Virtual Engineering:
Computer Simulation Modelling for Flood Risk Management in England

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This paper discusses computer simulation modelling in the context of environmental risk management. Approaching computer simulation as practice, performed in networks of heterogeneous elements, we examine the modelling undertaken by engineering consultants commissioned to provide knowledge about local flood risk to the Environment Agency of England and Wales (EA), the public body responsible for flood risk management. We propose that this simulation modelling is best understood as a form of engineering, work geared to solving the problems of clients. It is also a 'virtual' activity, articulating risks and possibilities in the digital space of the computer. We find that this 'virtual engineering' is shaped by the demands and protocols of the EA, first, by the establishment of long-term contractual agreements for delivering knowledge and second, by an EA requirement to use particular software packages. Fashioned between long-term contracts and black-boxed software virtual engineering becomes stabilised as 'the' way in which knowledge about flood risk in actual localities is generated and, consequently, becomes 'hard-wired' into flood risk management in England.[0]

Keywords: Computer simulation modelling, flood risk, virtual engineering

Introduction

Computer simulation modelling has been a topic of investigation in philosophy and social studies of science for almost two decades and a substantial body of knowledge has been developed. The majority of analyses by philosophers and sociologists focus on theory-driven research, in universities and scientific institutes (cf. Sismondo & Gissis, 1999; Morgan and Morrison, 1999; Lenhard, Küppers & Shinn, 2006; Heymann & Kragh, 2010). In contrast this paper considers modelling in the context of environmental risk management. This focus brings the present study in contact with a debate about the use of modelling in policy-making (e.g. Sarewitz & Pielke Jr, 1999; Pilkey & Pilkey-Jarvis, 2007; van Egmond & Zeiss, 2010). To these two fields, the philosophical and sociological analysis of modelling in science, and the discussion of computer simulation in policy-making, we contribute a case study of the emergence of a particular mode of computer simulation modelling in the context of environmental management. This investigation of the modelling that informs flood risk management in England highlights the relationships constitutive of 'virtual engineering', computer simulation modelling undertaken by engineering consultants who get commissioned to provide knowledge about local flood risk to the Environment Agency of England and Wales (EA), the body responsible for flood risk reduction and management.

This paper is based on nine in-depth interviews with employees and partners in engineering consultancy firms in England.[1] The interviews were thematically structured, covering: the educational and professional backgrounds of the interviewees; the characteristics and use of models and data; overviews of the companies in which the interviewees worked and their clients. Each interview lasted between sixty and ninety minutes, they were transcribed and qualitatively analysed as descriptions of practice (cf. Sundberg, 2006). We also interviewed six university scientists, three scientists working for national research centres and two researchers in commercial software manufacturing firms, in order to understand the articulation of flood modelling in different contexts. Further understanding of context was generated through ethnographic observation in an engineering consultancy firm, following the work of one modelling team over the course of one year with regular visits to their office. This approach provided a series of 'snapshots', capturing consultant engineering modelling work over time (cf. Sundberg, 2010, regarding the need to adapt ethnography to the practice of computer modelling). The material enabled us to follow the actors i.e. to gain an understanding of how modellers involved in this practice conceive of their activities and of their relationships with other actors. In addition we analysed scientific and policy documents and talked with EA officers. The documents were analysed with a critical discourse analysis approach in which the text in focus is interpreted as shaped by discourses and social practices (cf. Rogers-Hayden, Hatton & Lorenzoni, 2011). The interdisciplinarity of the team writing this paper has enhanced the analysis by enabling us to draw on scientific expertise in numerical hydrological modelling and geography, as well as social studies of science.

In the following we begin with a brief overview of the literature on computer simulation modelling most relevant for the present paper. Then we outline the co-evolution of a need for knowledge about flood risk and actors able to provide it in England. Next, we turn the attention to how knowledge about flooding in particular localities is generated by computer simulation modelling in the specific practices of virtual engineering. This part of the paper is divided into three sections: the first focuses on model elements, the second on the use of data for representing localities and processes, and the third on modelling past events and future risks. We conclude with reflecting on virtual engineering as a specific practice, pivotal in the current organisation of flood risk management in England.

Three Themes in the Literature on Computer Simulation modelling

Computer simulation modelling in science has been a topic for investigation in both philosophy and sociology of science; in the limited space of this paper we are only able to discuss the literature most relevant for the present study. Hence, we take from the extensive philosophical discussion about how to understand and characterise the role of models in the production of scientific knowledge, only their conceptualisation as tools. Our point of departure is Morrison and Morgan's (1999) discussion of models (in a broad sense) as neither fully determined by theory, nor by data, but to be considered as epistemically independent instruments of investigation. Contrasting models with simple tools, like hammers, they argue that a scientific model 'involves some form of representation' (1999: 11) that is able to 'teach us something about the thing it represents' whether it be some aspect of theory, or of the world. Morrison and Morgan remark that, in the context of modelling, the notion of 'representation' takes on the sense of partially rendering an object in a new medium. The importance of the medium is emphasised by Winsberg (2003) who argues that computer simulation models are unique in their capacity to semi-autonomously perform complex calculations (simulations) in which assumptions are made explicit. Recently Knuuttila (2011) elucidates the notion of representation in relation to the process of rendering something in the digital format of a computer model. She argues against an understanding of computer models as isomorphically related to the phenomena investigated, distinguishing the philosophical position of 'representationalism' from 'representation', the latter amounts to a 'standing for' that 'is not to be confused by the thing itself' (2011: 2). This strand in the philosophical analysis of models draws attention to computer models as things that are constructed, manipulated and studied by scientists in order to gain knowledge about nature. The concreteness of computer models is critical to their role as tools and in this paper we look closely at the models virtual engineers work with to learn about local flooding.

The variability of modelling practices between different academic disciplines and specialisations is an important feature, illuminated in sociological case studies. For example, Merz (2006) describes how the possibility of manipulating system representations has offered new opportunities for experimenting with complex systems in particle physics. She considers the model representations to be conceptually equivalent to the laboratory, because both involve artificial re-creations of known system properties. In her analysis the virtual space generated by modelling is understood to be a continuation of the physical laboratory space. Johnson (2006) analyses the close integration of computer simulation with technological creation in nanotechnology, a field that would not be possible without modelling. Here computer simulation modelling is constitutive of material intervention. In this field the relationship between virtual and actual is the reverse of Mertz's case, as the computer simulation modelling precedes material intervention. These examples demonstrate the importance of understanding the virtual not as opposed to the real, but as relating in different ways to actual phenomena (cf. Deleuze & Guattari, 1988). In both cases the value of virtual exploration for the generation of scientific knowledge is clear. However, in meteorology we find a tension between the virtual and the actual, highlighted in Sundberg's (2006) ethnography of the relationship between field researchers and modellers in one university department. Addressing computer simulation as comprised of situated practices, critical for both the production of scientific knowledge and social order, she analyses the co-production of modelling and social communities (cf. Sundberg, 2009; 2010). In a more philosophically orientated case study Knuuttila (2006) discusses modelling in linguistics as performative. In this field the models are valued for their output rather than their power to represent. This highlights the importance of modelling for the learning process; by interacting with simulation models scientists can learn about different possibilities, whether any of them actually occur is of less importance.

Another important issue is that models do not automatically travel from one context of use to another. This has been addressed by Mattila (2006) who interrogates the tension between the general and the specific in a study of a failed attempt to make a general epidemiological model useful to public health authorities. That not all scientific models can be made to work for policy and/or management needs is important, it indicates the gaps between scientific modelling and societal demands which practices like virtual engineering can fill.

The use of computer simulation modelling in policy-making and management has prompted criticism. For example, Sarewitz and Pielke Jr (1999) critique what they consider to be a conflation of the use of prediction in science with its use in society. They argue that, in science, prediction has an epistemological function: to test the understanding of phenomena by confirming or refuting specific hypotheses. They see this as different from the use of prediction for decision-making, which is concerned with enabling a better allocation of resources in anticipation of future needs. Sarewitz and Pielke Jr reject the use of computer simulation modelling in policy and decision-making because it does not provide predictive accuracy. A similar critique is formulated by Pilkey and Pilkey-Jarvis (2007) who illustrate what they consider to be failures of modelling to get things right in environmental management, with a number of empirical examples. They want to replace computer simulation modelling in environmental policy and management with field-based observational science.

Whilst the observation that the outcomes of computer simulation modelling are being used in policy-making in ways that diverge from science is important, the distinction between a correct use of models in science and an incorrect use in policy-making may not be that clear cut. In a 1994 article in *Science* (which is widely cited by academic modellers) Oreskes, Shrader-Frechette and Belitz claim that '[V]erification and validation of numerical models of natural systems is impossible' (Oreskes, Shrader-Frechette and Belitz 1994: 641). This paper is referred to by flood modellers in order to establish that they do not claim 'truth' on behalf of their models in the way critics like Sarewitz and Pielke Jr and Pilkey and Pilkey-Jarvis appear to assume. Perhaps, it is because computer simulation modelling does not claim to present unassailable scientific facts that it appeals to policy-makers. This seems possible in light of empirical studies of the use of modelling in policy-making, for example, Bickerstaff and Simmons's (2004) case study of the role of epidemiological modelling in the UK government's response to the 2001 outbreak of foot and mouth disease. They found that modelling became the favoured scientific approach because it corresponded with the existing political culture. Politicians wanted to be seen to be paying close attention to science, but there was very little 'hard' evidence to come by. The spatially-located practices of empirical scientists resisted centralisation by focusing on local circumstances and such practices could not predict the future. Modellers, in contrast, could deliver 'rapid and unambiguous results' (Bickerstaff and Simmons, 2004:410) which could not be subject to evaluation because they were concerned with the future, and generalised knowledge that facilitated centrally-governed strategies. Faced with two different scientific approaches and scant evidence, policy-makers came to rely on modelling. In a recent paper van Egmond and Zeiss (2010) discuss the ability of models to bring science and policy-making together. The comparison of two cases – macroeconomics and landscape planning, both in the Netherlands – shows how models came to incorporate aspects of both science and policy as they were developed, which explains their effectiveness as boundary objects. These boundary objects did not only coordinate the separate social worlds of policy-making and science, but also contributed to the shaping of them.

In the following, virtual engineering is analysed in ways that contribute to the understanding of models as tools; to the inventory of modelling practices and to the critical analysis of computer simulation in environmental management and policy-making. We approach virtual engineering as a practice made possible by developments in the fields of computing and hydrological science, continuing a historical trajectory of engineering as a way of dealing with flood risk. Since the 1950s the building of physical flood defences has been a key UK strategy and calculating the impact of new structures on flood inundation patterns has always been an aspect of flood risk reduction. The novelty of virtual engineering is the disconnection from physical engineering. Virtual engineers provide model-based expert assessment of flooding and risk management options, knowledge rather than solutions. We understand the appeal of computer simulation modelling for flood risk management in terms of its capacity to articulate hypotheses in ways consistent with accepted scientific theory and mathematically explicit relationships in a virtual realm. There is no way to know the future that does not move into the virtual; the critical issue is to make clear which science, whose expertise and whose needs are allowed to shape virtual engineering, and the conditions under which this shaping happens. By focussing on the relationships within which virtual engineering is constituted we articulate a new perspective on computer simulation modelling in society, turning the attention to a practice that has not previously been discussed while being of critical importance for the translation of scientific knowledge to environmental risk management.

In Need of Flood Risk Knowledge

In England and Wales four to five million people, two million homes and businesses, assets valued at £250 billion, are considered to be at risk from flooding (Defra, 2007). Defra (Department for the Environment, Food and Rural Affairs) and the EA (Environment Agency of England and Wales) are the designate bodies responsible for flood risk management, Defra formulates national policy and allocates resources and the EA, an executive non-departmental, public body, has the operational responsibility for flood risk reduction and management.[2] The EA accrues 60% of its funding from Government (via Defra) and is accountable through ministers to Parliament.[3] In 2007/2008 the EA employed around 12,500 staff in England and Wales, with a budget of £1 billion (EA, 2008). EA flood management activities range from building flood walls defending cities, to re-introducing wetlands. The EA is empowered, but not legally obliged, to manage flood risk from watercourses designated as main rivers and from the sea. It is also responsible for increasing public awareness of flooding, providing warnings and supervising local flood risk management. Other organizations, for example, local government, the Highways Agency, water companies and private landowners manage flood risk for non-main rivers, designated ‘ordinary watercourses’.[4] In parts of England drainage is managed by Internal Drainage Boards, who have permissive powers to undertake work on drainage and water level management and are involved in the maintenance of rivers, drainage channels and pumping stations in their areas (JBA, 2006). The EA is also a regulatory body that sets standards for environmental protection, issues permits for businesses and developments, monitors observance and enforces legislation (EA, no date). The EA is one actor in a formal network in which an interest in knowledge about flooding is continuously generated and is in focus in this paper because of its importance for virtual engineering.

In line with a 1999 Government White Paper–*Modernising Government*–the EA is committed to base its work on robust knowledge, on evidence.[5] There are many different research practices that could potentially inform the flood risk work of the EA. Defra guidelines explain that evidence can come from a range of sources, including: 'expert knowledge', 'existing research and statistics', 'new research commissioned specifically to inform the development of policy options', 'the results of horizon scanning and foresight work' and 'formal stakeholder consultation' (Defra, no date). However, in this evidence-based policy regime the EA relies predominantly on computer simulation modelling undertaken by engineering consultants. This arrangement was crystallised after the so called 'Bye report', a performance review following a severe flood incident at Easter 1998, affecting central and eastern England and Wales (Bye and Horner, 1998). The Bye report suggested that the knowledge required by the EA to manage flood risk should be procured from external experts, understood by the authors of the report to be independent from the EA. Extending this practice, already existing in some areas, to the entire country was intended to guarantee that the EA could access state-of-the-art, relevant and reliable knowledge on which to base the prevention and amelioration of flooding from the rivers and coasts for which it is responsible. Hence, knowledge about flood risk generated by computer simulation modelling became a product that the EA purchases from private businesses.

There are over a hundred companies in England capable of producing flood risk knowledge for the EA. They differ greatly in size and character, but in the terminology of organisation and management studies they are all 'professional service providers', organisations 'that trade[s] mainly on the knowledge of its human capital /.../ to develop and deliver intangible solutions to client problems' (Morris & Empson, 1998: 610). At one end of the scale there are multinational engineering firms that have England as one of many markets.[6] At the other end, there are small businesses, self-employed consultants, qualified engineers, who do work for local clients. In between there are some companies that specialise in water and do a lot of work for the EA, and others that have water as one among many applications and do different types of work for different clients. Some firms have a traditional consultant structure, where the partners own the firm together and share the responsibility of bringing in new business to generate income. Others are hierarchical corporations with shareholders, boards and executive directors. Some consultants work closer to the research end, doing collaborative projects with academic scientists in explorative and experimental studies, while others do more applied, run-of-the-mill studies for clients wanting knowledge for local risk management and reduction, some companies do both. However, they all work on water in England, they all offer flood risk modelling as one specialism and they are all interested in doing projects for the EA. In this competitive context for the EA to put every project out to tender would create an insurmountable mountain of administration. Instead they have set up 'Framework Agreements', contracting a small number of companies to do all EA projects in a region, over a specified period.

The Framework Agreements are put up for tender every five years. At that time the engineering consultants put in major effort in terms of time and money to prepare bids.[7] They have to submit substantial documentation in which they explain to the EA why their company should be included in the next Framework. According to one of our interviewees, over 30 companies applied for the tenders in 2003, across Europe. There was a short-list of about 15 competitors that were asked to provide detailed proposals. Consultants may join forces to put in a collective bid, where two or more firms commit to work together in a partnership for the duration of the Framework. This can produce more competitive bids since partners can complement each other, it also enables the smaller English firms to compete more effectively against large multinationals in the open international tendering process. The Agreements create a degree of continuity for the consultants, both in terms of income and skill development. For the consultants on a Framework it is a beneficial format. How firms cope if they are not in an EA Framework Agreement probably varies greatly. One interviewee worked in a company that was not, at the time, included. According to this interviewee, not being on a framework made it possible for them to do more interesting work, while avoiding routine projects they were still able to bid for and win, work in EA pilot projects. It is important to note that this company does water as one sub-specialism; it is a medium sized international engineering company offering a full range of engineering services, with 5000 employees across the world, not dependent on a regular income from flood risk research in England.

That there is a formal, contractual, relationship in existence before any particular research project commences ties this knowledge-producing activity very closely to the 'client', distinguishing it from the competitive situations of an open market, or a research grant system. The EA and the consultants in the Frameworks become collectives, within which expert modelling knowledge and flood risk management practice are coproduced. Engineering firms on an EA Framework Agreement are assigned projects according to their particular expertise. Projects vary in size and character, the interviewees talked about project size in spatial terms; the extent of the geographical area covered. Some of the geographically largest projects are the National Flood Maps, estimating risks posed to river flood plains and coastal areas under specific conditions.[8] These flood maps are important for other projects in which they can be used as reference points for tasks such as developing new systems to warn local residents. Other projects that our interviewees considered to be large were CFMPs (Catchment Flood Management Plans), outlines for flood risk management objectives for entire catchments, informing long-term planning. These were defined as 'broad scale' studies intended to provide overviews, not detailed information. More detail is required in Strategic Flood Risk Management projects, addressing recognised flood risk and possible management options. There are also numerous detailed local projects on rivers and reaches that pose specific risks to local residents and properties. Modelling is also needed by actors other than the EA, for instance, private developers as part of their statutory requirement to undertake detailed flood risk assessment of their proposed development, if it falls in certain of the national 'flood zones'. Regardless of the extent of a project there are some tasks that are undertaken in every consultancy modelling commission.

Standardised Black-boxed Science

Projects aiming to estimate flood risk in a particular locality undertaken by an individual modeller or a team, begin with what our interviewees talked about as 'conceptualisation', referring to the initial thinking through of the problem and deciding on an approach.[9] The work starts with a review of existing models and reports; today most of England's main rivers have been modelled and previous models inform new projects. When a model of a locality already exists the consultant must decide whether or not it is fit for purpose, needs to be developed, or whether a new modelling strategy is required. Talking about this our interviewees used the term 'model' with reference to representations of specific localities rendered in computer code. If existing models were considered insufficient a new modelling procedure began in which the first step was a field visit. Field visits were emphasised as crucial for forming an understanding of the problem at hand. During the visit modellers would look at gauging stations, major structures and other things that may restrict the water flow. In addition they would want to get 'a feel for what is going to control the water levels in the channel /…/ look at the bed, what that looks like, where there is sort of blockage obstructions'(Consultant interview 9).

The way in which the modeller conceives of the physical system and the problem to be solved informs which mathematical solutions will be used to represent a local system: one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D). This terminology refers to spatial dimensions in relation to the movement of water. These numerical solutions for processes are theoretically explained in hydraulics (fluid mechanics). Scientific research has generated numerous computer codes for simulating various aspects of river and sea flooding; however, virtual engineering modellers do not choose freely among the full range, but they use off-the-shelf proprietary software. All such software packages start with the theoretically-based physical rules of fluid mechanics, based on the conservation of mass and momentum. They are conceived to be deterministic, even if they are eventually run probabilistically, i.e. with very different boundary conditions to capture the uncertainty in input data. By averaging in the vertical, the 2D solutions can be derived from the 3D solutions and by averaging laterally, the 1D solutions can be derived from the 2D solutions. With each of these changes in dimension, processes that were explicit in the higher dimensional solution need to be accounted for in the lower dimension solution, normally using what is called auxiliary relationships. As the solution dimension is reduced, so the auxiliary relationships tend to have more impact on the solution when used in a model. What kind of dimensionality is needed can be determined by the scale of application: 3D over smaller scale, 1D over the largest scale. In some cases solutions of different dimensionality may be coupled, such as 1D for flow in the river channel and 2D to represent how water spreads out across a floodplain. There are established ways of approaching different problems, e.g. if the task is to investigate the volume of water that needs to be contained inside the riverbanks in order to prevent flooding a 1D solution is appropriate, if the question concerns determining which properties will be at risk when a river is inundating its floodplain a 2D solution may be used. In virtual engineering a 'model' is the outcome of applying a software package to a particular place, creating digital renderings, or representations, of actual rivers and coastal environments.

To create models for the EA the consultants normally use one of three 1D software packages – ISIS, HEC-RAS or MIKE11 – and any of the 2D packages in common use. This limitation in range is the result of customer preference. The EA desires transparency and stability of the core tools used to produce the knowledge they base decisions on. The interviewees told us about how this was effectuated by 'benchmarking' river modelling software. ISIS, HEC-RAS and MIKE11 were compared in joint Defra/EA project reported in a series of technical documents and a summary (EA, 2005). 1D software benchmarking was first initiated by the National Rivers Authority (NRA) in 1993 and the two-stage process was completed in 1997, when the NRA had been replaced by the EA.[10] The outcomes of this project were used by the EA (and other operating authorities) to 'identify and apply the best models [software packages] and practice' (EA, 2005). However, software packages change and in 2001 a new benchmarking project was needed. At that time the EA only supported three of the original eleven packages tested and it was decided that the test should be done on those three. The benchmarking project was undertaken by a team mixing Defra and EA staff with university academics and consultants. Commencing in 2002 the project devised twelve test specifications for different programme functions, e.g. subcritical, supercritical and transitional flows. The tests assessed numerical accuracy, capability and reproducibility. Completed in 2004 the tests were to be used by Defra, EA, other operating authority staff, research contractors and consultants, academics and students. They were also intended for use in training novice modellers, as well as testing software upgrades and new products.

The standardisation of mathematical solutions in software packages is pivotal in the relationship between consultants and the EA. Undertaken on the initiative of a client with ties to government it marks a critical difference from the modelling in universities. One of the interviewees noted that the standardisation of practice through benchmarking contributes to wider trust in the modelling process:

> Well, it is pretty complex and /…/ if you get something wrong, it may not be obvious, so it gives the consultant some degree of confidence /…/ because we have got standards means, standard methods. People are trained in using them, we know what to check, we know where the problems quite often are. Because it is not always a question of putting in numbers, getting /…/ the answers /…/ it is how you model a particular problem /…/ you do need to know the quirks and the difficulties of modelling with different packages. But if you /…/ standardise the approach for us /…/ it is much easier to check that a model has been applied correctly. If someone decides to develop their own model, you have to start at the beginning and check everything. (Consultant interview 5)

The standardisation which defines the representation of hydraulic processes, blackboxes the mathematical solutions to the virtual engineering modellers, it also distributes the responsibility for the quality of the modelling, in actor-network terminology a process of 'delegation'. This standardisation is seen as a means of reducing the dependence of simulation outcomes upon the modeller. The issue is not whether the model is fit for a particular purpose, as in conventional scientific activity, but whether or not different modellers would generate the same results, i.e. whether the software has been applied correctly. If a particular model fails it will be the fault of the modellers, not the mathematical structure of the model. Most of our interviewees appreciated standardisation as a beneficial development, improving the efficiency of the knowledge production process.[11]

The differences between the three approved 1D software packages are to be found in the user interfaces rather than the capacity to simulate geophysical processes. Choosing between them comes down to pragmatic factors, such as the cost of use. These are proprietary software; ISIS is owned and developed by two UK companies: Wallingford Software and Halcrow.[12] MIKE11 is a product from the Danish Hydrological Institute (DHI) who runs courses and provides customer support internationally.[13] HEC-RAS is developed by the US Army Corps of Engineers.[14] Due to US legislation on products developed with public funds, HEC-RAS is free to use and can be downloaded from a website by anybody, while the other packages come with 'dongles' that can cost a considerable amount, depending on the sophistication of the specific version. The number of dongles and user licences within a company is limited so modellers may, for example, choose to use HEC-RAS for a smaller job because it is free and they do not have to use a dongle that a colleague might need more. Other factors influencing software choice are the training and preferences of the modellers. Modellers develop skills in how to make particular software packages run well, which is important since the software is considered more reliable than any individual modeller.

Parallel with the production of models for particular places by consultants is the development of new software packages, which is primarily undertaken by a smaller number of consultants, sometimes in collaboration with research institutes or universities. Software development forces an instability upon the models of particular localities such that when a place is 'revisited' there can be justifiable reasons to develop an entirely new modelling strategy. Recently 2D models have become common, mainly because of the increased availability of digital terrain data, which has made them useful. The EA has initiated a standardisation process of 2D software packages; a review was published in 2009. This project, undertaken by a collaboration of EA, university scientists and consultants, compares TUFLOW, InfoWorks, Mike21 and JFLOW (EA, 2009). The review presents the hydraulic science and the equations central to 2D solutions. It also accounts for the results of a questionnaire asking modellers in consultant businesses, EA and universities, a range of questions concerning the use of the software packages, such as the quality of user manuals and technical references; the flexibility of data input, run time, visualisation and so on. The review is presented as the first stage in a benchmarking exercise that aims to assess 2D software in the same manner as Defra/EA previously compared 1D software.

The black-boxing of proprietary software packages establishes some mathematical representations of hydraulic processes as standard tools. The modellers' task is to use the tools to represent the conditions of a particular locality. The use of standardised tools to solve local problems maps onto the way the modellers we interviewed formulated the difference between science and engineering – as they saw it engineers are interested in solving problems in the world, not in representing the world in mathematical equations. This was mentioned by several interviewees who distanced themselves from 'the mathematics' of the software packages, and the academic interest in knowledge as such. These modellers were not interested in creating new representations of general natural phenomena, but wanted to use the standardised computer programmes to develop knowledge about the possible behaviour of a particular local natural system. The modelling software here becomes a device for translating unique local events into a general pattern of flood risk that has been scientifically established. The routine use of these black-boxes by consultants producing knowledge for the EA also means that the flood risk associated with rivers in England becomes that which is rendered calculable by the available software packages. Knowledge admissible in risk reduction and management has to be produced by using benchmarked packages, which defines what counts as evidence in the flood risk management strategies implemented by the EA. Other forms of evidence, e.g. local knowledge, are recognised only as long as it can be translated into numbers, e.g. water levels, compatible with model requirements.

Modelling Localities at Risk

In order to make a software package represent flooding as a process in a particular locality the modellers need data. To begin with they have to find out what data they need, which data sets exists and who holds them. The selection of modelling approach and software affects this, 1D models require data for cross-sections that extend across the river and onto the floodplain and 2D models require digital elevation data continuously across the floodplain. All modellers need hydrological data about river discharge, water levels and flood outlines to set up, calibrate and use models in simulations.

The interviewees told us that there had been significant technical developments in the area of topographic data collection for modelling in the last decades. Surveyors are still needed to undertake field surveys, i.e. direct physical measurements, of the river channels, but they are now aided by the use of satellite-based Global Positioning Systems (GPS), that geo-references the data they collect. Although not necessary for 1D modelling, GPS makes it easier for the modeller to link individual river cross-section surveys into the same elevation datum. There have also been changes in the formatting of data; surveyors now have software that automatically formats measurements for use in models. This saves modellers a lot of time that would otherwise have been used to enter numbers manually into the model.

The development of remote sensing technologies for generating floodplain elevation data has been a driver for the expansion of 2D modelling. Three different ways to generate this type of data were mentioned by our interviewees: InSAR (repeat-pass ERS interferometric SAR), stereo photogrammetry and LiDAR (Light Detection and Ranging). InSAR is produced from either satellite images acquired from different orbit positions, providing Digital Elevation Models with a resolution of 25 metres, or from airborne platforms covering England to a resolution of 5 m and a precision of ±5 m. Stereo photogrammetry, applied to aerial photography obtained by aircrafts whose flying height determines the spatial resolution and vertical precision, was the preferred method by one of our interviewees who appreciated the explicitness of human judgement in this process. The other interviewees favoured LiDAR data, also airborne, with laser linked to GPS, providing very high resolution (25 cm to 2 m) and precision at ±0.15 to ±0.25 m. LiDAR data, collected by the Geomatics Group a specialist business unit set up within the EA, are not available nationally. If LiDAR data are not available, the EA unit commissioning the consultant's work may request that the necessary area is over-flown and fund their business unit to do this. If the data are available the consultant can download them from the Geomatics Group website for use in their project.[15] For work that is being undertaken by consultants for the EA there is no charge, but LiDAR data are sold to others for both commercial and non-commercial use.

Having assembled the necessary data about the topography in the locality at risk of flooding, the modellers use the software to create a representation of relevant parts of the landscape. In a 1D model river cross-sections are defined in a model 'geometry' that represents the shape of the channel and the banks with survey measurements at specific points along the main river, sometimes extrapolating in-between in order to obtain better model resolution. 2D models layer terrain data over a grid with cell size related to the resolution of data, or using irregularly spaced data points represented in a mesh. Geo-referencing and visualisation in a GIS system assist the modeller in checking for errors; all the interviewees emphasised the many possible errors in the data. When the modeller is satisfied with the representation of the topography of the landscape in the computer software they need hydrological data to set the boundary conditions, telling the model how much water is coming in, for how long and at what intensity. Commonly this is based upon gauge data of river discharge. The main supplier of these data is the EA, which maintains gauging stations in many rivers. Historically, these were based upon continuous measurements of water levels, calibrated by being fitted statistically, or by using numerical models, to spot measurements of discharge. Since the 1990s, these have begun to be replaced by direct measurements of discharge using ultrasonic flow gauges. But, for longer records and those locations either unsuitable for ultrasonic gauges or of insufficient importance to justify the expense, calibrated water levels records are dominant. The modellers we talked to were aware of the complexity of these data:

> A gauging station is used in various empirical relationships to try and relate stage to discharge, but it is just an empirical equation, it doesn't necessarily relate to what actually happens at that point. /…/ If you then just pick that up and just use it without questioning it, then it completely can change the whole of your assessment /…/. (Consultant interview 6)

Flow record measurements need to be extrapolated to higher flows, a procedure whose effectiveness depends upon the characteristics of the local gauging station and may also need to be based upon 1D mathematical models. In addition most of the flow records have very few, if any, measurements of flood flow. One interviewee explained that floods are difficult and potentially dangerous to measure:

> If you see a river in flood it is not a flat surface, so what level you are measuring is one source of error. Building up a relationship between a level and flow is never easy. All sorts of things happen in floods that are not obvious when you go there when there is not a flood going on. /…/ if you actually try to gauge it in a flood there are enormous errors /…/ trying to measure the velocity of a river in flood it is extremely difficult. If you have a calibrated weir there are lots of questions about obstructions on the weir, backing up from downstream, whether the approach is correct, and the velocities are even across it. (Consultant interview 5)

The scepticism about some aspects of data generation expressed by the interviewees does not translate into any active critique. The reliance on these data for modelling is institutionally stabilised; the water levels records may be uncertain, but there are no other, less uncertain data to supplant them with. As with the topographic data and the models themselves, hydrometric data are also supplied under licence to the consultant which restricts the use of those data to the particular modelling project. Here, as with LiDAR, data are seen to have a value in a commercial sense and that value has to be carefully regulated.

Many areas in England and Wales do not have flow data of enough detail to be useful for modelling one watercourse, or a part of it. Then the modeller is most likely to turn to the Flood Estimation Handbook (FEH) a product for purchase on a set of CD-ROMs, created by the CEH.[16] This is a five-volume handbook facilitating the estimation of flood extents and frequencies for every river in England. The FEH provides modellers with estimated hydrological conditions for the river they are modelling, even if there are no gauges that apply to the particular locality. Using records of flood peaks going back over 170 years, or matching data for hydrologically similar catchments, the FEH statistically models the return periods, i.e. the average duration between flood events of different magnitudes, for any river. Such estimations of long-term regularity of the natural system were treated with scepticism by some interviewees:

> /…/ quite often we have to model return periods, I think these days, we haven't really got a clue what return period flow is. We used to think we did, there were some stability in the data, but in recent years there has been such variability, I think it is anyone's guess as to what a 100 year flow is these days. /…/ Then, of course, how frequently these events are going to occur, now and in the future, we really are struggling. So it just compounds error on error and we have only got a rough idea. (Consultant interview 5)

Despite any doubts modellers may have, the FEH has become the baseline reference for determining flow in English rivers. To facilitate modelling the FEH provides digital 'catchment descriptor information' which indexes hydrological similarity in terms of average annual rainfall, catchment area, hydrology of soil type, proportion of the catchment covered by lakes and reservoirs and more. The FEH can also produce flood hydrographs of given return periods to provide an indication of how rapidly the runoff might occur. To do this it uses rainfall of a specified frequency as input and applies it to a unit hydrograph, an instantaneous description of when, in the future, unit rainfall will appear as flow downstream for a set return period.

Working with data to make a digital representation of a specific locality is the core activity in virtual engineering. It amounts to building virtual representations of specific physical systems in order to assess intervention options. Agreeing with the interviewed modellers, we understand this to be a fairly new engineering practice, made possible by developments in computer technology, the advancement of powerful desktop computers that can do calculations very quickly, and the formulation of flooding in mathematical terms though hydraulic/hydrological scientific research.

Calculating Virtual Floods

When the modellers are satisfied that the virtual waterscape created captures the locality, it is time to calibrate the model with the actual system. This is necessary because although the models are physically-based, they are also simplified. The process of developing a model code requires process simplification, which requires new relationships, often semi-empirical or empirical to be introduced. These relationships can have a major impact upon model predictions and many of them contain parameters which have no simple relationship to measurements. In university research the choice of which relationships to use is a topic of debate, challenge and negotiation (Sundberg, 2007) and may lead to the refinement of existing parameterisations or development of new ones. In virtual engineering these relationships tend to be black-boxed in the software packages, the modeller must choose from a small number of options. In this field it is critical to ensure that the model can simulate the measurements generated by known events, which involves choosing these relationships and adjusting their parameters.

Calibration is a process known to modellers in many scientific fields, as well as to philosophers and sociologists of science. It is a subject of debate and there are formal definitions, however, we are interested in how it is understood and addressed by the modellers in virtual engineering. We found that they described calibration as the process of making the models simulate past events as accurately as possible. They told us that when using 1D software packages calibration is usually done by varying the roughness value. This is a mathematical function that slows down the water flow, hence, raising the water levels. Not being directly measurable, hydraulic roughness is usually parameterised as Manning's *n* (see Whatmore and Landström, 2010, for an in-depth discussion of this parameterisation). Roughness is also important in 2D modelling, but other features play more prominent roles in their calibration. In virtual engineering a model that has been successfully calibrated is considered trustworthy for simulating possible future events. The university scientists we talked to found this form of calibration problematic, in their view this was an outdated way to treat hydraulic roughness, simplifying the physical system more than necessary and risking to get the 'right answer for the wrong reasons' which casts doubt on the quality of simulations of possible future events. That the way in which models are calibrated in virtual engineering can be challenged has not diminished their importance in flood risk management in England. However, it does set this modelling practice apart from that of university scientists, which is more orientated towards interrogating model assumptions than getting known events right (c.f. Beven, 2002).

When the modellers are satisfied that the model represents the physical system and measurements from previous flood events as adequately as possible, they are ready to run simulations in which hypothetical boundary conditions are set and the model calculates what the response of the system would be if these circumstances were to occur. The simulations answer questions about what would happen in the particular locality given different hydrological and hydraulic conditions. Whilst the model is developed and calibrated using data from previous inundations, projections of possible future floods involves simulating 'design events', which are set with particular return periods estimated from historical records and commonly, modified for factors identified as important. One such factor, mentioned by the interviewees is the UK Government's estimation that river flow may increase by 20% over the next 100 years due to climate change. With a calibrated model, guidelines for boundary conditions, e.g. rainfall data, for different circumstances and return periods modellers can also simulate how interventions in the landscape could impact on flood risk.

Such questions are asked in relation to the planning of new structures e.g. buildings, bridges and roads. Another reason for asking this type of question is if the EA is considering flood reduction measures. One interviewee talked about this:

> ...within the strategic flood risk management strategies, we make an assessment of the existing flood risk. /.../ then we will come up with a number of options. /.../ those options can be either structural, non-structural or they can be maintenance driven. /.../ structural measures would include things like raised defences, improving the capacities of the existing defences, building in flood storage areas, and wetlands areas, trying to attenuate and store water. They could also be /.../ in channel structures such as sluice gates or control structures, trying to again sort of attenuate flows. (Consultant interview 6)

As is the case with all computer simulation modelling, ultimately the range of possible conditions that can be tried out is constrained by what the model allows. As mentioned above, 1D and 2D software packages enable different investigations of what could happen in a floodplain when it is inundated at various depths. Likewise, the geographical extent of a model restricts what the modeller can try to engineer in the landscape in an attempt to reduce flood risk.

Before finishing a project, the modeller might return to the actual locality for another field visit to check the viability of the simulations. When the modellers have established their own trust in the model and the simulations, the project outcomes are delivered to the EA in the form of the calibrated model on a CD-ROM, maps of how the water is likely to inundate the landscape under different conditions and a written report detailing the research process as well as the uncertainties, outcomes and recommendations. When the model and accompanying documents are handed over to the EA some active translation is often necessary, the modellers have to explain and show what the model means, the interviewees remarked on how useful the visualisation tools of the software packages are when it comes to explaining the product. They also mentioned the varying ability of EA project managers to actually understand the model and appreciate the uncertainty inherent in all modelling predictions. The calibrated model with the report is the end product of virtual engineering projects. The EA retains ownership of all of its commissioned models. When these are to be used for commercial purposes, even if it is by the company that developed the model, the client (e.g. a developer) is expected to pay for that use. If the EA decides to build a structure, or do some other physical intervention, then this would be commissioned as a follow-on project, which quite possibly would be undertaken by a different engineering company, and normally under the separate National Environmental and Engineering Consultancy Agreement (NEECA). The models, as with the data used in them are then released to the commissioned company under strict licence, i.e. to be used only in the specific project.

Virtual Engineering – Modelling Differently

The objective of this paper has been to describe and characterise a computer simulation modelling practice that we learned about when interrogating flood risk management in England. Drawing on the philosophical and social science literature on modelling we have highlighted this practice as virtual engineering, in which computer models are used as tools in commercial consultancy practice. The findings contribute to the understanding of models as tools the example of a modelling process not governed by the epistemic interests of the modellers. In virtual engineering models are elements in a process of sequential steps in which a range of objects and skills are involved. One critical element is ready-made modelling software that standardises practices and outcomes across companies and stabilise a network of actors in different societal fields. The process of applying generic software in particular localities renders rivers as virtual objects – models – that can be interacted with to answer hypothetical questions about flood risk. Building the model is not the end-point; when a locality has been digitally rendered modellers use it to simulate future events. This is something this practice shares with all other fields of computer simulation modelling, but focussing on virtual engineering emphasises modelling as producing knowledge about the particular, for use by others than researchers.

In virtual engineering, the events simulated are already scientifically explained. The models represent processes in ways considered to be true to the general physical dynamics of flooding and the historical experience of previous flood events. This articulation of local flood risk in scientific mathematical structures enables the exploration of 'what if' questions occupying the clients, who need this knowledge to make decisions. Practicing in a space historically and institutionally understood as the territory of engineering – flood risk reduction and management in England, the virtual engineering modellers we interviewed defined their work as different from science, as aiming to solve the problems of clients, rather than to construct mathematical representations of flooding. The scientists we interviewed also regarded such virtual engineering as different in nature, but not in a positive way, they considered it to rely on over-simplifying model structures and to lack critical perspectives on the parameterisations in the proprietary software packages.

Adopting an approach focussing on relationships and networks we found that although this modelling practice was undertaken by private businesses selling knowledge and expertise, it was shaped also by the demands and protocols of a primary client – the Environment Agency. We identified the long-term contractual agreements with a limited number of companies to deliver knowledge about local flooding, as enabling the engineering companies to invest in the skills and technologies that would increase the efficiency in producing knowledge and expertise useful to this client. We identified the EA's requirement to use particular software packages as stabilising the modelling across individual businesses and localities. There is no need to think outside of the black-box of approved software, benchmarking actively dissuades diversity in producing this type of knowledge for the EA. The standardisation effects a distribution of agency in which responsibility for the quality of the representations and simulations is shared between modeller and software. This social stabilisation of virtual engineering through contractual relationships and technical standardisation is a new variation on the computer simulation modelling practices mapped in social studies of science.

Virtual engineering has evolved in a space where environmental managers, decision-makers and developers need reliable modelling of local problems. This is not the remit of academic research or work that scientists find very interesting. As virtual engineering is stabilised in relationships with local environmental decision-making and national government it becomes the privileged way to generate knowledge for flood risk management in England in the 'evidence-based' policy regime of the 2000s. It then comes to define what society needs to know about flooding in order to undertake risk management that is considered satisfactory. Virtual engineering has become an obligatory passage point for local flood risk management, almost all river catchments in the country have been modelled, any call for local interventions have to demonstrate efficacy (physical and economical) via a consultant modelling the options. In the stabilisation of virtual engineering science and policy-making are entwined from the outset in a way not previously discussed in policy research.

Despite the limitations of this investigation we are confident in identifying virtual engineering as an important knowledge generating practice and its relationship with the EA as crucial for the stabilisation of computer simulation practices for local flood risk management in England. The material we have does not allow for conclusions regarding the impact of this practice on software development, nor about what difference more prominence of other types of clients (e.g. developers) would make for the generation of flood risk knowledge. Notwithstanding its limitations our study does have implications for environmental decision-making, as we emphasise the importance of understanding how virtual engineering differs from other ways of generating evidence for flood risk management. It is important to make clear that expert evidence in the form of reports from engineering consultants using computer simulation modelling software is not the same as information produced by academic scientists building new mathematical model structures, which is the reference point for many policy-makers and environmental managers. Virtual engineering is a practice in which the standardisation of models and the stabilisation of social relationships set the limits for which questions can be asked and which answers found with regard to local flood risk. Information produced in this practice can be trusted by clients because of the stamp of approval given to the software, not because specific knowledge claims have demonstrated their ability to withstand challenges from competing modelling approaches.

Notes

[0] This article was edited and approved for publication by Tarja Knuuttila.

[1] The research was undertaken within the framework of the three-year project 'Understanding Environmental knowledge controversies: The Case of Flood Risk Management'. Funded by the Rural Economy and Land Use (RELU) programme this transdisciplinary project addressed the public controversies generated by risk management strategies. The focus was on the science and politics of flood risk modelling and how to improve public involvement in determining the role of rural land management in the amelioration of flood risk (http://knowledge-controversies. ouce.ox.ac.uk).

[2] In this field the term 'reduction' is used with reference to removing risk through, for example, building bunds, while 'management' indicates activities aimed to help people to live with flood risk.

[3] This outline of the EA summarises a description published on Defra's website, (www.defra.gov.uk/environ/fcd/rolesandresponsibilities/opauthsea.htm, accessed 1/4/2009).

[4] The roles and responsibilities of different bodies are described on Defra's website (www.defra.gov.uk/environ/fcd/rolesandresponsibilities.htm, accessed 1/4/2009).

[5] This was an initiative aiming to reinvigorate the public services by, among other things, improving the use of evidence and research in all areas (www.archive.official-documents.co.uk/document/cm43/4310/4310.htm, accessed 7/1/2010).

[6] The diversity of PSFs becomes visible in professional directories, such as the one provided on the CIWEM (Chartered Institution of Water and Environmental Management) website: http://www.ciwem.org/index.asp, accessed 55/2010.

[7] There is no information about the EA Framework Agreements in the public sphere. Our understanding of them is based on interviews, information from consultant firms to the public, and the personal experience of one of the authors.

[8] Brown and Damery (2002) conducted a critical analysis of the first EA flood maps being made available to the public but they do not discuss how the maps were created.

[9] The academic modellers we talked to also used this term but with reference to the process of working out which physical principles to apply and on which mathematical formulations to base a model structure for encoding in a computer programme.

[10] The EA was established in 1996 following the Environment Act 1995.

[11] One of our interviewees disagreed, viewing the standardization as the creation of a near monopoly situation for one software company, hampering innovation.

[12] The software can be downloaded from the companies' respective websites, www.wallingfordsoftware.com and www.halcrow.com/software. Since dissolving the partnership with Wallingford in 2008 Halcrow offers a version of ISIS as a free download.

[13] In the UK DHI has one office from which customer contact is handled. They also offer software, tech support and user tutorials on-line, www.dhigroup.com/Software/WaterResources.aspx.

[14] See www.hec.usace.army.mil/software/hec-ras. The US Army Corps of Engineers do not offer any technical support or instruction courses to users other than US military.

[15] See: www.geomatics-group.co.uk/GeoCMS/AboutUs.aspx, accessed 23rd April 2010.

[16] The FEH is sold by Wallingford HydroSolutions, a technology transfer company (www.hydrosolutions.co.uk/index.html).

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