Frontiers in Flood Research / Le point de la recherche sur les crues
(IAHS Publ. 305, 2006).

Engineering and technical aspects of managing floods: hazard reduction, operational management and post-event recovery

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Abstract Whereas the three primary phases of flood management are widely accepted as providing a general framework, a large amount of innovative research and development is underway to improve the content and dynamic of each phase. Integration is a key principle, whether of data to generate new information such as a flood vulnerability index, or of models to simulate the complex meteorological–hydrological–hydraulic systems in which flood generation, propagation and impact can be understood and predicted, or of components of decision support systems to warn of impending floods or to aid disaster recovery using the best available technology for monitoring, modelling and reasoning. Inevitably the engineering and technology solutions are intimately dependent on people with appropriate skills, or stakeholders. Effective communication of information and knowledge is therefore another key principle to ensure that each phase of flood management is properly conceived and implemented. The paper focuses on the engineering and technical aspects of managing floods, though it acknowledges that flood management must of necessity be multi-disciplinary.

Key words communications; disaster management; flood forecasting; flood vulnerability index; flood warning; floods; hazard reduction; model integration; post event recovery; risk assessment; simulation modelling

Technologie et aspects techniques de la gestion des inondations: réduction de l'aléa, gestion opérationnelle et rétablissement post-événementiel

Résume Alors que les trois principales phases de la gestion des crues sont largement reconnues comme définissant un cadre général, un important effort de recherche et de développement innovateurs est en cours pour améliorer le contenu et la dynamique de chaque phase. L'intégration est le principe clé, que ce soit pour générer à partir des données une information nouvelle tel qu'un index de vulnérabilité à l'inondation, ou pour simuler à l'aide de modèles les systèmes complexes météorologique–hydrologique–hydrauliques dans lesquels la génération, la propagation et l'impact de l'inondation peuvent être compris et prévus, ou pour les composantes de systèmes interactifs d'aide à la décision pour avertir d'inondations imminentes ou pour faciliter le rétablissement de désastre en utilisant les meilleures technologies disponibles pour surveiller, modéliser et raisonner. Inévitablement, les solutions technologiques et techniques dépendent intimement des personnes possédant les qualifications appropriées, tout comme des décideurs. Aussi, la communication efficace d'information et de connaissances est un autre principe clé pour s'assurer que chaque phase de la gestion des crues est correctement conçue et mise en application. Cet article est centré sur les aspects technologiques et techniques des inondations, bien qu'il reconnaisse que la gestion des inondations doit être par nécessité multidisciplinaire.

Mots clefs communications; gestion de catastrophe; prévision de crue; index de vulnérabilité; alerte d'inondation; crues; réduction des risques; modèle intégré; rétablissement post-événementiel; gestion de risque; simulation

INTRODUCTION

The number of major flood disasters worldwide appears to be increasing, as well as the subsequent loss of life, the consequent multi-billion dollar damages to national economies, and the resulting untold stress placed on poor communities as they struggle to survive. Small wonder, therefore, that flood management and research should receive growing international attention. In particular, initiatives to alleviate the serious situation regarding flood disasters are high on the agenda of UN agencies. For example, the International Flood Initiative/Programme (IFI/P) was launched in 2005 at ICHARM in Japan as an interdisciplinary activity to mitigate the impacts of flooding worldwide, in cooperation with WMO and other relevant UN agencies and NGOs. IFI/P is an inter-agency programme led by UNESCO[1] that has synergy with a number of other goals and objectives of the UN. It contributes towards meeting the relevant Millennium Development Goals. It has an input to the UN Decade on Water for All (2005–2015). It forms part of the follow-up to the World Conference on Disaster Reduction held in Kobe, January 2005. It is a means of implementing the UN Decade on Education for Sustainable Development (2005–2014). Lastly it provides a framework for directing research to address key issues of floods.

At the heart of IFI/P is a focus on integrated flood risk management as a function of the flood hazard and its potential impacts. The aim is to reduce the human and socio-economic losses caused by flooding while at the same time taking into account the social, economic, and ecological benefits from floods and the use of flood plains. Care is taken to integrate land and water resources development, including the institutional components of flood risk management, and to recognize the critical importance of stakeholder participation. In general IFI/P aims at implementing recommendations arising from the World Summit on Sustainable Development (Johannesburg, 2002) and the World Conference on Disaster Reduction (Kobe, 2005), considering the physical aspects of flooding, its socio-economic conditions and the risk a society is prepared to take in order to achieve its development objectives. The IFI/P involves a paradigm shift from the traditional, fragmented approach to flood risk management to a more holistic methodology.

This paper addresses the operational and engineering aspects of flood research, with particular emphasis on the contributing role of advanced information and communication technologies.

CONTEXT OF FLOODING

The concept of a flood depends on its context. A river flood is the inundation of normally dry land (or wetlands) adjacent to a channel due to inadequate capacity of the channel to convey the current flow. The flood can be caused by the collection in the upstream channel network of excess rainfall–runoff over the catchment, or the failure of a dam or local embankment. The capacity of the channel may be limited due to

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[1] Organizations include UNESCO, the World Meteorological Organization (WMO), the United Nations University (UNU), the United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN-ISDR), UN/ISDR Platform for the Promotion of Early Warning (PPEW), and the International Association of Hydrological Sciences (IAHS).

obstructions in the channel or the morphological raising of the riverbed. An urban flood can be due to the inadequate capacity of the drainage system, whether of open channels or closed conduits, to evacuate excess rainfall–runoff that has collected locally from the immediate urban area. Alternatively urban flooding may occur because of the through flow of floodwater generated on catchments outside the urban area. Land in coastal areas may be inundated due to high water levels resulting from a storm surge or an earthquake-generated tsunami.

In general, floods are generated by precipitation of rain or melting snow, geophysical events such as earthquakes and landslides initiating tsunamis in oceans, lakes or reservoirs, debris/mud flows and ice jams, storm surges and wave overtopping, and failure of structures such as dams and embankments/levees. The generation of a flood from precipitation depends crucially on the nature of the local climate and the catchment: the land cover, soil type, terrain, even the geology so far as groundwater is concerned. Much, but not all, is understood about the complex hydrological processes that go to generate the runoff from rainfall.

Invariably floods are dynamic, propagating along streams and channels, rivers and canals. Floodwater can spread out over normally dry terrain such as flood plains or polder areas following the failure of an embankment. Existing deep water such as a lake, reservoir or the ocean can mask the rapid propagation of disturbances such as tsunamis. Floods can also be generated through groundwater seepage.

Damages due to floods arise from a number of different factors. The depth and duration of flooding are critical for the integrity of structures, preserving communications and the survival of crops and livestock. The velocity of flow can lead to scour, particularly round structures, over or through embankments, and due to the backwash generated by tsunami surges. High sediment transport loads can be associated with significant morphological changes in the alignment of the river channel(s) or in reducing channel capacity such as by raising the riverbed. Similarly water quality can be adversely affected, especially in washing out industrial animal waste and wastewater treatment works. The consequences of flood flows on vegetation and the rest of the ecology can also be serious.

BASICS OF FLOOD MANAGEMENT

The management of floods has benefited from the point of view of their spatial development from “source” through “pathways” to their impact on “receptors”; see Office of Science and Technology (2004). There is a progressive increase in the capacity to actually manage the event, with little opportunity at the source (rainfall or earthquake), more scope along the pathways (catchment, stream-channel network or coastal zone) and yet more potential with the receptors (property, communications or people). The different spatial phases of the flooding process demand an integrated approach to management along the lines of the catchment management plans promoted in the UK and the principles of integrated water resources management. But flood management also needs to be viewed in time: the preparation phase involving hazard reduction, the operational phase including emergency and disaster management, and the recovery–restoration phase leading to necessary reconstruction (see Fig. 1).

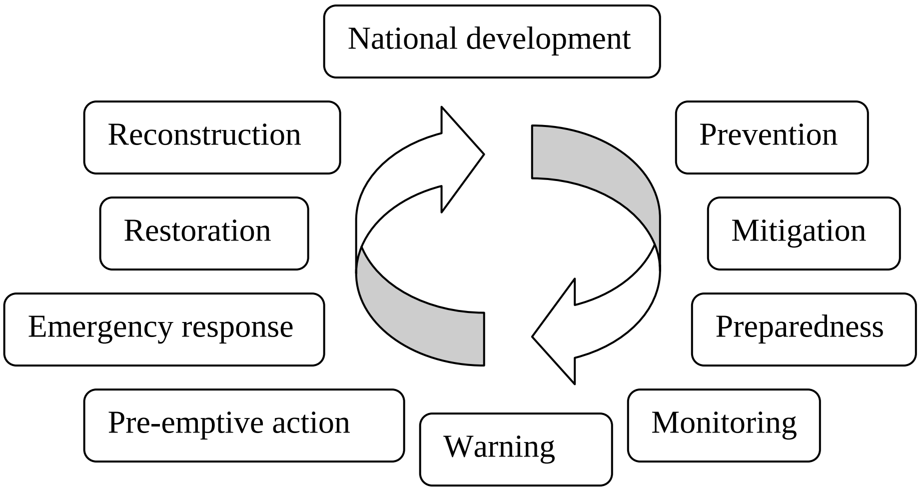

Fig. 1 The disaster management cycle.

HAZARD REDUCTION

Risk assessment

Preparedness for disasters is a key to improving the sustainability of communities and nations, and especially of developing countries. Awareness of potential hazards, the relationships between different hazard components with their consequences and the associated risks, mitigating identified risks, and risk sharing are some of the attendant issues. Economic risk is defined here as the product of the probability of failure of the (flood) defences given a particular extreme hydro-meteorological event and the cost of damages including both direct and indirect costs and the value of lives lost. Alternatively risk can be determined subjectively in terms of the unacceptability of the frequency and extent of flooding of a particular area. Risk assessment is a key tool in highlighting the relative significance of different events or threats, and their component contributions.

A reliable risk assessment involves particular data. An assessment of risk concerns an analysis of two types of data: (quasi-) static data defining the terrain, structures or infrastructure, and temporal data in the form of relevant time series that are amenable to statistical analysis. Accurate and reliable terrain data is needed for flood mapping, in particular to identify areas inundated for a given duration and for a prescribed frequency or return period, especially in urban areas where even small differences in ground level can make significant differences to the paths that flood water can take. In view of the considerable difficulty in defining flood risk accurately, it has been recognized that a flexible initiative is to define a flood vulnerability index. This still requires, however, the integration of a wide variety of data, including digital terrain, land cover, soil type, rainfall and evapotranspiration statistics, as well as population density, industrial development, economic value and so on. Some of these data can be obtained from remote sensing; other data have to be obtained from census and other surveys.

Unfortunately, some of the time series, such as for rainfall, are demonstrably subject to change induced by factors such as climate change, and therefore the time series can no longer be assumed to be stationary. This poses considerable problems for our existing statistical tools, at least in the short to medium term. The desire to assess risk for more rare return periods of a geological time scale brings us into the realm of extreme statistics. A number of research projects, including the EU project SPHERE, are looking at geological records to improve the database for such analysis.

Risk assessment is now viewed as an increasingly important tool for flood management. Done properly it quantifies the risk of flooding to communities in affecting their livelihoods and property. It finds expression in a vulnerability index or hazard mapping. It provides a motivation for making thorough investigations of frequent flooding at vulnerable sites. It highlights the risks attached to certain infrastructure or land use development. Determining flood risk, however, is a complex process because of the large number of contributing factors to a flood and the corresponding impacts; see DEFRA (2000).

Quantifying risk usually involves the identification of the probability of occurrence of a range of input variables times the impact in economic or other terms. The input variables can include the effects of climate change on rainfall and ecology, the consequences of human intervention on land use and hydro-morphological resilience, the occurrence of landslides, ice jams or debris flows, the possibility of dam or embankment failures, human errors in operating control facilities, and so on. The impacts can include damage to property, disruption to communications, delay of traffic, worry and stress to human beings, as well as loss of life.

Simulation modelling

Usually there is a causal chain along which physical effects and associated information, and therefore probability, can be said to propagate. Determining the nature of this propagation requires the supposition of a model that represents and integrates the relevant inputs and processes in the causal chain. The art of simulation modelling has for long been the focus of research and development. Physically-based modelling of water in the atmosphere, at and below the ground–air interface, and in the stream-channel network that drains a natural or urban catchments, is well developed, even if the accuracy is dependent on the data available, well formulated modelling software, and safe and reliable instantiated models that are properly calibrated and integrated; see Cunge (2003). Increasingly engineers and scientists are integrating models for the different phases of the flood generation–propagation–impact process to provide a more holistic prediction or forecasting of floods. In doing this they can track the influences of a wide variety of causal processes, as well as exploring the nature and degree of the impacts.

The development of modelling software has traditionally been done according to the specialist areas of the developers. So, for example, meteorologists have developed meteorological rainfall modelling software, hydrologists have produced software for rainfall–runoff modelling, hydraulic engineers for flow routing, economists for economic assessment, and so on. What is more, in some cases these software products are highly sophisticated and have taken years to refine; many of them are being continuously updated with the latest scientific knowledge and technical advances. Integrating these software products is a non-trivial exercise, especially in terms of data formats, time steps and ensuring stability of the software at the interfaces. Such issues have been the concern of European funded projects such as HarmonIT. These projects have achieved some limited success in linking different commercial products as well as publicly available software, but there are considerable problems still to be overcome. It is easier to link software that is developed consistently within one organization, or where the link is explicit with no feedback. So, for example, the Dutch National Institute for Coastal and Marine Management (RIKZ) links its WAQUA computational model of the North Sea to the HIRLAM model operated by the Royal Netherlands Meteorological Institute (KNMI), which in turn is linked to the European Medium Range Weather Forecast model, in order to forecast surge conditions along the Dutch coast; see Abebe (2004). There are now many other similar examples.

It is one thing to link detailed physically-based models. Another important set of links is between the physically-based models and management-type models, such as economic damage assessment, environmental/ecological impact, and optimization of structural planning for flooding. In addition, being able to track the propagation of uncertainty through the integrated system assists the determination of (flood) risk; see Maskey *et al.* (2004).

Instantiated models with good interfaces, where the flooding results are displayed graphically, and preferably in a dynamic, geographic and pictorial image (scene modelling), can become invaluable tools for stakeholder decision-making. Jonoski (2000, 2002) has described how fact (calculation) and judgement (consensus decision making) engines, together with a graphical, interactive interface, can be an effective means for helping stakeholders with different objectives to explore the consequences of different flood management options, say, and to come to consensus decisions. The fact engine provides a common resource, which can be manipulated directly by the stakeholders through a simplified interface, allowing them to test whatever reasonable options they wish. In turn, this requires an effective means of building scenarios and coupling the results for flood levels, say, to calculations of economic costs of potential damages and benefits accruing through mitigation schemes. Given an appropriate multi-criteria optimization tool, the costs and benefits can be minimized and maximized, respectively, over the entire river basin if necessary. Such an analysis could also test protection standards and levee safety programmes, bearing in mind the natural reactive tendency after major floods to increase the protection standards automatically. For example, standards of 500-years return period are being discussed for urban areas in the USA subject to flooding from a category 5 hurricane (following hurricane Katrina in 2005), and The Netherlands is working with 10 000 years for coastal defences and 1250 years for protection from river flooding; see Silva *et al.* (2004). Note that the design discharges and levels that accompany these standards are inevitably subject to the uncertainty inherent in the functional relationship between level and discharge during a dynamic event, due to climate and land-use changes, activities of different authorities in a transboundary river, and so on. What is needed is a strategy of flexibility (robustness) and resilience in any scheme for flood defence.

Engineering interventions

Engineering solutions to prevent or limit flooding include, among other possibilities:

- Increase online storage through dams and reservoirs to reduce flood peaks.
- Create controlled off-line storage through use of flood plains or lakes and wetlands, again to reduce flood peaks.
- Retain natural flood plains and their dynamic storage of floodwaters.
- Protect low-lying areas from flooding using embankments.
- Create dyke rings round low-lying areas with pumps (polders).
- Divert excess flows.
- Improve channel and flood plain conveyance to reduce water levels locally.
- Use groins to maintain sediment transport and flow depths.
- Decrease hydro-morphological resilience to improve drainage of upstream (sub-) catchments.
- Restore hydro-morphological resilience to improve natural storage of upstream (sub-) catchments.
- Limit runoff by increasing vegetation cover such as planting trees/forests.
- Unseal surfaces to reduce runoff and increase infiltration (source control).
- Elevate or flood-proof structures, including roads.
- Create floating structures on lakes.

Some of these solutions capitalize on increasing the storage of floodwater, whether on- or off-line, and static or dynamic, increasing the conveyance of the flow, or diverting or preventing access of water. River restoration schemes have recognized that it is all very well trying to remove excess rainfall–runoff as quickly as possible from catchments upstream, but doing so can amplify flooding and other problems downstream. Therefore, retaining excess water upstream by increasing the hydro-morphological resilience can be beneficial.

Non-structural solutions

Many of these structural solutions have brought about a positive feedback from those benefiting from the increased protection. Their expectations about the land and infrastructure have lead to increased pressure for development of protected land, with dire consequences for such development when flooding eventually recurs. The feedback therefore is for higher embankments, still better conveyance of flood flows, and yet lower hydro-morphological resilience, at least locally. The spiral is of course unsustainable. Fortunately, there is growing awareness that this positive feedback loop has to be broken, and we need to become more dependent on the negative feedback of having to live with floods. We therefore have to limit and maybe even remove some of the structural measures and to depend more on non-structural means of sustaining our communities in the face of flooding. These means can take the form of:

- Improve land-use (catchment) planning and management.
- Limit infrastructure in areas that flood frequently.

- Implement flood forecasting and warning systems.
- Introduce emergency preservation or evacuation procedures.
- Deliberately flood selected areas in an emergency.
- Use real-time operated systems such as flood gates or pumps.
- Use temporarily installed measures such as sandbags or stop-logs.
- Aim for flooding to occur more gradually so that people can see the event unfold and decide to respond.

The result is that there needs to be a judicious integration of structural and non-structural measures that will vary from catchment to catchment. In particular, certain structural measures will be reversed, such as removing embankments to make available more off-line and dynamic (flood-plain) storage, and restoring the hydro-morphological resilience. This could involve the restoration of wetlands and the natural meandering state of streams and ditches, especially in the upper parts of (sub-) catchments. Correspondingly, considerable emphasis will be given to flood forecasting and warning systems to improve the immediate response to large floods, and to improve land use and infrastructure planning in the long term, reinforced where necessary by appropriate legislation, taxation, and insurance or other risk-sharing agreements.

Community response

These are all devices to increase the negative feedback from the community in the face of potential flooding. In addition, there should be preparedness for future disasters and the formulation of procedures to manage the heterogeneous needs of the community at risk during an emergency. This involves building up the capacity of the relevant organizations to take effective responsibility and to share and adopt best practices, and providing educational and training programmes for technicians and managers as well as the various stakeholders and the general public on how to deal with and respond to floods. Khatibi *et al.* (2003) argue strongly for the strengthening of the negative feedback through the stress on flood forecasting and warning and temporary or real-time control measures. Johnson *et al.* (2004) explored human response to major floods and concluded that in order to change behaviour "*people need to be aware of the risk and aware of the options available for managing this risk*". Policies need to be in place that raise the awareness of the public to the threats they face. It would appear that this approach could be effective only in so far as it provokes a reaction based on fear. Baan & Klijn (2004) have analysed the psychological consequences of living with floods in The Netherlands, and conclude that any revision of flood risk strategy "*should be done in close cooperation with citizens and other parties*". Each stakeholder group "*should be involved from the beginning … to the end. … This calls for intensive communication with all parties involved, in a language people understand easily, whilst being honest about all uncertainties, and sincerely taking into account the feelings of the people involved.*" In their discussion about the strategy itself they argue strongly against permitting any uncontrolled (or unintentional) flooding in rivers in order to reduce potential flood damages. This may well require the inundation of less vulnerable areas (polders in the case of The Netherlands) in order to prevent (if possible) damage to more vulnerable areas. Inevitably this involves extensive preparatory discussions and agreements with all stakeholders, something that can be extremely difficult to conclude.

This highlights the need to recognize that, wherever possible, the level of flood protection should be set locally or regionally, while ensuring coordination with neighbours upstream and downstream. In particular, flood defences designed to give a certain level of protection to new development should not lead to an increased risk of flooding elsewhere. A corollary of this principle can be that developers should fund their own flood defences. This raises the role of the insurance sector in setting flood standards, assessing flood risk, deriving flood hazard maps and helping to formulate legislation.

Management planning

These issues point to the value of establishing and regularly reviewing flood risk management plans that identify measures to reduce flood risk, not only at the local or regional level, but where possible at the catchment or river basin level. This implies the need for communications and management facilities to be set up for flood hazard reduction and management at the river basin level. Such facilities should take advantage of similar facilities set up for other purposes at this level, namely water resources and quality control and management, and not set out to compete with them.

All flood defences have a design life. There needs to be regular inspections of the safety of flood defences carried out at the regional or national level. Such inspections should be based on protection standards agreed and accepted by society, safe and reliable modelling of the hydraulic boundary conditions, and a detailed consideration of the risks associated with the possible modes of failure of the structure; see Looff (2005).

Risk assessment of the safety of flood protection structures is but one application of risk. Flood hazard maps are another form. These can be derived at different scales. A critical factor in the reliability of such maps is the precision with which the ground terrain can be measured, whether done by ordnance survey, aerial survey or remote sensing from satellites. The spatial and vertical resolution of the ground terrain and the coverage of remote sensing have improved dramatically in recent years, so much so that terrain data is available on a continental scale (Vörösmarty, 2005). By combining different data sets, such as rainfall, evaporation, soil type, land cover, population and industrial development statistics, it is possible with the help of hydrological and economic models, to develop indices of water stress and flood vulnerability—at the large scale. This concept of a flood vulnerability index leads to a first order spatial scan of the priority needs in a region. Subsequently more focused attention can be given to specific vulnerable points, and comparison can be made between them through a refinement of the index. Balancing the economic costs and benefits, as well as the environmental and social (political) issues, would help to facilitate such a comparison.

All stakeholders, including the general public, should be involved at some stage in the process of flood risk reduction. The relevant authorities should actively seek their participation, and should in addition ensure that they are properly informed and aware of the issues involved. The general public is well known to have considerable inertia in responding to appeals about flooding, and various ways are needed to overcome it. Information and communication technologies in particular provide the necessary facilities and tools to generate national databases of flooding events, flood vulnerability indices for different locations, lessons learned from previous events, and advice on how to deal or cope with flooding.

OPERATIONAL PHASE

Flood forecasting

Preparedness for an actual emergency involves all of the aspects of the hazard reduction phase. In particular it concerns preparations made in anticipation of an actual operational event. So a reliable flood forecasting and warning system should be in place, together with the procedures for action in response to the warnings given.

Obviously, flood forecasting and warning systems need careful design, implementation and operation. Khatibi *et al.* (2003) point to five stages that have to be considered in their design:

- detection,
- forecast,
- warning,
- dissemination, and
- response.

Detection is about temporal data collection and analysis. We now have available a wide range of alternative sources of rainfall and flow or water level data including networks of (autographic) raingauges, ground- and satellite-based weather radars, and streamflow monitoring stations. However, the reliability of the ground-based monitors is of ongoing concern because of their vulnerability to vandalism and the need for regular maintenance.

Forecasting involves a prediction about what will happen to the system in the future. The lead-time of a forecast, coupled with the accuracy or uncertainty associated with the forecast, is important in determining the scope for action. It resolves around the time for information to propagate through the natural and technical systems from particular sources. For example, if recorded rainfall at the ground surface is the primary data source, then there is a certain lag time between the peak runoff and the nominal peak rainfall. Information theory (Shannon, 1948) can be used to derive an average mutual information content between two time series; see Abebe & Price (2004). This can be used to determine the lag time even in highly nonlinear systems together with a measure of the information content. The use of weather radar coupled with a forecast model of the propagation of the rainfall event can generate an additional lag time. Further extensions of the lag time can be gained from rainfall generation by meteorological models or from estimates of areal rainfall from remote sensing by radar from satellites of the temperature of cloud cover and other parameters. In taking such steps, the complexity of the rainfall forecasts become increasingly more complex to make. In order to get the resolution, global circulation models (GCMs) have to input data to meso-scale models, which in turn provide input to limited area models (LAM); see, for example Abebe (2004) and Bartholmes & Todini (2005). What is more, the GCMs are (deterministic) chaotic systems, which means that they are best handled by running the same event a number of times for random small changes in the initial conditions. Current practice is for an ensemble of 50 such runs to be cascaded down to the LAM, whether for forecasting spatially varying rainfall, or wind and pressure fields that generate storm surges in coastal waters. There is a considerable amount of research ongoing to improve the reliability of the meteorological models especially concerning the Earth surface–air interaction. The ocean–air interaction is itself complex. The land–air interaction is made more complex by the varying land cover and the irregular terrain. Steep and high terrain can induce considerable vertical accelerations in moist air masses that can lead to intense rainfall (Cerlini *et al.*, 2005). This is particularly noticeable in coastal regions with a hinterland of high mountains or hills, where flash flooding is common; see Abebe & Price (2005).

The availability of the ensemble forecasts is one thing; knowing how best to use the ensemble and to interpret the results is another. Also the uncertainty inherent in the process means that there are uncertainties in any resulting prediction. For this reason weather forecasters use a variety of data sources, including WSR-88D radar, TDWR radar, C-band radar, satellite imagery, lightening strikes, raingauges, surface and upper air observations, as well as model output and human interpretation; see the US programme OPESUMS, which is achieving 1 km × 1 km spatial resolution and 5 min time resolution. Research is being done at present on how best to integrate these different data sources to improve the reliability of rainfall forecasts in particular.

Forecasts of flood water levels are based on a chain of models beginning with a number of inter-dependent meteorological models of increasingly greater resolution, contributing to hydrological rainfall–runoff models that deal largely with the discharge, to hydraulic flow models in both discharge and stage (water level). It is almost invariably assumed that there is a uni-directional flow of information in the chain, and that there are no feedbacks. A wide variety of models are used for both the land phase components, including physically-based and data driven models. The physically-based models (as well as the conceptual models that rely on physically-based concepts) endeavour to use the *a priori* generic knowledge about the physical processes governing the behaviour of the water in its interaction with its environment to deduce what happens to the water in a specific situation. On the other hand, data driven models induce the response of the system by establishing the link between data sets; for example, the discharge in the river and the rainfall. Data driven models are very attractive in that they lay claim to incorporate in detail the consequences of all the physical processes in so far as they are reflected in the data. In this sense they are superior to the physically-based models, which only include a limited imperfect replication of those physical processes that are identified. Data driven models are inferior to physically-based models however, in that they are entirely dependent on the data on which they are trained. One implication of this is that some data-driven models, for example artificial neural networks, cannot deal with events that have input data outside the range of the training set (except in special circumstances; see

Varoonchotikul *et al*., 2005). Another advantage of data-driven models is that they can include as input the latest monitored data at the output site (for say, the discharge), as well as the normal monitored input data (for say, the rainfall). This implies that this form of data-driven model is always up to date, and ready for use as a forecasting tool. Correspondingly the physically-based model normally has a mismatch between prediction and observation at the target sites. Such a mismatch can be handled using, for example, a Kalman filter to adjust the state variables, or training a neural network or other data-driven model to model the error (either as a difference, as ratio or some other functional form—termed complementary modelling); see Abebe & Price (2004).

Both types of model then face the problem of extrapolating beyond the present time for which monitored data is available, to estimate the performance of the system in the future. The extrapolation may be carried out using the model up to a certain time threshold depending on the information lag times from upstream (in the case of a river flood forecasting system). The uncertainty usually grows with the time of the extrapolation according to the growth of the unknown or forecast information contribution(s) of the inputs, whether of rainfall or runoff. There is a threshold beyond which there is little point in extrapolating the output due to the input being unknown.

Uncertainty in forecasting

Much work is being done at present on identifying how uncertainty is both generated in time and propagated through the integrated set of models. Abebe (2004) has shown how variable confidence limits and fuzzy logic descriptors can be defined for errors in surge predictions at Hook van Holland on the Dutch coast. Similarly, Maskey *et al.* (2004) have determined improved means of tracking the uncertainty in rainfall through a conceptual flood-forecasting model; see also Pappenberger *et al.* (2005).

But uncertainty does not arise simply from errors or inadequacies of the input data, model structure, calibration and solution; it also arises from changes in the physical parameters over time, such as land cover, solar variability, and aerosols from volcanoes, and from human failures or inadequacies, including lack of knowledge, disagreements and improperly performed tasks. Researchers recognize these factors, and there is considerable effort being put into making forecasts more reliable; see the EU projects such as EURAINSAT, CARPEDIEM, FLOODSite, and MANTISSA.

The combination of short lead-time and uncertainty is especially important for many locations. Whereas such locations are prone to flash floods, even comparatively mild rainstorms can generate unacceptable flooding. Considerable effort is being put into assessing flash flooding potential through digital terrain modelling, and then coupling the assessment with forecasts of rainfall through WSR-88D Digital Hybrid Scan Reflectivity in order to improve lead times of flash flood events.

Flood warning systems

Many flood forecasting and warning systems are in place. The flood early warning system (FEWS) from Delft Hydraulics provides an interface to integrate different components to produce an appropriate warning. The European Flood Forecasting System (EFFS) is an EU 5th Framework project aimed at developing an early warning capability of between three and ten days. The EU 5th Framework project FLOODRELIEF addresses the issues of integrating flood forecasting and warning systems with support for decision making.

The decision to issue a warning according to a previously determined protocol is made complicated by the uncertainty in the forecast, whether unknown or estimated. The uncertain evolution of a flood ensures that there should be ample opportunities for feedback mechanisms in the whole process. So, for example, there may be a series of thresholds on water level for different types of warning. Similarly, tests of the accuracy of previous forecasts can be made as the event proceeds. An assessment of the confidence bounds, or the uncertainty in the forecast water level may also generate feedback.

The thresholds for using flood warnings need to be set in such a way as to raise the awareness of the different stakeholders, such as technicians, emergency services, local authorities and general public, to the impending threat. These and their associated actions need to be set with care.

The nature of a warning and its dissemination determine in part the response that is given by the recipients. Wherever possible, responsibility for deciding on the warning, its issuance and dissemination should be at the local level; in other words, at a level that is as close politically to the local community as possible. Mileti (1995) points out that the source of the warning must be credible, and comes best from a mix of people with different skills and responsibilities. Each warning message must be self-consistent, clear and unambiguous, accurate, timely and fully factual. A message must convey a high degree of certainty, and clear guidance about what people should do about the event being described. The warnings should be repeated frequently to alert people hearing them. All reasonable channels of communication should be used. In particular the media must abide by messages issued by authorities.

Whereas in decades gone by the siren was the primary means of alerting the community, communications are now much more varied. For example the telephone, with Automated Voice Messaging to pre-registered properties at risk, is reasonably reliable, and its development, mobile telephony increases the immediacy of access to individuals and groups. The advent of advice systems for groups such as farmers in developing countries can be paralleled by similar systems alerting flood wardens in village communities in Bangladesh, say. In addition, Internet, email, chat groups and network chains of people with responsibilities to receive and forward messages, are ways of mobilizing the increasingly versatile communications facilities. Obviously the media, including radio and TV, are effective means of informing the general public of impending threats, though they have to be careful how they broadcast warnings.

Mileti (1995) has also identified that people respond to a warning by going through a process of hearing a warning, understanding what is meant by it, developing a level of belief in the risk information it contains, assigning who should be responsible for reacting to the perceived risk, and deciding and acting on an appropriate personal response. He points out that the actual response depends on a number of complex issues, and they call for ongoing research to identify differences and commonalities in warning response, adoption constraints and incentives, the role of public education, warnings for fast moving or concurrent hazardous events, the media role in warnings, and improving communications.

A warning system depends on the integration of a number of different facilities in order to cycle the necessary information. Such facilities can be regarded as being set in a particular framework that integrates data monitoring and observations, data archiving and analysis, the causal chain of models and the associated uncertainties, support for decision making concerning the issuance of warnings, the dissemination of such warnings and monitoring the recipients' responses. This framework does not only feed information forward, it should also be designed with feedback mechanisms that enable data collection be adapted to modelling needs, modelling adjusted to meet the needs of the decision makers, and warnings to be amended or re-issued in the light of responses.

Critical decisions may have to be made during a flood event, depending on its severity. Such decisions may include pre-emptive action to divert floodwater (intentional flooding), or to issue an order for evacuation, or to reinforce flood defences. Everybody in the emergency services should know what their role and function is in response to instructions. This depends on good planning and coordination, preferably tested through exercises.

Pre-emptive action may be possible where storage is available, such as with reservoirs behind dams or with polders. Such systems may be subject to anticipatory water management procedures, including drawing down water levels in anticipation of a forecast rainfall event. Often, however, such actions need confidence in the reliability of the rainfall forecast.

RECOVERY AND RESTORATION

The aftermaths of the Indian Ocean tsunami in 2004 and hurricane Katrina in 2005 illustrate the huge problems that communities have in recovering from flood disasters. The gross extent of the devastation that occurred in both events has meant that many structures have had to be bulldozed to the ground, and whole areas stripped bare for renovation to take place. The risk to public health due to pollution meant that in some places access to the devastated areas had to be restricted. A priority had to be given to restoring basic services. Homes that survived had to be cleaned up, dried out, restored and repaired. An important task therefore is the assessment of damage. Depending on the scale of the disaster this can usefully involve remote sensing. Funding needs to be made available, especially in the case of declared disasters, which by definition require resources over and beyond those of the local community to aid recovery. A post-appraisal or review of the disaster needs to be carried out as soon as is reasonable in order to capture the relevant data before it is lost. The review should analyse flood maps and damages, review standards, and recommend policy revisions. These should be in place before reconstruction takes place. It is vital that lessons be learned about the inadequacy of the previous infrastructure. Reconstruction must bring about safer, more disaster-resistant homes and infrastructure with no reduction in construction standards (as might be the case in view of the urgency to reconstruct and the difficulties in securing adequate funding). Infrastructure that is critical for the whole community should be identified and be the focus of rehabilitation. The hydro-morphological resilience of wetlands and streams should be reviewed with the aim of improving it. Embankment or levee construction and maintenance must be optimized *vis-a-vis* reducing and even removing development on the flood plains, while ensuring protection of vital community facilities, such as hospitals and schools.

Disastrous flood events occur infrequently, and there may be several decades between them. This implies that without a good community memory much knowledge about maintaining preparedness and having the understanding about how to cope in critical situations may be lost. Preserving the knowledge in the form of lessons learned and ensuring the adequacy of the database concerning floods and flooding in a river basin is a knowledge management task. The appropriation of relevant knowledge is not just something that should be left to a select group of professionals. All stakeholders should take responsibility to be briefed on what is relevant to them, and to work out their own responses in their particular situations. There should therefore be a strong culture of sharing knowledge, but knowledge is only transferred effectively when it is owned at the individual and local level; see Krogh *et al*. (2000).

PRINCIPLES FOR MANAGING FLOODS

In the past society has reacted to floods by building engineering structures: dams, embankments, channel realignments, off-line storage, diversions, and so on, in an attempt to control the flooding. These structures have been complemented by non-structural measures, including forecasting and warning systems. But the demand for urban infrastructure development on flood plains has accentuated damages that are inevitable in many places. There have to be changes in attitude and approach.

The following six principles are adduced by the IFI/P for improving the management of floods (UNESCO-IHP, 2004):

Living with floods That is, recognizing floods as inevitable natural phenomena. Whereas there are some beneficial aspects of floods, their negative impacts can be reduced through an understanding that risks result from a combination of flood hazards and societal vulnerabilities. Hazards can be reduced through appropriate physical interventions and the introduction of various technologies for warning and control. Similarly, improved planning, social awareness and preparedness, legislation, and a number of other factors can affect societal vulnerabilities. Above all there needs to be a concerted effort to reduce risks through a holistic approach to flood management. Communities and governments should be assisted, through proactive multi-hazard and risk-based approaches, to develop culturally sensitive and sustainable flood risk management strategies that harmonize structural and non-structural measures.

Equity The burdens and benefits of flood risk management (prevention, response and recovery) must be equitably distributed. Such a distribution has both ethical and legal dimensions. It is not inevitable that flood risk management promotes appropriate policy processes and outcomes that are viewed as fair and legitimate among all the affected parties or stakeholders. This is also a sustainability issue such that the stakeholders should include future generations. Flood risk management strategies must therefore promote intergenerational equity.

Empowered participation Participation of all stakeholders, including individuals and communities, is widely recognized as a crucial factor for the successful implementation of flood risk management. Such participation becomes empowered only through appropriate institutional frameworks and innovative governance mechanisms, as well as through carefully designed enabling systems and environments using modern communication technologies that coordinate flood related activities at all levels. Flood risk management has to be part and parcel of social development.

Inter-disciplinarity Flood management is a process involving technical, social, ecological, economic, legal and political skills. There is an urgent need to develop and enhance the integration and communication between the knowledge systems necessary to facilitate all flood related activities. These include physical aspects such as identifying and monitoring data from the real world to generate the necessary information for decision making in all areas, improving the statistical and other inductive forms of analysing flood data, and developing robust and appropriate flood modelling and real-time forecasting and warning systems. The integration of appropriate skills is best achieved at the river basin level. All relevant natural, economic and social scientific knowledge, together with appropriate technologies for data and information acquisition and communication, should be brought together. The involvement of disciplinary stakeholders is also essential to ensure that the right institutional structures, participatory processes and policies are in place to promote fair and effective flood risk management.

Trans-sectorality All stakeholders need to be involved in flood risk management. Links should be established between the scientific community, decision makers inside and between governmental levels, the relevant UN bodies, national and international organizations, NGOs, and market actors. This multi-sectoral approach would increase the effectiveness of processes and the acceptance of flood risk management decisions, and therefore enhance their sustainability.

International and regional cooperation This principle recognizes the imperative for a cooperative, partnership approach for flood-related issues, especially when dealing with transboundary catchments and rivers. International and regional cooperation is also needed for transferring appropriate technologies for flood management, sharing of experiences in flood management, and for making the most beneficial local use of global systems for monitoring, observation and prediction of flood-generating natural events. Data, information and knowledge exchange and management are facilitated through cooperative networks, such as the IHP National Committees, UNESCO Water Centres, IAHS National Committees and other UN institutions and initiatives. The development, promotion and transfer of appropriate technologies in flood risk management are also a matter of international cooperation. Particular attention needs to be given to the specific problems of the poorest developing countries to enable them to cope effectively and fairly with flood hazards as a part of their national strategies for poverty alleviation.

From an engineering point of view, the following points can be added:

Anticipation rather than reaction It is far better to be prepared for a potential threat than to be taken by surprise and to have to react inefficiently. This is the counterpart of sharing the risk, and supporting sustainability. The anticipation may focus on flooding as a threat, but related threats, such as climate change, land subsidence, population growth, urban development, even changes in economic value, can all contribute to increasing the severity of the event and should be taken into account.

Making room for water This point of view complements the notion of living with floods, in this case sharing with water the space available for infrastructural development. Admittedly flood plains are very attractive for development, but we have to resist the temptation to grab as much as we can without thinking through the consequences for the economic, environmental and social health of the whole community; see Rijkswaterstaat (2000).

Preserving/increasing hydro-morphological resistance Enough has been said above to indicate that the hydro-morphological resilience is important in reducing the impacts of floods downstream, especially for the more frequent floods.

Managing (non-structural) rather than simply controlling (dams/storage – structural) floods Here it is acknowledged that there needs to be a shift away from structural intervention to a softer, more management-oriented approach, taking advantage of a variety of technical facilities that are becoming available, and which are focussed around forecasting and warning systems.

Accounting for uncertainty due to climate change and other factors Certainty about the severity of natural events in the future is not possible. Although calculations can be made about expected flows and flood levels, the assumptions behind the modelling of the real world inevitably involves approximations that in many cases are imprecisely quantified. The uncertainties that are introduced should properly be included in any decision making. Understanding how to account for any quantified uncertainty is itself still not a well-defined task, and relies in part on the intuition of the decision maker.

CONCLUSIONS

This paper aims to provide a review of the engineering and technical aspects of managing floods. The focus is on the hazard reduction–emergency management–post-event restoration phases that are now widely recognized. Underlying these phases is another progression, namely the generation–pathway–receptor model, adopted especially in the UK. Inevitably, the management of floods in their different phases and through their genesis–propagation–impact involves a strong integration of data from diverse sources, of models addressing distinctly different processes, and of a range of possible engineering and technical solutions to managing floods. What is more, there are many stakeholders, including the general public, that have to be involved for flood management to be successful. Effective communication is therefore also at the heart of effective management, whether in terms of data monitoring systems, between models, consulting stakeholders, disseminating warnings, or giving attention to feedback on actions taken.

Effective flood management is a non-trivial problem that requires concerted effort to share knowledge and best practices in order that all may have access to the experiences of others while taking responsibility for their own preparedness and procedural actions.

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