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Towards modelling flood protection investment as a coupled human and natural system

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Abstract

Due to a number of recent high profile flood events and the apparent threat from global warming, governments and their agencies are under pressure to make proactive investments to protect people living in floodplains. However, adopting a proactive approach as a universal strategy is not affordable. It has been argued that delaying expensive and essentially irreversible capital decisions could be a prudent strategy in situations with high future uncertainty. This paper firstly uses Monte Carlo simulation to explore the performance of proactive and reactive investment strategies using a rational cost-benefit approach in a natural system with varying levels of persistence/interannual variability in Annual Maximum Floods. It is found that, as persistence increases, there is a change in investment strategy optimality from proactive to reactive. This could have implications for investment strategies under the increasingly variable climate that is expected with global warming.

As part of the emerging holistic approaches to flood risk management, there is increasing emphasis on stakeholder participation in determining where and when flood protection investments are made, and so flood risk management is becoming more people-centred. As a consequence, multiple actors are involved in the decision-making process, and the social sciences are assuming an increasingly important role in flood risk management. There is a need for modelling approaches which can couple the natural and human system elements. It is proposed that Coupled Human and Natural System (CHANS) modelling could play an important role in understanding the motivations, actions and influence of citizens and institutions and how these impact on the effective delivery of flood protection investment. A framework for using Agent Based Modelling of human activities leading to flood investments is outlined, and some of the challenges associated with implementation are discussed.

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Towards modelling flood protection investment

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1 Introduction

Due to the perceived threat from climate change, prediction under changing climatic and hydrological conditions has become a dominant theme of hydrological research. Much of this research has been climate model-centric, in which GCM/RCM climate projections have been used to drive hydrological system models to provide predictions of impacts that should inform adaptation decision-making. However, adaptation fundamentally involves how humans may respond to increasing flood and drought hazards by changing their strategies, activities and behaviours which are coupled in complex ways to the natural systems within which they live and work. Humans are major agents of change in hydrological systems, and representing human activities and behaviours in coupled human and natural hydrological system models is needed to gain insight into the complex interactions that take place, and to inform adaptation decision-making.

Due to the apparent threat from global warming, governments and their agencies are under pressure to make proactive investments to protect people living in floodplains from the perceived increasing flood hazard. However, adopting this as a universal strategy everywhere is not affordable, particularly in times of economic stringency, and also since widespread solid evidence of increasing flood hazard induced by global warming has yet to emerge (IPCC, 2012). Matalas (1997) has suggested that, in a water resources context, the strategy of "wait-and-see" i.e. delaying the making of important, expensive and essentially irreversible capital investments could serve water managers well in coping with the uncertainties regarding climate change. Investment in flood protection infrastructure has frequently been reactive. During "flood poor" periods when no major floods occur, encroachment on floodplains and the value of assets grow, while levels of flood protection investment decline; conversely, during "flood rich" periods when major floods occur leading to major damage and possibly loss of life, there is public outrage and investment grows i.e. is reactive. The process that determines when and where investments take place increasingly involves interactions between a range of stakeholders, from those making government policy to individual floodplain dwellers.

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There is increasing evidence, particularly in the wake of major floods, that pressures can be exerted by stakeholder groups that have been affected by, or might be affected in the future, by flooding, resulting in investments which are driven by such pressures and not by the traditional "rational" norms of cost/benefit analysis or utility theory.

The hydrological research literature on flooding has historically been dominated by the engineering hydrology approaches that underpin the design of flood protection works. As the impacts of floods on society have grown, the narrow flood protection approach has evolved into broader flood risk management approaches that consider the economic, social and environmental dimensions of sustainability, and a portfolio of both structural and non-structural measures for addressing flood risk. The non-structural measures typically focus on the need for more structured approaches to land use management/development in floodplain areas, better institutional functioning, better flood warning and emergency service operation, and the development of flood resilience (McEwen and Jones, 2012; McEwen et al., 2012a). The social science literature on the complex socio-economic dimensions of flooding has therefore grown, and encompasses institutional analysis, the social impacts of flooding and how to address them, the evolution of flood protection investment policies, and of reactive institutional responses to major flood events. While there is evidence of increasing engagement between engineers and social scientists in developing interdisciplinary approaches to flood risk management, it is still the case that there is something of a "paradigm lock" between the quantitative modelling approaches of flood hydrology, and the more qualitative approaches that characterize the social sciences. Sivapalan et al. (2012) have proposed developing the new paradigm of socio-hydrology as a means of incorporating the social dimension into hydrological research. As a contribution to socio-hydrology, Di Baldassarre et al. (2013) have recently proposed a conceptual framework to describe the interactions and feedback mechanisms between hydrological and social processes in settled floodplains.

In dealing with the problem of how to model adaptation investment strategies, there is the key issue of how to represent the possible ways in which human activities at var-

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ious levels, ranging from policy-making/decision-making on investments to the tactics of individual floodplain dwellers in seeking to gain better protection, might be modelled. Agent-based modelling offers interesting possibilities in this regard, and these are explored in this paper.

The overall aim of this paper is to explore how a Coupled Human and Natural System (CHANS) modelling approach to determining flood investment strategies might be formulated and developed. Two specific aspects are investigated:

1. The performance of proactive and reactive investment strategies is explored, in terms and costs and economic damage over a design life, using rational cost-benefit analysis in the first instance, and a Monte Carlo approach to modelling floods with high levels of persistence/interannual variability in the Natural System, to mimic "flood rich" and "flood poor" periods.

2. The way in which multiple stakeholders interact to influence/determine flood investment decisions is reviewed, and we explore how the Human System component of a CHANS modelling approach to flood protection investment might be represented. In particular, we focus on how agent-based modelling might be used to represent the various stakeholders that are involved in, or influence, flood protection investment, and the interactions that take place between them, in determining when and where in a region flood investments take place.

2 Institutional responses to changing flood risk

The inexorable rise in flood damage across Europe and beyond (Munich Re, 2008) that has resulted from a series of major floods (e.g. the Oder, 1997; the Yangtze, 1998; the Elbe, 2002; the Rhone, 2003; the Danube, 2006 and in the UK, 2000, 2007 and 2009) has led to major policy reviews by many countries on how to deal with increasing flood risk. This is attributable to the growth in vulnerability of people, priority and economic activities in floodplains, and the possible increase in flood hazard from global

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warming. This reappraisal has also been driven by the EU Floods Directive (Directive 2007/60/EC) which requires that flood risk management plans must be prepared and published by member states, and that stakeholder engagement should be an integral part of this process. The need for those stakeholders affected by, or at risk from floods, to be involved has also been driven by public outrage following major floods; stakeholders have attitudes and aspirations, and voices that need to be heard when decisions are being taken by the responsible agencies that affect them. The media also play a role in post-flood inquests, and ramp up the pressure on politicians and government agencies for changes in policy, increased investment in flood protection, and implementation action. It is frequently the case that policy changes are crisis driven, and that catalytic change results only as a consequence of major flood crises (Penning-Rowsell et al., 2006).

Following a series of damaging floods in the UK in the 1990s and the year 2000, the government recognised that the traditional approach of providing protection to all those at risk was not economically viable. The OST Future Flooding project (Evans et al., 2004a, b) developed the thinking for a new, more holistic approach to managing flood risk, which has now been taken on board in formulating the new government strategy for managing flood and coastal erosion risk in England – "Making Space for Water (MSW)" (Defra, 2004). This holistic MSW approach is risk-driven and requires that adaptability to climate change becomes an integral part of all flood and coastal erosion management decisions. A whole catchment and whole shoreline approach is being adopted that is consistent with, and contributes to, the implementation of the EU Water Framework Directive. The MSW strategy requires the consideration of a broad portfolio of response options for managing risks including changes to land use planning in flood prone areas, urban drainage management, rural land management and coastal management as part of the integrated holistic approach. Similar responses to managing future flood risk are being taken in other European countries, including "Room for the River" in the Netherlands (Wiering and Driessen, 2001) and "Room for Rivers" in Germany (Krieger, 2012). There is to be more emphasis on warning, adap-

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tation, and emergency planning. Stakeholders are to be engaged at all levels of risk management, with the aim of achieving a better balance between the three pillars of sustainable development (economic, social and environmental) in all risk management activities (Defra, 2005). The requirement for stakeholder participation is steered also by the EU Water Framework Directive's and the EU Floods Directive's requirements to involve participatory methods in water/flood risk management planning. One consequence of this is an increasing focus on how key elements of flood risk management planning can be implemented at community level, where the impacts of flooding have occurred, or might occur, in the future.

The increasing involvement of local communities in flood risk management has implications for how investments in flood protection infrastructure are being made, and will be made in the future. Decision-making processes relating to investments are becoming increasing participatory and require "transparent targets" (Johnson and Priest, 2008) i.e. there is a shift from a top–down state-centred approach towards one in which other organisations, agencies, local pressure groups and individuals are playing an increasing role. The traditional top-down models for investment in flood protection infrastructure have either been standard based (e.g. the 100 yr flood), or evaluated using a cost/benefit approach, with at-risk sites prioritized on the basis of a benefit/cost (B/C) ratio, for example. At a time when the economies of many countries are struggling, state allocations of funds for investment in all sectors, including flood risk management, are under threat or are being reduced, and so the competition for scarce funds is increasing. While the traditional B/C approach still has a dominant role in determining which sites are prioritized for investment in the UK, there is evidence of new funding models emerging in which state level funds are augmented by local government agency funds to enable some sites to move up the priority queue and gain state funding that would otherwise not be gained based on a B/C criterion. Political pressures at local level play a role in this. This co-funding model will inevitable create winners and losers, and raise questions about equity and fairness in investment allocation. On the other hand, it marks a shift in responsibility for flood risk management downwards and outwards that

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means that those affected by flooding have an increasing role to play in flood risk management, and presages increasing cooperation between the state, operating agencies, public bodies and citizens which is highly desirable.

One area of flood risk management in which local communities have a key role to play is in building flood resilience. While it is well recognised that technical developments in flood science provide essential underpinning to improved flood risk management, a key question for UK resilience planning is how different and wider flood knowledge bases can be built into the policy process and sustainability governance at the local, lay, level (McEwen and Jones, 2010). To develop flood knowledge beyond the "strategic/managerial/expert" levels requires different conceptual frameworks, knowledge and skills which operate at the community, family and individual levels. McEwen and Jones (2012) discuss the role of local/lay flood knowledge in building community resilience post the 2007 floods in Gloucestershire, UK which caused economic damage valued at more than £3 billion. They reflect on how flood knowledge can be captured, used and harnessed in flood resilience planning, and on the role of local knowledge and "sustainable flood memory" in developing community flood resilience. They conclude that the 2007 UK flood experience is generating new understandings of the value of local knowledge, and how this knowledge might be successfully used in flood risk management practice. Further, McEwen et al. (2012b) advocate the concept of "sustainable flood memory" for effective flood risk management. "Sustainable flood memory" is conceived as community focused, archival, integrating individual/personal and collective/community experiences, involving inter- and intra- generational communication and strategies for incorporating it into flood risk management (McEwen et al., 2012b). This is clearly necessary when there are "flood rich" and "flood poor" periods to avoid vulnerability growing in the latter periods.

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3 Coupled human and natural systems

An increasing focus on Coupled Human and Natural Systems (CHANS) and how to model them has developed primarily within the literature on ecological systems and their sustainability. A review of this extensive literature is beyond the scope of this paper; selected papers are referenced here to provide an indication of how this interdisciplinary field is developing, particularly the characterization/modelling of the human system, and the coupling/integration of the natural and human systems.

Liu et al. (2007b) provide a well structured, informative overview of CHANS research. Firstly, CHANS research focuses on the patterns and processes that link human and natural systems. Second, CHANS research emphasizes reciprocal interactions and feedbacks – both the effects of humans on the environment and the effects of the environment on humans, climate change being the paramount example of this. Third, understanding within-scale and cross-scale interactions between human and natural components is viewed as a major challenge for the science of CHANS. Liu et al. (2007b) synthesize major characteristics of complex organizational couplings (among organizational levels), spatial couplings (across space), and temporal couplings (over time) of CHANS, and discuss their implications for sustainable environmental/natural resource management and governance. Liu et al. (2007a) review complex patterns and processes in CHANS which are not evident when studied by social or natural scientists separately. A synthesis of six case studies from around the world shows that couplings between human and natural systems vary across space, time, and organizational units. They also exhibit nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises. Furthermore, past couplings have legacy effects on present conditions and future possibilities.

O'Connell (2005) set out some ideas and principles for modelling catchments as CHANS. A great deal of research has been carried out on the impacts of land use change on the hydrological functioning and responses of catchments, but these impacts have invariably been treated as passive. He advocated an active modelling approach to representing changes in which the agents of change (e.g. farmers and farm managers) respond to socio-economic drivers that determine land use patterns and management practices, and the use of social simulation techniques to represent human activities and decision-making. Monticino et al. (2007) describe such a CHANS modelling approach that couples natural system dynamics for a forest ecosystem to human land-use decision making, where the primary focus is on development decisions and their consequences. Interactions between human stakeholders are represented using multi-agent models that act on forest landscape models in the form of land use change. Feedback on the effects of these actions is received through ecological habitat metrics and hydrological responses.

The use of Agent Based Modelling (ABM) to model human activities and human decision-making in CHANS has received considerable attention in the literature, and there are some major challenges in this regard. Kurtz and Snowden (2003) list several challenges when seeking to capture the complex patterns of human behaviour in agent-based simulations, and in particular note that humans are not limited to (a) one identity or any common set of emotions; (b) acting in accordance with predetermined rules, or (c) acting on local patterns. Batten (2004) discusses one class of social systems – self-referential systems – that seems relatively immune from these problems. These relate to situations where the forecasts made by agents serve to create the world they are trying to forecast. The emergent complexity in these systems arises more from ways in which the agents interact and affect each other, and less from each agent's individual idiosyncrasies (Batten, 2004).

In discussing fairness principles in allocating water in Australia, Nancarrow and Syme (2004) note that the allocation, or re-allocation, of water to achieve environmental sustainability in farming communities can be a source of considerable conflict. They note that different stakeholders have different views of what constitutes fairness, and explore whether investigation of water allocation rules can contribute to gaining community consensus. They challenge the three basic assumptions of order, rational choice and intent in organizational decision support approaches, and observe that the

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Kurtz and Snowden (2003) discussion on the realities of contextual complexity and unorder epitomises the water allocation process they had analysed. By incorporating the justice criteria of stakeholders in different allocation rules, they suggest that ABM could be a useful decision support tool for assisting lay people to achieve social justice. In the context of flood risk, Vojinović and Abbott (2012) argue that social justice should underpin approaches to flood risk management, and integrate the human-social and the technological components to provide a holistic view.

An (2012) has carried out a comprehensive review of various decision models used in agent based simulations of CHANS dynamics, discussing their strengths and weaknesses. Nine different modelling approaches are considered that range from more empirical to more process-based modelling approaches. An (2012) observes that humans make decisions in response to changing natural environments, which will in turn change the context for future decisions. Their abilities and aspirations for learning, adapting, and making changes may undergo evolution in their decision-making paradigm. Given all these features, An (2012) considers that it is "something that is still far away" to incorporate realistic reasoning about beliefs and preferences into understanding and modelling human decision-making processes (Ligtenberg et al., 2004). Without a more process-based understanding of human decision-making (e.g., the way-finding process model of Raubal, 2001), An (2012) considers that it is very difficult to appreciate complexity at multiple dimensions or scales, and to achieve in-depth coupling of the natural and human systems. An (2012) concludes by advocating development of more process-based decision models as well as protocols or architectures that facilitate better modelling of human decisions in various CHANS. The challenges of modelling the human activities influencing decision–making in making flood protection investments are discussed in Sect. 6.

CHANS research has not yet established a significant presence in flood risk management research although, with the increasing focus on human and not just technical aspects of flood risk management noted in Sect. 2 above, it seems likely that this will happen. Di Baldassarre et al. (2013) describe a very interesting, essentially

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CHANS approach, to conceptualizing and modelling hydrological and social processes, and their complex interactions, in settled floodplains. They develop a simple, dynamic model to represent the interactions and feedback loops for hypothetical human-flood systems. The model, which is based on a set of four functional relationships, is then used to explore the dynamics of the human-flood system and the effect of changing individual characteristics, including external forcing such as technological development. The results show that the conceptual model is able to reproduce reciprocal effects between floods and people as well as the emergence of typical patterns. Grelot and Barreteau (2012) modelled population and vulnerability at the national scale in France as a test-bed for evaluating the resilience of insurance scenarios to flood risk from extreme events. Brouwers and Boman (2011) implemented a flood-risk management model as a basis for discussion of alternative policy strategies. The model, which integrates aspects of geographical, hydrological, economical, land use and social context, was used to assess the relationship between the role of the insurance industry and local government.

Taking a broader sustainable engineering perspective, Allenby (2000), in characterizing the new paradigm of "Earth Systems Engineering and Management" (ESEM), observes that managing the future evolution of tightly coupled human and natural systems will require the development of a capability to rationally "engineer" them through new management and engineering approaches that accommodate the balance between social, economic, and environmental capital. He represents this as the next great challenge for the engineering profession, and the new broader approaches to flood risk management under climatic and socio-economic change, and with a greater focus on humans, fall clearly within the scope of CHANS and ESEM.

The US National Science Foundation (NSF) has been funding a cross-cutting programme on the Dynamics of Coupled Natural and Human Systems (CNH) since 2001. Funded by NSF, an International Network of Research on Coupled Human and Natural Systems) has been setup to foster interdisciplinary collaboration in the field. Details of currently funded NSF projects are provided on the website (http://chans-net.org/). Most

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of the projects are focussed on ecological systems, natural resource management and sustainability, and some intersect with hydrology.

4 The natural system: stochastic flood model

4.1 Rationale

As noted in Sect. 1, an overarching issue for flood investment strategies is the influence of global climate change on climatic and flood extremes. In the context of water resources management, Milly et al. (2008) suggest that, in assessing climate change impacts, the assumption of stationarity is no longer tenable, and that nonstationarity should be invoked. O'Connell and O'Donnell (2013) discuss the evidence for dismissing stationarity, and argue that, in the absence of clear and equivocal evidence of nonstationarity that can be incorporated into modelling nonstationary hydrological variables, invoking nonstationarity presents somewhat intractable challenges. Rather, it would seem prudent to explore the limits of stationarity in the first instance, particularly in representing the long-term natural climatic variability that pre-existed global warming. By increasing the memory in a stationary stochastic model, the resulting increase in long-term variability can be indicative of the increased variability to be expected under global warming, and under which adaptation investment decisions will have to be made.

The traditional approach to making investment decisions in flood protection infrastructure is to estimate the probability distribution function (pdf) of Annual Maximum Floods (AMFs) from the available data, to integrate the tail of the pdf with the damage function for the site at risk, and then to find the optimum design flood level that maximizes the difference of discounted benefits and costs over the design life. The assumption of independence in AMFs underpins this approach. However, this is evidence that this assumption may be questionable when longer records of extreme rainfalls and floods are analysed. Ntegeka and Willems (2008) has identified multidecadal variability

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in extreme rainfalls for a 100 yr rainfall record in Belgium using a sliding window method of analysis. Significant deviations in rainfall quantiles were found, which persisted for periods of 10 to 15 yr. In the winter and summer seasons, high extremes were clustered in the 1910s–1920s, the 1960s and recently in the 1990s. The authors note that this temporal clustering highlights the difficulty of attributing "change" in climate series to anthropogenically induced global warming.

Persistence/interannual variability in UK AMFs has been identified by Lane (2008), with clustering of floods in "flood-rich" periods and few floods in "flood-poor" periods. Pattison and Lane (2012) have constructed and analysed a long flood record dating from 1770 for the River Eden in the UK and identified three main flood-rich periods: 1873–1904, 1923–1933, and 1994 onwards. Their analysis of climatic drivers suggests that systematic organisation of the North Atlantic climate system may be manifest as periods of elevated or reduced flood risk, and with major implications for analyses that assume that climatic drivers of flood risk can be either statistically stationary or are following a simple trend. However, it is not necessary to discard the assumptions of stationarity to model this interannual variability; there are stationary stochastic models that can reproduce this variability (Koutsoyiannis, 2011; O'Connell and O'Donnell, 2013; O'Connell et al., 2010).

Periods that are flood rich and flood poor will be reflected in behaviours on investments by decision-makers. During flood poor periods, encroachment on floodplains and the value of assets grow, while levels of investment decline; conversely, investment grows in flood rich periods i.e. is reactive, as noted in Sect. 2 above. There is evidence of an "escalator effect" whereby progressively higher levels of flood defence are provided to protect against progressively increasing flood damage potential, caused mainly by post-defence development (Parker, 1995).

In a first investigation of proactive and reactive investment strategies under an increasingly variable climate exhibiting flood rich and flood poor periods, a univariate ARMA (1,1) model (O'Connell, 1971) was used to represent increasing levels of long-term variability and persistence in simulated Annual Maximum Floods (AMFs)

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(O'Connell et al., 2010; O'Connell and O'Donnell, 2013). A Monte Carlo sampling approach combined with a rational Cost Benefit approach was used to evaluate proactive and reactive strategies for a single hypothetical site at risk from flooding. Here, this approach is extended to a hypothetical region with multiple sites at risk from flooding that are competing for limited funds available for investment in flood protection.

4.2 Multisite ARMA model

A set of N randomly distributed floodplain sites at risk from flooding is assumed for a hypothetical region with a domain size of 100 × 100 km. The chosen area is arbitrary but broadly corresponds to the size of area under the jurisdiction of a Regional Flood and Coastal Committee in the UK; such committees have a key role in ensuring there are coherent plans for identifying, communicating and managing flood and coastal erosion risks across catchments and shorelines. No implicit linkages between the sites are assumed, other than through spatial correlation.

A multivariate ARMA (1,1) model for annual maximum floods at the N sites is assumed (O'Connell, 1974; Bras and Rodríguez-Iturbe, 1985); the model can be parameterized so that the level of persistence and interannual variability in AMFs can be controlled at each of the sites, so that the effect of this on investment strategies can be explored. The level of spatial coherence between the sites can also be controlled through a spatial correlation function, the parameters of which can also be varied to explore the sensitivity of investment decisions to spatial coherence. The distribution of annual maximum floods at each of the sites is assumed to be described by a three parameter lognormal distribution with mean 1000, standard deviation 400, and coefficient of skewness 1.5 (these can be varied across the sites to be more realistic, but were kept constant in the first instance to facilitate the interpretation of the results in Sect. 5). If $Y_t^{(i)}$ denotes a lognormal AMF variable at site i, then the corresponding normal variable $X_t^{(i)} = \mathrm{Ln}\left(Y_t^{(i)} - a_i\right)$ will have mean $\mu_x^{(i)}$ and standard deviation $\sigma_x^{(i)}$. If

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$x_t^{(i)} = \left(X_t^{(i)} - \mu_x^{(i)}\right)/\sigma_x^{(i)}$, then a multivariate normal ARMA (1,1) model with mean zero and unit standard deviation at each site can be written as

$$\boldsymbol{x}_t = \mathbf{A}\boldsymbol{x}_{t-1} + \mathbf{B}\boldsymbol{\varepsilon}_t - \mathbf{C}\boldsymbol{\varepsilon}_{t-1} \tag{1}$$

where $\boldsymbol{x}_t$ and $\boldsymbol{x}_{t-1}$ are $(N \times 1)$ vectors with elements $x_t^{(i)}$ and $x_{t-1}^{(i)}$, respectively, $\boldsymbol{\varepsilon}_t$ and $\boldsymbol{\varepsilon}_{t-1}$ are vectors of $N(0,1)$ independent normal random variables, and **A**, **B**, and **C** are $(N \times N)$ matrices of coefficients that are defined from $\mathbf{M}_0$, $\mathbf{M}_1$, and $\mathbf{M}_2$, the lag zero, lag one and lag two cross-correlation matrices.

If the matrix **A** is assumed to have a diagonal form with all diagonal elements predefined and equal to φ, the autoregressive parameter of a univariate ARMA (1,1) model, then the following relationships can be used to solve for the matrices **B** and **C**:

$$\begin{aligned}\mathbf{B} + \mathbf{C} &= (\mathbf{I} + \mathbf{A})\mathbf{M}_0(\mathbf{I} + \mathbf{A})^{\mathrm{T}} - \mathbf{M}_1(\mathbf{I} + \mathbf{A})^{\mathrm{T}} - (\mathbf{I} + \mathbf{A})\mathbf{M}_1^{\mathrm{T}} \\ &= \beta\beta^{\mathrm{T}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathbf{B} - \mathbf{C} &= (\mathbf{I} - \mathbf{A})\mathbf{M}_0(\mathbf{I} - \mathbf{A})^{\mathrm{T}} + \mathbf{M}_1(\mathbf{I} - \mathbf{A})^{\mathrm{T}} + (\mathbf{I} - \mathbf{A})\mathbf{M}_1^{\mathrm{T}} \\ &= \gamma\gamma^{\mathbf{T}}\end{aligned} \tag{3}$$

Without loss of generality, a lower diagonal form can be assumed for the matrices **B** and **C**, and Eqs. (2) and (3) can then be solved for the elements of **B** and **C.** As the matrix **A** has been predefined, the matrix $\mathbf{M}_2$ is not required to solve for **A** ($= \mathbf{M}_2\mathbf{M}_1^{-1}$ otherwise). With this definition of **A**, the parameter φ, together with the lag-one serial correlation ρ, can be used to control the level of persistence at each site; both are kept constant here across sites. As φ approaches the upper stationarity boundary of 1, the level of persistence/interannual variability increases, with increasingly extended flood rich and flood poor periods. The elements of the matrix $\mathbf{M}_0$ are filled using the spatial correlation function and the distance between the sites; an exponential isotropic correlation function was used with a rate of decay based, as a guideline, on the observed dependence between extreme sea surge, river flow and precipitation data in eastern

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Britain (Svensson and Jones, 2002). If $\rho_{ij}(0)$ denotes an element of the matrix $\mathbf{M}_0$, $i, j = 1,2,\ldots N$, then the elements of $\mathbf{M}_1$ are specified as $\rho.\rho_{ij}(0)$, based on the diagonal specification for the matrix **A**.The matrices **B** and **C** can then be solved for using Eqs. (2) and (3).

5 Rational flood protection investment within the coupled human and natural system

5.1 Evaluation of investment strategies using cost benefit analysis

Three alternative strategies were evaluated:

i. A reactive strategy in which no investment in flood defence is made until the existing level of flood protection (assumed to correspond to a return period of 50 yr Q_{50}) is exceeded at each of the N sites (wait and see);

ii. A proactive strategy where the existing level of flood protection is upgraded at each site at the beginning of the "design life";

iii. A "do nothing" strategy where the existing level of protection remains unchanged.

The natural system, represented by AMF floods, is coupled to the human system (the floodplain residents) through the interaction created by investments in flood protection infrastructure, and associated costs and economic damage. The human decision-making approach to investments was based on a rational cost benefit approach in the first instance; a more people-centred approach is presented in Sect. 6 in which a framework is outlined for modelling the human activities that drive flood protection investment.

Three levels of persistence were considered for the ARMA (1,1) model of AMFs; these corresponded to (a) independently and identically distributed AMFs – the IID case with no persistence; (b) a moderate level of persistence corresponding to $\varphi = 0.95$

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and lag-one serial correlation $\rho = 0.1$; (c); a high level of persistence corresponding to $\varphi = 0.95$ and lag-one serial correlation $\rho = 0.3$.

The following steps are involved in the Monte Carlo evaluation of investment strategies (O'Connell and O'Donnell, 2013):

i. generate populations of AMF data at each of $N = 10$ sites for each of the three selected levels of persistence (a), (b) and (c); all sets had a mean, variance and skewness of 1000, 400 and 1.5, respectively. An ensemble of 50 000 150 yr realizations was extracted from the generated series of AMFs for each of the three persistence levels;

ii. a "historical record" (taken as 50 yr) and subsequent "design life" record (taken as $n = 100$ yr) was abstracted from each 150 yr realization;

iii. different levels of knowledge about the probability distribution function (pdf) of AMF were assumed at each site: (a) assume full knowledge of the population pdf; (b) estimate the pdf by fitting a lognormal distribution to the available sample using L-moments (Hosking and Wallis, 1997). In the case of the proactive strategy, 50 yr of sample data corresponding to the "historic record" were used for each realization, while, for the reactive strategy, $50 + n_r$ years of data were used, where n_r is the number of years in the design life period before the existing level of protection is exceeded (Fig. 1);

iv. estimate the average annual damage for the current situation, by combining the AMF distribution with a damage function (Fig. 2), that yields the expected flood damage for the current level of protection;

(v) determine the optimal level of flood protection by optimizing a cost-benefit function (Fig. 2 and Eq. 5);

(vi) assess the level of performance of each strategy by calculating the actual damage over the design life in each case, and compare the strategies as a function of the level of variability in the generated AMF data.

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For the proactive strategy, the investment is made at the start of the design life, while, for the reactive strategy, the investment is made when the current level of protection is first overtopped during the design life. In the latter case, the "historical record" used for estimating the pdf is augmented by the additional data corresponding to the waiting time to the first overtopping of the existing protection level. Under the reactive strategy, investment is only undertaken if the existing protection is overtopped in the first 75 yr as later investment would not provide sufficient discounted benefit to ensure a valid comparison.

The pdf, damage function and cost function are shown schematically in Fig. 2. The cost function consists of an initial cost and a linear proportional cost, while the damage function is expressed as

$$\text{Damage} = a(Q-c)^{0.5} + b(Q-c) \tag{4}$$

where c is the level of protection i.e. all floods where $Q < c$ cause no damage, and a and b are parameters.

As this is a hypothetical case study, the choice of a and b is arbitrary. However, the parameter values were selected to provide a damage function shape that resulted in a larger amount of damage occurring with the initial overtopping of the defence, reflecting substantial development on the floodplain ($a = 30$; $b = 2$). The cost and damage functions shown in Fig. 2 have the same monetary units, but as this is a hypothetical case, the values are just indicative.

In the case where the pdf is assumed known (perfect information), the optimal level of investment/protection is known precisely, while in the case where it is estimated, the level of investment will vary as a function of the sample information. The objective function to be optimized is

$$\text{NPV} = \sum_{t=1}^{n} \left[1/(1+r)^t (\text{EAD}_{t,\text{DN}} - \text{EAD}_{t,\text{IMP}} - \text{cost}_t)\right] \tag{5}$$

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where NPV is net Present value, $EAD_{t,DN}$ is the annual average damage corresponding to the current level of protection (corresponding to the do nothing strategy); $EAD_{t,IMP}$ is the level of damage corresponding to the improved level of protection (to be obtained by optimising NPV), and $cost_t$ is the level of investment. $EAD_{t,DN}$ and $EAD_{t,IMP}$ are obtained by integrating the damage function given by Eq. (4) with the tail of the pdf. This formulation is used to decide on the level of protection for both the proactive and reactive strategies (O'Connell and O'Donnell, 2013; O'Connell et al., 2010).

The total damage over the design life has been computed as a function of the levels of protection provided by the different strategies, and the level of knowledge of the pdf [population (pop) or sample estimated (sample)].

The damages and costs have been discounted to present value using a time variable discount rate taken from the HM Treasury Green Book (HM Treasury, 2011). This rate is roughly 3.5 % but declines over time. An increased discount rate puts more weight on net benefits in earlier periods.

5.2 Results

The net benefits (reduction in damage minus costs) are shown for the IID case, the low persistence ($\varphi = 0.95, \rho = 0.1$) and high persistence ($\varphi = 0.95, \rho = 0.3$) cases in Fig. 3. The values are the average over the 50 000 realisations across all 10 sites. In the proactive case the net benefits are similar for all persistence levels, although there is a significant advantage in using the population rather than the sample statistics. Where full knowledge of the population is assumed, the optimal level of investment is known precisely, which is roughly equal to the 100 yr flood. Where the pdf is estimated from the historical record, the effect of persistence influences the cost-benefit analysis in determining the level of protection, but the average net benefit taken over 50 000 realisations is similar for all levels of persistence.

In the reactive case, net benefits are lower than those for the proactive case when using the population statistics. In the reactive case, investment is only made after the first flood exceeding Q_{50} and hence there is an initial damage prior to improvement

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in defences. Of greatest interest is the increase in net benefits as the persistence increases, with a reactive strategy performing better than the proactive strategy under high persistence when the sample statistics are used i.e. there is a crossover from proactive to reactive as the best strategy. These results can be explained by examining frequency of flooding and the damages in greater detail.

The percentage of 100 yr AMF records in which no flood exceeded the current level of protection was 13 % in the IID case (which is as expected given the relationship $P = 1 - (1 - 1/T)^n$, where $n = 100$ and $T = 50$) and 27 % in the high persistence case. This means that in the reactive case, no investment is made at a larger number of sites, reducing the average cost across all realisations.

The above analysis does not consider the effects of the combined temporal clustering and spatial correlation between the 10 sites. In Fig. 4, the number of floods exceeding the current level of protection (Q_{50}) across all 10 sites in each set of 100 yr design-life records was calculated for each of the 50 000 realisations. High persistence results in a positively skewed distribution, reflecting flood poor periods, but also a fatter tail, representing flood rich periods. Hence there are many more highly damaging regional events in the high persistence case.

In Table 1, the percentage of realisations (50 000) in which the damage exceeded given thresholds aggregated across all 10 sites are provided for the IID and high persistence cases. As expected, highly damaging regional floods are more frequent under the high persistence case. However, it is also noted that taking a proactive or a reactive strategy has little bearing on the percentage of damage exceedences for the most damaging floods.

The propensity for extreme events to cluster, both spatially and temporally, is of great concern to the insurance industry (Vitolo et al., 2009), with firms required to have sufficient capital to cover the 1 : 200 yr event across the portfolio in any given year under EU Solvency Capital Requirements.

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6 The human system: towards agent based modelling of human activity affecting flood investment decision-making

An Agent Based Modelling (ABM) framework is being developed in conjunction with the regional ARMA Natural System AMF model presented in Sect. 4 to explore the decision-making process for flood investment at the regional level within this Coupled Human and Natural System. This work draws upon experience of institutional/citizen interplay studies conducted throughout the UK, and the wider agent-based modelling literature. The primary aim is to provide insight into how communities respond to actual flooding, and whether this influences the funding of flood protection. Firstly, the institutional actors are introduced, and then their interaction with floodplain communities within an agent-based context is presented.

6.1 Institutional actors involved in the decision making process

The main institutional actors in the decision making process for flood risk management (FRM) are shown in Fig. 5. An English perspective is used in the following, but many of the roles of actors and feedbacks between them have parallels in many Europeans countries. The US approach differs from that in Europe in that preparation, response and recovery dominate over prevention (ten Brinke et al., 2008).

6.1.1 Central government

The institutional framework for flood management in England is fragmented with the environment ministry (Defra) responsible for policy-making and the Environment Agency (EA) for operational responsibility. Defra's role is constrained by the economic orientated Treasury, which controls public financial resources and sets the principles of public sector financial operations (Krieger, 2013). As a result of this relationship that is based on financial accountability, FRM historically has relied primarily on a project level risk-based cost-benefit ratio as a basis for investment, although recent reforms

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have strengthened the social and environmental dimensions (Johnson et al., 2007). It is interesting to contrast the UK and German models, with the latter aiming to provide a similar level of protection to the population at risk through the adoption of the 100 yr flood level (HQ100) standard (Krieger, 2012).

6.1.2 Operating authority

Defra provides priority-defined guidance to the operating authority (EA) to prevent flood protection projects entering the funding process unless they achieve some economic, social and environmental performance levels (Johnson et al., 2007). However, the EA is a quasi-independent agent of the government with laws giving only permissive powers rather than duties (Harries and Penning-Rowsell, 2011). Thus, the organisation has a degree of autonomy on how to spend the annual budget it receives from Defra. Additionally, there is devolved power within the EA, with local staff left some discretion about the design and content of the proposals that they put forward to the decision-making committees.

6.1.3 Regional flood and coastal committees

Regional Flood and Coastal Committees (RFCCs), a requirement of the Flood and Water Management Act 2010, are central to achieving the government's new Partnership Funding approach (Defra, 2011). These committees can raise local levy to reduce the cost of projects to the national tax payer, thereby bringing forward scheme delivery, or to fund schemes that satisfy local strategy. The aim is to provide communities with choice and provide localism to decision making (Defra, 2011). RFCCs also provide for local democratic input through the majority local authority membership (Defra/EA, 2011).

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6.1.4 Local authorities and land use planning

Autonomous, directly elected local authorities have traditionally had a major control over land-use/development decisions, which has caused tension with the EA to whom blame is attributed in times of flood disasters. However, the recent UK Government's Planning Policy Statement 25 (PPS 25) requires recognition of flood risk and climate change projections in development appraisal, strengthening the role of the EA. This involves avoiding new development plans in high flood risk areas and ensuring that flood risk is adequately addressed in planning appraisal. PPS 25 has additionally spread the risk towards those that are benefitting from development within flood prone areas, with developers required to implement flood alleviation measures. However, there remains a tension as government policy strongly favours the redevelopment of brownfield land, much of which lies in areas at risk of flooding (Porter and Demeritt, 2012).

6.1.5 Insurance

Flood insurance provision in the UK is based on the "Statement of Principles" between the Government and the Association of British Insurers (ABI), which guarantees existing customers access to home insurance in flood-risk areas. (This agreement will expire in 2013). UK flood insurance provision is unusual in Europe in that risk is reflected in premiums paid by individual households, although there is a subsidy from low to high risk households. There is a concern that, if left to the market, there will be differentiation between households at different levels of risk which may leave many low-income households effectively uninsurable, leading to social blight (O'Neill and O'Neill, 2012).

6.2 Influence of community responses on the decision making process

The above discussion demonstrates that institutional responsibilities for managing flood risk are fragmented, with the institutions involved having a degree of autonomy.

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This means that there is some regional flexibility in the provision of flood protection. For example, the EA has been historically reactive and responsive to flood events that have stimulated public demand for defences (Harries and Penning-Rowsell, 2011). The powers imparted to the RFCCs, with the inclusion of local authority members, has the potential to increase the influence of community action in gaining flood protection.

6.2.1 ABM framework

Before commencing to describe an exploratory ABM framework that might encompass the above human decision-making process in greater detail than the somewhat outdated Cost Benefit approach, it is appropriate to highlight some key aspects of the methodology, including limitations. ABMs are often criticised for a lack of verification, calibration and validation. The proposed model is not to be used in predictive mode, but rather to explore futures in which there is deep uncertainty. Under such situations accurate predictions are not possible (Lempert, 2002; Bankes, 2002). However, given that ABMs correspond quite closely to the ways that individual stakeholders generally think about actions and interactions, there is the potential for model appraisal, and for actors/stakeholders to gain insight into the decision-making process that they seek to influence. A model can be deemed useful if stakeholders view it as plausible and it enables them to explore the consequences of actions that they may wish to undertake (Moss et al., 2001). Such participatory agent-based simulation has proved useful in exploring the achievement of policy objectives with stakeholders (e.g. Downing et al., 2001; Becu et al., 2003).

In designing an ABM, there is a tension between the perceived need to represent the human system decision-making problem domain in as rich a manner as possible, while retaining simplicity. There is a risk that richness will introduce multiple complexities that will obscure the significance of the model. Simpler models are often preferable, as the data requirements are more manageable and they can be described and understood (Pellizzari, 2005; Crooks et al., 2008), which is particularly important if a participatory

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approach is used. However, ambiguity remains over the specification of agents' motivations, interactions and beliefs.

A schematic of the proposed ABM framework is provided in Fig. 6, which is an abstraction of the institutional relationships described above that operate at the regional level. The Natural System is represented using the ARMA AMF model (Sect. 4), in which the level of persistence can be varied to create clusters of floods in the AMF series. This controls the timing and extent of flooding in a given number of virtual cities (sites) at risk from flooding. The "memory" in the ARMA model is imparted to the community, both in terms of greater demands for protection in flood rich periods, but also in terms of the citizens' flood memory and emotional intensity. If sufficiently motivated, the citizens in the community will form pressure forums, Flood Action Groups, and generate media attention. Both in the UK and Europe, there is a public perception that managing flood risk is a public rather than private matter (Lara et al., 2010; Kellens et al., 2013); hence, pressure is placed on elected officials, who influence local authority decision making. Ultimately, if sufficient, this pressure will influence the decision making authority, which comprises Local Authority members and the Operating Authority (the EA). There is a need to assess whether "event-driven" responses provide good decision making and good value for public money, and whether those with weak representation lose out (Naess et al., 2005; Parliamentary Select Committee, 2013).

A primary reason for selecting an agent based approach is the ability to model the actions and interactions of the individual decision-making entities; hence the groupings in Fig. 6 must typically represent many agents. For example, a virtual city requires a spatial representation of the areas in which the citizens reside to allow representation of the social interactions that are important in group activity and mobilisation (e.g. DeMarzo et al., 2003).

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6.2.2 Community responses

There is a need to explore the motivations and competence of the citizen agents involved and how hierarchical relationships are formed, and whether this impacts on the funding process. Citizen agents can be broadly divided into the following categories:

- influentials, whom have strong motivation and competence;
- reluctants, whom do not accept that their property is at risk, which may be explained in terms of economic interests (insurance) and the psychologically unsettling nature of accepting risk (Burningham et al., 2008; Cashman, 2009; Grothmann and Reusswig, 2006), or fear of the loss of aesthetics (Whatmore and Landström, 2011);
- others, whose opinions may be swayed by the views of their social networks.

Influentials are important agents in the formation of Flood Action Groups, which are the key pressure groups involved in mobilising community outrage, and media attention after a flood event. For example, following the 2008 flood which impacted upon 1000 properties in the town of Morpeth in North East England, there were calls that "It must never happen again!" Additionally, there were demands for action "to lobby councillors, push our MP's to keep the issues before parliament and press the Environment Agency to bring forward their plans for flood alleviation." There is a significant body of agent based literature exploring the role of influentials (e.g. Deffuant et al., 2002; DeMarzo et al., 2003) and how social relationships influence the shaping of a community's views (e.g. Gulati et al., 2011; Hamill and Gilbert, 2009).

Politicians are assumed to be primarily motivated by maintaining or gaining power, which can be achieved by gaining public support through their actions. The national politician (Member of Parliament) representing the community of Morpeth spoke in Parliament seeking Government support to help to rebuild the town and "to prevent a similar occurrence". It was also argued that an improved flood defence scheme

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would release valuable riverside land for redevelopment. This raises questions regarding a community's acceptance of policies such as Making Space for Water and the viability of future land use planning to reduce risk. Cashman (2009) describes the politicising of a flood event at a time approaching a local election, despite the absence of political involvement after an event several years previously. The role of the strength of a community's flood memory and how this can result in a single electoral issue are therefore important aspects (DeMarzo et al., 2003; McEwen et al., 2012a).

Use of the media is an important method that can be utilised by a community in gaining support, both within their own community and regionally. Following the devastating flood in Hull in 2007, local residents and councillors were unhappy at the lack of media coverage. It was believed that certain communities geographically closer to the centre of power are given preference, with Hull dubbed by the lead councillor "the forgotten city" (Kim et al., 2012). Alternatively, a regional newspaper used the headline "Sick of sandbags and sympathy" to highlight the angry reaction to flooding in Belford, UK (Wilkinson et al., 2010). This village subsequently received local financial support for flood alleviation measures.

The above aspects will influence public consultation exercises which are held with members of the public and the decision making authority. Local decision makers may perceive those that are most vocal as the public to whom they are responsible (Irvin and Stansbury, 2004). Consequently, national level policies may not be met, with a distortion of the decision making process in which recent flood victim views are paramount and have an appeal beyond a rational cost benefit approach (Harries and Penning-Rowsell, 2011). In times of flood crises, there will be multiple demands for flood protection from several communities, which can be viewed as an auction for protective measures, in which the outrage a community generates becomes the principle currency.

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7 Discussion, conclusions and further work

With the prospect that flood hazard may increase in the coming decades due to global warming, there is a need for methodologies for evaluating adaptation strategies under increasingly variable climates. It is advocated here, that, since clear and unequivocal evidence has yet to emerge for quantifiable sources of nonstationarity in flood records, the limits of stationarity should first be explored in assessing the performance of flood protection investment strategies.

To provide insight into how we may deal with flood protection investment under an uncertain future, rational cost-benefit analysis coupled with Monte Carlo simulation of Annual Maximum Floods (AMFs) has been used to explore the performance of proactive and reactive investment strategies for flood protection. A stationary stochastic model capable of representing increasingly variable climates has been used to create AMF series at a number of virtual city sites lying within a region. Firstly, it was found that, irrespective of the level of persistence and the investment strategy taken, it is difficult to make good decisions with the short historic records (~ 50 yr) that are typically available to engineering hydrologists. Secondly, it was found that, while a proactive strategy performed best for IID and low persistence AMF floods, the reactive "wait and see" strategy outperformed the proactive strategy, in terms of net benefits delivered, at very high levels of persistence. This demonstrates that the call for proactive investment to combat the impacts of an increasingly variable climate may be premature, given that natural climatic variability has been manifested in the past through flood rich and flood poor periods.

In practice, decision making at a regional or national level is never simply reactive or proactive. In the UK, a proactive case is taken for cities that are of greatest importance to the national economy (Lavery and Donovan, 2005), with a more reactive approach taken elsewhere. Additionally, although cost-benefit analysis plays an important role in prioritising those sites that receive protection, the more holistic approaches that are now being taken to flood risk management (FRM) encompass environmental, so-

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cial and economic objectives, as well as widening stakeholder participation. Decision-making now encompasses multiple objectives and multiple stakeholders, and flood risk management is becoming increasingly people-centred. While there is an expanding literature on the social science aspects of flood risk management such as institutional structures and responses, building flood resilience at the community level, and social justice aspects, there is an evident paradigm lock between the quantitative technical aspects of FRM, and the more qualitative treatment of the social science aspects. It is therefore difficult to quantify how the social dimensions of FRM bear upon decisions relating to flood protection investments. It is suggested that Coupled Human and Natural System (CHANS) modelling, which has developed primarily in the ecological modelling field, offers a framework for integrating the social and technical aspects, with Agent Based Modelling (ABM) providing a basis for modelling the human activities of multiple stakeholders that influence decision-making.

Developing an ABM framework to describe the complexity of decision-making in CHANS modelling is a major challenge. However, meeting this goal would help in gaining an understanding of whether policy initiatives such as Making Space for Water can be effectively delivered, and the implications for social justice (Johnson et al., 2007) as well as delivering value for money for investments in the traditional economic sense. By coupling the ABM model to the Natural System AMF model, and quantifying the costs and damages that ensue from decision-making in flood rich and flood poor realizations that emerge from the CHANS model, the value for money that results can be assessed, and compared with what emerges from proactive and reactive strategies determined using rational Cost Benefit analysis. Moreover, community action groups will have an opportunity to view the consequences of their activities in securing prioritization of investments, on the availability of funding for investment elsewhere, and on the wider implications for equity and social justice.

Based on a review of the main actors/stakeholders that currently influence decisions on flood investments in the UK, an ABM modelling framework has been outlined. Current work is exploring how this can be implemented, bearing in mind some of the known

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limitations of ABM. Future work will explore how an ABM representation of decision-making can play out in terms of investments in the virtual region considered above, and what the value for money and social justice consequences can be. In the first instance, selected flood rich and flood poor realizations from the multivariate ARMA (1,1) model will be used to gain insight into how the coupling between the Human and Natural System affects investments as the level of persistence/interannual variability increases. Moreover, the influence of the different aspects of "Memory" within CHANS models of flood protection investment and other FRM responses (e.g. building resilience) will be explored. Firstly, there is the long memory in the natural climate system (Mesa et al., 2012; Fraedrich et al., 2009) which is on decadal/centennial/millennial scales, and which is represented here using a stationary ARMA (1,1) model. Secondly, there is the institutional/stakeholder memory of past floods which decays in flood poor epochs, and which influences floodplain encroachment and the allocation of government funds for investments. The need for "Sustainable Memory" (McEwen et al., 2012b) has been noted above. Thirdly, flood protection infrastructure has memory (C. G. Kilsby, personal communication, 2013), as its effectiveness decays over time, and repeated loadings in flood rich periods can lead to failure and greatly increased damage (Dyer, 2004; Dawson et al., 2005). It is therefore evident that CHANS modelling of flood protection investments and flood risk management in the current people-centred approaches, and under the pressures of global climate and socio-economic change, offers exciting possibilities for developing the new paradigm of socio-hydrology.

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Table 1. Percentage of realisations across the 10 sites in which flood damage exceeds given thresholds.

Damage $	IID (%)		High persistence (%)	
	Proactive	Reactive	Proactive	Reactive
> 15 K	2.8	3.8	6.0	7.0
> 25 K	0.4	0.5	1.6	1.6
> 35 K	0.1	0.1	0.5	0.6
> 45 K	0.0	0.0	0.1	0.1

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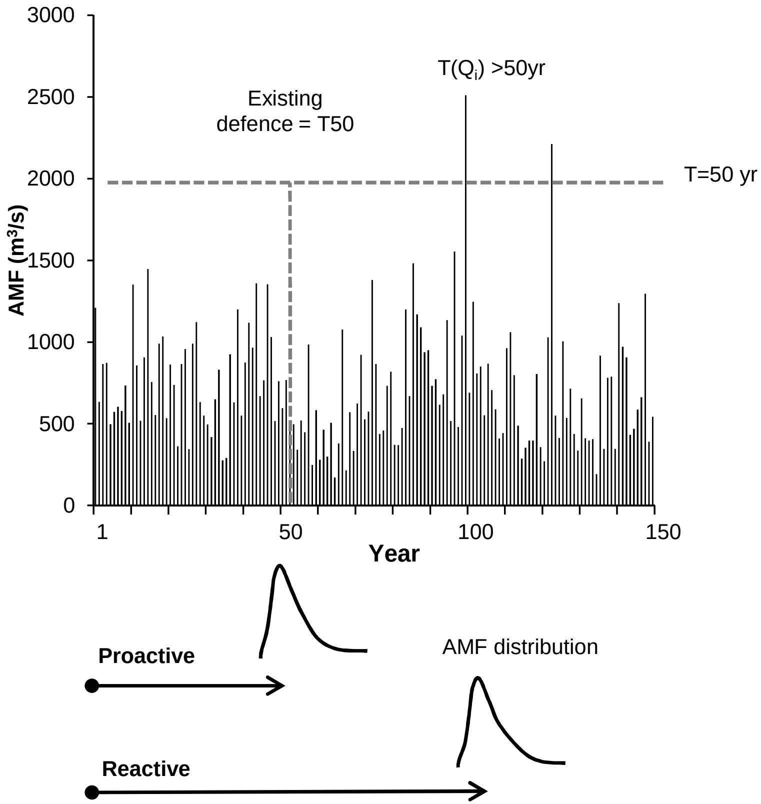

Fig. 1. Typical realization of "historic record" (50 yr) and "design life" (100 yr). An exceedance of the current level of protection takes place around $n_r = 50$ yr, so $50 + n_r$ years of data are available to estimate the pdf of annual maximum floods for the reactive case.

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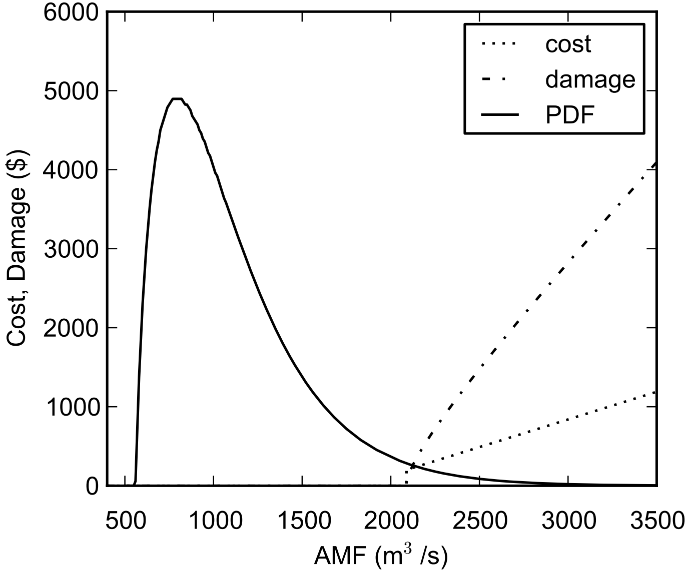

Fig. 2. Schematic of pdf of annual maxima floods, cost function and damage function.

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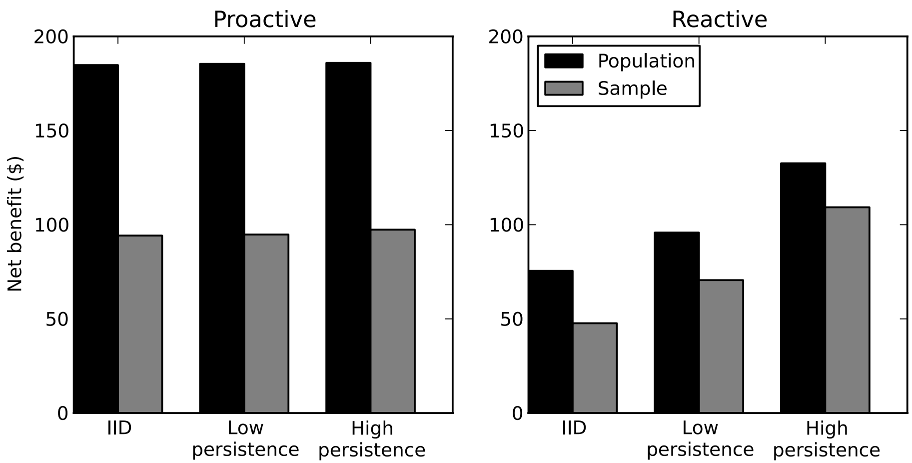

Fig. 3. Comparison of net benefits for the proactive and reactive cases.

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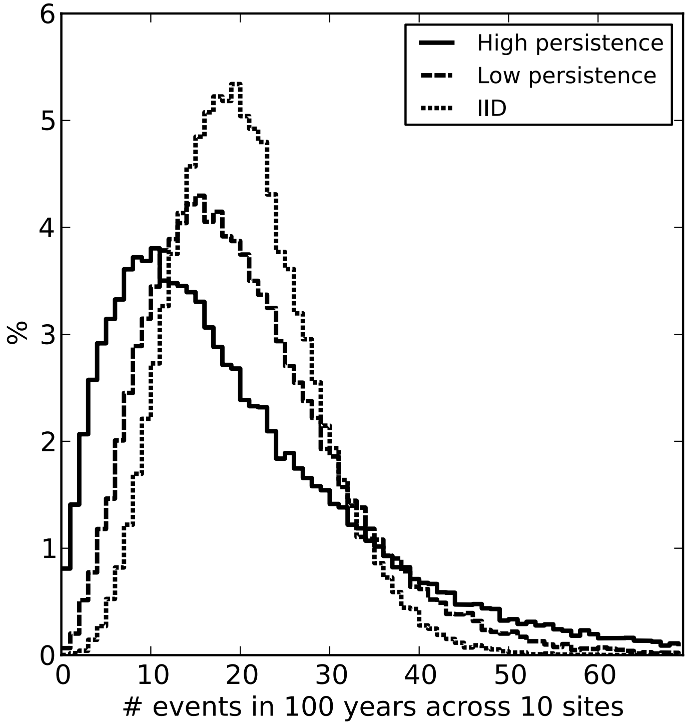

Fig. 4. Frequency of events exceeding the current level of protection Q_{50}.

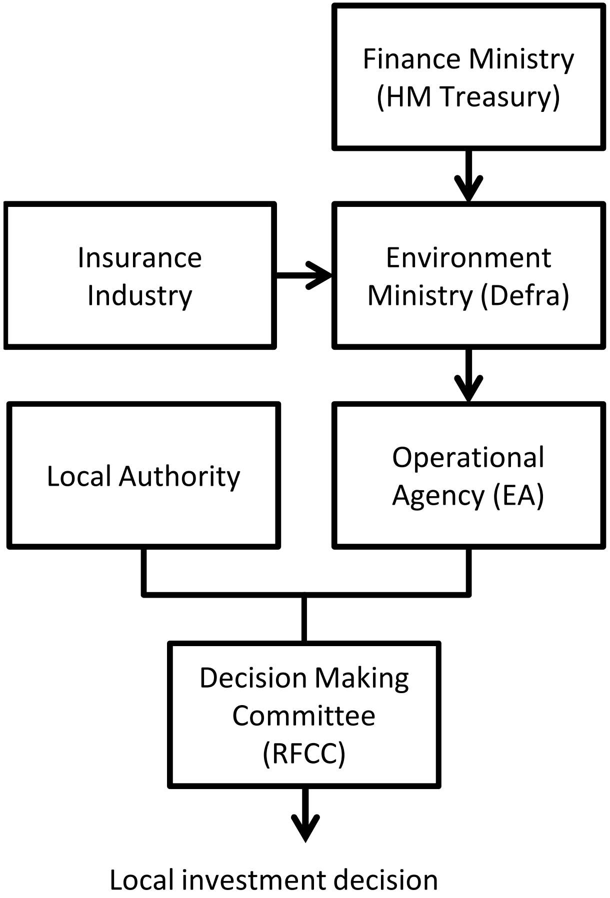

Fig. 5. Institutional actors in the decision making process.

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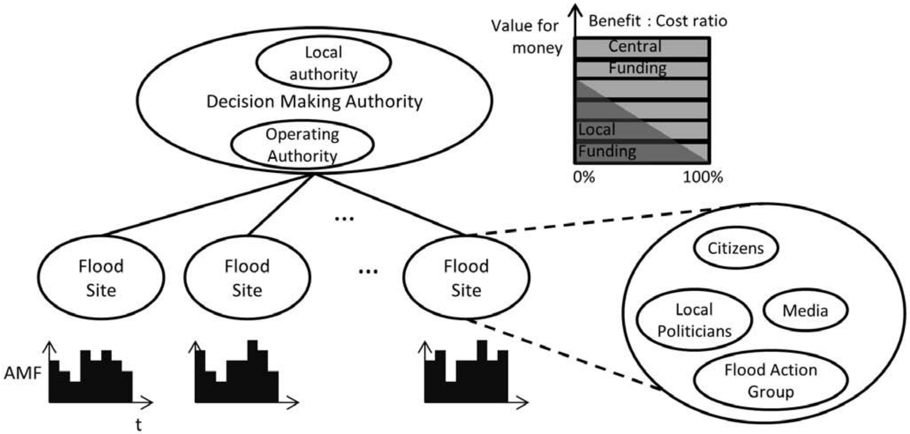

Fig. 6. Schematic of ABM for regional decision making. The box is a simplified representation of the UK Partnership Funding scheme, where those projects with the highest benefit to cost ratios receive 100 % central funding, with others requiring a local funding contribution to proceed.

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