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Virtually Expert: Modes of Environmental Computer Simulation Modeling

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Argument

This paper challenges three assumptions common in the literature on expertise: that expertise is linearly derived from scientific knowledge; that experts always align with the established institutional order; and that expertise is a property acquired by individuals. We criticize these ideas by juxtaposing three distinct expert practices involved with flood risk management in England. *Virtual engineering* is associated with commercial consultancy and relies on standardized software packages to assess local flood inundation. *Mathematical experimentation* refers to academic scientists creating new digital renderings of the physical dynamics of flooding. *Participatory modeling* denotes research projects that aim to transform the relationships between experts and local communities. Focusing on different modes of modeling we contribute an analysis of how particular models articulate with specific politics of knowledge as experts form relationships with flood risk management actors. Our empirical study also shows how models can contribute to re-distribution of expertise in local flood risk management.

Introduction

Since the 1990s computer simulation models and modeling have become established as topics of research in the history, philosophy, and sociology of science (e.g. Morrison and Morgan 1999; Winsberg 2003; Sundberg 2009; Knuuttilla 2011). Another issue subject to long-time investigation in the social study of science is expertise (e.g. Jasanoff 1990; Collins and Evans 2002; Wynne 2003; Fischer 2009). The two topics are not normally addressed together, but in light of developments in environmental science and decision-making the need to do so is becoming obvious. Environmental computer models have come to take their place amongst those scientific objects that traffic between science and policy as vehicles of expertise. The knowledge informing environmental

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management is becoming closely associated with computer simulation modeling, which brings models and modeling into society in ways that differ from their roles in the research undertaken in universities and other scientific institutions. The association of modeling with environmental expertise also brings computer simulation models into controversies over environmental management, contexts in which all knowledge is political.

This paper explores the relationships between computer simulation models and expertise in flood risk management in England. We draw on research conducted in an interdisciplinary project and develop the discussion of it further than in previous publications as we relate the empirical findings to the literature analyzing expertise as an aspect of science in society.

Having conducted empirical research on flood risk expertise, studying it as well as generating it in a new way, we propose that it is best understood as the outcome of situated knowledge generating practices. Empirical studies of particular rivers and theoretical analyses of the mechanisms of flooding are examples of such practices, which are situated in different social networks. In these practices the heterogeneous elements of flood risk management, e.g. research protocols, modeling software, river gauges, and research reports, become essential for the performance of epistemic authority, i.e. expertise. The tools that experts use join scientific knowledge about flooding with local flood risk management. Our practice-focused approach provides a perspective on environmental expertise that differs from the views expressed in the literature and it prompts us to challenge three prevailing assumptions about expertise: (i) that it is linearly derived from scientific knowledge (an assumption common in analyses of science in society, such as Beck (1992); (ii) that it is always aligned with the established institutional order, a view shared by political theorists, e.g. Fisher (2009) and science studies critics, for example, Wynne (2006); and (iii) that it is a property acquired by individuals (e.g. Collins and Evans 2002). Our criticism is presented in an empirical analysis of the ways in which specific modeling practices connect with particular environmental management actors, thereby consolidating different politics of knowledge in relation to flooding in England. By juxtaposing three different flood modeling practices we are able to illuminate how the expertise informing policy and management is constituted in specific modes of modeling. Additionally, by discussing the participatory modeling approach of competency groups in which we took an active part, we also demonstrate the possibility of generating new modes of modeling and scientific knowledge in ways that re-configure the politics of knowledge in local flood management. This paper thus contributes two distinct elements to the existing literature: an understanding of model-based environmental expertise to the science studies investigation of computer simulation modeling, and an example of critical participatory modeling to the critical interrogation of expertise in democracy.

In the following we begin with positioning the present analysis in relation to the wider body of work on computer simulation models in science studies and discuss approaches to expertise. Thereafter we introduce the practice-focused perspective we

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consider more useful to address the role of computer modeling in environmental expertise. Next, we briefly connect the present paper to previous publications from the research project on flood modeling in England that underpins the discussion. This is followed by the main part of the paper which juxtaposes the empirical examples of flood risk management expertise in England, outlining three distinct practices centered on different modes of modeling. The analysis of the examples details the relationships between models and expertise and explicates the links between different expert practices and specific social actors in the politics of knowledge in local flood risk management.

Environmental management bring studies of models and expertise together

Our interest in linking analyses of computer simulation models with studies of expertise originates in developments within the field of environmental management. As noted above computer simulation modeling is becoming increasingly important in the generation of knowledge relied upon in the management of environmental risks. The models central in environmental management originate in the environmental sciences, where computer simulation have made it possible to explore complex natural systems in new ways.

The role of models in scientific research has been investigated in the philosophy, history, and sociology of science since the 1990s. In-depth critical analyses have rejected naïve realist ideas about computer models as mirroring nature. Morrison and Morgan argue that we need to approach models as tools that invest the notion of representation by partially rendering an object in a new medium. They explain that a model is able to "teach us something about the thing it represents" (Morrison and Morgan 1999, 11) be it an aspect of theory or of the world, by allowing us to manipulate it in ways specific to the medium. Models become relatively independent instruments for investigation due to their intermediary position between theory and data, as they render both in a different medium. Elucidating the understanding of models as epistemic tools, Winsberg (2003) argues that computer simulation models are unique in their capacity to do complex calculations (simulations) semi-autonomously and that they force scientific assumptions about the world to be explicitly spelled out. Knuuttila (2011) further elaborates the notion of representation in this context, criticizing an understanding of computer models as isomorphically related to the phenomena investigated, arguing instead that as epistemic tools, constructed with specific purposes in mind, they are shaped by the scientific questions prompting their invention, rather than by the object of investigation. This strand in the philosophy of science draws attention to computer models as things that are constructed, manipulated, and studied by scientists in order to gain knowledge about the physical world. Philosophers share this understanding of computer simulation modeling with social scientists, who investigate the practices of modeling in different scientific disciplines empirically, for example, in ethnographies (e.g. Sundberg 2009). The conclusion that computer simulation models cannot be

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understood as representations of the physical world, but rather as renderings of complex assemblages of theory, data, and computer code is a critical insight, pivotal for addressing their role in environmental management.

Environmental management has been characterized as an aspect of risk society (Beck 1992), and as such it relies on expert knowledge, which raises issues explored by political theorists. Bocking (2004) discusses the problem of expertise in environmental decision-making, arguing that it erodes the authority of science in relation to environmental matters because of an association with industry interests, promoting resource exploitation over environmental sustainability. Concerned that the use of scientific expertise in environmental management poses a challenge to democratic decision-making, as it disregards the interests of local communities, Bocking calls for the democratization of science, to make sure that it is used to inform, but not determine, policy options. To limit the influence of science is also the ambition of Fischer (2009), who discusses how the reliance on expertise in decision-making marginalizes the ordinary citizen. In addition to constricting the influence of scientific experts, Fischer advocates the promotion of more public participation through deliberative democratic decision-making processes. Both these political theorists view the role of experts in society as a problem originating in the different rationales of science and democracy, and they share a view of science and expertise as always associated with elites, to the detriment of democracy and local communities. Science Studies authors, such as Wynne and Jasanoff, also share this negative view on the political role of expertise and they add empirical detail to the critique in case studies. Wynne (2003) anchors a critical approach to expertise in decades of studying controversies. Reaching back to a public inquiry into the construction of a re-processing plant for nuclear fuel (Wynne [1982] 2011), he explains how the scientific criteria, requiring controlled empirical observation and analysis, depleted the decision-making process of democratic content. The close study of the inquest demonstrates how rules guaranteeing sound science prevented local democracy. Jasanoff has also analyzed science outside of academia; looking at expert advisory committees in the US she identified regulatory science as a practice specific to the context and divergent from university science (Jasanoff 1990). Regulatory science centers on risk assessment and the objective is to set standards for new substances; it is prompted by disasters caused by mainly chemical substances, for example PCB. Although driven by the need to protect society from hazards, regulatory science also poses a risk to democracy as the framing of issues constrains the knowledge produced about them and learning about effects is not considered to be internal to the problem (Jasanoff 2003).

A related discussion in the social studies of science concerns who becomes expert and how. Collins and Evans introduced a normative theory of expertise that sparked a lively debate in the science studies community as they constructed a scale of expertise with three levels: "no expertise," "interactional expertise," and "contributory expertise" (Collins and Evans 2002, 254). A person's position on this scale is determined by her relationship with a particular field of knowledge. No expertise is the default position.

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If we begin to study a field, we may gain the expertise needed to interact with the participants. If we proceed to become practitioners in the field we will be able to contribute knowledge to it. This scale clarifies how to distinguish between those with different positions relative to the scientists practicing in a specific field of knowledge. Collins and Evans also construct expertise as a property that individuals can acquire through learning more about a field of scientific research. In their discussion of how to progress from a state of no expertise they give an example of their own trajectory:

> As empirical researchers in the sociology of knowledge, we act as though there is something in the nature of expertise that can be acquired if we work at it. Furthermore, at least some of us have found that we have been unable to acquire sufficient expertise to analyse certain scientific fields to our satisfaction, and this too is a salutary experience. Again, just occasionally, we do manage to acquire enough expertise in some field we study to begin to contribute. (Ibid., 255)

This quotation makes explicit the assumption that expertise is acquired by individuals and also portrays it as an intellectual accomplishment; there is no sense of expertise as a practical activity or as something that experts do, in this conception. That this individualistic and cerebral approach to expertise has not been remarked upon by the many critics of Collins and Evans' analysis can be interpreted as a sign that it is widely shared. However, we believe it is the wrong way to approach expertise, that it obscures the critical issue of how experts learn about the problems on which they advise decision-makers. While the individualism of Collins and Evans has gone unremarked, the idea of expertise as co-extensive with scientific research has been challenged. Rip (2003) considers Collins and Evans's scale to be a narrowly internalist understanding of expertise. In Rip's view expertise must be further contextualized, since the need for it arises in the world outside of the scientific laboratory. Nowotny had already expressed such an understanding, arguing that expertise "constitutes and is constituted by transgressive competence" (Nowotny 2000, 5), because it always exceeds the boundaries of established scientific knowledge. Rip and Nowotny agree that expertise rests upon scientific knowledge, but when addressing issues at stake in society, such as environmental risks, it must stretch beyond that which is scientifically knowable.

So far we have identified three recurring assumptions about expertise: that it always poses a problem in democracy; that it is fully derived from scientific knowledge; and that it is an individual property of the expert. Only the second of these has been challenged in the science studies literature, for example by Nowotny (2000) and Turner (2001) whose analyses inform the present discussion. We fully agree with the notion of expertise as by necessity transgressing any existing body of scientific knowledge; the problems in society on which experts are called to advise are not scientific problems. We add to this view more empirical information about how the necessary transgression of existing scientific knowledge can be achieved in different ways by experts constituted

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in different networks addressing the same environmental problem of flooding. To the discussion of expertise in democracy we also bring computer simulation modeling. All three assumptions are premised on modern science, where epistemic authority originates in the ability to establish facts through experiment and observation, which can be used for decision-making. Environmental computer simulation modeling does not establish facts in this way, but it makes the non-linear behavior of complex systems accessible through rendering theory and data in computer code. To approach expertise based in computer simulation modeling we draw on work in science studies by Callon, Lascoumes, and Barthe (2009) and the philosophy of science of Stengers (2010).

Callon and collaborators (2009) take the sociology of translation (or Actor-Network Theory) forward when directing attention to science outside of the laboratory, in the wild of society. In contrast to the political theorists and science studies critics discussed in the previous part of this section, Callon, Lascoumes, and Barthe do not worry about the survival of democracy in the encounter with science. Their empirical tracing of science in the wild demonstrates that in the controversies and negotiations where expertise is called upon to solve problems, new collectives of actors emerge in relation to specific matters of concern to challenge the authority of the scientific experts. The society that science encounters outside of the laboratory is, in their view, not so easily subdued. The confrontations with non-scientists force the emergence of hybrid forums in which experts and the newly established collectives can negotiate, these can take the shape of, for example, consensus conferences. Thus, Callon and collaborators approach controversy as a dynamic source of change that brings new collectives of humans and things into being. Such controversies draw attention to the legitimacy of experts, in ways that have previously been understood to show their problematic role in democratic society, but that can also be viewed as an important aspect of putting knowledge to the test. With regard to putting knowledge to the test in encounters with society we take the cue from Stengers' (2010) interest in the power of things to force thought. This capacity is invested in those things mobilized as multi-vocal witnesses in the construction of scientific propositions or knowledge claims, and as matters of concern capable of sparking publics into life around questions to which their interests make them sensible. Refusing to break the attachment to things, whether of working scientists putting their knowledge practices at risk, or of emerging publics affirming their sensibility to what causes them to think and to object, is the defining ethic of her experimental constructivism (Whatmore and Landström 2011). Stengers' experimental ethos encourages the invention of research apparatuses capable of staging collaborations between the experimental protocols of scientific knowledge practices and the experiential repertoire of everyday knowledge practices. This ethos draws attention to the ways in which flood modelers work with the tools and practices which provide the substance matter on which their expertise relies.

The practice-centered approach of Callon and collaborators, and Stengers prompts us to look closely at the objects at the center of expert knowledge and at the collectives emerging in relation to specific matters of concern. This is an approach that understands

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expertise as relational in a wider sense than Turner's conception, although he provides important clues. Focusing on the social relationships constitutive of expert legitimacy Turner (2001) distinguishes between five different types of expertise; the first is based on the possession of in-depth knowledge about a field of reality, the ideal of scientific expertise. However, the authority of experts relies on the recognition by a wider, non-expert audience. In this sense a religious cult leader is also an expert, since the followers recognize their cognitive authority. These are type-one and type-two experts in Turner's terminology. Type-three experts create their own followers by providing some sort of service. Type-four experts are subsidized by social institutions and advance views to create a following. Type-five experts emerge through professionalization, in the development of formal educational credentials of, for example, social work. This classification is illuminating, but it leaves out the relationship between humans and things.

Following Stengers we recognize that experts are as much identified by the things involved in their practices as the people who legitimize their authority, for example, a surgeon depends on the operating theater as well as on the medical licensing body. To expand the example, we also argue that it is the surgeon's encounters with the human body that forces her to think and act to address the problem. This force of physical entities encourages us to pay attention to the specificity of the matters of concern in which expertise becomes involved. This paper attends to the things involved in the creation of expertise and the social relationships positioning it in a politics of knowledge specific to local flood risk management.

Flood risk management in England

Water is one of the most extensively managed parts of the geo-physical world, not surprising given the critical importance of this element to all life on the planet. Not always behaving in a manner conducive to human enterprises, water is also a constant matter of concern: there can be too little or too much of it for human purposes in any given place and time. In the UK flooding from rivers and the sea has always been a threat to human activities. Still, today people die in floods, but more commonly property and economic activities suffer badly when flooding occurs (Defra 2009). Hence, flood risk management is an important field of environmental management in England.

Flood risk management is an activity that aims to prevent loss of life and property due to flooding (EA/Defra 2011). Using knowledge about previous flood events to prevent future flooding is pivotal in management strategies. Knowledge of past floods exists in measurement records, but since floods have multiple interacting causes, historical data need to be related in ways that account for complex dynamic processes. Computer simulation models are the best tools available for rendering such complex dynamic processes comprehensible and open to analysis. It is easy to understand why

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scientific computer simulation models are attractive tools for this type of environmental management: they make it possible to use information about the past of a locality at risk to plan for the protection in the future. However, academic scientists are not particularly interested in modeling for local risk management. Assessing flood risk in English localities to choose the best management options is not likely to generate papers publishable in scientific journals of international repute. Flood risk management needs scientific tools, but does not offer scientific problems, which is why expertise enters the process. Expert knowledge specific to a local problem is the site where particular forms of scientific modeling intersect with environmental management. Flooding from rivers and the sea are recurring phenomena in the UK, and there is a long history of managing flood risk in England; therefore, the science is mature and responsibility is institutionalized in risk management networks. In spite of this, expertise is still, at times, subject to challenge in local controversies. Such challenges are occasions on which the connections between modes of modeling and politics of knowledge become visible, which was one reason for the focus on controversies over flood risk management in the project that generated the empirical materials used in this article.

The discussion in this paper of the relationships between the ways in which distinctive modes of modeling underpin specific types of expertise which relate in different ways to the societal actors involved in flood risk management builds on the research conducted in an interdisciplinary project on flood risk science in England.[1] The materials and insights generated in this project have informed a number of publications addressing topics discussed in different disciplines and the present paper advances our ongoing science studies analysis of flood inundation modeling.[2] Here we build on one previous article describing and characterizing the commercial flood modeling practice of virtual engineering, a practice in which proprietary software packages are used to produce knowledge about local flood inundation patterns and flood reduction options for use in risk management (Landström, Whatmore, and Lane 2011). We also draw on an analysis of the participatory modeling undertaken within the project, which highlighted how the physical scientists had to dissociate from their established scientific networks and attach to the agenda of the local residents in order to do science differently (Landström, Whatmore, Lane, Odoni, Ward, Bradley 2011). Our present discussion of objects is informed by a previous examination of the history of hydraulic roughness, a pivotal parameter in one-dimensional flood modeling software (Whatmore and Landström 2010). In previous papers we have discussed

[1] The research was undertaken within the framework of the project "Environmental Knowledge Controversies: The Case of Flood Risk Management," running from 2007 to 2010, and was funded by the Rural Economy and Land Use (RELU) program. This trans-disciplinary project addressed the public controversies generated by risk management strategies. The focus was on the science and politics of flood risk modeling 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] The natural science outcomes of this project have been discussed in Odoni and Lane 2010 and Lane et al. 2011.

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each mode of modeling separately – interrogating the socio-material constitution of virtual engineering, discussing the relationship between scientific modelers and local participants in the coproduction of flood inundation knowledge in an environmental competency group, and examining the details of modeling with a parameterization of hydraulic roughness as a singular number. The present paper takes the analysis of flood inundation modeling forward by relating different modeling practices to each other and through this, the paper positions the competency group approach in the wider field of flood risk expertise. In the following, we use the empirical materials generated in the project to discuss three expert practices associated with different assemblages of models, localities, and institutions involved in flood risk management in England. The aim is not to be empirically exhaustive; there may be other forms of expertise involved in flood risk management, in the UK and elsewhere. We are interested in the interwoven assemblages of different practices, models, and social relationships, examining how these amount to different kinds of expertise that link with society in various ways.

Modes of modeling

For the first example – virtual engineering – we use interviews with and ethnographic study of modelers working in private businesses.[3] The second example – mathematical experimentation – is based on interviews with scientists in universities and research institutes, published literature, and project documentation.[4] Our third example – participatory modeling – draws on published literature and interdisciplinary participatory research experience.[5] At first glance we find that these three modes of modeling fit with the different notions of expertise outlined in the previous section. Virtual engineering, carried out by commercial consultants, maps onto the practices addressed critically by Wynne and Jasanoff. The mathematical experimentation undertaken by university scientists fits with Collins and Evan's notion of a core set contributing to new knowledge. Participatory modeling resonates with the visions of political scientists Bocking and Fischer. This indicates that none of these conceptualizations fits addressing expertise as a multiple phenomenon, encompassing diverse knowledge generating practices and socio-material relationships. In the next three sub-sections we focus on each of the different modeling practices using the object-focused approach presented in the introduction.

[3] For an in-depth study of this mode of modeling, see Landström, Whatmore, and Lane 2011.

[4] The qualitative interviews were semi-structured, exploring the respondents' research practices and understanding of modeling. They lasted between 60 and 90 minutes, were electronically recorded, later transcribed and qualitatively interpreted as stories about individual experiences, as is common practice in social studies of science (cf. Sundberg 2006).

[5] This research has been described and analyzed from different angles in Landström, Whatmore, Lane, Odoni, Ward, Bradley 2011 and Whatmore and Landström 2011.

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Virtual engineering – business as usual

Mapping the production of flood inundation knowledge in England we found virtual engineering to be the dominant form of expertise used by the institutional actors responsible for risk management (Landström, Whatmore, and Lane 2011). In virtual engineering, skill at modeling different scenarios of possible future flood inundation produces a good in projects commissioned by clients. Carried out by an individual modeler, or a team, a project begins with a review of existing models and reports, in order to decide whether an existing model can be developed, or if a new modeling strategy is required. When developing a new model, virtual engineers use a computer program to create a virtual rendering of a local river or coastline. There are many computer programs that can be used to represent local flooding, but the use of specific software packages is prescribed by the relationship with the Environment Agency for England and Wales (EA). The EA is responsible for managing flood risk from main rivers and coasts. It is also the dominant customer in the market for flood inundation knowledge. As a client commissioning virtual engineering projects, the EA requires that certain benchmarked software packages are used in the assessment of local flood risk.

The software packages used in virtual engineering are based on three different mathematical structures, distinguished as being one-, two- or three-dimensional (1D, 2D, and 3D respectively). They all start with the physical rules of fluid mechanics, based on the conservation of mass and momentum. 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. The selection of dimensionality is determined by the application: 3D over smaller scale, e.g. to assess the impact of building a structure in the water, and 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 customary approaches to 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, while determining which properties will be at risk when a river floods a 2D solution would be used. Virtual engineering modelers working in projects for the EA can choose between three proprietary software packages for 1D modeling: ISIS, HEC-RAS and MIKE11.[6] These have been compared in a joint Defra (Department of Environment, Food, and Rural Affairs)/EA project, reported in a series of technical documents and a summary (EA 2005). This was the second benchmarking of 1D software, the first was completed in 1997; but software packages change and in 2001 a new evaluation was needed. At the time the EA supported three of originally eleven software packages tested and it was decided that the test should be done on those

[6] ISIS is owned and developed by two UK companies: Wallingford Software and Halcrow. MIKE11 is a product from the Danish Hydrological Institute (DHI) which runs courses and provides customer support internationally. HEC-RAS is developed by the US Army Corps of Engineers.

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three. The benchmarking was undertaken by a team mixing Defra and EA staff with university academics and consultants. 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 modelers, as well as testing software upgrades and new products. The differences between the three benchmarked 1D 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.[7] Recently 2D models have become common in flood risk assessments; they have been made useful by the increased availability of digital terrain data. The EA has initiated a benchmarking of 2D packages in which TUFLOW, InfoWorks, Mike21 and JFLOW are compared (EA 2009).

In order to make a selected software package represent flooding as a process in a particular locality, the modelers need data. Different modeling approaches require different data: 1D models need data for cross-sections extending across the river and onto the floodplain; 2D models use digital elevation data continuously across the floodplain. All approaches require hydrological data about river discharge, water levels, and flood outlines to set up, calibrate, and use models in simulations. Some data are provided by surveyors aided by the use of satellite-based Global Positioning Systems (GPS) and software that automatically formats measurements for use in models. Remote sensing technologies, most commonly LiDAR (Light Detection and Ranging) generate floodplain elevation data. Using data derived from the local topography, modelers begin with creating a representation of the landscape, using the software. In a 1D model, river cross-sections are defined in a simplified 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 use irregularly spaced data points represented in a mesh. When the modelers are satisfied with the representation of the topography of the landscape in the computer software they use 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. However, many areas in England and Wales do not have flow data of enough detail to be useful for modeling one watercourse, or a part of it. Then the modeler 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, a research institute.[8] This five-volume handbook provides modelers with estimated hydrological

[7] 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 licenses within a company is limited so modelers 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. Recently Halcrow released a free version of ISIS, a part of the full software package.

[8] The FEH is sold by Wallingford HydroSolutions, a technology transfer company.

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conditions even if there are no gauges. The FEH enables the estimation of flood extents and frequencies for every river in England.

When the modelers are satisfied that the virtual rendering of the physical system works as defined in theory and expected from experience, they calibrate the model with actual flood events. When using 1D software packages calibration is usually done by varying the roughness value, a mathematical function that slows down the water flow, hence, raises the river level. Not being directly measurable, hydraulic roughness is usually parameterized as Manning's *n*.[9] Roughness is also important in 2D modeling, but other features play more prominent roles in their calibration. When the model is calibrated, simulations can be run 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. Modelers can also simulate how landscape interventions could impact on flood risk. In virtual engineering a model that has been successfully calibrated is considered trustworthy for the simulation of possible future events. When the model, in the sense of a virtual rendering of the projected inundation patterns in a locality at risk under different conditions and with different risk reducing interventions, has been finished and quality checked it is delivered to the client. The calibrated model – with graphic visualizations, maps of inundation outlines and a written report detailing the research process with uncertainties, outcomes, and recommendations – is the final product of a virtual engineering project. This is the expert knowledge on which the EA, developers, and local authorities in England base their flood risk management. Virtual engineering has evolved as an expert practice in a niche emerging between the formal institutions and legislative frameworks governing flood risk management in the UK. Provided by consultant engineering businesses, this expertise is purchased by users involved in risk management, building, and other development projects. The EA is dominant in this highly constrained market, being a large customer needing expert knowledge to carry out its government mandated flood risk management. To make its relationships with hundreds of businesses manageable the EA sets up Framework Agreements, contracting a small number of companies to do all projects in a region over a specified period, normally five years.

Virtual engineering exemplifies Nowotny's (2000) argument that expertise always exceeds the boundaries of scientific knowledge in important ways. The modelers, the mathematical structures, and the data generating technologies all originate in university science. However, in order to provide the knowledge needed by the client, the modelers have to focus on the representation of particular floods, rather than the general dynamics of flooding. The virtual engineering modelers using the software do not work with the mathematical formulae driving the simulations. The standardization of software

[9] See Whatmore and Landström 2010 for an in-depth discussion of this parameterization.

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shapes this modeling; new practitioners have to learn to use the particular computer programs to become experts regardless of their background. The standardization of software packages also stabilizes knowledge production into reliable expertise. The user-friendly proprietary software incorporates graphical user interfaces, visualization tools, which also make it possible to convey modeling results to customers with very little knowledge of flooding and models. Virtual engineering merges modeling outcomes with information about localities into an expert knowledge product for clients; this activity produces commodities. This is a commercial pursuit, but in distinction from the association of expertise with economical actors in resource management criticized by Bocking (2004), knowledge production is the resource in virtual engineering. The stabilization of the knowledge production guarantees the quality of advice across localities, but it also constrains the questions that can be asked and answered. If a local problem does not fit the standard tools, virtual engineering experts lack the authority to change the tools. The reliability of this expertise in relation to the existing institutional order makes it vulnerable to challenge when local circumstances do not fit within the limits of what the software can do.

Mathematical experimentation – the freedom to invent

Compared to virtual engineering modelers, academic scientists who are modeling flooding face very few constraints. They can choose how they want to represent flooding, concerned only with finding the best model to address the problem they have constructed. The freedom to select a modeling approach is clearly expressed in scientific journals; one example reads:

> In this paper, the CA-Markov model and HEC-HMS model system were used as an integrated system to quantify the annual runoff and flood response to urbanization. The main objective of this study was to develop and test the integrated modeling system for analyzing the effects of sub-urban development on runoff and flood events under urbanization scenarios taken from multi-temporal satellite imageries. (Du et al. 2012, 2)

This quotation from the introduction of a journal article makes it clear that the authors selected the mathematical structures they thought were most appropriate for the objective they had devised. It also indicates that scientists focus on creating new models, computer algorithms, in order to simulate processes which are not well understood, or could be better rendered. This is a mode of modeling that we conceive of as mathematical experimentation.

In the time before computer models, flood scientists would build scale models of typical river features. Computer models were first introduced in the 1960s and since then they have become ever more important. Today computer simulation models have replaced physical models in the majority of research projects. Some of the scientists we

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interviewed had been working in the field for a long time and could comment on the evolution of models:

> Well, when I started developing these models, what you actually [got] out of them was a print out that was, you know, six inches thick and consisted of a whole pile of numbers, so yes I had to understand what these numbers meant to interpret it. So that did mean in those days that it was a specialist that needed to do it. (Interview 1)

This quotation also draws attention to the fact that computer models have become increasingly user friendly since the 1980s, which has changed the skills required for their use, making it possible for models to be deployed in knowledge production outside of research institutions, in private businesses, and by public authorities.

In spite of the many automated processes in present day computing and the ability of models to represent hydraulic and hydrological processes, the creation of new computer models remains an important aspect of flood science. Scientists expand the body of knowledge in flood science by attempting and succeeding with new mathematical experiments from which they learn about flooding and also about computer simulation modeling: "there [are] still many academics doing research developing their own numerical codes and software, and proving solution techniques that they then publish in academic literature, that people then may take up and use as a case may be" (Interview 4).

The scientific modeling activities result in an abundance of computer programs, some of which are used only by the scientists who invented them while others become popular and are used by other researchers within and outside of academia. One interviewee reflected on why a model he had created became widely used:

> What has been so important about [a well-known named model] is that the calculations are very simple, you can map the predictions back into space; so you can actually create visualisations of how the catchment wets and dries and so on and so forth. But of course if you can map things back into space you can also look at whether that matches up to what is actually going on in space over time. (Interview 3)

Among flood scientists there is a range of criteria for what constitutes a good model; the scientist quoted emphasized the simplicity of the model, which makes it transparent to other scientists who want to represent the same processes. The interplay between simplicity and complexity, as a phenomenon in nature and in models, is particularly fascinating according to this scientist:

> Hydrology is a particularly interesting subject area to explore . . . because the overall responses of the system are rather simple – in that you get a rainfall that comes in and the discharge responds by going up and then coming down again. So that is not difficult to capture. Except that how much comes out depends so much on the antecedent wetness of a catchment area . . . how much comes out is a very non-linear function of the rainfall

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> and the antecedent wetness. So you have these non-linearities in this rather simple up-and-down type of response that makes it interesting. From what we know about the processes you have also got spatial factors that arise. (Interview 3)

The non-linearity of flooding makes it interesting as a field for environmental computer simulation modeling: it is too complex for non-computerized predictions. It is not enough to describe the initial state and variables; every change has to be calculated through time-steps. Another interviewee talked about the process of developing computer models that would render the processes comprehensible:

> So we are essentially representing the runoff reduction through some soil moisture accounting process. We are then representing two translation paths. The slow translation path, that is representing flow to groundwater, commonly we might be using non-linear storage. And in the fast response pathway, we are trying to typically equate that to channels. But it might flow through macro pores. We are using some either non-linear storage, or a cascade of linear storages to represent that system. (Interview 2)

The scientific modelers we interviewed focused on creating computational representations of physical processes; starting with theories, they selected mathematical formulae and transformed these into computer code. This interest in creating new models shaped the research practice in the field, emphasizing intellectual reasoning over empirical observation: "You don't model everything, so you have to work out what matters, both in terms of what you want the model to do, but also what you need to go into the model in order to get there" (Interview 5). The process does involve fieldwork, but the way in which the academic modeler goes about rendering a river virtual is by:

> sitting down writing out the equations and how you are going to solve them . . . and then the third area is putting them into code. Checking the code is right. . . . does it give you the right answer? And then there is a whole sort of activities to work out what the model is doing, whether its sensitivity analysis, grid resolution testing, comparisons of predictions with observations . . . all those kinds of things. (Interview 5)

When the mathematical structure of models is a matter of choice relating to the theoretical problem of interest, disciplinary territories impact on model construction. One interviewee explained:

> There isn't a clear-cut distinction between hydrological modelling and hydraulic modelling, at one level. At one level, you start with Navier-Stokes equations and move to simplified forms, which might be called St Venant equations.[10] Then you might start to

[10] Navier-Stokes and St Venant are equations based in Newtonian physics used to represent fluid motion; the latter can be derived from the first and is commonly used in 1D models, such as HEC-RAS.

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> develop simplified forms of those that relate specifically to moving water down rivers. And it has become convenient between hydrologists and hydraulicians to talk about simple storage models as hydrological models, and models that are based on partial differential equations that, as an example, a St Venant equation, as hydraulic equations. (Interview 2)

The way in which this interviewee talks about models in terms of the equations, which can be coded in different ways to run on computers, demonstrates the scientist's approach to models as mathematical objects. The quotation also shows how scientific modeling reproduces distinctions, which the modelers recognize as conventions, because of tradition rather than reflection of the physics of the environmental system, or the characteristics of the mathematical formulae. River flooding involves the two natural processes of rainfall, traditionally the domain of hydrology, and river flow, the territory of hydraulics. Computer models have been developed in the two fields, but usually not in connection, as the interviewee explained. The disciplinary organization has been inscribed in the computer code defining model simulations.

Despite the limited number of interviews we have with scientists, a very clear message is coming through about their freedom to choose the problems they want to investigate and about their desire to create computer programs that enable virtual representation of previously inaccessible processes, or processes not well rendered. Scientific models are always in the process of further development, change, and improvement. Computer programs are outputs from research projects that can be picked up and used by others, but the main product is the scientific publication.

Academic scientists are of interest to flood risk management actors, because of their knowledge of how to create models that render the complex physical processes accessible. The scientific mathematical experimentation maps onto Collins and Evan's (2002) understanding of expertise. The scientists with experience in analyzing, explaining, and mathematically conceptualizing physical processes bring this knowledge to collaborations with other actors in society. The ability to perform mathematical experiments with flooding is a skill developed by practicing in a scientific research field. Using Turner's (2001) categorization, the academic modelers are type-one experts; their authority is granted by their connection to the academic institution; they are recognized as experts in their field; their audience is their peers and other experts with links to policy-making institutions on the national level in the UK.

Scientists working in universities and research institutes contribute expert knowledge to flood risk management in England in a different way from modelers in virtual engineering. Academic scientists are rarely involved with the routine assessments of flood risk in particular localities, but they often work with the EA and Defra in projects providing more general knowledge about physical processes and mathematical modeling structures, e.g. benchmarking software. One such project investigated hydraulic roughness, a key parameter function in 1D models. The Conveyance Estimation System (CES) project was a three-year program involving more than fifty researchers, half from academia and half from business and institutions

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(Defra/EA 2004). The objective of this program was to investigate, conceptualize mathematically, and translate into computer code, the surface roughness of river beds, which affects river levels (i.e. flooding). The standard parameterization of hydraulic roughness as a Manning's *n* value was considered to be over-simplifying to the degree of distortion. The CES project was intended to generate new knowledge for use by the experts providing flood risk knowledge to local decision-makers. According to one of our interviewees who participated, the project had two aims: one, to deliver tools that could be used by people from the EA or industry or other organizations. The other aim was to go towards the blue skies end, on to the next generation of models. This example demonstrates how academic scientists relate to models as objects in need of improvement: they are called upon as experts able to invent and refine the tools used by others, e.g. virtual engineering modelers.

In light of the political critique of expertise (e.g. Fisher 2009), the academic modeling involved with flood management is a relationship that troubles democracy; scientific expertise informs decision-making on a level that has repercussions for local flood risk management without any local representation being even remotely possible. The academic scientists' modeling is disconnected from local flooding, their point of reference is the digital rendering of disciplinary knowledge. The driver for modeling floods in science is to develop new knowledge about general mechanisms involved in the process. The localities scientific modelers choose to model are often incidental, selected because they fit the problem, as examples. This is made explicit in scientific articles, an example reads: "To present our methodology, we selected the Halilrud basin and Jiroft city in southeastern Iran as an example of hazardous regions" (Sarhadi et al. 2012, 68). Scientific discourse is not interested in local problems, but in the way local phenomena can be explained and studied by using general models.

Participatory modeling – re-distributing expertise

Virtual engineering and mathematical experimentation are the two expert practices most commonly informing flood risk management in England. However, if the scope is expanded to viewing flood knowledge as one aspect of water management, we also find participatory modeling in which scientists work together with local people and stakeholder organizations. While this approach is less common in England, it is relevant, partly because it shows how modeling can become a technique for democratizing expertise and partly, because participation is becoming increasingly important in environmental management.

Across the field of participatory modeling there is significant variation among methods for involving local communities. One strand uses modeling platforms in which decisions and social actors can be represented and linked to the physical system. The ambition of such projects is to bring together knowledge from "various stakeholders, sources, and research disciplines" (van Kouwen et al. 2009, 63). This

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mode of modeling positions software differently from both virtual engineering and mathematical experimentation; here it is used "in support of a decision-making process that involves stakeholders" (Voinov and Bousquet 2010, 1269). In water management, such models are understood as "platform[s] for integrating scientific knowledge with local knowledge and when executed well provide an objective, value-neutral place for a diverse group of stakeholders to contribute information regarding water resource issues of interest" (Voinov and Gaddis 2008, 198). A variation, Companion Modeling (ComMod), involves representatives for institutional stakeholders, or categories of local residents, e.g. farmers, in order to "facilitate dialogue between the different stakeholders concerned by a given local issue of natural resource management" (Souchère et al. 2010, 1360). Another form, agent-based modeling, draws on computer science, particularly research in the field of Distributed Artificial Intelligence in which agents are "autonomous computerized entities that interact" (Barretau et al. 2004, 262). The modeler decides what the agent represents; it can be any component of the system, e.g. an individual, a group, an animal, or a technical object. The agent's behavior is then governed by rules hypothesized by the modeler. In the simulation each agent reacts to stimuli, the inputs are diverse, as are the responses to them. This allows for representation of both physical elements and social actors in the digital rendering of an environmental process. When the modelers have constructed the model representation of a specific system and gathered information about the rules that the represented social actors will follow, scenarios are developed in collaboration with the lay participants and simulations can be run.

One strand in participatory modeling uses System Dynamics (SD) platforms (Videira et al. 2009). In this process the collaboration is focused on the conceptual representation of the system, while the computer modeling contributes to the social learning process with quantitative treatments of physical processes. Such participatory projects proceed in well-defined steps with different participants addressing particular issues, for example, in a flood risk management project in Ukraine, the third step involved:

> a small group of scientists and some key expert stakeholders – that is mainly 2 members of the waterboard, a scientist from the national Hydromet Institute and another scientist from an NGO – developed a series of interlinked quantitative system dynamics (SD) models based on the group model. (Haase 2013, 86)

Participatory modeling is mainly a scientific practice, funded as research rather than as a service and the software is normally scientific, not proprietary. The outcomes are local management advice, procedures, decisions, and scientific publications. The projects described in the literature aim to democratize decision-making and local water management. Interestingly, participatory modeling brings the politics of knowledge to the forefront. This practice engages scientific modelers who choose to work in ways that open channels for local people to get involved with the generation of knowledge relevant to the local matter of concern. This is a different practice from the modeling

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that generates expertise in virtual engineering or mathematical experimentation. Many scientists who choose to contribute to re-distributing expertise in participatory modeling, rather than affirm existing institutional relationship, consider their research to be applied and they engage in this practice with the ambition to improve local environmental management, often in developing countries. However, it is possible to construct participatory modeling as intervention in established flood risk science and management in England.

A recent project with local Competency Groups (CGs) demonstrated the potential of critical participatory modeling to change the knowledge and politics of flood models in England.[11] This is an approach developed for extreme situations in which normal flood management has failed and controversy ensued, situations in which new knowledge is needed to invent new options not conceivable with established means. Unlike the participatory modeling discussed above, CGs are not intended to bring local participants' knowledge into the formal decision-making process, but to bring science out of the institutional networks which have the authority to manage flood risk. The CG approach, informed by Stengers' experimental ethos, requires participants to take part as individuals with unique knowledge and skills, not as representatives of others. This is critical because the process demands that participants change, learn, and create.

The scientists who participated in the CG project wanted to learn about local catchment processes by trying out hydrological and hydraulic modeling approaches not normally applied to local flooding. They had accepted that the methods they would use would arise from discussion within the groups and recognized the possibility of prioritizing other approaches than modeling. To participate the scientists had to be willing to allow their practices to be shaped by the new relationships created in the local groups, not by the authorities and institutions formally responsible for managing flood risk in the locality. Bringing science to the local community prompted the participating scientists to dissociate from their established networks and to instead attach their aims to a collectively defined agenda. The CG approach requires that scientists who are able to perform mathematical experiments choose to commit their knowledge and skills to an agenda driven by local residents, rather than to the needs of the formal authorities.

Like the SD projects mentioned above, CGs work with physical model structures; the objective is to create new knowledge about the local problem, not to represent local actors or decision-making. Different from SD projects, the CG practice makes physical modeling a shared activity within the entire group, shifting the focus of expert knowledge from the output to the process. Addressing local flooding the scientists in the project were prompted to invent a new modeling approach that coupled hydrology and hydraulics in order for the model to answer the questions generated in the collective. The CG context pushed the scientists to break the traditional convention separating hydrology from hydraulics that academic science preserves. Starting with an existing

[11] The competency groups were part of the project underpinning the present paper, described in note 1.

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mathematical structure the modelers found that it was not possible to explore the impacts of landscape interventions, such as upstream bunds and riparian buffer zones, and the initially selected mathematical structure had to be abandoned. Instead they chose to work with a new model structure based on a simple flow routing algorithm, developed from the in-depth knowledge about the specific river and catchment developed in the group, which exceeded the data generated by instruments. The development and use of this model in the group meetings involved constructing a simple graphical user interface (GUI) that enabled all participants to understand the modeling process. The GUI enabled local participants to compare model simulations with experiences of flood events, to approve of and criticize the model results, and to propose interventions in the landscape and the built environment. The work resulted in both new, locally specific, flood mitigation measures and new scientific knowledge (Odoni and Lane 2010). The competency groups brought together scientific modeling skills with local knowledge of flooding in the particular place; thereby expertise emerged in the collective, exceeding the knowledge and abilities of any individual participant.

The expertise generated in participatory modeling does not fit with the analyses and critiques developed in political theory, or in science studies. The participatory practices generate expertise as the outcome of located research, bringing together the experimental skills of scientists with the experiential knowledge of local residents. Contrasting participatory modeling with Collins and Evans' three types, we can see how their typology constructs scientific and lay knowledge as separate kinds, which can only be brought together by another form of knowledge that they call interactional. Similarly, the critiques of expertise by Wynne and Jasanoff only recognize confrontational relationships between scientific and lay knowledge. In contrast, participatory modeling shows how knowledge from different sources about a local phenomenon can be brought together through the use of computer models. It also demonstrates that scientific modeling can articulate expertise with a different politics of knowledge than the technocratic and non-democratic activities documented in critical case studies. However, both Wynne and Jasanoff have identified and criticized failed attempts to democratize expertise and decision-making. Wynne (2006) notes that participation easily becomes a tool for creating public acceptance rather than democracy, and Jasanoff (2003) observed how institutional actors often came to dominate formal participatory events. While addressing a disturbing development, both these criticisms interrogate and extrapolate situations in which the scientists involved have chosen to ally with the dominant political institutions and corporate interests. This pessimistic view of expertise, as always detrimental to democracy, captures the default alignment of science with the established institutional order, which has no interest in change, or in doing things differently. In participatory modeling scientists choose to work with local communities, to dissociate from the institutions of science and government and instead attach their research skills to the local problem and the people living with it. Participatory modeling fits Stengers' idea of scientists having to make a choice to

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orientate their research towards constructing experimental apparatuses that can bring scientific ways of approaching an issue together with local experiences of living with a matter of concern. The participatory modeling projects described in the literature show capacity to improve local decision-making and risk management, thus democratizing expertise. The competency group project also demonstrates that the redistribution of expertise can bring about new knowledge in situations of controversy where standard approaches do not suffice. Participatory modeling of all types shows that the experimental ethos of science can be combined with local experiences to create new knowledge about how to better manage local environmental risks. Of course, not all participatory projects succeed, nor are they all sufficiently democratic, but what is interesting in the present context is that they construct expertise differently by changing the mode of modeling.

Concluding discussion

This paper has examined the role computer simulation models and modeling play for the expertise involved in flood risk management in England. To start with we identified and criticized three assumptions about expertise commonly found in the literature: that expertise is linearly derived from scientific knowledge; that experts always align with the established institutional order; and that expertise is a property acquired by individuals. Combining philosophical perspectives on computer models as partly autonomous epistemic tools with science studies understandings of science as practice, we could diagnose these assumptions as originating from a lack of attention to the practices and objects fundamental in expert knowledge. We demonstrated the benefit of employing an approach that illuminated the objects, practices, and relationships constitutive of environmental expertise, hence, bringing models and modeling into another analytical framing. Drawing on material gathered in an interdisciplinary and participatory study of the knowledge involved in flood risk management in England, we formulated an approach focusing on models and modeling in practices and relationships, using concepts developed by Callon and collaborators (2009) and Stengers (2010). This approach provided more detail about the role of models in environmental expertise than what has been illuminated in the literature. By juxtaposing three examples of model-based expert practices – virtual engineering, mathematical experimentation, and participatory modeling – we could show how different relationships between models, modelers, localities, institutions and local residents could articulate as different politics of knowledge.

The dominant form of expertise, virtual engineering, is the default modeling practice underpinning flood risk management in England. A closer look at this practice showed how models and modeling were standardized and stabilized in formal contractual relationships between actors in a market place. Institutions of environmental governance in a democratic state require transparency and accountability which impacts

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on knowledge production. Virtual engineering is constituted in the relationships of standardized proprietary software, the EA (a dominant institution), and people skilled in rendering localities virtual by using the software. Close scrutiny showed that the software is of equal importance as the modeler in this practice, which is an aspect of expertise not previously illuminated. Virtual engineering has become hard-wired into the political order of risk management, which also makes it vulnerable to discontent. If institutional actors fail to address flood risk locally the expertise on which their actions are based can become subject to challenge.

In contrast scientists performing mathematical experiments could choose how to render flooding computable. We found that this freedom resulted in divisions between modeling approaches mirroring the disciplinary boundaries of hydrology and hydraulics. The mathematical experimentation of scientists constructs flooding as a general physical process, rendering the mechanisms of floods virtual. The scientific practices focus on creating models to render anew, or better, the theoretical explanations of the physical process of flooding. Mathematical experimentation does not directly provide expert knowledge for use in local flood risk management. Occasionally scientists choose to offer their knowledge and skills to projects devised to improve the computer programs used in virtual engineering. The constitutive social relationship for this form of expertise links scientific disciplines with the national government responsible for ensuring equity across localities, in a way that generates new computer code that can be used to model local floods. The institutions within which scientists work also produce people with knowledge and skills who might become modelers in consultancy firms providing virtual engineering expertise.

We also found that some scientists with the knowledge and skills to perform mathematical experiments choose to work with local residents rather than established institutions. Participatory modeling involves different choices; scientific modelers engaged in such projects recognize the limits of science outside of the academic institutions. In such redistributions of expertise the models got to do a new type of work and they brought scientists and local residents together. The juxtaposition of the three modes of modeling clarified the possibilities and constraints of innovative participatory methods for generating expert knowledge in flood risk management in England.

With regard to the politics of knowledge, we have illuminated expertise as the outcome of practices shaped by modeling approaches and social relationships. By making the choice to become involved in participatory modeling, scientists make the politics of all modeling visible, because they show that things could be otherwise. It becomes clear that if some scientists can choose to engage with local actors in projects rendering the problem differently than modeling as usual, most modelers have chosen to ally with the existing institutional order. This is certainly a reasonable choice, as the institutions in a democratic society have the duty to guarantee equity and accountability, but it is not neutral. If the dominant connections are with formal institutions, the expertise will fit in with their agendas and not necessarily be sensitive

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to local needs. The juxtaposition of different modes of modeling showed that specific models played different roles in the politics of knowledge. The analysis made visible the ways in which the standardized software packages make virtual engineering expertise co-extensive with the current institutional order. It is not possible to render flooding in ways not aligned with the dominant politics of risk management and knowledge using the tools of virtual engineers. In contrast the freedom of scientific modelers to create new mathematical tools can be understood to correlate with a distance from the local politics of knowledge. The scientific expert does not address local problems as such, but as instantiations of general processes, hence they normally bypass the risk management while re-affirming a politics that privileges science over other forms of knowledge. The major strand in participatory modeling led by scientists, also re-affirms the privilege of science by not opening up modeling structures for scrutiny, but they re-configure risk management to include local residents. The competency group experiment demonstrated that local participation can be made to impact on model structure in the context of knowledge controversies, in which the politics of knowledge privileging science is challenged. The competency group example also shows that it is possible to generate new scientific knowledge through participatory modeling. For intervention in extreme situations, when existing expert knowledge is insufficient, this method can provide an option for redistributing epistemic authority in relation to failing institutions. All three examples showed that expertise originated in practice, in the activity of modeling a particular phenomenon, as location specific or general; and that it was not linearly derived from science, but rather transformed scientific knowledge in different ways. We also showed that expertise emerged in relationships between modeler(s) and models, between modeler and decision-making actors, and between modeler and local residents; it was not a property of individuals.

List of interviews

Interview 1, by S. J. Whatmore, November 2007
Interview 2, by C. Landström, December 2007
Interview 3, by C. Landström, April 2008
Interview 4, by S. J. Whatmore, November 2008
Interview 5, by S. J. Whatmore, July 2008

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