also required, plus daily weather data.
Processing demands	Relatively high
Parameter complexity	High
Output complexity	High, provided in individual netCDF files
Availability and cost	Free for download
Input data assumptions	Land cover class must be of one of a list of specified types. Model only applicable for grassland, agricultural, forest and savannas.
Relevance to extreme events	Moderately robust, some of the relationships fail under extreme climatic conditions. Does not incorporate flooding of freeze/thaw.
Degree of empiricism	Process submodels based on observed relationships converted to mathematical functions.
Parallelisation & 'cloudability'	Source file available for Windows, could be parallelised relatively easily.
Policy/management specificity	Highly relevant for a range of land management policy questions.

Research priority relevance	High
Flexibility to environmental conditions	High
Predictive accuracy	Good
Model formulation codes	GRW, LIN, DIR, IND
Other comments	Latest versions include additional parameters (P, S)
Model name	CenW
Primary publication(s)	Kirschbaum, M.U.F., 1999. CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. Ecological Modelling 118(1), 17-59.
Weblink	http://www.kirschbaum.id.au/CenW_equations.pdf
Model class	E
Spatial scale	3
Temporal scale	2
Data demands	Moderate, requires daily climate data
Processing demands	High
Parameter complexity	High
Output complexity	High
Availability and cost	Free for download
Input data assumptions	Unknown
Relevance to extreme events	Good
Degree of empiricism	Moderate, a combination of observed and theoretical functions.
Parallelisation & 'cloudability'	Code free to download (Delphi), so could be parallelised.
Policy/management specificity	Relevant for forest management.
Research priority relevance	Relevant for forest management research.
Flexibility to environmental conditions	Good
Predictive accuracy	Moderate/good
Model formulation codes	GRW, LIN, DIR, IND
Other comments	
Model name	CERES
Primary publication(s)	Laryea, K.B., Monteith, J.L., Smith, G.D., 1990. Modelling soil physical processes and crop growth in the semi-arid tropics. Edited by: Ahmad, M., Akhtar, M.E., Nizami, M.I., Proceedings of the International Symposium on Applied Soil Physics in Stress Environments, 22-26 January 1989, Isalamabad, Pakistan, 399-421.
Weblink	http://www.cost734.eu/reports-and-presentations/cost-734-wg4-meeting-in-berlin/CZ_Trnka_CERESmodel.pdf http://ecobas.org/www-server/rem/mdb/ceres-maize.html
Model class	E
Spatial scale	3
Temporal scale	2
Data demands	Moderate, requires standard management, climate and soil information
Processing demands	
Parameter complexity	Moderate
Output complexity	Moderate
Availability and cost	Source code (Fortran) available from authors.

Input data assumptions	Does not factor in the effects of soil carbon content.
Relevance to extreme events	Low, needs to be calibrated to site conditions.
Degree of empiricism	High
Parallelisation & 'cloudability'	Good, but coding required.
Policy/management specificity	Relevant for agricultural yield estimates.
Research priority relevance	Relevant for research into nutrient cycling within agricultural soils.
Flexibility to environmental conditions	Potentially good, but needs calibration for different conditions.
Predictive accuracy	Moderate, better for soil water balance & yield than for nitrogen & soil temperature.
Model formulation codes	GRW, NL, MIT, INH
Other comments	
Model name	CIPS
Primary publication(s)	Kuka, K., Franko, U., Ruhlmann, J., 2007. Modelling the impact of pore space distribution on carbon turnover. Ecological Modelling 208, 295–306.
Weblink	http://www.ufz.de/index.php?en=13897&action=print&print=1
Model class	S
Spatial scale	2
Temporal scale	2
Data demands	Low, similar to RothC in initialisation.
Processing demands	Low/moderate, although requires coupling to the CANDY model.
Parameter complexity	Moderate
Output complexity	Moderate/low
Availability and cost	Contact authors for code.
Input data assumptions	Unknown
Relevance to extreme events	Low
Degree of empiricism	High, model parameters required from field measurements
Parallelisation & 'cloudability'	High
Policy/management specificity	Carbon turnover, storage & sequestration.
Research priority relevance	Useful for improving our understanding of carbon pool dynamics
Flexibility to environmental conditions	Moderate
Predictive accuracy	Moderate
Model formulation codes	GRW, LIN, NA, CM
Other comments	
Model name	CN-SIM
Primary publication(s)	Petersen, B.M., Berntsen, J., Hansen, S., et al., 2005. CN-SIM - a model for the turnover of soil organic matter. I. Long-term carbon and radiocarbon development. Soil Biology & Biochemistry 37(2), 359-374. Petersen, B.M., Jensen, L.S., Hansen, S., et al., 2005. CN-SIM: a model for the turnover of soil organic matter. II. Short-term carbon and nitrogen development. Soil Biology & Biochemistry 37(2), 375-393.
Weblink	http://www.sciencedirect.com/science/article/pii/S0038071704003128
Model class	S

Spatial scale	2, 3
Temporal scale	2, 3
Data demands	Moderate, requires soil temperature, pressure potential and organic amendment regime.
Processing demands	Moderate
Parameter complexity	Moderate
Output complexity	Low, mostly organic matter pool sizes.
Availability and cost	Coded in C++, but the code is not available to download.
Input data assumptions	Topsoil only, so impacts of and interactions with soil at depth are not considered.
Relevance to extreme events	Low
Degree of empiricism	Low, based on pedotransfer functions with some calibration.
Parallelisation & 'cloudability'	High
Policy/management specificity	Carbon, nitrogen dynamics and availability.
Research priority relevance	High relevance for soil carbon and nitrogen dynamics.
Flexibility to environmental conditions	High, but does not consider freeze/thaw.
Predictive accuracy	Good, tested in Scandinavian conditions.
Model formulation codes	G&M, LIN, NA, DIR, INH
Other comments	
Model name	Community Land Model
Primary publication(s)	Boisserie, M., Shin, D.W., Larow, T.E., et al., 2006. Evaluation of soil moisture in the Florida State University climate model - National Center for Atmospheric Research community land model (FSU-CLM) using two reanalyses (R2 and ERA40) and in situ observations. Journal of Geophysical Research-Atmospheres 111(D8), Article Number D08103.
Weblink	http://www.cesm.ucar.edu/models/clm/
Model class	G
Spatial scale	3
Temporal scale	2
Data demands	High
Processing demands	High
Parameter complexity	High
Output complexity	High
Availability and cost	Free to download. Code access restricted to close collaborators.
Input data assumptions	Uses specific land cover and climate classes.
Relevance to extreme events	High
Degree of empiricism	High, contains a lot of empirical relationship information.
Parallelisation & 'cloudability'	
Policy/management specificity	Interactions between climate change, ecology and soil systems.
Research priority relevance	High
Flexibility to environmental conditions	High
Predictive accuracy	Moderate, depends on coupling with other submodels of the CCSM.
Model formulation codes	G&M, NL, SIMP, MIX

Other comments	This model is the land component of the Community Climate System Model (CCSM).
Model name	Coup-Model
Primary publication(s)	Mellander, P.E., Laudon, H., Bishop, K., 2005. Modelling variability of snow depths and soil temperatures in Scots pine stands. Agricultural and Forest Meteorology 133(1-4), 109-118. Jansson, P-E., Moon, D., 2001. A Coupled model of water, heat and mass transfer using object orientation to improve flexibility and functionality. Environmental Modelling & Software 16(1), 37-46.
Weblink	http://www2.lwr.kth.se/CoupModel/index.html
Model class	H
Spatial scale	2
Temporal scale	1
Data demands	Fertilisation management and a large number of soil properties are required. However, a database is provided that gives ranges. This data is largely derived from arable land in Sweden. Also requires weather data.
Processing demands	Moderate/high
Parameter complexity	High
Output complexity	Moderate
Availability and cost	Free to download
Input data assumptions	Unknown
Relevance to extreme events	Moderate
Degree of empiricism	A combination of theory and empirical calibrations.
Parallelisation & 'cloudability'	High
Policy/management specificity	Relevant for soil hydrology and the impacts of different management practices.
Research priority relevance	Moderate/high
Flexibility to environmental conditions	High
Predictive accuracy	Moderately good
Model formulation codes	Uses a flexible approach that allows the user to specify processes
Other comments	
Model name	CQESTR
Primary publication(s)	Rickman, R.W., Douglas, C.L., Albrecht, S.L., et al., 2001. CQESTR: a model to estimate carbon sequestration in agricultural soils. Journal of Soil and Water Conservation 56(3), 237-242. Liang, Y, Gollany, H.T., Rickman, R.W., Albrecht, S.L., Follett, R.F., Wilhelm, W.W., Novak, J.M., Douglas, C.L., 2008. CQESTR simulation of management practice effects on long-term soil organic carbon. Soil Sci. Soc. Am. J. 72:1486-1492.
Weblink	http://www.ars.usda.gov/Main/docs.htm?docid=13499
Model class	S
Spatial scale	2
Temporal scale	1-2
Data demands	Weather, biomass additions, composition of plant residues, soil properties and management regime information.
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Algorithms available but code does not seem to be freely available to download.

Input data assumptions	Assumes mineral soils
Relevance to extreme events	Calibrated to long-term studies, extreme events will go outwith the bounds of the model.
Degree of empiricism	Moderate, uses theoretical relationships calibrated to observations.
Parallelisation & 'cloudability'	High, if the code can be acquired.
Policy/management specificity	Highly relevant to carbon storage/sequestration in arable soils.
Research priority relevance	Relevant to soil carbon dynamics in agricultural soils.
Flexibility to environmental conditions	High, recently adapted to tropical as well as temperate conditions.
Predictive accuracy	High
Model formulation codes	GRW, NL, MIT, CM
Other comments	

Model name	**CREAMS**
Primary publication(s)	Platford, G.G., 1983. The use of the CREAMS computer model to predict water, soil and chemical losses from sugarcane fields and to improve recommendations for soil protection. Proceedings of the Annual Congress, South Africa Sugar Technologists' Association 57, 144-150.
Weblink	http://www.tucson.ars.ag.gov/unit/Publications/PDFfiles/312.pdf
Model class	H
Spatial scale	3
Temporal scale	2
Data demands	Soil characteristics, weather data, topography, pesticide and fertiliser regime.
Processing demands	High
Parameter complexity	High
Output complexity	High
Availability and cost	Later adaptations of the model, including SWIM (http://www.pik-potsdam.de/~valen/swim_manual/swim-chapter1.pdf) are available for download.
Input data assumptions	Mineral soils only.
Relevance to extreme events	Moderate/low
Degree of empiricism	Low – based on hydrodynamic theory with some calibration from field measurements.
Parallelisation & 'cloudability'	Possible, but coding would be required.
Policy/management specificity	Chemical runoff and erosion in agricultural land.
Research priority relevance	Very relevant for a lot of agricultural catchment research.
Flexibility to environmental conditions	High
Predictive accuracy	Good
Model formulation codes	GRW, NL, MIX, INH
Other comments	
Model name	CREEP
Primary publication(s)	Rosenbloom, N.A., Doney, S.C., Schimel, D.S., 2001. Geomorphic evolution of soil texture and organic matter in eroding landscapes. Global Biogeochemical Cycles 15, 365–381.
Weblink	http://www.cgd.ucar.edu/ccr/aboutus/staff/nanr/creep/indexCreep.html
Model class	H
Spatial scale	3
Temporal scale	5
Data demands	Topography, soil structure & organic composition.
Processing demands	Moderate
Parameter complexity	Low
Output complexity	Moderate
Availability and cost	Compiled program available, source code possibly not.
Input data assumptions	Mineral soils only.
Relevance to extreme events	Low – ignores extreme weather events.
Degree of empiricism	High
Parallelisation & 'cloudability'	High, although code may not be available.
Policy/management	Soil erosion and formation in relation to biological activity.

specificity	
Research priority relevance	Soil formation processes.
Flexibility to environmental conditions	Moderate, assumes gentle slopes and vegetated landscapes.
Predictive accuracy	Unknown
Model formulation codes	NA, LIN, NA, CM
Other comments	
Model name	DAISY
Primary publication(s)	Hansen, S., Jensen, H.E., Nielsen, N.E. et al., 1991. Simulation of nitrogen dynamics in the soil-plant system using the Danish simulation model DAISY. Edited by: Kienitz, G., Milly, P.C.D., Van Genuchten, M.T. et al. Conference: Hydrological interactions between atmosphere, soil and vegetation. IAHS Publication 204, 185-195.
Weblink	http://code.google.com/p/daisy-model/
Model class	E
Spatial scale	3
Temporal scale	2
Data demands	Hourly or daily weather data, management information, soil characteristics.
Processing demands	High, but runs on a PC
Parameter complexity	High
Output complexity	High
Availability and cost	Free to download.
Input data assumptions	Assumes homogenous fields with no horizontal flow.
Relevance to extreme events	Moderately good, but the lack of horizontal flow restricts relevance in extreme weather event scenarios.
Degree of empiricism	Theoretical submodels calibrated from observations.
Parallelisation & 'cloudability'	High
Policy/management specificity	Relevant for investigating the effects of land management on a wide range of soil and soil water characteristics.
Research priority relevance	High, can be used to study a wide variety of processes and their interactions.
Flexibility to environmental conditions	High
Predictive accuracy	Good
Model formulation codes	G&M, LIN, DIR, IND
Other comments	
Model name	DAYCENT
Primary publication(s)	Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Shaffer, M.J., Ma, L., Hansen, S. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management. Lewis Publishers, pp. 303–332.
Weblink	http://www.nrel.colostate.edu/projects/daycent/
Model class	E
Spatial scale	3
Temporal scale	2
Data demands	Cropping, management and other landscape details (e.g. fire) required in formatted input files, also daily weather data and site parameterisation. Setting up requires detailed specifications.
Processing demands	Moderate/high
Parameter complexity	High

Output complexity	High, but given in structured output files.
Availability and cost	Available for download.
Input data assumptions	Unknown, but a number of assumptions are made about processes taking place.
Relevance to extreme events	Good, has been designed to accommodate extreme weather events.
Degree of empiricism	Uses a wide variety of calibrated and theoretical functions to describe processes.
Parallelisation & 'cloudability'	Moderate, would need recoded.
Policy/management specificity	Highly relevant to a lot of agricultural management and policy objectives.
Research priority relevance	High
Flexibility to environmental conditions	High
Predictive accuracy	Moderate
Model formulation codes	GRW, LIN, DIR, CN
Other comments	
Model name	**DEMETER**
Primary publication(s)	Foley, J.A., 1995. An equilibrium-model of the terrestrial carbon budget. Tellus Series B – Chemical and Physical Meteorology 47, 310–319.
Weblink	http://ecobas.org/www-server/rem/mdb/demeter_soil_mod.html
Model class	G
Spatial scale	5
Temporal scale	5
Data demands	Distribution of climate and plant functional types.
Processing demands	Moderate
Parameter complexity	Moderate
Output complexity	Low, gives estimates of a number of carbon pools and NPP
Availability and cost	Description available but code access is unknown.
Input data assumptions	Unknown
Relevance to extreme events	Operates at a longer timescale than extreme events, so not relevant.
Degree of empiricism	Functions parameterised from observations
Parallelisation & 'cloudability'	High
Policy/management specificity	Useful for global carbon cycling and budgeting.
Research priority relevance	Carbon budgets at national and global scale.
Flexibility to environmental conditions	High
Predictive accuracy	Good
Model formulation codes	GRW, LIN, NA, CM
Other comments	
Model name	**DHSVM**
Primary publication(s)	Nijssen, B., Haddeland, I., Lettenmaier, D.P., 1997. Point evaluation of a surface hydrology model for BOREAS. Journal of Geophysical Research-Atmospheres 102(D24), 29367-29378.
Weblink	http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/
Model class	H

Spatial scale	4
Temporal scale	1
Data demands	Requires topography, weather and vegetation data across the landscape of interest.
Processing demands	Moderate
Parameter complexity	High, incorporates hydrological interactions with atmosphere, vegetation, soil and also includes temperature and other environmental factors.
Output complexity	Moderate
Availability and cost	Source code available for free
Input data assumptions	Water drainage through the landscape stays within the soil; no percolation to bedrock.
Relevance to extreme events	High, relevant for modelling water flow in extreme weather events including flooding.
Degree of empiricism	Moderate, based on robust hydrological theory and known physical interactions between water and the landscape.
Parallelisation & 'cloudability'	High, could be split into landscape sections for large-scale modelling.
Policy/management specificity	Highly relevant for modelling the effects of climate and climate change on landscape hydrology, including soil moisture.
Research priority relevance	High
Flexibility to environmental conditions	High, assuming vegetation conditions can be parameterised correctly. Would not work on extremely steep or fragmented landscapes.
Predictive accuracy	Good, when appropriate grid sizes are used (model works better with smaller grids).
Model formulation codes	GRW, NA, NA, NA
Other comments	This is more of a hydrological model than a soil model, but it does have strong relevance to soil moisture scenario modelling across landscapes.
Model name	DNDC
Primary publication(s)	Li, C.S., Frolking, S., Frolking, T.A., 1992. A model of nitrous-oxide evolution from soil driven by rainfall events. 1. Model structure and sensitivity. Journal of Geophysical Research-Atmospheres 97(D9), 9759-9776.
Weblink	http://www.dndc.sr.unh.edu/
Model class	E
Spatial scale	3
Temporal scale	1
Data demands	Requires climate, soil, vegetation and management descriptions
Processing demands	Moderate
Parameter complexity	Moderate
Output complexity	Moderate
Availability and cost	Executable available for free, but code is not freely available
Input data assumptions	Assumes agriculture as standard, with limitations on types of soil amendments.
Relevance to extreme events	Low – does not consider the impacts of extreme weather events on soil.
Degree of empiricism	Moderate
Parallelisation & 'cloudability'	Moderate
Policy/management specificity	Relevant for modelling soils in agricultural systems.
Research priority relevance	Useful for exploring the impacts of land management options on agricultural land.
Flexibility to environmental conditions	Good, within agricultural settings. Can be applied globally.
Predictive accuracy	Good, within target conditions.
Model formulation codes	G&M, NL, DIR, INH
Other comments	Can be run either for local sites or spatially, and exists in various versions including one for forestry (FOREST-DNDC) and one for wetland (WETLAND-DNDC).

Model name	DRAINMOD-DSSAT
Primary publication(s)	Negm, L.M., Youssef, M.A., Skaggs, R.W., et al., 2014. DRAINMOD-DSSAT model for simulating hydrology, soil carbon and nitrogen dynamics, and crop growth for drained crop land. Agricultural Water Management 137, 30-45.
Weblink	http://www.bae.ncsu.edu/soil_water/documents/Drainmod.Model.Use.Calibration.And.Validation.pdf
Model class	H
Spatial scale	3
Temporal scale	1
Data demands	Weather data (hourly) and other climatic data; soil properties and other site descriptors. Also, the model requires calibration to site conditions.
Processing demands	Depends on the size of the area being modelled, but
Parameter complexity	Moderate
Output complexity	Moderate
Availability and cost	Code freely available
Input data assumptions	Assumes an impermeable layer at a user-specified depth.
Relevance to extreme events	Limited to hourly timestep, so flash flooding cannot be accurately modelled.
Degree of empiricism	Moderate, based on calibrated equations.
Parallelisation & 'cloudability'	Already done, with a version for mainframes written in Fortran.
Policy/management specificity	Useful for modelling hydrology of poorly and artificially drained soils.
Research priority relevance	Soil hydrology in poorly drained soils.
Flexibility to environmental conditions	Good
Predictive accuracy	Good, provided sufficiently accurate calibration can be carried out.
Model formulation codes	NA, NA, NA, NA
Other comments	Other versions of this model exist, including DRAINMOD-FOREST

Model name	DSSAT
Primary publication(s)	Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.L., White, J.W., Uryasev, O., Royce, F.S., Ogoshi, R., Gijsman, A.J., Tsuji, G.Y., Koo, J., 2012. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii. Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. DSSAT Cropping System Model. European Journal of Agronomy 18:235-265.
Weblink	http://dssat.net/
Model class	I
Spatial scale	User-defined
Temporal scale	1, 2
Data demands	Daily weather data, soil information, crop management
Processing demands	Moderate/high
Parameter complexity	Moderate/high
Output complexity	Moderate, gives information about balances of water, carbon and nitrogen daily
Availability and cost	Can be downloaded for free
Input data assumptions	Specific crop types required, but many are included in the available options.
Relevance to extreme events	Low, does not incorporate erosion.
Degree of empiricism	Depends upon the models implemented within the framework.
Parallelisation & 'cloudability'	Low, operates using code designed for a desktop.

Policy/management specificity	Specifically designed to allow scenarios of land management to be explored.
Research priority relevance	Useful for scenario modelling and also as a teaching tool.
Flexibility to environmental conditions	High, can be applied to conditions across the globe.
Predictive accuracy	Depends on the models implemented
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	DyDOC
Primary publication(s)	Michalzik, B., Tipping, E., Mulder, J., et al., 2003. Modelling the production and transport of dissolved organic carbon in forest soils. Biogeochemistry 66(3), 241-264.
Weblink	http://www.academia.edu/4851634/194_Modelling_the_production_and_transport_of_dissolved_organic_carbon_in_forest_soils
Model class	S
Spatial scale	3
Temporal scale	2
Data demands	Site-specific soil characteristics and weather data
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Code not available
Input data assumptions	Assumes that the soil is composed of three horizons, so cannot explore outside this constraint.
Relevance to extreme events	Moderate to low, does not incorporate many of the effects of extreme weather, e.g. erosion and surface runoff.
Degree of empiricism	Developed using experimental data.
Parallelisation & 'cloudability'	Unknown
Policy/management specificity	Low relevance to policy objectives.
Research priority relevance	Can be used to explore the DOC outputs of forest soils.
Flexibility to environmental conditions	Low, based on its assumptions about soil type and land cover.
Predictive accuracy	Moderate
Model formulation codes	GRW, LIN, NA, CM
Other comments	

Model name	**ECOSSE**
Primary publication(s)	Smith, J., Gottschalk, P., Bellarby, J., et al., 2010. Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. Climate Research 45(1), 179-192.
Weblink	http://www.scotland.gov.uk/Publications/2007/03/16170508/0
Model class	E
Spatial scale	2
Temporal scale	1
Data demands	Moderate, needs detailed climate, soil and management information
Processing demands	Moderate/high
Parameter complexity	High
Output complexity	High
Availability and cost	Code not available
Input data assumptions	Uses predefined vegetation classes, but can use user-defined classes also.
Relevance to extreme events	Moderate, does not incorporate processes radically altering soil such as erosion, and uses a relatively simply hydrology component.
Degree of empiricism	Based on relationships that are calibrated from empirical data.
Parallelisation & 'cloudability'	High, if code is made available.
Policy/management specificity	Broadly applicable to agricultural/grassland scenario modelling in multiple soil types.
Research priority relevance	Scenario modelling of land management and climate change impacts on soil.
Flexibility to environmental conditions	Moderate, more applicable to temperate than tropical or frozen soils.
Predictive accuracy	Moderate/high
Model formulation codes	G&M, MULT, MIX, MIX
Other comments	
Model name	EPIC
Primary publication(s)	Becker, H., 1983. Soil productivity modelling through EPIC. Agricultural Research 31(9), 4-7. Jones, C.A., Cole, C.V., Sharpley, A.N., Williams, J.R., 1984. A simplified soil and plant phosphorus model .1. Documentation. Soil Science Society of America Journal 48, 800–805. Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the ASAE 27, 129–144.
Weblink	http://epicapex.tamu.edu/epic/
Model class	E
Spatial scale	3
Temporal scale	2
Data demands	Moderate, requires standard soil and daily climate data
Processing demands	Moderate
Parameter complexity	High
Output complexity	High
Availability and cost	Executables free to download, code not available.
Input data assumptions	Assumes agricultural conditions, designed for use in the US but transferable to other countries.
Relevance to extreme events	Moderate, includes effects of surface runoff and erosion processes.
Degree of empiricism	Moderate
Parallelisation & 'cloudability'	Unknown, as code is not available.

Policy/management specificity	Can be used to assess impacts of agricultural management on different soils, in terms of crop productivity and soil erosion.
Research priority relevance	High, allows land management options to be explored and described both in terms of biophysical and socioeconomic factors.
Flexibility to environmental conditions	High, can simulate many different crop types and climate/soil conditions.
Predictive accuracy	Moderate/high
Model formulation codes	GRW, NL, MIT, MIX
Other comments	This is actually a cropping systems model but it contains a lot of information and processes relevant to soil erosion.
Model name	EUROSEM
Primary publication(s)	Morgan, R.P.C., 1994. The European soil erosion model: an update on its structure and research base. Edited by: Rickson, R.J. Conserving soil resources: European perspectives. Selected papers from the First International Congress of the European Society for Soil Conservation, 286-299.
Weblink	http://www.es.lancs.ac.uk/people/johnq/EUROSEM.html
Model class	H
Spatial scale	3, 4
Temporal scale	1
Data demands	Rainfall data, topography and surface roughness at high resolution.
Processing demands	Moderate
Parameter complexity	Moderate/high
Output complexity	Moderate, gives information about sediment transport and water movement over the time of simulation.
Availability and cost	Freely available for download, including code.
Input data assumptions	Unknown
Relevance to extreme events	High, can be used to simulate extreme rainfall events and their impact on soil erosion.
Degree of empiricism	High; based on experimental results and field observations
Parallelisation & ‘cloudability’	Coded in Fortran, so potentially could be parallelised.
Policy/management specificity	Could be incorporated into considerations of land management impact on soil health and fertility.
Research priority relevance	The effects of extreme rainfall events on soil under different land cover types.
Flexibility to environmental conditions	High
Predictive accuracy	Moderate/good
Model formulation codes	NA, NA, Na, NA
Other comments	
Model name	HOST
Primary publication(s)	Boorman, D.B., Hollis, J.M., Lilly, A., 1995. Hydrology of Soil Types: a hydrologically-based classification of the soils of the United Kingdom - IH Report 126.
Weblink	http://www.ceh.ac.uk/products/publications/documents/ih126hydrologyofsoiltypes.pdf
Model class	H
Spatial scale	3
Temporal scale	NA
Data demands	Soil horizon classification maps
Processing demands	Low
Parameter complexity	Low/moderate
Output complexity	Low; consists of maps of specific soil hydrology categories
Availability and cost	The description of the model is freely available, but it is not coded.
Input data assumptions	Assumes similarity of characteristics such as permeability for specific soil horizon types.
Relevance to extreme events	Moderate, can accommodate processes such as runoff but does not consider soil erosion.

Degree of empiricism	High, based on field observations.
Parallelisation & 'cloudability'	High, if coded.
Policy/management specificity	Important in relation to flood risk assessments and other factors of soil hydrology
Research priority relevance	Useful as a tool for modelling catchment hydrology.
Flexibility to environmental conditions	High, although the original model is designed for Northern European soils and so would not accommodate tropical soils.
Predictive accuracy	Good
Model formulation codes	NA, NA, NA, NA
Other comments	This is a classification of soil types rather than a dynamic model, but it is based on a number of conceptual models and does provide a framework for integrating multiple types of knowledge about soil hydrology and for producing assessment maps.
Model name	IBIS
Primary publication(s)	Kucharik, C.J., Foley, J.A., Delire, C., Fisher, V.A., Coe, M.T., Lenters, J.D., Young-Molling, C., Ramankutty, N., Norman, J.M., Gower, S.T., 2000. Testing the performance of a Dynamic Global Ecosystem Model: Water balance, carbon balance, and vegetation structure, Global Biogeochemistry Cycles 14(3), 795-826, 10.1029/1999GB001138.
Weblink	http://en.wikipedia.org/wiki/Integrated_Biosphere_Simulator
Model class	G
Spatial scale	4
Temporal scale	2
Data demands	Climate, topography, soil and land cover characteristics required.
Processing demands	High
Parameter complexity	High
Output complexity	High
Availability and cost	Free to download
Input data assumptions	Unknown
Relevance to extreme events	Moderate/high
Degree of empiricism	Mixed, some calibrated submodels and some theoretical relationships.
Parallelisation & 'cloudability'	Would need to be rewritten for parallelisation.
Policy/management specificity	Broad policy relevance including land management, climate change and agricultural productivity.
Research priority relevance	Potentially useful as a tool for modelling complex interactions and feedback processes within the landscape.
Flexibility to environmental conditions	High, designed to allow modelling at the global scale and incorporate any environmental conditions.
Predictive accuracy	Good, in comparison with other dynamic global ecosystem models.
Model formulation codes	GRW, LIN, DIR, CN
Other comments	IBIS is a model of the terrestrial biosphere but has a strong soil component.
Model name	ICBM
Primary publication(s)	Andren, O., Katterer, T., 1997. ICBM: The introductory carbon balance model for exploration of soil carbon balances. Ecological Applications 7(4), 1226-1236.
Weblink	http://www.oandren.com/ICBM/1-55.pdf
Model class	S
Spatial scale	2-3
Temporal scale	2-4
Data demands	Daily weather data, crop types, soil water release function, manure application data.
Processing demands	Low
Parameter complexity	Moderate

Output complexity	Low (soil carbon pool sizes)
Availability and cost	Does not appear to be available
Input data assumptions	Assumes soil carbon is composed of only two pools.
Relevance to extreme events	Low, assumes normal growing conditions for crops.
Degree of empiricism	Calibrated to regional data
Parallelisation & 'cloudability'	Low – code not available. Relatively easy to code from model description, however.
Policy/management specificity	Allows exploration of land management on soil carbon pool size.
Research priority relevance	Relevant to soil carbon budget research.
Flexibility to environmental conditions	Good, provided input data (e.g. crop and soil parameters) can be parameterised.
Predictive accuracy	Moderate
Model formulation codes	GRW, LIN, DIR, IND
Other comments	
Model name	INCA
Primary publication(s)	Wade, A.J., Whitehead, P.G., Butterfield, D., 2002. The Integrated Catchments model of Phosphorus dynamics (INCA-P), a new approach for multiple source assessment in heterogeneous river systems: model structure and equations. Hydrol Earth Syst Sci 6, 583–606.
Weblink	http://www.reading.ac.uk/geographyandenvironmentalscience/research/INCA/
Model class	S
Spatial scale	4
Temporal scale	2
Data demands	Topography, soil and vegetation parameters required; also climate.
Processing demands	Moderate
Parameter complexity	High, includes many parameters and processes within soil, water and vegetation in the catchment.
Output complexity	Moderate/high – daily time series data for flow and concentrations, daily pollution loads. Can be selected by the user as appropriate.
Availability and cost	Available as a Windows executable, code not available.
Input data assumptions	Unknown
Relevance to extreme events	Moderate, does not incorporate erosive effects.
Degree of empiricism	Unknown
Parallelisation & 'cloudability'	Unknown, code not available. Could be run on the cloud.
Policy/management specificity	Different versions can be used to look at transport and fate of a number of different soil nutrients and elements.
Research priority relevance	Can be used to investigate a wide range of soil/catchment issues and questions.
Flexibility to environmental conditions	Good, although has not been tested on tropical or desert conditions.
Predictive accuracy	Good, varies somewhat with different parameters.
Model formulation codes	NA, CONS, SIMP, IND
Other comments	Model exists in a range of versions for different parameters of interest.
Model name	KINEROS2
Primary publication(s)	Smith, R.E., Goodrich, D.C., Quinton, J.N., 1994. Dynamic, distributed simulation of watershed erosion – the KINEROS2 and EUROSEM models. Journal of Soil and Water Conservation 50(5), 517-520.
Weblink	http://www.tucson.ars.ag.gov/kineros/
Model class	H
Spatial scale	2, 3 – depends on user specification
Temporal scale	1
Data demands	Requires information about soil depth, existing moisture content and permeability, and rainfall data from multiple gauges (or simulation data)

Processing demands	Depends on size of study area – could be very high for complex landscapes.
Parameter complexity	High
Output complexity	Simple in terms of parameters, high in terms of the number of cells
Availability and cost	Free to download
Input data assumptions	Assumes precipitation is rainfall, not snow.
Relevance to extreme events	High, can accommodate sudden rainfall events.
Degree of empiricism	Low/medium, a lot of the hydraulic flow is expressed using differential equations based on hydraulic theory.
Parallelisation & 'cloudability'	This is a distributed model, meaning that it is applicable for parallel processing.
Policy/management specificity	Suitable for exploring the risk of flooding in urban watersheds, while at the same time incorporating soil hydrology.
Research priority relevance	High for urban planning and development.
Flexibility to environmental conditions	Moderate – does not seem to consider vegetative effects on soil.
Predictive accuracy	Good at smaller scales, not so good with larger scales or large watersheds.
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	LISEM
Primary publication(s)	DeRoo, A.P.J., Offermans, R.J.E., Cremers, N.H.D.T., 1996. LISEM: A single-event, physically based hydrological and soil erosion model for drainage basins .2. Sensitivity analysis, validation and application. Hydrological Processes 10(8), 1119-1126. DeRoo, A.P.J., Wesseling, C.G., Ritsema, C.J., 1996. LISEM: A single-event physically based hydrological and soil erosion model for drainage basins .1. Theory, input and output. Hydrological Processes 10(8), 1107-1117.
Weblink	http://blogs.itc.nl/lisem/
Model class	H
Spatial scale	2, 3 depending on user requirements
Temporal scale	1
Data demands	DEM and rainfall data required, also land cover and soil parameters.
Processing demands	Moderate
Parameter complexity	High, many different hydrological and soil processes included
Output complexity	Moderate
Availability and cost	Free to download
Input data assumptions	Unknown
Relevance to extreme events	High, incorporates multiple soil/hydrological processes related to extreme events.
Degree of empiricism	Processes based on a combination of theory and empirical relationships.
Parallelisation & 'cloudability'	This was under development, as of 2012.
Policy/management specificity	Runoff, soil erosion and flooding
Research priority relevance	Relevant for landscape development and land management research.
Flexibility to environmental conditions	High
Predictive accuracy	Better for runoff than soil erosion.
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	MAGIC
Primary publication(s)	Cosby, B.J., Hornberger, G.M., Galloway, J.N., Wright, R.F., 1985. Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and stream chemistry. Water Resources Research, 21, 51-63. Jenkins, A., Ferrier, R.C., Cosby, B.J., 1997. A dynamic model for assessing the impact of coupled sulphur and nitrogen deposition scenarios on

	surface water acidification. Journal of Hydrology 197, 111-127.
Weblink	http://www.ceh.ac.uk/sci_programmes/magic.html
Model class	S
Spatial scale	1
Temporal scale	4
Data demands	Soil mineral composition and organic matter, atmospheric deposition and climate.
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Code not available, would have to be constructed from model description.
Input data assumptions	Assumptions are made about the nature of atmospheric deposition.
Relevance to extreme events	Low
Degree of empiricism	High
Parallelisation & ‘cloudability’	Unknown
Policy/management specificity	Soil and water chemistry model.
Research priority relevance	Examination of the effects of acid deposition on soil and water chemistry.
Flexibility to environmental conditions	Moderate, designed for soils in Europe
Predictive accuracy	Moderate
Model formulation codes	GRW, CONS, MIT, CO
Other comments	
Model name	MBL-GEM
Primary publication(s)	Rastetter, E. B., Ryan, M.G., Shaver,G.R., Melillo, J.M., Nadelhoffer, K.J., Hobbie, J.E., Aber, J.D., 1991. A general biogeochemical model describing the responses of the C and N cycles in terrestrial ecosystems to changes in CO_2, climate and N deposition. Tree Physiology 9:101-126. Le Dizès, S., Kwiatkowski, B.L., Rastetter, E.B., Hope, A., Hobbie, J.E., Stow, D., Daeschner, S. 2003. Modeling biogeochemical responses of tundra ecosystems to temporal and spatial variations in climate in the Kuparuk River Basin (Alaska). Journal of Geophysical Reseach D - Atmospheres 108(D2), 8165. doi:10.1029/2001JD000960.
Weblink	http://ecosystems.mbl.edu/Research/Models/gem/welcome.html
Model class	E
Spatial scale	3
Temporal scale	4
Data demands	Requires detailed climate information and some soil inputs for setup.
Processing demands	Moderate
Parameter complexity	High
Output complexity	Moderate/high
Availability and cost	Free to download
Input data assumptions	No interaction between adjacent grid cells.
Relevance to extreme events	Low
Degree of empiricism	High
Parallelisation & ‘cloudability’	Feasible
Policy/management specificity	Useful for carbon sequestration scenario modelling.
Research priority relevance	General ecosystem model, so useful for investigating feedbacks of specific environmental changes.
Flexibility to environmental conditions	High

Predictive accuracy	Moderate
Model formulation codes	GRW, LIN, MIT, INH
Other comments	
Model name	**MILLENIA**
Primary publication(s)	Heinemeyer, A., Croft, S., Garnett, M.H., Gloor, E., Holden, J., Lomas, M.R., Ineson, P., 2010, The MILLENNIA peat cohort model, predicting past, present and future soil carbon budgets and fluxes under changing climates in peatlands. *Climate Research* 45(1), 207-226.
Weblink	http://www.int-res.com/articles/cr_oa/c045p207.pdf
Model class	E
Spatial scale	1
Temporal scale	5
Data demands	Climate data (long term, 10,000 years)
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Code not available
Input data assumptions	Assumes historical climate data determined using other research is accurate.
Relevance to extreme events	Low
Degree of empiricism	High, based on empirical research from the literature.
Parallelisation & 'cloudability'	Could be done, but probably unnecessary.
Policy/management specificity	Carbon storage/sequestration in peat.
Research priority relevance	Research into the effects of climate change on peat carbon storage.
Flexibility to environmental conditions	Moderate, relationships expressed could not explore dramatic climatic shifts in some directions.
Predictive accuracy	Moderate for estimation of carbon accumulation in peat.
Model formulation codes	G&M, NL, DIR, IND
Other comments	
Model name	**MONICA**
Primary publication(s)	Nendel, C., Berg, M., Kersebaum, K.C., Mirschel, W., Specka, X., Wegehenkel, M., Wenkel, K.O., Wieland, R., 2011. The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics, Ecological Modelling 222(9), 1614-1625.
Weblink	http://monica.agrosystem-models.com/en
Model class	E
Spatial scale	1
Temporal scale	1, 2
Data demands	Land management, soil, climate details required
Processing demands	Moderate
Parameter complexity	High
Output complexity	Moderate/high
Availability and cost	Free to download
Input data assumptions	Assumes agricultural land.
Relevance to extreme events	Low, does not include erosion or overland flow.
Degree of empiricism	Process codes based on calibrated relationships and some theory.
Parallelisation & 'cloudability'	Source code not available, so would be difficult.
Policy/management specificity	Crop yield estimates under different management and climate scenarios
Research priority relevance	Land use management impacts; carbon storage and sequestration; climate change impacts.

Flexibility to environmental conditions	High, incorporates snow and supports a wide range of crop types and environmental conditions.
Predictive accuracy	Moderate
Model formulation codes	G&M, NL, MIX, INH
Other comments	
Model name	N14C
Primary publication(s)	Tipping, E., Rowe, E.C., Evans, C.D., Mills, R.T.E., Emmett, B.A., Chaplow, J.S., Hall, J.R., 2012. N14C: A plant–soil nitrogen and carbon cycling model to simulate terrestrial ecosystem responses to atmospheric nitrogen deposition. Ecological Modelling 247, 11-26.
Weblink	http://nora.nerc.ac.uk/19678/
Model class	S
Spatial scale	1
Temporal scale	4
Data demands	Mean annual temperature and precipitation, N deposition
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Moderate
Availability and cost	Code not available.
Input data assumptions	Assumes one of four broad vegetation functional types.
Relevance to extreme events	Low
Degree of empiricism	Moderate, requires calibration with measurements from study site.
Parallelisation & 'cloudability'	Unknown
Policy/management specificity	Effects of N deposition on soil carbon and nitrogen cycling.
Research priority relevance	Leaching from agricultural soils.
Flexibility to environmental conditions	Moderate
Predictive accuracy	Good if site is well parameterised for model calibration.
Model formulation codes	G&M, NL, MIX, MIX
Other comments	
Model name	Roth-C
Primary publication(s)	Coleman, K., Jenkinson, D.S., 2014. RothC - A model for the turnover of carbon in soil. Model description and users guide (Windows version) (updated June 2014).
Weblink	http://www.rothamsted.ac.uk/sites/default/files/users/kcoleman/RothC_guide_WIN.pdf
Model class	S
Spatial scale	3
Temporal scale	4
Data demands	Monthly temperature, rainfall, evaporation; soil clay content and vegetation characteristics; manure additions.
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low
Availability and cost	Free to download
Input data assumptions	Assumes a mineral soil type.
Relevance to extreme events	Low
Degree of empiricism	Moderate; relationships calibrated to observations.
Parallelisation & 'cloudability'	Could be coded for parallel processing quite easily.

Policy/management specificity	Soil carbon storage and sequestration.
Research priority relevance	Useful for 'spinning up' more sophisticated soil models.
Flexibility to environmental conditions	Moderate
Predictive accuracy	GRW, LIN, NA, CM
Model formulation codes	A more recent version of this model, RothPC-1, has additional parameterisations and processes included.
Model name	SCOPE
Primary publication(s)	van der Tol, C., Verhoef, W., Timmermans, J., Verhoef, A., Su, Z., 2009. An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. Biogeosciences 6, 3109–3129.
Weblink	http://www.biogeosciences.net/6/3109/2009/bg-6-3109-2009.pdf
Model class	G
Spatial scale	1
Temporal scale	1
Data demands	Top of canopy incident radiation at high spectral resolution.
Processing demands	Low
Parameter complexity	High
Output complexity	Moderate – outgoing spectral radiation at high spectral resolution
Availability and cost	Model implemented in Matlab, need to ask authors for code.
Input data assumptions	Assumes modular model components of plant radiative transfer are accurate.
Relevance to extreme events	Low
Degree of empiricism	Low, based on theory of radiative transfer
Parallelisation & 'cloudability'	Possible.
Policy/management specificity	Monitoring of vegetation condition.
Research priority relevance	Unknown.
Flexibility to environmental conditions	Moderate, requires extensive parameterisation.
Predictive accuracy	Good
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	SOMKO
Primary publication(s)	Gignoux, J, House, J., Hall, D., Masse, D., Nacro, H.B., Abbadie, L., 2001. Design and test of a generic cohort model of soil organic matter decomposition: the SOMKO model. Global Ecology and Biogeography 10(6), 639–660. DOI: 10.1046/j.1466-822X.2001.t01-1-00250.x.
Weblink	http://onlinelibrary.wiley.com/doi/10.1046/j.1466-822X.2001.t01-1-00250.x/abstract
Model class	S
Spatial scale	3
Temporal scale	2
Data demands	Organic matter input rates
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Low/moderate (size of different soil organic matter pools)
Availability and cost	Code not available, would have to be developed from model description.
Input data assumptions	Does not take into account variations in soil microbial functional groups.
Relevance to extreme events	Low
Degree of empiricism	High, relationships are based on calibrated parameters.

Parallelisation & 'cloudability'	If coded, would be possible.
Policy/management specificity	Soil organic carbon sequestration
Research priority relevance	Soil organic carbon sequestration
Flexibility to environmental conditions	High, but requires parameterisation.
Predictive accuracy	Good
Model formulation codes	G&M, NL, DIR, INH
Other comments	
Model name	SUNDIAL
Primary publication(s)	Smith, J.U., Bradbury, N.J., Addiscott, T.M., 1996. SUNDIAL: A PC-based system for simulating nitrogen dynamics in arable land. Agronomy Journal 88,38-43.
Weblink	http://www.rothamsted.ac.uk/aen/sundial/sundial.htm
Model class	S
Spatial scale	3
Temporal scale	3
Data demands	Soil, crop and management details, and weekly rainfall, temperature and evapotranspiration data.
Processing demands	Low
Parameter complexity	Moderate
Output complexity	Moderate
Availability and cost	Executable available upon request
Input data assumptions	Designed for crops common to the UK, not valid for tropical crop types.
Relevance to extreme events	Low, does not incorporate relevant processes.
Degree of empiricism	Uses parameterised and calibrated theoretical relationships.
Parallelisation & 'cloudability'	Code not available, would be difficult.
Policy/management specificity	Impacts of land management upon nitrate leaching.
Research priority relevance	Nitrate leaching into the soil and the fate of fertilisers added to the soil.
Flexibility to environmental conditions	Good, within a relatively small range.
Predictive accuracy	Moderate to good, depending upon the scenario being investigated.
Model formulation codes	GRW, LIN, DIR, INH
Other comments	
Model name	SWAT
Primary publication(s)	Arnold, J.G., Allen, P.M., Bernhardt, G., 1993. A comprehensive surface-groundwater flow model. Journal of Hydrology 142(1-4), 47-69.
Weblink	http://swat.tamu.edu/
Model class	H
Spatial scale	4
Temporal scale	2
Data demands	High, requires a lot of input data relating to soil, vegetation, management and climate.
Processing demands	High
Parameter complexity	High
Output complexity	High
Availability and cost	Multiple versions available for download, depending upon requirements.
Input data assumptions	Catchment is subdivided into uniform hydrological response units.
Relevance to extreme events	High

Degree of empiricism	Based on calibrated submodels.
Parallelisation & 'cloudability'	Existing versions of the software may not run on parallel devices, but certainly it could be run in the cloud.
Policy/management specificity	Soil erosion control.
Research priority relevance	Impacts of land management on soil erosion.
Flexibility to environmental conditions	Good
Predictive accuracy	Good, if input data is accurate.
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	TOUGHREACT-N
Primary publication(s)	**Maggi, F., Gu, C., Riley, W.J., Hornberger, G.M., Venterea, R.T., Xu, T., Spycher, N., Steefel, C., Miller, N.L., Oldenburg, C.M., 2008. A mechanistic treatment of the dominant soil nitrogen cycling processes: Model development, testing, and application. Journal of Geophysical Research: Biogeosciences 113(G2).**
Weblink	http://onlinelibrary.wiley.com/doi/10.1029/2007JG000578/pdf
Model class	S
Spatial scale	2
Temporal scale	2
Data demands	Needs field data for calibration
Processing demands	Low
Parameter complexity	Moderate, examines multiple chemical species involved in nitrogen cycling.
Output complexity	Moderate
Availability and cost	Code not available
Input data assumptions	Assumes constant saturation rate at depth, no lateral flow.
Relevance to extreme events	Low
Degree of empiricism	High, calibrated against field measurements.
Parallelisation & 'cloudability'	Unknown
Policy/management specificity	Nitrogen leaching in soils.
Research priority relevance	Effects of land management on soil nitrogen cycling.
Flexibility to environmental conditions	Moderate, depending on model calibration and parameterisation.
Predictive accuracy	Moderate
Model formulation codes	GRW, NN, NA, IND
Other comments	
Model name	WATEM
Primary publication(s)	Van Oost, K., Govers, G., Desmet, P.J.J., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecology 15(6), 579-591.
Weblink	http://www.kuleuven.be/geography/frg/modelling/erosion/watemsedemhome/
Model class	H
Spatial scale	User dependent
Temporal scale	User dependent
Data demands	Requires topography, land cover, soil and vegetation parameters.
Processing demands	Moderate, runs using GIS software (Idrisi)
Parameter complexity	Moderate
Output complexity	Low; sediment export and deposition information.
Availability and cost	Free to download

Input data assumptions	Has a restricted number of land cover classes.
Relevance to extreme events	Moderate
Degree of empiricism	Uses field-measurement calibrated equations.
Parallelisation & 'cloudability'	Low
Policy/management specificity	Estimation of soil loss through erosion.
Research priority relevance	Scenario modelling of catchment management.
Flexibility to environmental conditions	Moderate
Predictive accuracy	Moderate/good
Model formulation codes	NA, NA, NA, NA
Other comments	
Model name	Yasso
Primary publication(s)	Liski, J., Palosuo, T., Peltoniemi, M., Sievänen, R., 2005. Carbon and decomposition model Yasso for forest soils. Ecological Modelling 189(1–2), 168-182.
Weblink	http://www.sciencedirect.com/science/article/pii/S0304380005002012
Model class	S
Spatial scale	3
Temporal scale	4
Data demands	Litter addition rates to the soil, litter composition information.
Processing demands	Low
Parameter complexity	Moderate, but does require quite a lot of site-specific calibration.
Output complexity	Moderate
Availability and cost	Should be available to download from www.environment.fi, but link appears to be broken.
Input data assumptions	Ignores some of the processes involved in organic matter stabilisation and decomposition.

Model formulation code legend

Respiration model	
GRW	Growth respiration
MNT	Maintenance respiration
G&M	Both growth and maintenance respiration
CO	Respiration defined to compensate stoichiometric imbalances
Decomposition model	
CONS	Constant rate
LIN	Linear model with respect to C_S
LINB	Linear model with respect to C_B
MULT	Multiplicative model
MM	Michaelis-Menten model
NL	Other nonlinear or mixed formulations
Mineralisation scheme	
DIR	Direct hypothesis
MIT	Mineralisation-Immobilisation Turnover

PAR	Parallel hypothesis
MIX	Other schemes with simultaneous mineralisation and immobilisation
SIMP	Simplified model or regression equation (no microbial stoichiometry)
N-limitation model	
CM	C-only (or dry weight-only) models neglecting N dynamics
IND	No N-limitation
INH	Inhibition factors
CO	Carbon overflow
CN	N-limitation effects on microbial or substrate C/N
MIX	Multiple N-limitation effects are considered

A2.5 Land Use Land Cover Change and Marine Ecosystem Services

A2.5.3 KEY FEATURES OF MARINE PHYSICAL MODELS THAT HAVE BEEEN USED IN SCENARIOS RELATED TO MARINE EUTROPHICATION, POLLUTION, BIOGEOCHEMICAL CYCLING, AND ECOSYSTEM STATUS

Model	Scenarios/General description	Resolution / applications	Operation	/Cost/ availability	Organisation / File download information
Coupled ECHAM6/MPIO(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and	Describe in climate scenarios the atmospheric and ocean-sea ice components of the MPI Earth system model (also including a tidal component). Also used in downscaling scenarios	T63 horizontal resolution (approximately 1.875° on a Gaussian grid) with 47 vertical levels in MPI-ESM-LR, and 95 levels in MPI-ESM-MR/ Global-regional	1.1Gb in ‘EXTRA’ or 1.25 GB in NetGDF for a 10 year annual mean.	Public domain /MPI-M Software License Agreement	Max Planck Institute for Meteorology (MPIM) http://www.mpimet.mpg.de/en/wissenschaft/modelle/echam/echam5.html (Jungclaus et al., 2013)

Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)(Li and Heap, 2014, Wild and Roeckner, 2006, Stier et al., 2006, Roeckner et al., 2006, Manzini et al., 2006, Hagemann et al., 2006, Roeckner et al., 2003)					
GETM (General estuarine circulation model) (Burchard and Bolding, 2002, Stips et al., 2004, Stips, 2005, Burchard et al., 2012)	Simulate hydrodynamics and sediment transport at the land-coastal sea interface/3D numerical hydrodynamic baroclinic model (flooding/drying, a *k*-ε turbulence closure model, momentum advection, mass conservation and the general vertical coordinates. The horizontal curvi-linear coordinates can be implemented to simulate, tidal rivers (e.g. Elbe River).	Grid s of 600 m 390 subdomains each of size 30 x 30 cells in the horizontal and 50 levels in the vertical.	12 hours to simulate one year in the North-German Supercomputing Alliance (HLRN).	Public domain	http://www.getm.eu/
GOTM	1-D water column model for marine and		PROTEX tool embedded	Public domain	Baltic Sea Research Institute Warnemünde,

(General Ocean Turbulence Model) (Umlauf et al., 2006, Aveytua-Alcázar et al., 2008)	limnological applications, sediment transport and the dynamics of sea grass in coastal waters.		in FORTRAN code /community based software environment		Dept. for Physical Oceanography and Instrumentation http://www.gotm.net/
MOM **(Modular Ocean Model)**	Numerical ocean climate model based on the hydrostatic primitive equations using generalized horizontal coordinates, assumed to be locally orthogonal. The latest version enables an interactive Lagrangian parcel scheme, with parcels dynamically coupled to the traditional Eulerian grid cell properties.	1 nm spatial resolution / Several ocean and coastal regional applications supported by test cases (including the Baltic Sea)	community code	open-source software-model	NOAA/GFDL-Princeton Univers ity Forrestal Campus http://www.gfdl.noaa.gov/mom-ocean-model
NEMO **(Nucleus for European Modelling of the Ocean)** (Levier et al., 2007, Madec, 2008, PHAM et al., 2014)	Ocean engine of the NEMO modelling coupled with sea-ice, biogeochemistry, adaptive mesh refinement, and assimilation components. It is designed for operational oceanography seasonal forecast and climate studies. Prognostic variables are the 3-D velocity field, a linear or non-linear sea surface height, temperature and salinity.	Horizontal direction: curvilinear orthogonal grid Vertical direction: a full or partial step z-coordinate, or s-coordinate, or a mixture of the two. Distribution of variables: Arakawa C-type grid.	FORTRAN 90 / use of coding standard close to the ECMWF rules, named DOCTOR	Public domain (CeCILL license)	CNRS, MetOffice, NERC, INVG, Meractor Ocean, CMCC http://www.nemo-ocean.eu/ (Madec, 2008)
OCCAM **(Ocean Circulation and Climate Advanced Model)** (Booij et al., 1999, Webb et al., 1998, Coward and De Cuevas, 2005)	Primitive equation numerical model of the global ocean used in climate scenarios. It is based on the GFDL Modular Ocean Model Array version of the Bryan-Cox-Semtner ocean model but includes a free surface and improved advection schemes	Horizontal: 1/4 ^{o} grid Vertical: 36 levels ranging in thickness from 20m near the surface to 255m at a depth of 5500m / use of Arakawa-B grid in the horizontal and level surfaces in the vertical	OCCAM output data is stored in HDF format.	Public domain	National Oceanography Centre, Southampton http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__DPT_592586a6-0455-11e0-af69-00e081470265
RCAO **Rossby Centre Atmospheric-Ocean** **(SWECLIM)** **Swedish Regional Climate Modelling Program** (Doscher et al., 2002)	3-D coupled regional model system set up for climate studies in n. Europe and as part of the Swedish Regional Climate Modelling Program. The component models are the Rossby Centre Atmospheric (RCA) and Ocean (RCO) coupled via the OASIS coupler. RCO for can be forced for hind-cast runs either by calculating surface fluxes form observations, or by an interactive flux coupling to the RCA.	RCA resolution: 44 km and time-step is 30 minutes. RCO resolution: 6 nm with 41 vertical levels (3 m to 12 m level thickness) Baroclinic time-step=10 minutes			Rossby Centre
SWAN (Booij et al., 1999)	Third generation wave model. It accounts for Wave generation by wind, Dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud. Output includes significant wave height and wave periods, dissipation, wave-induced force etc.	computations can be made on a regular, a curvilinear grid and a triangular mesh in a Cartesian or spherical coordinate system	Fortran90	GNU General Public License	Delft University of Technology http://swanmodel.sourceforge.net/download/download.htm
WAM	2-D Wave prediction and analysis model,	Global: 0.5 x 0.5	For a global	Freely available	Royal Netherlands Meteorological Institute

(Group, 1988)	which computes directional spectra of random short-crested wind-generated waves, based on the energy density balance equation. It solves the complete action density equation, including non-linear wave - wave interactions. The model is forced by time series of wind fields at 10 m above sea surface, wave spectra at open boundaries, currents and water level fields. Output includes Significant Wave Height (m) and direction, Swell Height (m) and direction. The model runs on a spherical latitude-longitude grid and can be used in any ocean region.	Regional (Mediterranean): 0.5X0.05	run 20 min cpu time is needed for a ten day forecast for a 3 o by 3 o lat - lon grid , 26 frequencies , 12 directions and 512 gridpoints in a block.		(KNMI) http://www.dkrz.de/Nutzerportal-en/doku/imdi/workflow-models/?searchterm=WAM
HadCM3H (Pope et al., 2000, Palmer and Totterdell, 2001)	Coupled climate model that has been used extensively for climate prediction, detection and attribution, and other climate sensitivity studies. It is a hydrostatic model. It uses an Eulerian advection scheme. The ocean model incorporates a thermodynamic-dynamic sea ice model with primitive equations	Atmospheric model: 2.5° latitude by 3.75° longitude grid and 19 model levels, and a 30-min timestep. Ocean model: 1.25 × 1.25 degrees, 20 levels, and a timestep of one hour. It uses an Arakawa B grid and hybrid vertical co-ordinates		British Atmospheric Data Centre (BADC) at the BADC is open to all academic researchers, the only requirement is that the user has electronically accepted the Met Office conditions of use, as part of the LINK dataset requirements	Hadley Centre for Climate Prediction and Research – MetOffice http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_12024019658225569
SLIM-EC2 **Second-generation Louvain-la-Neuve Ice-ocean Model** (Gourgue et al., 2013, Elskens et al., 2014, de Brauwere et al., 2014b, Dagnelie, 2014)	It is a 2nd generation hydro-environmental model solving the governing equations on unstructured meshes using the discontinuous Galerkin finite element method. It consists of a 1D river model, a 2D depth averaged model and 3D barotropic/baroclinic model.				http://sites.uclouvain.be/slim/index.php?id=24
TELEMAC-3D (Bedri et al., 2013)	3-D hydrodynamic model using a finite element unstructured grid. This allows selective refinement of the mesh at key locations in the domain and boundary fitting. Favourable features include sigma transformation method for vertical		FORTRAN	Free under GPL-v2	National Laboratory of Hydraulics and Environment of Electricité de France http://www.opentelemac.org/index.php/presentation?id=18

	discretisation; density-driven hydrodynamics allowing for a robust treatment of the stratified plume; heat exchange with the atmosphere; the availability of a range of options for vertical turbulence modelling (e.g. facility to incorporate a user-defined subroutine to fine tune the vertical temperature and salinity profiles to measurements); provision of a subroutine for the modelling of source/sink of tracers.				

A2.5.4 MAJOR APPROACHES FOR DESCRIBING NUTRIENT TRANSPORT FROM LAND TO SEA ALONG THE RIVER-SEA CONTINUUM

Model / approach	Resolution	Description	Model Input	Basic equations for Nutrient/Contaminant export load(ExLOAD)	State Variables	Examples
Global NEWS Hybrid /Steady state: Mass balance approach based on regression of nutrient inputs with measured runoff; generally these	Catchment, 0.5 X0.5^o Annual	Independently formulated sub-models based on multiple linear regressions and several single-regressions. For dissolved forms inputs into rivers are assessed from fluxes estimated from models (transport, diffusion, deposition) and existing national and regional socioeconomic and land use information allowing for source apportionment to total export; the design allows for extrapolation of particulate nutrient loads where such measurements are lacking. River basin information taken from the STN-30p global river system dataset. In NEWS2 regression in each sub-model is based on spatially explicit characterisation of the river basin and particulate nutrients are estimated using empirical relationship with suspended sediment concentration; source apportionment is possible for both dissolved and particulate nutrients	Land use, Catchment size (A), runoff (R), Reservoir (lake or dam) size (D), water abstraction (IR), point sources (PS), diffuse sources (DS), including fertiliser/manure application, precipitation, N-fixation, N-uptake by vegetation. Calibrated parameters: α=in-stream retention; β=catchment retention. River basin information taken from the STN-30p global river system dataset.	*ExLOAD*= a.f(A,D,IR).[DS.β.f(R)+ PS)]	DIN, DON, DOC, DIP, DSi	(Seitzinger et al., 2005, Alexander et al., 2007, Strokal et al., 2014, Mayorga et al., 2010)
MONERIS Conceptual/1-D	Catchment, >50k^2 (version 3 <50km2) Annual	GIS-oriented model with sub-models that simulate main generation and transport processes and pathways: groundwater, erosion, overland flow for dissolved nutrients, tile drainage, atmospheric deposition, urban areas, point sources. It includes a scenario manager to calculate effects of measures on nutrient emissions	Land use, runoff (partitioned), point sources (PS), diffuse sources (DP) as e.g. soil N surplus, and management alternatives n(land use changes, soil conseravtion, mitigation). Calibrated parameters: α= retention in each transport pathway	ExLOAD=∑(for all pathways) a.f(residence time).[DS,+PS)	DIN, DON, DIP, PON, POP, POC, Si	(Behrendt, 2000, Artioli et al., 2005, Palmeri et al., 2005, Behrendt et al., 2007b, Behrendt et al., 2007a,

SPARROW Semi-distributed, hybrid	Reach to catchment (multiple scales) Annual	Hybrid with deterministic incorporation of non-linear physical based functions and statistical in that calibration is based on statistical fit between modelled and observed data	Catchment data: Temperature, precipitation, slope, soil permeability, stream network density and wetland area. Drainage network: runoff, channel size (cz), time of travel (tt). Constituent sources: N in precipitation, nutrients in fertilisers, livestock nutrient wastesnutrients in urban and rural runoff. From diffuse (DS) and point (PS) sources used to to calculate upstream load (UL). Calibrated parameters: α=in-stream retention, β=catchment retention	ExLOAD in each reach= a.f(cz, tt).[DS.β.f(R)+PS+UL)]	TP, TN, Organic Carbon, Suspended sediment, dissolved solids (salinity)	(Roberts et al., 2009, Brakebill et al., 2010, Roberts and Prince, 2010)
SWAT Process-based, semi-distributed or fully distributed	Catchment Day	Hydrological model used to predict nutrients cycles in agricultural catchments. It is also used to assess the effectiveness of best management practices and alternative management policies. The model uses sub-catchments, land use and soil type discetisations: areas with the same soil type and land use are assumed to have the same response.	Weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer.	Description of water, nutrients, and persticide trasport; mixing equations and parametric relationships for catchment processes (river network)	Nitrates, Ammonia, dissolved organic N, Particulate organic N)	(Rollo and Robin, 2010, Samaras and Koutitas, 2014)
HSPF Process-based, semi-distributed or fully distributed	Catchment from 1 minute to 1 day	Hydrological model useed to assess the effects of land use change, reseravoir operations, point or nonpoint source treatment alternatives, flow diversions. The model simulates runoff, interflow, baseflow, snowpack depth, snowmelt, evapotraspiration, groundwater recharge, pH, temperature, pollutant transport pathways (sediment by particle size, channel routing, reservoir routing, constituent routing). It can simulate any period from a few minutes to hundreds of years.	Meteorologic data: precipitation evapotranspiration, snowmelt (air temperature, dewpoint temperature, wind, and solar radiation), water-quality (air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point sources, pesticide applications), land area, channels, and reservoirs.	Hundreds of process algorithms based in theory, laboratory experiments and empirical relationships	dO2, BOD, Sediment, pesticides, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic P, phytoplankton, and zooplankton	(Hunter and Walton, 2008, Park et al., 2008); Skahill, 2004

RIVERSTRAHLER/SENEQUE Process-based, semi-distributed or fully distributed	Drainage network, 100 to 100,000 km^2 or more 10-Day	The Riverstrahler approach is mainly used to evaluate the effect of general measures concerning urban wastewater treatment on coastal marine eutrophication processes. It is a GIS based approach (interfaced with SENEQUE) using a simplified characterisation of the drainage network of large regional basins, together with a distributed representation of stream microbiology to estimate of nutrient fluxes at the outlet. A favourable feature is the representation of part of the catchment as a regular scheme of confluence of tributaries, thus shortening calculation time in large river basins. The approach has been adapted (interfaced with SENECAM) to adress erosion or cattle waste management pressures, for which a very high spatial resolution is required.	Meteorologic data: precipitation and estimates of evapotranspiration, snowmelt (air temperature, dewpoint temperature, wind, and solar radiation), water-quality (air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point and nonpoint emissions from each land use class)	Mathematical representation of each process	sediment, nitrates, Ammonia, dissolved organic N, Particulate organic N, P, Si, organic C, bacteria, algae, zooplankton	(Garnier et al., 2002, Sferratore et al., 2005, Cugier et al., 2005, Ruelland et al., 2007, Lancelot et al., 2007, Lancelot et al., 2009, Lancelot et al., 2011)
AQUATOX Process-based semi-distributed model		Water quality/Ecosystem model used in 1. assessing which of several stressors is causing observed biological impairment; 2. determining effects of land use changes on aquatic life (e.g. linkage with BASINS); and 3.developing numeric nutrient targets based on desired biological endpoints . It links environmental fate of pollutants with their direct and indirect effects on the resident organisms.	Biological processes: Photosynthesis, Food consumption, Respiration, Growth and reproduction, Natural mortality and mortality from high temperature, low dissolved oxygen, or salinity, Trophic interactions, ecological Changes, biogeochemical cycles involved in the transport of pollutants (Nutrient cycling and oxygen dynamics, Bioconcentration and bioaccumulation). Multiple AQUATOX river, lake, reservoir, or estuarine segments are linked into a single simulation of flow and the passage of state variables from segment to segment.		Algae (multiple species); aquatic vegetation (multiple species); Plankton and benthos (multiple species); fish (multiple species); Nutrients and dO2 Organic and inorganic sediment;20 Toxic organic chemicals;	(Park et al., 2008)

AVGWLF (after 2011 upgraded to **MapShed**) Hybrid, semi-distributed		**AVGWLF, upgraded as Mapshed is used in assessing of the effects of best management practice (BMP) implementation on pollutant load reduction and for this it is used the federally (USA)-mandated "total maximum daily load" (TMDL) studies. The model is composed of the catchment model Generalized Watershed Loading Functions (GWLF), integrated with an ArcView interface to allow for easier and more accurate extraction of input data to the model. The surface loading component of the model assumes that the land cover and soil characteristics are homogeneous within each source area, however it permits multiple source areas (distributed parameter model). The subsurface loading component applies a water balance approach for the unsaturated and saturated subsurface zones treating groundwater as one source (lumped parameter model). The new software (MapShed) is upgraded to a free GIS tool (MapWindow, see www.mapwindow.org). Model's major advantage is its simplicity compared to SWAT, HSPF, etc.**	**MapShed simulates pathogen loads, pollutant transport processes in urban settings and flow processes. Dissolved nutrient loads are computed from rural runoff, groundwater, septic systems, and point sources from rural or urban runoff or stream bank erosion (using a ctachment-specific lateral erosion rate). Mandatory input shapefiles include: weather station point data, catchment boundaries, river networks, soil data polygons, elevation grid, land use/cover. Optional shapefile input data include locations of point sources (point data), tile drain (polygon data), numbers and types of septic systems (polygon data), locations of water abstraction points (point data), unpaved roads and map of roads (line data), animal density (polygon data), hydrological parameters (polygon data); optional grid file input data include groundwater-Nitrogen, and Soil-Phosphorus.**	**Algorithms for simulating most of the main mechanisms influencing nutrient fluxes within a catchment**	**nutrient, sediment, and bacteria loads**	**(Volf et al., 2013, Strobl et al., 2009)** **Evans et al., 2008**

A2.5.5 OPERATING REQUIREMENTS OF THE MODELS DESCRIBED IN A2.5.4

Model	Operating requirements	Cost / availability	Web site (manual, developer, datasets, download)
Global NEWS/ NEWS2	Python	Freely available	http://marine.rutgers.edu/globalnews/index.htm
Moneris	C# Software MONERIS 3.0 System software: Microsoft Windows XP or Windows 7; Microsoft .NET Framework 2.0 MONERIS Import tool ArcGIS Desktop 9.3 Service Pack 1 whit .Net Support; ArcGIS 9.3.1 (also supported), Spatial Analyst extension Hardware 3 GB RAM memory (4 GB or more recommended); about 100 MB free hard disk (without data); display resolution: 1024 x 768	open software under a GNU General Public *Licence* *(*Version3 soon to be released)	http://www.moneris.igb-berlin.de/index.php/moneris-30.html
SPARROW	SAS (Statistical Analysis System Institute) software components, supported by Windows NT or higher; Hardware 64MB display resolution: 800X600	Freely available	http://www.water.usgs.gov/nawqa/sparrow
RIVERSTRAHLER (SENEQUE)			http://www2.mumm.ac.be/emosem/methodology/river-basin-model.php
AQUATOX		Freely available	http://www2.epa.gov/exposure-assessment-models/aquatox
HSPF	Fortran 77 HSPF, HSPNODSS, WDM, ADWDM, and UTIL libraries from LIB required to recompile	Freely available	http://water.usgs.gov/software/HSPF/
SWAT	LINUX, Windows	Freely available	http://swat.tamu.edu/
AVGWLF (after 2011 MapShed)	Free GIS tool MapWindow	Freely available	http://www.mapshed.psu.edu/

A2.6 Flood and Climate Modelling for Urban Eco-System Services

A2.6.1 Water Flow Models And Integrated Assessment Models

Name of model	Type of model	Objective	Spatial scale	Calculations	Input data (main)	Input data (additional)	Simulated time frame and time resolution for simulation	Output presentation	Primary Enironmental Objectives
'Bath Tub'	GIS	Sea Innundation	Any	Spatial extent of a flood at a given height above sea level	Digital Elevation Model & Sea level prediction	Land cover or other infrastructure of concern.	Minimal	Map	Potential danger to life, housing, crops, habitats, transport links..
Cost Path Flooding	GIS	Sea Innundation	Local to regional	Takes into account potential barriers to sea inundation for areas below the predicted flood level.	Digital Elevation Model & Sea level prediction	Land cover or other infrastructure of concern.	Minutes – hours depending on DEM resolution and area.	Map	Potential danger to life, housing, crops, habitats, transport links..
Simple Dynamic Innundation Model	GIS + Code	Sea Innundation / Lake Overflow	Local to regional	Similar to Cost path, but more factors may be included to determine where water flows (e.g. momentum of water)	Digital Elevation Model & Sea level prediction. Calibration parameters	Land cover or other infrastructure of concern.	varies	Map	Potential danger to life, housing, crops, habitats, transport links..
MIKE	CFD	Storm surge, overland	Local	Flow is modelled as an uncompressible liquid, using dynamic drivers and as such	Depening on the application : DEM, DSM, tidal storm surge	Land cover or other infrastructure of concern.	varies	Map, stats, graphs	Potential danger to life, housing,

		flow, momentum dispersion, tidal potential, soil erosion, pollutant dispersal an more		it is relevant to complex terrain with funnel effects	prediction data, bathymetry, landcover momentum dispersal callibration data. Land cover or other infrastructure of concern, stream discharge rates, wind data, ground water level data, ground absorbtion parameters.				crops, habitats, transport links..Pollution. Erosion
TELEMAC	CFD	Storm surge, overland flow, momentum dispersion, soil erosion, pollutant dispersal and more			Depending on the application : DEM, DSM, Geometry, Bathymetry, Boundary Conditions, and Friction more	Land cover or other infrastructure of concern.	varies	Map, stats, graphs	Potential danger to life, housing, crops, habitats, transport links. Pollution, Erosion.
DIVA	Ecological Landscape Spatial Simulation	Sea Inndation, Ecosystem Response Economic impact	Regional	Coastal nnundation model plus eestimates of impact on various socio-economic and bio-physical variables	DEM, landcover, sea level estimates plus application related data. Data Included or accessed via integrated online database link.		unknown	Maps, stats, graphs	Strategic estimates of how many people, habitats etc may be affected by different sea levels and spatial plans.

SimClim	Ecological Landscape Spatial Simulation Model Framwork	Many applications e.g. storm water, coastal inundation, drought impact, agricultural change impact.			SIMClim is a modeling framework rather than a model itself. So the inputs depend on the application. In this context it appears to use shoreline response time (in years), closure distance from the shoreline (m) and DEM. May also use depth of material exchange or closure depth (m), dune height (m) and residual shoreline movement (m/year). *MAGICC and IPCC data compatible.*	Inbuilt extreme events likelihood estimator but this needs historical data or inbuilt estimates can be used.	unknown	Maps, stats, graphs	Strategic estimates of how many people, habitats etc may be affected by different sea levels, dourght events or rain storms.
Flow Accumulation Curve Numberes	Parametric	Rate of accumulation and output per catchment	Catchment	Catchment flow response range.				Peak flow accumulation volume (can be estimated spatially in a GIS)	Effect of land cover change on catchment water flow rates – only works within historical parameter space.
2D Flow Accumulation	GIS	Peak flow or total accumulation over	Local to regional	Catchment flow response and potentially prediction from physical model parameters of future	DEM, rainfall estimates, Opt: ground absorbtion index.		Varies by area and DEM resolution but usually minutes to hours.	Peak flow accumulation. If or absoption friction	Potential danger to life, housing, crops,

		space.		states.				params used then total accumulation at time t can also e estimated.	habitats, transport links. Effect of green infrastructure and LID.
Low Impact Drainage	Various (See (Elliott and Trowsdale, 2007)	To predict the capacity for green structure to handle urban water	Local	Catchment flow response and potentially prediction from physical model parameters of future states.	DEM, landcover, water absorbtion indices.		Vares	Maps	Total potential rainfall absorption, catchment out flow.

A2.6.2 URBAN CLIMATE MODELS

Name of model	**Type of model**	**Objective**	**Spatial scale**	**Calculations**	**Input data (main)**	**Input data (additional)**	**Simulated time frame and time resolution for simulation**	**Output presentation**
ENVI-met	Numerical CFD model	Urban microclimate Local air quality analysis	Single objects to neighbourhood level	Gas and Particle dispersion Mean radiant temperature (Tmrt) Predicted Mean Vote (PMV) Radiation fluxes (shortwave and longwave) Reflection Re-radiation Sensible heat flux (from vegetation) Shading Transpiration Evaporation Surface and wall temperature Water and heat exchange in soils	Date and Time Geographical information Initial temperature atmosphere Relative humidity Roughness length Specific humidity Wind speed Wind direction	Soil data (initial and relative temperature) Building inside temperature Building heat transmission walls Building heat transmission roofs Building albedo walls Building albedo roofs Sun height Cloud cover fractions Plant data (leaf area density)	24 to 48 hours 10 sec	Fluid dynamic presentation in 2D, 3D and in sections
Rayman	Numerical	Urban bioclimate Thermal indices	Single objects to regional levels	Global radiation (mean, max, sum values) Mean Radiant temperature (Tmrt) Predicted Mean Vote (PMV) Physiologically Equivalent Temperature (PET) Radiation fluxes (short wave and long wave) Shade quantification Sky View Factor	Air temperature Air humidity Date and Time Cloud cover Geographical information Relative humidity Personal data and clothing/activity (relating to PET)	Albedo Environmental morphological properties. Fish eye pictures. Free drawing of solid elements in the hemispherical view. Geometrical dimensions of buildings and trees.	Hourly Daily Monthly 1 hour	Graphs and text data

				Standard Effective Temperature (SET) Sunshine duration (with or without sky view factor) Universal Thermal Climate Index	Vapour pressure Wind speed	Topography		
SOLWEIG	Numerical,	Urban microclimate	Single objects to neighbourhood level	Global radiation (mean, max, sum values) Mean Radiant Temperature (Tmrt) Radiation fluxes (short wave and long wave) Shade quantification Sky View Factor Sunshine duration (with or without sky view factor)	Direct, diffuse and global shortwave radiation Air temperature Relative humidity Urban geometry Geographical information	Mean values for buildings and surface materials Solar transmission values for vegetation		

A2.7 Data Mining and Spatial Data Infrastructures

A2.7.1 DATA MINING METHODS AND PAPERS

End Note Reference	**Software Used**	**Task / Technique**	**Domain / Topic**	**Goal**
(McLeod et al., 2010)	MATLAB (Palani et al., 2008)	Clustering / ANN	Urban / Perception	Prediction and Grouping of factors by relative importance to net perceived service quality in public transport given data from survey of passengers. "ANN are proposed in this research because of its numerous advantages over more traditional parametric models (such as regression models, structural equation models or logit/probit models), but also over other non-parametric models, such as decision trees. ANNs provide higher fits of the phenomenon under study.".. "The main disadvantage of this approach is the duration of the calculus, since a large number of ANN must be trained and tested,"
(McLeod et al., 2010)	(Xu et al., 2014)	Interpolation / ANN	Marine / Eutrophication	Prediction of water quality (salinity, temperature, dissolved oxygen and Chl-a concentrations) in non-monitored locations of Singapore coastal waters both temporally and spatially using continuous weekly measurements of water quality variables at different stations.
(TWC, 2012)	GPKernel	Interpolation / ANN & GP	Marine / Eutrophication	Comparison of variable selection between ANN, GA and deterministic techniques, when predicting algal bloom in marine environment. *Useful Section on Model variable selection methods.*
(Webb, 2007)		Regression & Classification / Decision Trees	Landscape / Wildfire	Modelling the anthropogenic component of wildfire ignition. Comparison with Linear regression.
(Reese, 2011)		Classification	Marine / Oil pollution	Comparison of 7 different classifiers for detecting oil spills based on Radar satellite imagery. *NB- ANN do not perform well in this example.*
(Maier and Dandy, 2000)	NA	REVIEW / ANN	Marine / Freshwater	This paper is an early review of the role of ANN in marine and freshwater modelling including a summary of 45 papers on the subject up to 1998.
(Langella et al., 2010)		Interpolation / ANN	Soil	Downscaling of precipitation for use in Soil-Vegetatation-Air transfer models. Comparison with geostatistics
(Malekmohamadi et		Classification &	Marine / Wave	Compares several alternative Machine Learning algorithms for the estimation of wave height

al., 2011)		Interpolation / ANN, ANFIS	Height	based on spatially sparse wave height data and temporally frequent wind speed data.
(Olawoyin, 2013)	(GoldenSoftware, 2012) – visualisation & kriging only	Interpolation / ANN, SOM.	Marine / Oil pollution	Uses ANN, Self Organising Maps and Geostatistics to map likely exposure to various oil pollutants with respect to the manner of their absorbtion into the human body.
(Suryanarayana et al., 2008)		REVIEW : classification, interpolation. ANN,Fuzzy Logic,Wavelets	Marine / Fisheries	Reviews use of Machine Learning in Fisheries research 1978-2008. “Forecasting in fisheries covers distribution of eggs, recruitment, fish growth/age, biomass and fish catch. Other major areas are identification, abundance and food products, environmental factors and collapse of fishery industry.”
(Alonso Fernández et al., 2014)		Regression (Multivariate Adaptive Regression Splines)	Freshwater / Eutrophication	Predicts Eutrophication in reservoir some days ahead based on monitored parameters. MARS fits polynomial regression splines to different sections of the data, thus allowing the function to change between system states.
(Areerachakul et al., 2013)		ANN	Fresh water	Prediction of dissolved oxygen content via supervised and unsupervised ANN to model impact of pollution.
(Ferrarini and Tomaselli, 2010)		Association Rules	Landscape	Modelling landcover patch spatial adjacency for ecological networks. Association rules allow inference as to the probability of an ecological network work landscape patches based on how many relevant adjacencies there area between different types of landcover.
(Levers et al., 2014)		Decision Trees	Landscape / Forestry	Uses Boosted Regression Trees to predict spatially forest harvesting intensity across Europe based on bio-physical and socio economic explanatory variables.
(Marcot, 2006)		BBN		Review of the use of BBN in ecological modelling
(Aitkenhead and Aalders, 2009)	Netica	BBN, GA,	Landscape / Forestry	Combines Genetic Algorithms with Bayesian Belief Networks to predict land use / land cover change.
(Troldborg et al., 2013)		BBN	Soil	Uses BBN to identify risk to soil.

14 Appendix 3 –Municipality Survey

The questionnaire focused on eliciting what interest there may be in scenario modelling in general within municipalities, the kind of issues being prioritized and what generic skills are available to use such models if their use were to be recommended. Responses were collected online via the Netigate software package. Municipalities do not all employ the same management structure or job titles so it is not possible to identify the equivalent personnel in each with respect to this issue. Furthermore the intention was to understand how municipalities can (or could) use models within their decision making processes thus both the planning/environmental management perspective and that of technical specialists is relevant. Invitations to participate were therefore sent to the municipalities' generic contact e-mail address, with the following covering letter:

> *"Hej,*
>
> *SLU har av Naturvårdsverket fått i uppdrag att göra en översikt av scenario-modellering och hur denna typ av verktyg kan vara ett stöd i beslutsprocesser inom den fysiska planeringen, och i förlängningen i uppfyllandet av de nationella miljökvalitetsmålen. Därför skulle vi vilja att den här enkäten besvaras av någon inom er organisation som aktivt arbetar med kommunal planering, klimatanpassning och/eller miljömålsarbete. Vänligen vidarebefordra det här meddelandet till den medarbetare som kan besvara enkäten.*
>
> *Syftet med enkäten är att få kunskap om det faktiska planeringsarbetet som bedrivs på olika håll runt om i landet samt i vilken utsträckning som exempelvis GIS och miljörelaterad scenario-modellering används när olika beslut fattas. Vi vill också få en så tydlig bild som möjligt av vilket slags stöd som olika aktörer efterfrågar när det gäller användandet av avancerad modelleringsteknik.*
>
> *Enkäten tar ca 5-10 minuter att besvara och alla svar kommer att behandlas konfiden tiellt."*

It was hoped that by this method the survey would be passed within each organization to an appropriate respondent. While this appears to have been largely effective, it is unsurprising that several respondents stated they found the questionnaire difficult to answer since they did not necessarily have a good overview of all the relevant skills and processes within their municipality. All questions were optional thus each question has a different N, as reported, which should be born in mind when considering the results, as should the fact that the net statistics represent responses from individuals with a range of roles.

It must be assumed that those who did not answer a question did not know the answer. An important, if evident, finding from the survey is therefore that few if any municipalities employ an individual with the necessary skills and remit to answer such a survey comprehensively – or at least these individuals were not easily located. Indeed such individuals probably do not exist, so introducing a greater role for modelling will require a structural approach involving committees of individuals charged with that task.

Results

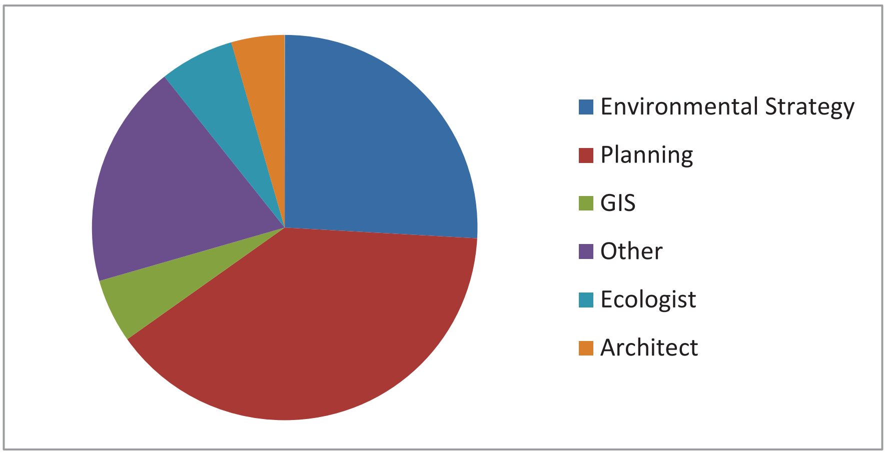
Date Sent : 23/10/2014
Date Closed : 25/11/2014
Total Returns N : 218

Scenario Modelling

Svar: 143 / =NA (Anonyma resultat)

1. Namn:

2. Befattning:



Classified responses to Role / Department

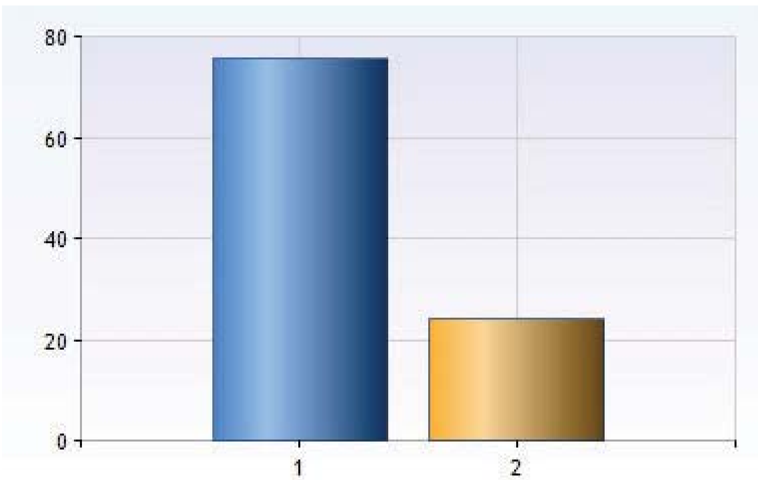
3. Organisation

4. Jag skulle vilja delges en kopia av resultaten från den här enkäten via e adress

5. Refererar du eller kollegorna på din avdelning/förvaltning regelbunde Naturvårdsverkets 16 nationella miljökvalitetsmål som en del av ditt/ert varda arbete? (Ringa in Ja eller nej)

Besvarad av: 132 (61%) Ej besvarad av: 86 (39%)

1		Ja	100 (76%)
2		Nej	32 (24%)



6. Gradera följande ämnesområden utifrån de fyra högsta prioriteringarna inom den fysiska planering och kommunens målsättningar.

Du kan bara välja fyra av alternativen nedan och ge dem prioriteringsordning, där 1 är högst prioritet.

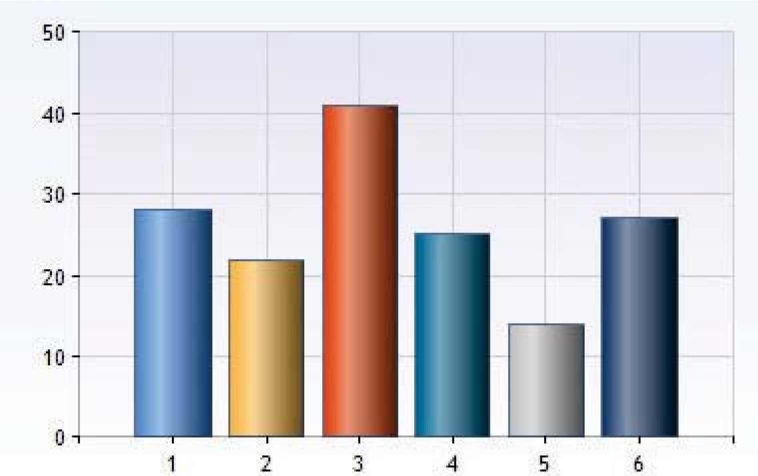
	1	2	3	4	Svar
1 Stigande havsnivå (översvämning av saltvatten)	12 (57%)	2 (10%)	5 (24%)	2 (10%)	21/218 (10%)
2 Övergödning av saltvatten, havsvatten (algblomning etc.)	9 (56%)	3 (19%)	1 (6%)	3 (19%)	16/218 (7%)
3 Översvämning av sötvatten	19 (45%)	7 (17%)	5 (12%)	11 (26%)	42/218 (19%)
4 Övergödning av sjöar, åar och andra vattendrag	6 (16%)	13 (35%)	9 (24%)	9 (24%)	37/218 (17%)
5 Skydd av jordbruksmark	1 (5%)	7 (32%)	5 (23%)	9 (41%)	22/218 (10%)
6 Skydd av natur och utbyggnad av tätortsnära grönområden	12 (29%)	9 (22%)	11 (27%)	9 (22%)	41/218 (19%)
7 Minskning av växthusgaser	13 (32%)	10 (25%)	11 (28%)	6 (15%)	40/218 (18%)
8 Minskning av bilköer (trafikarbete)	6 (32%)	3 (16%)	6 (32%)	4 (21%)	19/218 (9%)
9 Skydd av våtmarker eller återskapande av våtmarker	2 (18%)	1 (9%)	5 (45%)	3 (27%)	11/218 (5%)
10 Skydd mot påverkan av landskapsbilden	0 (0%)	8 (38%)	9 (43%)	4 (19%)	21/218 (10%)
11 Säkerställande av ett bra klimat i urbana miljöer	5 (20%)	8 (32%)	7 (28%)	5 (20%)	25/218 (11%)
12 Tillhandahålla rekreationsmöjligheter i natur och skogsområden	2 (4%)	18 (38%)	15 (31%)	13 (27%)	48/218 (22%)

7. Hur ange du att du/ni svarar upp mot framtida potentiellt riskfylld utveckling som exempelvis översvämning

Besvarad av: 85 (39%) Ej besvarad av: 133 (61%)

Anse ifall 'ja'

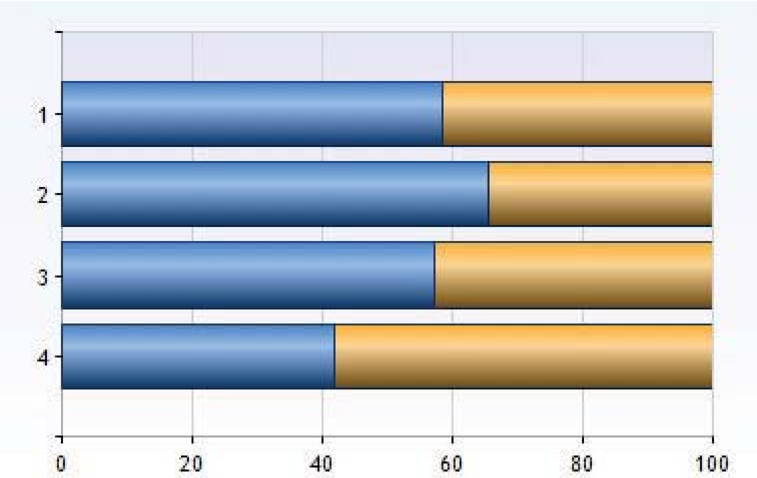
1	1) Vi anlitar experter för att utarbeta scenarios i form av plankartor och beskrivande text	24 (28%)
2	2) Vi tar hjälp av experter och efter diskussion med berörda sakägare utarbetar vi scenarios i form av plankartor och beskrivande text.	19 (22%)
3	3) Vi drar upp olika scenarios utifrån en standard-användning av våra GIS-program (exempelvis genom att överlappa olika kart-skikt och lägga buffert-zoner kring vissa företeelser och verksamheter.	35 (41%)
4	4) Scenarios tas fram utifrån statistiska underlag som förutspår framtida utmaningar/problem.	21 (25%)



5		5) Specialist-program används för att modellera fram scenarios för särskilt utvalda teman.	12 (14%)
6		6) Att använda sig av scenarios är något som är ovanligt hos oss.	23 (27%)

8. Om du/ni använder er av GIS-program för att utveckla scenarios, vem utför i så fall arbetet? Välj det eller de alternativ som stämmer där du jobba

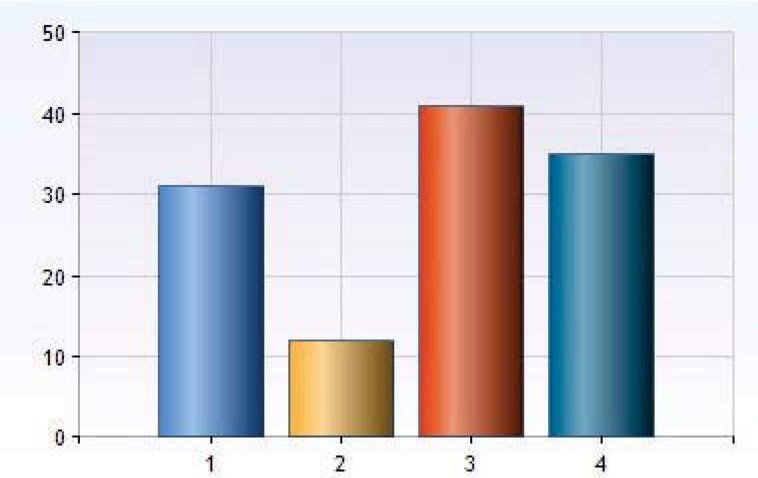
		Ja	Nej	Svar
1	1)Arbetet utförs av planerare eller miljövetare som har GIS-kunskaper.	31 (58%)	22 (42%)	53/218 (24%)
2	2) Det finns en särskild GIS-avdelning som utför arbetet, efter förfrågan.	40 (66%)	21 (34%)	61/218 (28%)
3	3) Vi använder oss oftast av privata konsultfirmor för att utföra arbetet.	35 (57%)	26 (43%)	61/218 (28%)
4	4) Vi använder oss inte av det här arbetssättet.	20 (42%)	28 (58%)	48/218 (22%)



9. Om du/ni använder er av statistiska förutsägelser för att utveckla scenarios, vem utför i så fall det arbetet? Välj det eller de alternativ som stämmer där du jobbar:

Besvarad av: 81 (37%) Ej besvarad av: 137 (63%)

1		1) Arbetet utförs av planerare eller miljövetare som har kunskaper om statistiska underlag.	25 (31%)
2		2) Det finns en särskild enhet som utför arbetet, efter förfrågan.	10 (12%)
3		3) Vi använder oss oftast av privata konsultfirmor för att utföra arbetet.	33 (41%)
4		4) Vi använder oss inte av det här arbetssättet.	28 (35%)

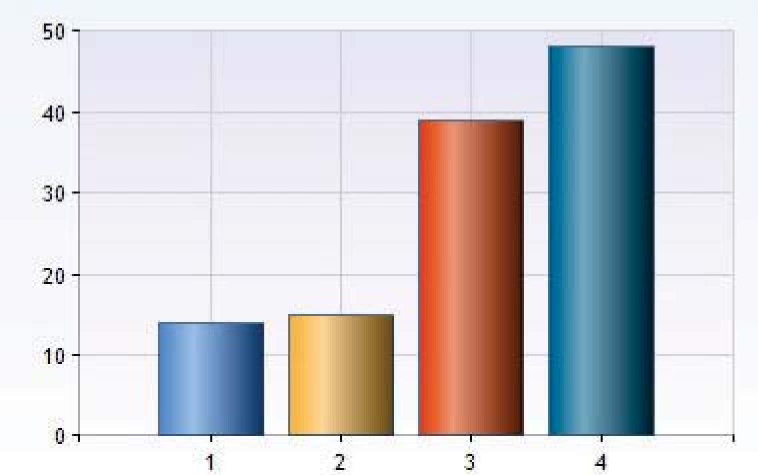


10. Om du/ni använder er av andra specialiserade programvaror för att göra

modeller, och för att utarbeta framtida scenarios, vem utför i så fall denna typ av arbete? Välj det eller de alternativ som stämmer där du jobbar:

Besvarad av: 80 (37%) Ej besvarad av: 138 (63%)

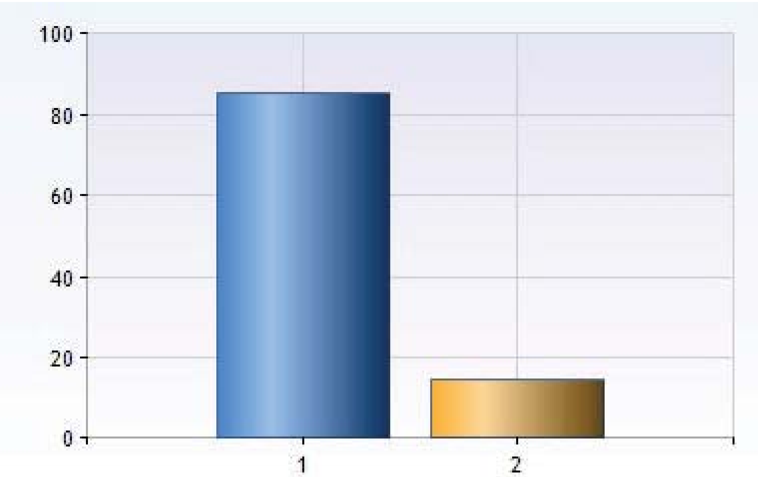
1		1) Arbetet utförs av planerare eller miljövetare som har specialkunskaper.	11 (14%)
2		2) Det finns en särskild enhet som utför arbetet, efter förfrågan.	12 (15%)
3		3) Vi använder oss oftast av privata konsultfirmor för att utföra arbetet.	31 (39%)
4		4) Vi använder oss inte av det här arbetssättet.	38 (48%)



11. Anser du att din avdelning/förvaltning skulle tjäna på att ha större tillgång på statistiska underlag eller ha bättre möjligheter till att göra simuleringar som baserats på modelleringar av framtida scenarios? Ringa in Ja eller Nej och utveckla gärna ditt svar här nedan:

Besvarad av: 83 (38%) Ej besvarad av: 135 (62%)

1		Ja	71 (86%)
2		Nej	12 (14%)



12. Om du svarade ”Nej” på frågan 11, varför inte?

(response followed by English Translation)

"Vi har tillräckligt underlag."
We have sufficient basis for decision making.

"I dagsläget saknas personalresurser för att hinna arbeta med detta, tjänster köps in.

“In the current situation we are lacking human resources to have time to work on this so services are purchased.”

"Vi har inte kompetensen på kommunen att ta fram scenarier med hjälp av GIS"

"We do not have the competencies within the municipality to develop scenarios using GIS"

"Vi hinner inte eller har inte organisation för att titta på olika scenarier"
"We do not have time or do not have the organization to look at different scenarios"

"Metoder för att insamla och analysera olika typer av geografisk information förbättras och Inspiredirektiv m.m. hjälper till. Däremot finns stora brister när det gäller olika typer av befolkningsdata."
"Methods used to collect and analyze various types of geographic information are improving and INSPIRE helps. However, there are major shortcomings when it comes to different types of population data."

"Just nu är det nog mer en intern resursfråga. fakta och statistiskt underlag finns det massor av."
"Right now it's probably more of an internal resource issue. Facts and statistical data are plentiful."

"Knappa resurser på GIS sidan.
"Scarce resources on the GIS side."

"Vi anlitar konsulter"
"We employ consultants"

13. Om du svarade "Ja" på frågar 11 så utveckla gärna din syn på era behov här nedan:
(response followed by English Translation)

"För att konsulterna som gör ex riskbedömningar ska kunna leverera ett säkrare resultat."
"So the consultants doing risk assessments would be able to deliver more accurate results."

"Allt som kan underlätta arbetet med klimatanpassning är till godo."
"Everything that can facilitate the process of climate adaptation is useful"

"Ofta är det besvärligt att komma över statestik på kommunnivå. Dyrt eller besvärligt."
"It is often difficult to get the statistics at municipality level. It is expensive or difficult."

"Vi har behov av mera underlag på lokal nivå t ex risker för ras/skred och översvämningskarteringar."
"We need more information at the local level on, for example, risks of landslides and flood mapping."

"Enklare tillgång till data ger bättre förutsättningar för bättre kartläggning."
"Easier access to data provides better conditions for better mapping."

"Vi arbetar inte med scenarios men kommer troligen behöva göra det framöver."
"We do not work with scenarios currently but will probably need to do so in future."

"Små kommuner med en tillväxt som = noll har inte de resurser som tillväxtkommuner har.
Vi har samma problem men i mindre skala. Vi har närmare till problemet. Skulle vilja kunna disskuera senarier men sådan som jobbar med sådana frågor."

"Small municipalities which are not growing do not have the resources as growing municipalities have.
We have the same problems but in smaller scale. We are closer to the problem. We would like to discuss scenarios with those working with such questions. "

"Man vi ha tillgång till tillförlitlig data."
"We want access to reliable data."

"Färdigbehandlad statistik behövs”
"Pre-calculated statistics are needed”

"Att arbeta med bättre och kunskapsförebyggande underlag är alltid bra. Dock saknas det pengar för att genomföra mer ingående kunskapsunderlag och utredningar. till. Exempel,. från konsulter. "
"Working with improved evidence base and material surface is always good. However, there is no money to provide a more in depth knowledge-base and investigations. e.g. from consultants."

"vi har väldigt grova modeller för översvämning, de behöver förfinas efter hand"
"We have very rough models for the flooding, they need to be refined over time"

"Vi har en nyanställd GIS utvecklare vid kommunen och arbetar för närvarande med att utveckla internt kartmaterial. Förhoppningen är att vi ska kunna göra fler egna analyser efter hand. Här tittar vi också på 3Dverktyg. De som sedan kommer att arbeta med själva tillverkningen av kartor och diverse material är troligtvis planarkitekter. "
"We have a newly employed GIS developers at the municipality who are currently working to develop internal map material. It is hoped that we can make more of our own analyzes gradually. Here we are also looking at 3D tools. These who will work with the production of maps and various materials themselves are likely to be plan architects. "

"I mindre projekt kanske vi skulle kunna, med sådant stöd, göra scenarios själva"
"In smaller projects, perhaps we could, with support, making scenarios ourselves"

"Viktiga frågor att hantera i framtiden, exempelvis klimatförändringen."
"Important issues to deal with in the future, such as climate change."

"Det är alltid bra att ha ett brett underlag för att förbereda sig för delvis oförutsägbara framtidsfrågor."
"It's always good to have a broad basis to prepare for partly unpredictable future issues."

"Alltid bra med mer underlagsmaterial."
"Always good to have more background material."

"Mer kunskap är alltid av godo. "
"More knowledge is always a good thing."

"Vi är väldigt underbemannade, så vi skulle ha mest nytta av enkla modeller (enkla att hantera). Dock skulle detta vara till stor hjälp då man relativt snabbt vill få fram en prognos, och vill slippa leverera allt data till konsult, därefter invänta svar, och sedan ändå behöva revidera. Gäller det omfattande undersökningar måste vi antagligen fortsätta anlita konsult, men det är ändå en stor nytta med att ha egen kunskap om modellerna, så att man vet vad man beställer och kan granska resultatet."
"We are very understaffed, so we would have the most benefit from simple models (easy to handle). However, this would be a great help when needing to relatively quickly produce a forecast when not wanting to deliver all data to the consultant, then wait for an answer, and then still have to revise. As to more extensive investigations we must probably continue to hire a consultant, but it is still a great advantage in having one’s own knowledge of the models, so that you know what to order and can view result."

"Det är väl oftast bra med bättre beslutsunderlag men det behöver ställas mot arbetsinsats, personalens kunskapsläge och kostnader."

"It is usually good with better decision support but it needs to be set against the effort, staff knowledge and costs."

"Lättare att göra bedömningar i olika processer."
"Easier to make assessments of different processes."

"Det finns generellt ett behov av att på ett enkelt sätt få till ett bra beslutsunderlag. Kraven ökar ständigt på riskanalyser av olika slag samtidigt som kraven på snabba processer och enkelhet ökar från andra håll. Bra hjälpmedel är viktigt för att motsvara olika typer av förväntningar. "
"There is generally a need for a simple way to get a good basis for decisions. The demands are constantly increasing for risk analysis of various kinds while demands for fast processes and simplicity increases elsewhere. Good tools are important to meet these different types of expectations. "

"Ju mer och bättre statistik, ju bättre resultat av analysen"
"The more and better data, the better the results of the analysis"

"Vi behöver användarvänliga verktyg. Vi har tidsbrist och systemet används inte om det är för komplicerat. Det borde gå att utveckla ett system som kommuner kan använda, eftersom alla arbetar med fysisk planering."
"We need user-friendly tools. We have time constraints and a system is not used if it is too complicated. It should be possible to develop a system that municipalities can use since all are working with physical planning. "

"Vi har en gammal översiktsplan. När den nya ska tas fram finns avsikten att lägga in scenarios i det arbetet främst pga klimatanpassning förändrat väder."
"We have an old master plan. When the new one is developed it is intended to add scenarios, primarily in relation to climate adaptation changing the weather. "

"Utmaningen är att hålla bedömningar och scenarios aktuella, utan att behöva beställa hela jobbet flera gånger, då inte all kunskap finns i organisationen."
"The challenge is to keep the assessments and scenarios in question relevant, without the need to order the whole job several times, since not all the necessary knowledge is available in the organization."

"Det blir lättare att göra mera korrekta analyser om man har tillgång till bra data."
"It is easier to make more accurate analyzes if you have access to good data."

"Data om vattenföring"
"Data on water discharge"

"Som enskild kommun är det svårt och dyrt att ta fram egna underlag och modeller. vi drar idag nytta av sådant som har tagits ram av länsstyrelser och kommuner i samarbete.
Exempel är översvämningsscenarierför Dalälven."
As a single municipality, it is difficult and expensive to develop your own data and models. We draw today from things that have been undertaken in a framework of regional and local authoroities in cooperation. Examples are flood scenarios for the river Dalälven."

"Översvämningskartering (data) baserat på 10, 20, 50och 100 års regn vore väl bra.
Hur sekundära avrinningarna ser ut vore bra och vad som händer om större grad av ytan hårdgörs."
"Flood Mapping (data) based on 10, 20, 50 and 100 year rains would be good.
How secondary drainage is working would be good to know, and what happens if a greater degree of surface sealing occurs. "

"Kommunen har hittills inte jobbat med klimatanpassning. Vi avser att inkludera detta i den fördjupade planeringen för centralorten och i nästa omgång av översiktsplan."
"The municipality has so far not been working with climate adaptation. We intend to include this in the in-depth planning for the central area and in the next round of the comprehensive plan. "

14. Här nedan följer några exempel till skäl som kan vara anledningar till ett begränsat användande av statistiska underlag och data-modellering på din avdelning/förvaltning. Vänligen skatta anledningarna (från 1-10) utifrån hur relevanta du upplever att de är på just din avdelning/förvaltning. (Sätt 1 på icke-relevanta skäl och 10 för de anledningar som är mest relevanta.)

	1	2	3	4	5	6	7	8	9	10	Medel	σ	Svar
1 Brist på medel för att köpa in program och annan teknisk utrustning.	5 (7%)	6 (9%)	11 (16%)	3 (4%)	7 (10%)	4 (6%)	5 (7%)	13 (19%)	1 (1%)	14 (20%)	0	0	69/218 (32%)
2 Brist på utbildad personal som kan använda aktuella program (och göra relevanta tolkningar av modellering).	2 (3%)	5 (7%)	9 (12%)	2 (3%)	6 (8%)	9 (12%)	6 (8%)	11 (15%)	7 (10%)	15 (21%)	0	0	72/218 (33%)
3 Avsaknad av tillgång till nationella eller regionala databaser som kan stödja modellering.	8 (12%)	3 (4%)	3 (4%)	8 (12%)	16 (24%)	7 (10%)	9 (13%)	7 (10%)	1 (1%)	5 (7%)	0	0	67/218 (31%)
4 Avsaknad av tillgång till lokala data.	7 (11%)	4 (6%)	6 (9%)	5 (8%)	14 (21%)	4 (6%)	7 (11%)	10 (15%)	2 (3%)	7 (11%)	0	0	66/218 (30%)
5 Tidsbrist för att hinna undersöka vilken typ av modellering som kan vara aktuell på avdelningen.	4 (6%)	3 (4%)	4 (6%)	5 (7%)	7 (10%)	3 (4%)	5 (7%)	11 (16%)	12 (17%)	16 (23%)	0	0	70/218 (32%)
6 Det behövs inte göras några modelleringar i avdelningens planprocesser.	29 (43%)	10 (15%)	7 (10%)	5 (7%)	9 (13%)	2 (3%)	3 (4%)	2 (3%)	0 (0%)	1 (1%)	0	0	68/218 (31%)
7 Befintliga konsulter är för dyra.	9 (14%)	7 (11%)	3 (5%)	5 (8%)	21 (32%)	3 (5%)	5 (8%)	4 (6%)	6 (9%)	3 (5%)	0	0	66/218 (30%)
8 Befintliga konsulter ger oss inte det vi behöver.	20 (31%)	14 (22%)	7 (11%)	4 (6%)	10 (16%)	1 (2%)	4 (6%)	3 (5%)	0 (0%)	1 (2%)	0	0	64/218 (29%)
9 Brist på vägledning till hur vi ska välja vid anlitandet av extern	12 (18%)	6 (9%)	11 (17%)	7 (11%)	8 (12%)	6 (9%)	6 (9%)	5 (8%)	2 (3%)	3 (5%)	0	0	66/218 (30%)

expertis.													
10 Brist på förståelse från ledningen när det gäller modelleringens potential och kapacitet.	8 (12%)	5 (8%)	11 (17%)	8 (12%)	11 (17%)	5 (8%)	4 (6%)	6 (9%)	4 (6%)	4 (6%)	*0*	*0*	66/218 (30%)

15. Vänligen indikera de data program som du vet/tror att personer på din avdelning/förvaltning använder och på vilket sätt respektive program används.

Utgå ifrån siffrorna 1 - 4 där 1 = Basal användning (upprättar exempelvis kartor och grafer), 2 = Avancerad användning (använder exempelvis standardanalytiska funktioner), 3 = Utvecklingsnivå (bygger och utvecklar exempelvis egna grafiska modeller och/eller utvecklar och skriver kod). 0 = Om du inte vet hur det förhåller sig, eller om användandet är obefintligt.

GIS

	0	1	2	3	4	Svar
1 ESRI ArcGIS	15 (24%)	19 (30%)	15 (24%)	8 (13%)	6 (10%)	63/218 (29%)
2 ESRI ArcScene	47 (94%)	2 (4%)	1 (2%)	0 (0%)	0 (0%)	50/218 (23%)
3 ESRI ArcServer	43 (83%)	5 (10%)	2 (4%)	0 (0%)	2 (4%)	52/218 (24%)
4 MapInfo	28 (47%)	14 (24%)	11 (19%)	4 (7%)	2 (3%)	59/218 (27%)
5 IDRISI	48 (98%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	49/218 (22%)
6 QGIS	41 (79%)	9 (17%)	2 (4%)	0 (0%)	0 (0%)	52/218 (24%)
7 GRASS GIS	48 (98%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	49/218 (22%)
8 PostGIS	45 (92%)	2 (4%)	2 (4%)	0 (0%)	0 (0%)	49/218 (22%)
9 R-Spatial	48 (98%)	0 (0%)	1 (2%)	0 (0%)	0 (0%)	49/218 (22%)
10 CGAL	49 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	49/218 (22%)
11 ERDAS Imagine	48 (96%)	2 (4%)	0 (0%)	0 (0%)	0 (0%)	50/218 (23%)
12 Google Earth	12 (19%)	37 (60%)	8 (13%)	2 (3%)	3 (5%)	62/218 (28%)
13 Sketch Up	22 (39%)	17 (30%)	9 (16%)	5 (9%)	3 (5%)	56/218 (26%)
14 FME	43 (86%)	1 (2%)	3 (6%)	2 (4%)	1 (2%)	50/218 (23%)
15 Auto CAD	19 (32%)	19 (32%)	13 (22%)	5 (8%)	3 (5%)	59/218 (27%)
16 MIKE	46 (94%)	3 (6%)	0 (0%)	0 (0%)	0 (0%)	49/218 (22%)
17 ENVIMET	49 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	49/218 (22%)
18 BASINS	48 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	48/218 (22%)

Statistik Och Databas

	0	1	2	3	4	Svar
1 MS Excel	7 (11%)	19 (30%)	22 (34%)	9 (14%)	7 (11%)	64/218 (29%)
2 MS Access	32 (63%)	8 (16%)	6 (12%)	2 (4%)	3 (6%)	51/218 (23%)
3 SPSS	48 (96%)	1 (2%)	1 (2%)	0 (0%)	0 (0%)	50/218 (23%)
4 GenStat	48 (96%)	2 (4%)	0 (0%)	0 (0%)	0 (0%)	50/218 (23%)
5 R-Statistics	49 (98%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	50/218 (23%)
6 SAS	48 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	48/218 (22%)
7 MATLAB	47 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	47/218 (22%)

8 ORACLE	37 (67%)	7 (13%)	6 (11%)	5 (9%)	0 (0%)	55/218 (25%)

Språk och OS

	0	1	2	3	4	Svar
1 VB.Net	45 (96%)	1 (2%)	0 (0%)	1 (2%)	0 (0%)	47/218 (22%)
2 Python	46 (96%)	1 (2%)	0 (0%)	1 (2%)	0 (0%)	48/218 (22%)
3 Java	38 (78%)	7 (14%)	1 (2%)	2 (4%)	1 (2%)	49/218 (22%)
4 OpenGL	44 (96%)	0 (0%)	1 (2%)	1 (2%)	0 (0%)	46/218 (21%)
5 SQL	30 (60%)	9 (18%)	10 (20%)	1 (2%)	0 (0%)	50/218 (23%)
6 Delphi / Pascal	45 (98%)	0 (0%)	1 (2%)	0 (0%)	0 (0%)	46/218 (21%)
7 C / C# / C++	42 (93%)	1 (2%)	1 (2%)	1 (2%)	0 (0%)	45/218 (21%)
8 HTML	35 (73%)	7 (15%)	4 (8%)	1 (2%)	1 (2%)	48/218 (22%)
9 Ruby	45 (98%)	0 (0%)	1 (2%)	0 (0%)	0 (0%)	46/218 (21%)
10 BATCH	43 (93%)	2 (4%)	1 (2%)	0 (0%)	0 (0%)	46/218 (21%)
11 Google Apps Script	43 (93%)	2 (4%)	0 (0%)	0 (0%)	1 (2%)	46/218 (21%)
12 MATLAB	44 (96%)	1 (2%)	1 (2%)	0 (0%)	0 (0%)	46/218 (21%)
13 ORACLE	38 (79%)	4 (8%)	5 (10%)	1 (2%)	0 (0%)	48/218 (22%)
14 R	45 (98%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	46/218 (21%)
15 VBA	42 (91%)	3 (7%)	1 (2%)	0 (0%)	0 (0%)	46/218 (21%)

Selected Over all Comments (Q16)

"Vi har ett nära samarbete med länsstyrelsen *[anonymised]* tillsammans med övriga kommuner i länet för konsultuppdrag (bl.a. till SMHI och DHI) i frågor som rör klimatanpassning och framtidsscenarier. "

"We are working closely with the County Administrative Board [anonymised] along with other municipalities in the county for commissioning consulting (Including SMHI and DHI) in matters relating to climate change adaptation and future scenarios. "

"Vi är ur den här aspekten en liten organisation och har relativt litet behov av egna analyser. Det vore inte ekonomiskt försvarbart att ha egen expertis. Vi har just nu två uppdrag upphandlade inom området. Det ena rör flybildstolkning av gröna värden i den bebyggda miljön, ett forskningsuppdrag där högskolan deltar. Rör bl.a. ekosystemtjänster. Det andra rör "ett framtidssäkrat *[anonymised]* och analyserar tillgänglig mark ur bl.a. de perspektiv som enkäten behandlar."

"We are a small organization and have relatively little need for our own analysis. It would not be economically justifiable to have our own expertise. Right now we have two missions procured in the field. One for remote sensing of green values in the built environment, a research assignment in which the University participates, looking at ecosystem services. The other concerns a future-proofing [anonymised] and analysis of the available land including the perspectives that the survey covers."

”Ni borde även ha frågor om det finns några politiska uppdrag till tjänstemännen att jobba med frågan. Vi gör inte så mycket utan politiska uppdrag."

"You should also have included issues of whether there is any political 'mission' to officials working with these issues. We cannot do much without a political mission."

"Svår enkät med många alternativ. Hjälp till scenarier kommer säkert många kommuner att uppskatta."

"Difficult questionnaire with many options. Help with scenarios is something surely many municipalities would appreciate."

15 Appendix 4 Citizen Science – The ExCites Approach

Modelling and scenario development has traditionally been an expert lead undertaking, both because experts have access to the data and skills needed to produce technologically advanced predictions and because experts have been tasked with setting the agenda as to which questions should be addressed. This runs the risk of giving the impression that the subject is beyond “ordinary” people, and thus also someone else’s problem to solve. The contrary argument, as set out in chapters 1 and 2, is that people are an integral part of helping to identify the problems and effect a solution.

Citizen Science is not a new idea but it is being given new impetus by the advent of mobile technology allowing people to interact with and create spatial data. Yet, at its root, it remains a process of engagement between people in their roles as local residents, visitors, scientists, NGOs or governmental agencies.

A long standing example of this is the social enterprise[12] “mapping for change” project http://www.mappingforchange.org.uk/ . The origanisation has looked at a wide range of social issues, usually in an urban context, such as noise pollution, air pollution, accessibility and community facility provision, all built on a common internet mapping platform http://www.communitymaps.org.uk/ .

The online maps are not, however, the primary function of the project, nor where most effort is expended. They are preceded by significant on site community work to identify the interested groups, find a means to engage them in the project and work with them as to what they wish to map and how. Each demographic needs to be engaged individually, as one member of the community mapping team put it “simply setting up a meeting in the local community hall doesn’t work, sometimes no body turns up”. Rather individual groups need to be contacted and the issues framed in their terms. It may not be necessary or possible that the individual facilitators are from those communities, but it is worth considering the implications of this.

Some key lessons learnt through these engagement processes include.

- Don’t ‘pilot’ the technology live because function failures may risk losing the interest of key individuals and organisations – permanently.
- Keep the engagement as low-tech as possible, certainly in the initial few (2-4) meetings, and instead focus on the issues using paper maps, post-it notes, pins etc. to aid discussion and ensure participants are comfortable with using map data.
- Introduce people to the map representation of their area, from a few streets at first to walkable scales.
- Turn up with something to offer, to stimulate discussion. For example maps of relevant *local* statistics such as air quality, demographic data, predicted flooding levels etc.
- Invite participants to question and challenge the official data with their own experience.
- Don’t use a template, start from scratch.

[12] Social Enterprise is a form of company set up for charitable purposes.

While the last bullet point might seem to be unnecessarily costly, each community has defined different subjects of interest, with different classifications. The process of building a typology is thus part of the process of exploring what about an issue matters to people in that area.

When an initial typology has been determined, the mapping may at first be entirely paper based and upload to a website remains optional to each community. Some have, ultimately, been able to map directly to the website via a login system, or even use equipment such as low cost noise level monitors to provide data based on peoples own perception of when noise levels were excessive (http://www.mappingforchange.org.uk/wp-content/uploads/2009/03/noise_toolkit.pdf).

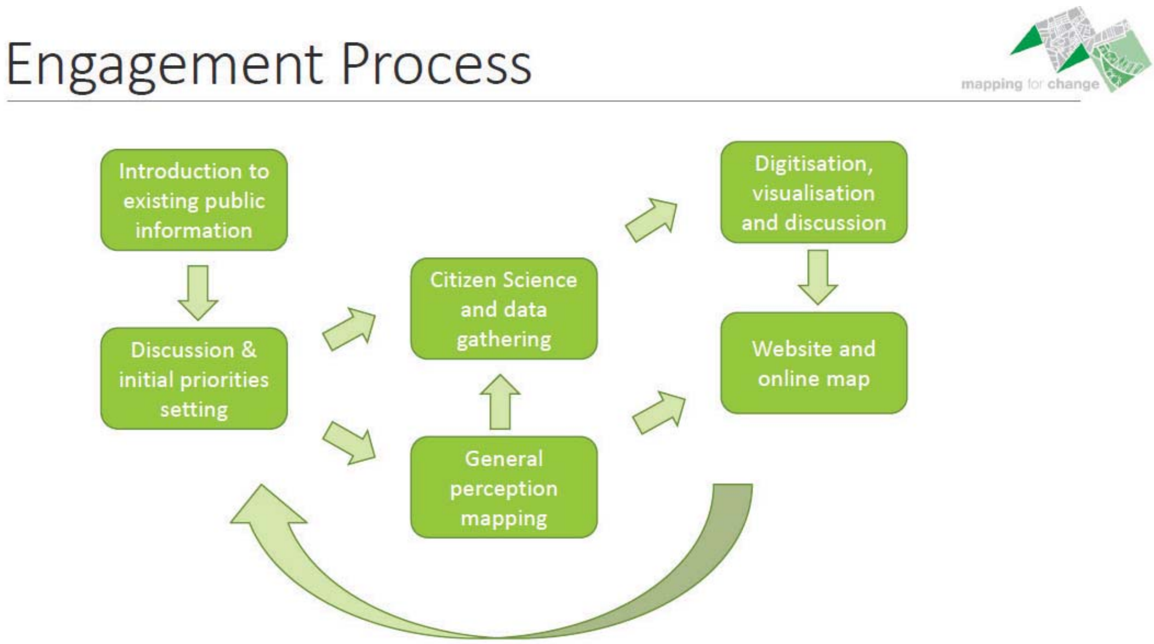


Figure A4-1 The Mapping For Change Engagement Process

The underlying typology may be returned to as experience shows some limitation or need for change. Thus the process is iterative in the same way as design requires an exchange of information and ideas between client and professional, except that in this case the 'client' is many people with perhaps different perspectives (Figure A4-1).

Diversity in opinion is valuable, but to aggregate data some structure is also necessary. An important part of the engagement process is the development of protocols to be followed when information is uploaded (see above link), in order to place some bounds on the conditions which might be assumed to pertain to each measurement. In this context scientific advice is an important component of the process. This does not mean, however, that such measurement presents a means to expand objective measurement of environmental and planning issues. Portable equipment may not equate in accuracy to more professional measurements and there is no guarantee that protocols will be followed. Spatial sampling will likely reflect some bias due to autocorrelation with where participants live and because the ExCiteS team's experience suggests formal sampling approaches, such as grid square coverage, are not completed.

Rather, the data is a means to give representation to perceived issues. For example, when and where a sound measurement is recorded is as important as the value measured, particularly if it can be correlated to a cause such as aeroplane traffic.

The approach is resource intensive. While web mapping itself map be relatively easily developed via commercial services, issues of trust worthiness, the ethical use of data and intellectual property influence whether a bespoke solution might be needed. Training of community engagement staff is essential both in how to engage with the public and the capabilities of the technology. It is also important to retain staff from one project to the next because personal experience is an important component, particularly as regards communicating the needs of the community to technical staff.

From a planning and environmental management perspective, therefore, the question to be answered is how to use community based mapping as part of the decision approach, when to deploy it and how to use the information within a democratically representative decision making processes. In some senses this approach is more about providing the community with an understanding of the problems affecting them, where these are and what might be done, than aggregating data for expert analysis. It helps to foster community lead action or give community lead issues the necessary data to attract expert and political attention. At an individual level it may help people better understand an issue, for example if someone is concerned about the air quality in their area, they can see when and where it is a particular issue.

Non-Verbal Approaches

Literacy, both technical and verbal, is an important potential source of bias in crowd sourced data. Sappelli (http://www.ucl.ac.uk/excites/software/sapelli) is a data collection application under development at UCL which relies only on pictoral image representations that allow end users to navigate a decision-tree of options to register the item of interest, e.g. the presence of tree species. It then tags GPS co-ordinates and allows other media such as images and sound to be added before sending the information via GSM text message to a receiver phone and ultimately an online mapping service.

It is currently being tested with indigenous communities in South America to help register important locations, plants and siting of endangered animals to help understand where is important to these peoples and why, but also gain ecological data which would otherwise be very difficult to obtain. At the same time it can be used to register illegal logging and hunting activities to help communities protect their land and provide evidence to local police. The simplicity of the interface means the method holds considerable potential not only in very remote places but also for engagement across age groups, community mapping for people with a range of disabilities, and helping professionals achieve more consistent categorisations.

The method is also, however, very labour intensive - the development team estimate that 6 person years have been invested in the first prototype. On going running costs include the fact that decision trees must be built as bespoke sets for different user groups, images to represent each item designed and tested across those groups and the usage monitored so it is properly understood – are all the views of the community being gathered or only those of a privileged or vocal demographic? UCL is working with anthropologists to understand how the technique works in indigenous communities but some similarly deep observation might be merited to give the technique validity for informing environmental issues in Sweden. Again, the core method is the creation of the decision tree, not the technology, which is only added later once the underlying structure has been agreed with the community in an iterative design process, including relevant protocols for both data collection and the ultimate uses to which the data may be put.

Given the considerable investment required, further investment included "future" proofing of the technology by supporting multi-platform interfaces with the core code, adoption of standard encoding methods such as XML, and data delivery via text message.

Mobile Sensors

Putting monitoring equipment in the hands of citizens is a growing area of interest in a wide range of academic disciplines. The EU Project EveryAware focused on air quality and sound pollution. In the case of sound pollution the method aimed to make use of mobile phones (http://cs.everyaware.eu/event/widenoise), while air quality was based on developing a bespoke sensor linked to a mobile application (http://www.everyaware.eu/activities/case-studies/air-quality/). The technology is not yet mature, other methods are also proposed such as one reliant on only the inbuilt camera of a mobile phone to assess particulate air pollution (http://robotics.usc.edu/~mobilesensing/Projects/AirVisibilityMonitoring)[13].

Calibration of the data is the most difficult issue, so assessing absolute levels of pollution is still in the experimental stage. As with the community mapping however, the simple provision of information about relative changes over space and time may be useful in allowing people to adjust their behavior to avoid 'hot spots' and give a sense of control over exposure levels back to individuals. Applications which simply provide localized estimates from official monitoring data (e.g. http://www.londonair.org.uk/LondonAir/MobileApps/) thus may helping achieve some of the health and social goals in relation to pollution by separating people from it through changed behavior (e.g. http://www.scmp.com/news/hong-kong/article/1374678/new-air-quality-monitoring-system-announced).

The use of un-calibrated sensors raises ethical considerations as to whether individuals may become unduly alarmed by readings from their own environs. Equally, people may find the reality to be not as bad as they had assumed given media reports which focus on the worst case. Accuracy issues and guidance as to the medical implications of pollution levels are thus an educational issue which is likely to arise over the coming years regardless of whether the methods and technology are promoted via academic and government sources or private industry.

A Matter of Trust

From the Excites experience the process for user engagement is one of slowly building up mutual understanding and common vocabulary (possibly pictoral) during which process a sense of trust is developed between participants. In addition to the benefits for each individual case, experience is built up as to what engenders trust or diminishes it which could aid conflict resolution in planning. For example, the risks which experts consider for the disposal of nuclear waste are more extensive and complex than those the public perceive (A. Skarlatidou, 2012). Understanding and addressing public concerns should raise confidence more than information relating to all the issues which may simply overwhelm, but informing the public about the experts considerations may improve the public understanding of site selection. Building trust is not only a matter of the content of communications, but also the manner in which it is undertaken, the design of a website for example may serve to improve trust in its content or consultation process (Skarlatidou, 2013).

[13] Some of the more popularly available environmental sensor technologies are listed here http://www.treehugger.com/clean-technology/environmental-sensors.html

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A Review on the State of the Art in Scenario Modelling for Environmental Management

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This report presents the core findings from a review of environmental scenario modelling. The focus is on several categories of problems which together represent coupled systems that will have impact on Sweden's 16 Environmental Objectives.

The subjects cover different stages in relevant natural cycles (e.g. carbon, nutrients), the role of Land Use / Land Cover change within these and the socio-economic drivers involved. Models have been selected with respect to availability, predictive accuracy and applied utility, and have been evaluated in respect of their relevance for land management decision making.

Methodological issues in respect of integrating stakeholder opinions and citizen science into models are considered, as are broader issues of how infrastructure can facilitate use of scenario models. The increasing interest in participatory modelling approaches reflects a growing recognition that models can serve as extremely valuable platforms for assisting stakeholders in understanding current conditions and the causes behind these conditions. Approaches of this type are considered likely to increase in popularity in the future.

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