Flood Risk Management: Research and Practice – Samuels et al. (eds)

ISBN 978-0-415-48507-4

Strategic appraisal of flood risk management options over extended timescales: combining scenario analysis with optimization

J.W. Hall, T.R. Phillips, R.J. Dawson, S.L. Barr, A.C. Ford
Tyndall Centre for Climate Change Research, School of Civil Engineering and Geosciences, Newcastle University, Newcastle-upon-Tyne, UK

M. Batty
Bartlett Faculty of the Built Environment, University College London, London, UK

A. Dagoumas
Department of Land Economy, University of Cambridge, Cambridge, UK

P.B. Sayers
HR Wallingford, Wallingford, Oxfordshire, UK

ABSTRACT: Strategic flood risk management seeks to identify portfolios of flood risk management options that can be implemented in a staged and adaptive way. This raises substantial challenges from the point of view of risk analysis, two of which are addressed in this paper. First we examine the problem of dealing with scenarios of long term change and in particular socio-economic and climate changes. We build substantially on the scenarios approach adopted in the UK Foresight project and subsequent studies by introducing a quantified high resolution coupled econometric and land use simulator. This is used in an assessment of the combined effects of land use and climate change. Again against the background of climate change, we go on to address the complexity of constructing and analysing portfolios of intervention flood risk management systems. Specifically, we illustrate how a genetic algorithm can be used to search the very high dimensional option space of flood defence management options and sequences. This new integrated approach of scenario analysis and optimisation is illustrated with examples from the Thames Estuary in the UK.

1 DECISION SUPPORT FOR STRATEGIC FLOOD RISK MANAGEMENT

The notion of integrated risk-based approach to flood management is now well established (National Academy of Engineering, 2000; National Research Council, 2000; Sayers et al., 2002; Hall et al., 2003) and methods for probabilistic risk analysis have been used for some years in the narrower context of flood defence engineering (CUR/TAW, 1990; Vrijling, 1993; USACE, 1996; Goldman, 1997). Indeed the notion of risk-based optimisation of the costs and benefits of flood defence was laid out in van Dantzig's (1956) seminal analysis. However, modern flood risk management does not rely solely upon engineered flood defence structures, such as dikes, channel improvement works and barriers, but also considers a host of measures that may be used to reduce the severity of flooding (for example land use changes in upstream catchments) or reduce the consequence of flooding when it does occur, by reducing vulnerability. The criteria for assessment of flood risk management options are seldom solely economic, but involve considerations of public safety, equity and the environment. Furthermore, an increasing recognition of non-stationarity (Milly et al., 2008) means that flood risk management involves explicit consideration of the ways in which flood risk may change in future, due, for example, to climate change or floodplain development. This leads to the notion of flood risk management being a continuous process of adaptive management.

There is seldom a single solution to managing flood risk. Instead, portfolios of flood risk management measures, be they 'hard' structural measures such as construction of dikes, or 'soft' instruments such as land use planning and flood warning systems, are assembled in order to reduce risk in an efficient and sustainable way. The makeup of flood risk management portfolios is matched to the functioning and needs of particular localities and will be adapted as more knowledge is acquired and as systems change.

Implementing this approach involves the collective action of a range of different government authorities and stakeholders from outside government. This places an increasing emphasis upon effective communication and mechanisms to reach consensus. Some features of this approach are now becoming embedded in national government policy, for example in the UK policy document *Making Space for Water* (Defra, 2005), the European Directive on the *Assessment and Management of Flood Risks*, and progressive evolution of floodplain management in the USA (Interagency Floodplain Management Review Committee, 1994; Galloway, 2005; Kahan, 2006).

Compelling as modern integrated flood risk management certainly is, it brings with it considerable complexity. The risk-based approach involves analysing the likely impacts of flooding under a very wide range of conditions. As the systems under consideration expand in scope and timescale, so too does the number of potentially uncertain variables. There are many potential components to a portfolio of hard and soft flood risk management measures and they can be implemented in many different sequences through time, so the decision space is potentially huge.

To support this integrated approach to flood risk management, it is evident that a corresponding integrated holistic approach to risk analysis and decision making is needed. Traditional assumptions of stationarity need to be replaced by better informed scenarios of long term change. A recent study for the UK Environment Agency (Wheater et al., 2007) indicated that a new holistic modelling framework is need to encompass the following:

- Quantitative scenario modelling of the drivers and pressures that impact upon flood risk, including global climate and socioeconomic change;
- Whole catchment and shoreline modelling of flood and erosion risks under uncertain future climatic and socioeconomic conditions, and under a wide range of response options;
- Integrated assessment of portfolios of response options based on economic, social and environmental criteria, including measures of vulnerability, resilience, adaptability and reversibility;
- Integration of technical and socioeconomic modelling through agent-based modelling approaches;
- Quantification of the various sources of uncertainty and their propagation through the modelling/decision-making process;
- Be capable of supporting a multi-level participatory stakeholder approach to decision-making.

In this paper we seek to address two of the challenges set out by Wheater et al. (2007), specifically:

1. Development of high resolution regional scale scenarios of climate and socio-economic change, as a basis for identification of sustainable flood risk management measures.
2. Optimisation of the composition and sequence of implementation of complex portfolios of flood risk management measures.

2 GENERATING HIGH RESOLUTION CLIMATE AND SOCIO-ECONOMIC SCENARIOS FOR OPTIONS APPRAISAL

Development of scenarios of long term change requires a coherent framework which includes the main drivers of change and the processes by which they influence flood risk. Such a framework (Figure 1) has recently been developed in the Tyndall Centre for Climate Change Research where downscales climate change scenarios are combined with high resolution analysis of the functioning of the regional economy and land use change. These issues can hardly be divorced from its global context. Our framework for integrated assessment, shown in Figure 1, therefore is driven by a global climate and economics models. This provides the boundary conditions for the city scale analysis, in this case study of London. These boundary conditions drive scenarios of regional economy and land use change, ensuring that whilst they are influenced by local policy, these scenarios are also globally consistent. It is at the level of land use modelling that the analysis becomes spatially explicit. Scenarios of land use and city-scale climate and socio-economic change inform the analysis of long term change in flood risk. The final component of the framework is the integrated assessment tool that provides the interface between the modelling components, the results and the end-user. These components

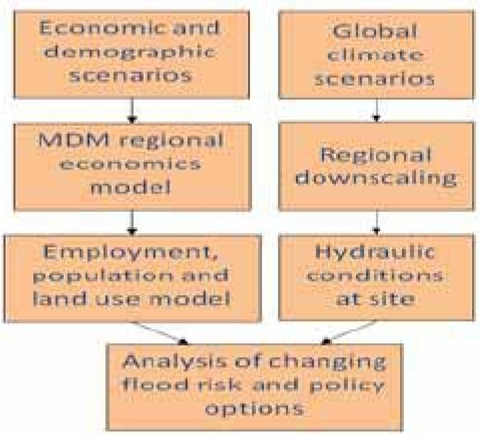

Figure 1. Overview of the analysis framework.

are discussed in more detail in the following sections, before moving to the question of option choice.

2.1 *Scenarios of climate and socio-economic change*

Scenarios represent alternative storylines of the future rather than predictions or forecasts. Analysis of a set of scenarios can assist in the understanding of the behaviour and long term changes to complex systems to support policy making. Scenarios provide an internally consistent and reproducible set of assumptions about the key relationships and driving forces of change in order to integrate qualitative narratives about future global change and quantitative estimates of the magnitude of those changes. However, the scenario space is large and multi-dimensional. A central tenant of scenario analysis is to ensure that the various dimensions of a scenario are internally consistent with one another. Key dimensions of the scenario and policy space for regional scale assessments are:

- Economic growth (including issues of equity, wealth, property prices, regional disparities etc.),
- Demography (including population growth, profile of age groups, in and out migration etc.),
- Landuse changes and planning regulations,
- Governance (is power centralised, or are key decisions made in a top down manner by a (supra) national policy maker or is there a laissez-faire approach to governance).
- Climate change.

2.2 *Case study location: London*

London is the capital city of the United Kingdom and has been a settlement for around two millennia. It has a wide and diverse cultural, social, economic, environmental and built heritage and is one of the most culturally diverse cities in the world with 29% of the population from ethnic minorities, speaking almost 300 languages (ONS, 2003). The population is currently approximately 7.2 million and is expected to be over 8.1 million by 2016 (GLA, 2004). The London Plan (GLA, 2004) is the strategic plan setting out an integrated social, economic and environmental framework for the future development of London for the next 15–20 years. The plan provides the London-wide context within which individual boroughs (local administrative authorities, of which there are 33 in London) must set their local planning policies.

2.3 *Regional macroeconomic modelling*

A regional economic model is used to provide the overall context for the analysis of economic changes that are key determinants of vulnerability to flood risk. The Multisectoral Dynamic Model (MDM) developed by Cambridge Econometrics has been applied to the integrated assessment in London. This is a coupled macroeconomic model designed for long term economic analysis based on Keynsian macroeconomic theory, and is described by Junankar et al. (2007). The model is based upon time series and cross-section (input-output) data from the UK Office of National Statistics. It is dynamic in that it incorporates behavioural equations with effects from previous outcomes. In this sense the model represents time dependency, with a corresponding emphasis upon "history" rather than more conventional equilibrium concepts. The model is use to provide forward projections annually or in 5 or 10 year steps. The model provides measures of economic activity and employment in 42 different economic sectors (which have been aggregated for clarity in Figure 2). It takes as its inputs baseline projections of long term growth and population, as well as past observations of the relationships between different industrial sectors, and then disaggregates the long term projections to generate gross value added and employment projections for 42 different economic sectors. These provide inputs to the land use model described below. Figure 2 provides one illustrative scenario of economic activity and employment in London, with a general trend towards decline in industry but a growth in finance and business related employment.

2.4 *Land use change model*

Land use modelling is used to understand potential changes in vulnerability to flood risk. The land use transport model comprises two components (Figure 3). A population and employment allocation model uses gravity concepts to distribute different population and employment types according to the 'attractiveness' of different administrative zones (known as 'wards' in the UK). A key feature of this attraction is the spatial interaction between zones, which is a function of travel time, cost, distance and capacity of the transport network. Planning strategies, such as encouraging development on previously used land or halting development on floodplains allow users to explore how spatial planning can reduce vulnerability to climate impacts.

Figure 4 shows a typical output from the land use change model that indicates the change in employment in different wards of London given the employment changes (and existing transport infrastructure) predicted by the economic modelling. Finer scale outputs are required for meaningful testing of planning strategies and their impact on flood risk, so a second component of the land use change model disaggregates changes in land use for each ward onto a 50 - 50 m grid as shown in Figure 4.

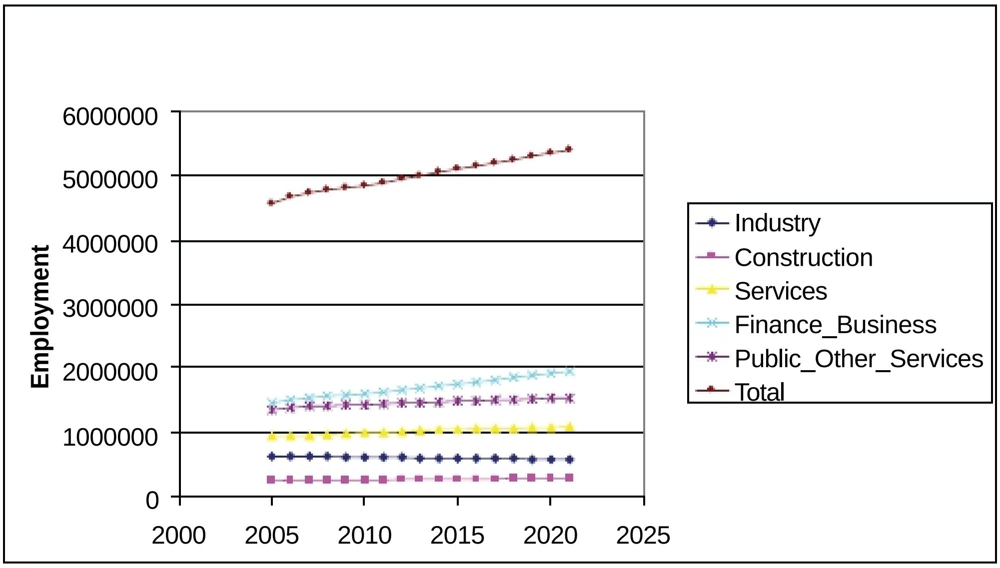

Figure 2. An illustrative projection of economic activity and employment in London, with a general trend towards decline in industry but a growth in finance and business related employment.

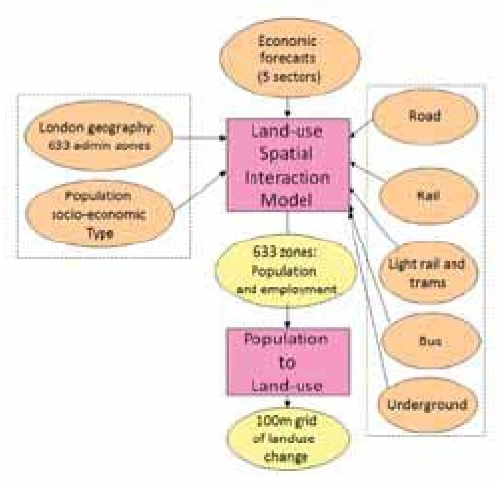

Figure 3. Structure of the land use interaction model.

2.5 *Disaggregation to a 50 m grid*

The land use model described above operates at the scale of administrative wards. A further module is used to allocate population changes to changes in built land use by the application of a system of rules and constraints:

- Construction is preferred close to existing development.
- Construction is preferred close to transport nodes.
- Environmentally designated land is prohibited from development.

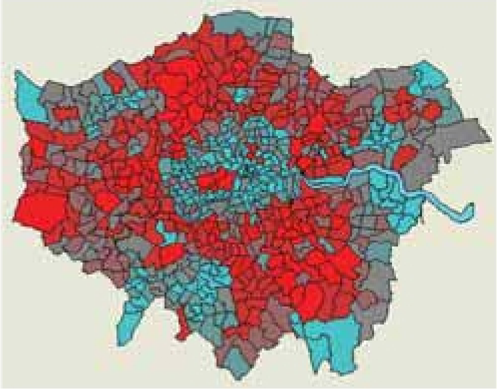

Figure 4. Scenario of the projected location of increased population in London in 2050.

- Construction on previously developed (brownfield) land may be favoured.
- Csonstruction on the flood plain may or may not be permitted.

Figure 2 provides an example from the South Hornchurch ward on the river Thames (along the south-west boundary of the ward) in East London. The red squares are currently developed land, the green squares are land available for development and the blue squares are our projection of land that will be developed for housing by 2020 in the absence of any land use constraints.

3 FLOOD RISK ANALYSIS IN THE NEW SCENARIO FRAMEWORK

The type of analysis described in the preceding section forms the basis for analysis of changing vulnerability to flood risk in this low-lying floodplain area. It has been repeated for all of the areas at risk of flooding in Greater London and is in the process of being extended to the Thames Gateway.

The simulation of changing vulnerability has been combined with scenarios of sea level rise and changing storm surge frequency to understand the combined effect of land use and climate change on flood risk and the potential effectiveness of land use planning, in adapting to the effects of climate change. Other work described by Dawson et al. (2008) extends this further to consider insurance and other non-structural measures.

The analysis has initially been repeated for three economic growth scenarios and for a number of land use planning policies. The lowest line in Figure 5 shows a scenario where there is no further growth in economic vulnerability in the floodplain. The increase in flood risk is driven only by the projected increase in mean sea level. The upper curves show a range of scenarios including sea level rise, economic growth and consequent changes in vulnerability in the floodplain. It is evident that sea level rise contributes about one third of the increase in flood risk, whilst changing vulnerability, under all scenarios contributes about two thirds of the projected increase in flood risk.

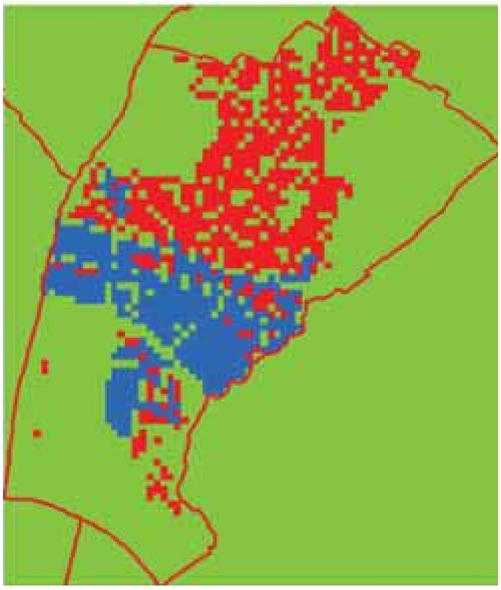

Figure 5. 2020 land use simulation on a 50 m grid for the South Hornchurch ward of London (High Economic Scenario, previously developed land desirable, floodplain development permitted).

One attraction of this model-based approach to scenario generation (as opposed to the more qualitative approach used in Foresight) is the ability to run a larger number of possible scenarios to explore uncertainties and optimise policy responses.

4 OPTIMISATION OF FLOOD RISK MANAGEMENT RESPONSES

Here we consider the problem of strategic optimisation of responses to flood risk at a site in the Thames Estuary which is dependent upon flood defences. Flooding in 1953 was the trigger for a major flood defence improvement scheme which was carried out in the 1970s and 1980s. As part of this improvement scheme new earth embankments were designed, reinforced concrete walls added to raise existing embankments, floodgates put into place to provide flood protection and access to the docks, private frontages raised and existing sheet pile walls refurbished. The design standard was for a 1:1000 year return period water level, with additional freeboard allowances for wave overtopping. This system of defences continues to provide a high standard of protection to the urbanised floodplain. Considerable sums are invested annually in inspection and maintenance, and the strategy for maintaining and/or upgrading the defences during the coming decades is now being reviewed.

Given the scale of potential investment in flood defence measures, there is concern that these should be implemented in a phased and optimal way. However, there is a very large number of potential combinations of intervention and sequences of implementation. In fact, if maintenance, upgrade and replacement are all taken into account, the number of options for management of a flood defence system of moderate complexity is potentially huge. It we consider a system with n defence sections, each of which may be subject to m alternative interventions (e.g. “do nothing”, “routine maintenance”, “upgrade”, “replace”) on up to q occasions over the appraisal period, then the total number of options is $m^{n\wedge q}$. In this paper we demonstrate the use of a genetic algorithm (GA) for solving this risk-based optimisation problem.

The use of GAs is now commonplace in, for example, optimisation of maintenance of water supply and sewer networks, but GAs have not previously been used to optimise implementation of flood risk management options. The principles of a GA will not be repeated here. Suffice it to say that the GA was used to search possible combinations of flood risk management options and possible sequences in which they could be implemented in future.

4.1 *Demonstration for a simplified case*

The approach was first verified in a simplified problem for which the optimal solution can be determined by direct search. The system consists of three flood defence sections assessed over six time intervals, with potential interventions during three of these intervals. Three improvement options are considered, including a ‘do nothing’ option. Even for this modest problem there are 19683 possible solutions, though this number is sufficiently small to permit an exhaustive search for validation purposes.

In the flood risk assessment the following assumptions are made:

- Response of each defence section is independent, conditional upon load
- Each section is considered to behave homogenously
- Each section is considered to fail by breaching or overtopping.
- The damage cause by flooding is dependent on the mode of failure
- The consequences of a section failing are assumed to the same irrespective of where the breach occurs

The improvement scheme can be conveniently encoded in a matrix:

$$\begin{matrix} 2 & 2 & 2 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{matrix}$$

where each column of the matrix represents a defence section whilst each row represents the epoch of improvement. 0 indicated “do nothing”, 1 indicates the option to raise by 0.25 m and 2 indicates the option to raise by 0.5 m. The matrix therefore is a complete description of the improvement strategy over the appraisal period.

A genetic algorithm was implemented with standard operators of:

- “Reproduction” in which two parent solutions are selected and exchange information to create offspring, and
- “Mutation” in which one or more elements are randomly selected and altered to a new value.

Figure 5 illustrates the convergence to the (known) global optimum of the genetic algorithm in this simple test case, from a variety of different starting conditions. Most of the GAs have converged to the optimum after about 40 generations (reproductions and mutations), though some are still converging.

4.2 *A test case in the Thames Estuary*

We now apply the genetic algorithm methodology to a practical test case in the Thames Estuary. For convenience we use the existing system model developed for the Environment Agency and made available as part of the UK Flood Risk Management Research Consortium. The analysis model incorporates:

- Random water levels in the adjacent Thames Estuary and tributary river.
- Reliability analysis of the flood defence system, which is a series system of independent defence sections, each of which is characterised by a fragility curve.

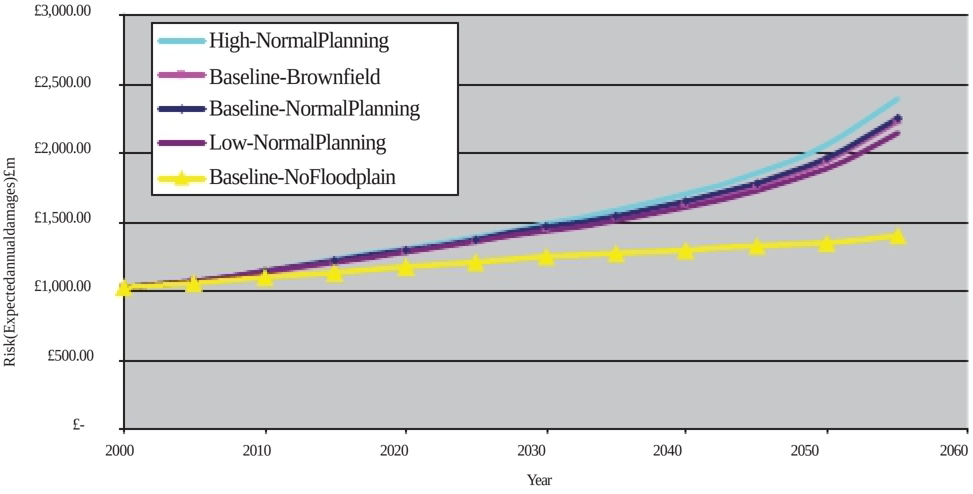

Figure 6. 2020 land use simulation on a 50 m grid for the South Hornchurch ward of London (High Economic Scenario, previously developed land desirable, floodplain development permitted).

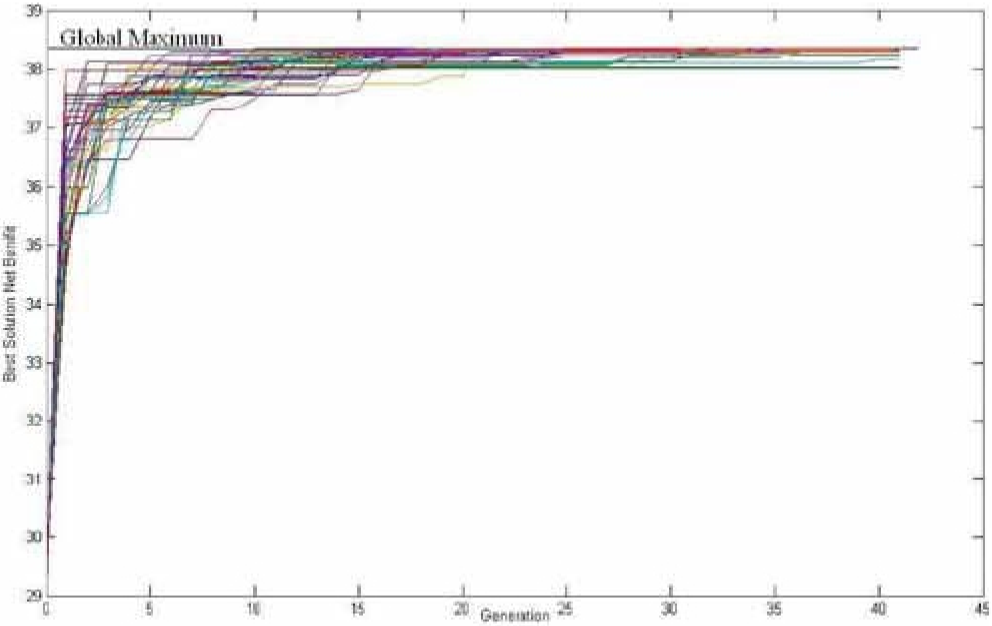

Figure 7. Convergence of genetic algorithm to global optimum for simplified problem.

- Deterioration of the reliability of the flood defence system, at an uncertain rate, which is reflected by a progressive shift in the fragility curve.
- Flood inundation modelling for the defended area, to simulate the effects of overtopping or breaching.
- Damage calculations, based upon maps of the location of properties and standard depth-damage functions.

A cost model has been established that calculates unit costs of maintenance and replacement (which has the effect of reducing the conditional probability of flood defence failure), as well as fixed mobilisation costs. Inclusion of mobilisation costs in the optimisation problem tends to disadvantage options that might involve frequent work on a given defence section and favours options that involve working on a number of neighbouring defence sections at the same time. The system of defences has been simplified somewhat by combining some defence sections so that there is a total of 60 sections were incorporated in the analysis. The analysis was conducted in the context of Defra's (2006) sea level rise scenarios. The options identified by the GA have been compared in terms of net present value. Given that the calculation is based upon a calculation of risk, rather than simply upon probability of failure, intervention in the flood defence system will tend to be targeted at areas with high consequences in the event of flooding, as well as at sections of the flood defence system with a high probability of failure.

The problem of this scale carries considerably more computational expense, but, as Figure 8 illustrates, the genetic algorithm is still effective in finding efficient solutions. The three lines show the convergence of the solution for three different initial conditions of the GA.

Further constraints have been added to the analysis:

- The total permissible expenditure in any given year may not exceed a given value.
- The total spend over a number of years is constrained by some inter-annual variation in spend is permitted.
- No constraint is applied but options with uneven annual spend are penalised in the objective function.

Whilst in this instance the GA has been applied to a flood defence system optimisation problem, the approach can be extended to the broader problem of optimisation of more diverse portfolios of measures under the scenarios of long term change developed in Sections 2 and 3 of this paper.

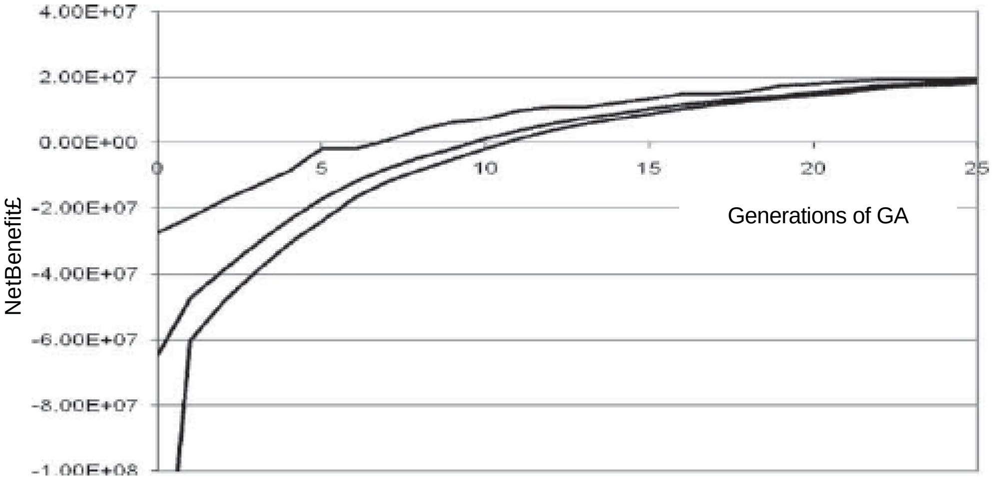

Figure 8. Convergence of genetic algorithm to an efficient intervention sequence for a realistic flood risk management system.

5 CONCLUSIONS

Risk-based approaches to flood management are becoming increasingly accepted by governments in practice. Information on risk is being communicated to the public and risk estimates are being used to inform decision making both before and during flood incidents. However, there is increasing recognition of the significance of long term change in flooding systems, for example due to climate change and socio-economic changes. Against this background of change, flood risk managers must plan and implement adaptive portfolios of measures that are matched to the characteristics of particular localities and robust to future changes. The outstanding challenge of dealing in this way with long term change is not well treated in existing approached to strategic management. In this paper we have demonstrated approaches pioneered in the Tyndall Centre for Climate Change Research for high resolution quantified treatment of long term scenarios of socio-economic change. These have been set alongside scenarios of climate change in order to understand the combined effects of these processes. The methodology has been demonstrated in the context of London, where for the scenario presented here, projected increase in flood risk is attributable mostly to socio-economic change, though sea level rise contributes about a third of the projected growth in flood risk. Whilst here we have presented only one scenario, the treatment of uncertainty, through exploration of broader scenario spaces, is also accommodated in the overall framework under development and will be the subject of future publications.

Having established a scenario framework for examination of long term change we have then gone on to examine how optimisation techniques, specifically the use of Genetic Algorithms, can be used to identify portfolios of flood risk management options that are implemented in a staged way through time. The approach has been applied to a limited but realistic case of flood defence improvements, so is of particular relevance to questions of optimal maintenance and improvement of flood defence systems. However, it is being extended to explore much broader portfolios of flood risk management measures, including non-structural as well as structural measures. The approach has so far only dealt with aleatory uncertainties in the hydraulic loading on the flood defence system, but the treatment of epistemic uncertainties is of great significance, particularly where the time-frame of analysis is long-term. In this context it is desirable to identify options that are as far as possible robust to future uncertainties. We have explored a range of methods of dealing with this problem of option choice under severe uncertainty (Hine & Hall, 2006, Hall & Solomatine, 2008) and will in future be integrating them within the broader scenario analysis and options choice framework introduced in this paper.

ACKNOWLEDGEMENTS

The work described in this publication was supported by the EPSRC Flood Risk Management Research Consortium (grant GR/S76304/01), The Tyndall Centre for Climate Change Research and the European Community's Sixth Framework Programme through the grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420. This paper reflects the authors' views and not those of the European Community. Neither the European Community nor any member of the FLOODsite Consortium is liable for any use of the information in this paper. The support of the Greater London Authority and the Environment Agency is gratefully acknowledged.

REFERENCES

CUR/TAW 1990. Probabilistic Design of Flood Defences. Gouda, the Netherlands, Centre for Civil Engineering Research and Codes (CUR), Technical Advisory Committee on Water Defences (TAW).

Dantzig, D.V. 1956. Economic decision problems for flood prevention, *Econometrica* 24(3): 276–287.

Dawson, R.J., Roche, N., Ford A.C., Barr S.L., Hall J.W., Werritty J., Ball T., Werritty A., Raschke M. & Thürmer K. 2008. Measuring the effectiveness of non-structural flood risk management measures. *FLOODrisk 2008*. Oxford, Balkema, this volume.

Defra 2005. Making space for water: Taking forward a new Government strategy for flood and coastal erosion risk management in England: First Government response to the autumn 2004 Making space for water consultation exercise, Department of the Environment, Food and Rural Affairs, London.

Defra 2006. Flood and Coastal Defence Appraisal Guidance. Supplementary Note to Operating Authorities. Climate Change Impacts. London, Department of the Environment, Food and Rural Affairs, London.

Galloway, G.E. 2005. Corps of Engineers Responses to the Changing National Approach to Floodplain Management Since the 1993 Midwest Flood. *Journal of Contemporary Water Research and Education* (130): 5–12.

GLA 2004. The London Plan. London, Greater London Authority

Goldman, D. 1997. Estimating Expected Annual Damage for Levee Retrofits, *Journal of Water Resource. Planning and Management* 123(2): 89–94.

Hall, J.W., Meadowcroft, I.C., Sayers, P.B. & Bramley, M.E. 2003. Integrated flood risk management in England and Wales. *Natural Hazards Review* 4(3): 126–135.

Hall, J.W. and Solomatine, D. 2008. A framework for uncertainty analysis in flood risk management decisions, *J. River Basin Management*, 6(2): 85–98.

Hine, D. and Hall, J.W. 2007. Analysing the robustness of engineering decisions to hydraulic model and hydrological uncertainties, in *Harmonising the Demands of Art and Nature in Hydraulics: Proc. 32nd Congress of IAHR*, Venice.

Interagency Floodplain Management Review Committee. 1994. Sharing the Challenge: Floodplain Management into the 21st Century. Report to the Administration Floodplain Management Task Force. Washington, DC, U.S. Government Printing Office.

Junankar, S., Lofsnaes, O. & Summerton, P. 2007. MDM-E3: A short technical description. Cambridge, Cambridge Econometrics.

Kahan, J.P., Wu, M., Hajiamiri, S., & Knopman, D. 2006. From Flood Control to Integrated Water Resource Management: Lessons for the Gulf Coast from Flooding in Other Places in the Last Sixty Years. Santa Monica, RAND Corporation.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M.,. Kundzewicz, Z.W., Lettenmaier, D.P. & Stouffer, R.J. 2008. Stationarity Is Dead: Whither Water Management? *Science* 319(5863): 573–574.

National Academy of Engineering, 2000. Risk Analysis and Uncertainty in Flood Damage Reduction Studies. Washington D.C., National Academy Press.

National Research Council, 2000. Risk Analysis and Uncertainty in Flood Damage Reduction Studies. Washington D.C., National Academy Press.

ONS 2003. Focus on London (D. Virdee, T. Williams (Eds.). Newport, Office of National Statistics.

Sayers, P.B., Hall, J.W. & Meadowcroft, I.C. 2002. Towards risk-based flood hazard management in the UK. *Civil Engineering* 150(1): 36–42.

USACE, 1996. Risk-based analysis of flood damage reduction studies. Washington, D.C., U.S. Army Corps of Engineers.

Vrijling, J.K. 1993. Development in probabilistic design of flood defences in the Netherlands. Reliability and uncertainty analysis in hydraulic design. B.C. Yen and Y.-K. Tung. New York, ASCE: 133–178.

Wheater, H., K. Beven, Hall, J.W., Pender, G., Butler, D., Calver, A., Djordjevic, S., Evans, E.P., Makropoulos, C., O'Connell, P.E., Penning-Rowsell, E.C., Saul, A.J., Surendran, S., Townend, I. & Watkinson, A. 2007. Broad Scale Modelling for planning and policy, Department for Environment, Food and Rural Affairs, R&D Technical Report FD2118, London.