

Title:

Challenges for Achieving Sustainable Flood Risk Management

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Abstract

This paper presents the challenges for effectiveness and sustainability of flood risk management strategies and technologies by critically reviewing flood management practices. The study reveals that reliable flood prediction is limited by the characterization of floods that have multiple causes and hydrological uncertainties due to variability in climate and river morphology. Moreover, changing land use in floodplains and potential of creating new risks limit the risk assessment and evaluation process of flood control projects. Hence, sustainability analysis mechanisms, including ‘Dynamic Sustainability’ concepts, should be adopted in the flood management planning process. Investigations into the proportional contribution of structural and non-structural measures to reduce total flood risk could assist in better decision making. Gaining improved understandings of the perception on flood risk and safety, and risk communication methods, for present and future stakeholders, is crucial. Extensive research on the above challenges would reveal pathways for developing sustainable flood risk management strategies.

Keywords

Flood risk management, risk assessment, sustainability, flood control project

1 Introduction

Flood risk reduction is a prime concern for flood vulnerable countries around the world. Over the centuries, in different regions, a variety of strategies and technologies for flood risk reduction have evolved. Flood risk management processes, in general, include flood risk identification, flood risk assessment, and structural and non-structural interventions to reduce flood risk (McBain 2012). In all aspects of flood risk management, moreover, scientific and technological advancements have been introduced, although many critical issues are yet to be solved. Similarly, flood risk reduction policies and strategies have shifted from localized, reactive and isolated approaches to regional, integrated and proactive approaches (Sayers *et al.* 2012). With the progress of scientific knowledge and international collaboration, similar strategies and technologies are being applied around the world, and customized based on geographical and socio-economic contexts.

Despite all international efforts and technological advancements, flood risk management remains a challenging task for many developed and developing nations. This situation is particularly salient in light of unprecedented flooding events occurring in flood protected areas in recent years, believed to be triggered by global climate change (Kelman 2001; Melillo *et al.* 2014). Additionally, more frequent and catastrophic floods are expected in future. Also, currently practiced flood risk assessment processes seem to have gaps, which have led to improper planning and design of flood risk reduction measures, and, consequently, function ineffectively during various catastrophic flood events.

Scientists have been examining the present knowledge base of flood risk reduction strategies and technologies to identify the gaps and to strengthen the processes. Such efforts have been made in the current study which critically reviewed the strategies and technologies applied to flood risk reduction in different regions. The historical background of the strategies and changes, made over time, have been critically examined in the context of achieving greater effectiveness and sustainability in the strategies, both in terms of technology and societal

development. The study also examined cases of flood mitigation measures implemented in different floodplains to discover the gaps in the planning and implementation process. This critical examination revealed new dimensions in developing future flood risk management strategies. More research and development needs to be carried out on the identified gaps to minimize future flood risk.

2 Dimensions of flood risks

Floods, as one of the most common natural hydrological hazards, have been occurring in floodplains over millennia. They are caused by river overflows, heavy rainfall, tidal surges, snow melts, and groundwater seepage. In recent times, severe floods have occurred in China (1998: Yangtze River, 2013: Southeast China), Central Europe (1997, 2005), the United Kingdom (2000, 2007, 2009), Bangladesh (1988, 1998, 2007), the United States of America (USA) (2005: New Orleans), and Australia (2011: Queensland) (Sayers *et al.* 2012; QFCI 2012). Predictions on changing climatic conditions and rising sea levels suggest, in the near future, more catastrophic flooding in some parts of the world (IPCC 2014). Many areas have already experienced increased flooding due to climate change (e.g. USA), in areas where there were no earlier severe flooding (Melillo *et al.* 2014).

Irrespective of the causes and nature of the floods, the elements impacted by flooding are common: human life and livelihoods, settlement and housing, agriculture, industries, commercial activities, and communication infrastructures. Usually the major urban settlements that develop along rivers are particularly at risk of flooding, especially as the pattern of flooding and risk elements are changing spontaneously through rapid land use conversion and urban development. Rural areas are also affected by flood; it is mainly agricultural economies and livelihoods that are disrupted (Islam, 1997; Messner and Meyer 2006).

The characteristics of a flood and the vulnerability of the elements in the floodplain to the particular flood events appear to determine the risk to the elements. Defining flood hazards through meteorological, hydrological, and hydraulic investigations, as well as determining the vulnerability of elements, by estimating the impact of floods, can be carried out separately. However, then, both hazard and vulnerability have to be combined for the final risk analysis (Mileti 1999; Merz and Thielen 2004; EU 2007; Wu *et al.* 2011). Sayers *et al.* (2012) have further elaborated the fundamental concept of flood risk by defining the multiple dimensions of risks covering the dimensions of flood characteristics, i.e. source and pathways of the water that determine the probability of flooding; whereas the consequences of a flood are determined by the exposure and vulnerability of the receptors. Such vulnerability depends on the value, susceptibility, and resilience of the receptors.

3 Complexities in flood risk assessment

Flood risk analyses are gaining more importance in the fields of infrastructure design and flood management. These analyses enable agents to evaluate the cost-effectiveness of the flood control projects and provide risk information to residents, insurance companies, and municipalities to prepare for disasters (USACE 1996; Olsen *et al.* 1998; Al-Futaisi and Stedinger 1999; Ganoulis 2003; Merz and Thielen 2004; Hardmeyer and Spencer 2007). Several models and analytical methods are now available to identify and define flood hazards, vulnerability, and flood risk. Over the years, the simple approach of defining flood events, with a return period through frequency analysis (Stedinger *et al.* 1993), has been transformed to more complex methods to determine probabilistic flood scenarios with consideration for exceedance probability (Merz and Thielen 2004) and uncertainties (Merz *et*

al. 2008; Wu *et al.* 2011). Advances have been made in regional flood frequency analysis (e.g. Bayesian Generalised Least Squares (BGLS) regression in a region-of-influence (ROI) framework was developed for regional flood frequency analysis in eastern Australia) (Haddad and Rahman 2012; Nguyen *et al.* 2014). Moreover, linear interpolation models to complex 1D/2D hydraulic models are now being used to analyse the extent of a flooding and inundation area (Apel *et al.* 2009).

Also, in light of the increasing understanding of flood characteristics, approaches to vulnerability analysis have been transformed. Vulnerability analysis has developed from a simple calculation of flood effects, by stage-damage function (Smith 1994), to more comprehensive assessments of flood effects. These effects include, for instance, inundation depth, flow velocity, inundation duration, flood warning, and response (ICPR 2002; Kelman and Spence 2004; Kreibich *et al.* 2005; Penning-Rowsell *et al.* 2005; Thielen *et al.* 2006). Further, flood loss estimation techniques are available on a micro to macro scale. A micro-scale loss analysis can be undertaken in small areas with detailed information about types and use of individual buildings and structures. In contrast, a meso/macro scale approach is suitable for large areas, as it is based on aggregated land cover categories linked to specific economic sectors. The loss in each sector is then aggregated to estimate the total damage (Messner and Meyer 2006). While most of the damage assessment functions provide results in monetary terms related directly to quantifiable buildings/infrastructures, some methods provide relative loss functions, for instance, loss in the percentage of the building or content value (Dutta *et al.* 2003; Thielen *et al.* 2006), or as index values, such as loss expressed as an equivalent to the number of median-sized family houses totally destroyed (Blong 2003). An enhanced understanding of flood risks has revolutionized traditional flood risk reduction measures by decreasing the probability of floods through mounting a structural defence encompassing all dimensions of flood risks (Sayers *et al.* 2012).

4 Analysis of current flood risk management strategies and technologies

Flood risk management strategies and technologies have evolved over centuries with the development of civilizations in different parts of the world. The earliest civilizations settled along rivers or floodplains, with critical infrastructure and houses being located on higher ground. These settlements also adapted to floods by the population choosing flood sensitive economic, social and cultural activities (Sayers *et al.* 2012; McBain 2012). Since the early 20th century, structural engineering solutions have taken a key role in flood risk management, as the demand has continued for human safety, food security, and safe urban and rural development.

During the 1960s to 1980s, the construction of embankments, dykes, polders, diversion channels, dams, and similar structures were the main flood mitigation and control measures to be used. Alongside structural measures, non-structural measures have been used, including reducing the severity of flooding through land use changes in upstream catchments, increasing preparedness through early warnings, and reducing the consequence of flooding by reducing both exposure and vulnerability (White and Richards 2007; Richards *et al.* 2008; Tapsell 2002). Historical evidence suggests that flood risk management began and developed from a willingness to live with floods when there was limited technology. However, population pressures and food shortages have forced societies to utilize floodplains and, therefore, to control floods with structures. In recent years these strategies were followed by both increasing efforts to reduce flood damage and addressing whole risk management (Sayers *et al.* 2012; McBain 2012).

The effectiveness and sustainability of both structural and non-structural flood control measures vary greatly according to the local context and planning processes. In the short term, many structural flood control projects have proved their performance by preventing flood; this outcome has led to a strong belief in our ability to protect ourselves from floods through engineering solutions. In the long term, however, some of these structural measures, due to unplanned development, population growth, and land use changes inside the flood-protected areas have been found to be inefficient during catastrophic flood events. As a result, flood losses have continued to increase; they have also required further risk assessment and risk management approaches in different ways (Hall *et al.* 2011; Sayers *et al.* 2012). For instance, over the decades following the UK catastrophic flood events of 1874, 1928, and 1953, and the latest concerns related to future sea level rises by the year 2100, flood defences in the Thames estuary have been re-designed and renovated. Initially, the flood embankments were raised to prevent the flood waters; then storm surge barriers were built to prevent tidal waters. Next, all the structures were renovated to prevent flooding with the annual exceedance probability of 1 in 10,000, with a consideration of the combined effect of pluvial and fluvial flooding, as well as the future sea level rise scenarios.

The paradigm of flood risk management has shifted from a reactive approach, after having huge flood damage, to a proactive approach (Tarrant and Sayers 2012). Similar kinds of flood management strategies have been adopted in the coastal floodplain of the Ganges–Brahmaputra River basin in Bangladesh; there coastal polders were built to prevent tidal flooding from the 1960s to the 1980s. Those polders proved to be effective for the following two decades, but they are now creating severe drainage congestion in the area. With sedimentation in the river channels having raised the level of the river beds, compared to land inside the polders, which have obstructed the storm water drainage through natural gravity flow. The government of Bangladesh is now planning to renovate the coastal polders with a new design, a response to the sea level rise scenarios. A new approach, such as the ‘Tidal River Management (TRM)’, has been proposed to be implemented in the coastal area of Bangladesh (BWDB 2013). However, the effectiveness of these re-designed flood defences can only be proved when flood events actually occur.

The application of similar structural flood defence technologies may not be effective in all floodplains, as observed when the structural flood defences were successfully implemented in small river basins like the Rhine River in Europe. However, these have proved not to be as sustainable in large river basins like the Yantze River in China. The dynamic nature of large river basins creates huge uncertainties in flood predictions, as well as improper design of flood defences (Plate 2002).

Although structural flood control projects have brought some benefits in flood mitigation, still the floodplain ecosystem appears to be largely destroyed and the ecosystem dependent livelihoods and economy are impacted. Taking into account the cost of irreversible change in the floodplain ecosystem, the benefits of flood mitigation would tend towards a negative position (Tapsell *et al.* 2002; Saha *et al.* 2012). The question of the sustainability of floodplains comes into focus when large scale destruction has already taken place. Concepts of integrated river basin management or floodplain management were introduced in recent decades, in an attempt to reduce the impact of structural flood control measures (Sayers *et al.* 2012).

Unlike the instant visualization of the benefits of structural flood defences, it is often difficult to quantify the effectiveness of non-structural flood management measures. Owing to non-structural measures, the response and adaptation to floods of the flood vulnerable communities varies widely, and is impacted upon by various factors, such as community

resilience, and susceptibility to flood. Also, the effectiveness of the non-structural measures appears sensitive to socio-economic changes and governance arrangements (Dawson *et al.* 2011). Nevertheless, non-structural measures provide flexible flood management options for adapting to the ever-changing river basins, socio-economic and climate scenarios, and are in line with the spirit of environment-friendly and sustainable development (Kundzewicz 2002).

5 Transformation of policies and strategies towards sustainable flood risk management

Changes in flood risk management policies and practices, as so far considered, have been triggered, in the main, by catastrophic flood events that have provided new insights and perspectives on the performance of past interventions and future needs. As seen in the early decades of the 20th century, major flooding events in the USA (1917, 1927: Mississippi River) and China (1931: Yellow, Yangtze and Huai Rivers) have led to the transformation of local level flood control in the development of basin scale flood control infrastructure and coordination policies for flood mitigation. In both USA and China, the central government has undertaken responsibilities for implementing large scale interventions in the river basins. Relying on a 'levee only' option has been widened to the integration of other options, such as improvements in the channel, cut-offs of river bends (that were seen to be delaying the flow of waters), flood ways (to relief pressure in the channel during extreme flood events), and flood storage dams. The extreme flooding across Europe in 1947, and the coastal floods devastating Europe in 1953, also led to the re-shaping of flood risk management policies towards food security, the strengthening of flood defence systems, the defining of clear local and national government responsibilities for flood management, and the strengthening of early warning systems. For the first time, in late 1950s, Netherlands undertook a national-scale benefit–cost analysis of flood management to establish standards for each protective dyke ring (Sayers *et al.* 2012).

Over the decades of the 1990s and 2000s, flood risk management has been transforming towards new perspectives in relation to total disaster mitigation approaches. For example, floods in China in 1991 and 1998 gave rise to an emphasis on preparedness, emergency planning, and the building of structural defences to a variable standard (i.e. flood defences along important sections of major rivers would be designed for flood of 100 year return period, whereas the defences along minor rivers would be designed for flood of fifty year return period). Recognizing the continued existence of residual risk, the Chinese government has moved from total flood control strategies towards the promotion of risk awareness (through flood hazard mapping), and enhancing the socially focused management of flood control areas. In Mississippi, USA, the floods in 1993 and 1997 also opened up new dimensions for assessing flood risks. A number of studies have considered uncertainties in flood events and the formulation of rules and regulations for planning and implementing flood control projects. During the same period in the 1990s, basin wide and strategic flood management approaches, combining structural and non-structural measures, have also been taken up in the UK, as well as in the Rhine River basin (Europe). Following additional flood events in 2000s, the European Commission established flood directives related to the 'assessment and management of flood risks', with the aim of reducing adverse consequences of flooding to human health, the environment, and cultural-economic activity in the European Community (EU 2007).

The Asian Tsunami in 2004 put a new focus on the vulnerabilities of coastal communities, as well as the importance of spatial planning, better warning systems, and emergency planning. Since then, substantial efforts have been made to establish sophisticated early warning systems, and the mapping the flood vulnerability areas to enhance spatial planning and

emergency response decisions. However, the performance of these measures is yet to be tested. In 2005, cyclone Katrina hit New Orleans, USA, bringing with it the realization of levee failure and a need to adopt better risk management approaches and the communication of residual risks. The USA Federal Government began to shift their flood risk reduction strategy towards flood risk management (FRM). For example, in 2006, the United States Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) started a national FRM programme to integrate and synchronize the ongoing, diverse flood risk management projects, programs, and administrative authorities of the Federal agencies, state organizations, and regional and local agencies. In addition, the FEMA increased its efforts to improve flood risk identification and communication for facilitating the National Flood Insurance Program. The UK flood in 2007 also directed flood management efforts towards the consideration of all sources of floods and spatial extents when pluvial (direct rainfall), fluvial (river) and tidal floods occur together. The necessity for an appropriate legislative framework for FRM was identified as a way to integrate public and private bodies, which were separately engaged in coastal and fluvial flooding, or groundwater management, or, more importantly, pluvial flooding. A surface water management plan was developed in the UK; it considered all sources of flooding and integrated management strategies. Most recent floods in Pakistan (2010), Japan (2011) and the USA (Mississippi 2011) again put into perspective the need to evaluate floodplain management, performance, and limitations of structural measures, and to improve the resilience of critical infrastructures, as well as reducing the development of secondary and tertiary levels of risk (Sayers *et al.* 2012).

Scientists are now suggesting that modern flood risk management strategies should be embedded with a number of major aspects, such as the selection of management options through risk based assessment, a consideration of the whole system approach to flooding and its effects, a portfolio based integrated management by multiple organizations and stakeholders, multilevel analyses, evidence based management options, adaptations to physical and socio-economic changes over time, a consideration of the uncertainties for the whole process, the engagement of all levels of stakeholders, and the integration of the sustainable development of river basins and coastal systems (Hall *et al.* 2011; Sayers *et al.* 2012; Sahin *et al.* 2013).

6 Future challenges for achieving sustainable flood risk management

Flooding types and characteristics are similar across the world. Nevertheless, the characteristics of flooding caused by multiple events occurring simultaneously (e.g. heavy rainfall and a tidal surge) are not clearly understood yet. Moreover, the impact of climate change on flooding needs further investigation within the context of local and regional climatic conditions (Melillo *et al.* 2014). Although many flood prediction models have incorporated hydrological uncertainties, the reliability of the models' results still need to be improved and so need to consider hydrological data reliability and analytical methods (Melching *et al.* 1990; Juston *et al.* 2013; Sikorska *et al.* 2014), as well as the uncertainties of other factors, such as the ever-changing river morphology (Wu *et al.* 2011).

Along with the uncertainties in flooding events, available flood risk assessment processes, while having multiple dimensions, cannot address, in tangible terms, all aspects required to estimate a flood risk (Blong 2003; Messner and Meyer 2006; Thielen *et al.* 2006). Because of the range of complexities, such as changing land use patterns and uncontrolled developments in flood prone areas, flood risk assessment methods face difficulties in their attempt to describe future scenarios of the elements at risk or the impacts from floods. In

addition, the changing values of the assets in a global scenario, and the technology of building structures, may lead to gaps in risk assessment and the outcome of the project. Often in flood control projects, designed and implemented decades ago using simple deterministic risk assessment processes, now are able to create a new environmental risk (flooding, pollution, and drainage congestions). These risks are facilitated by uncontrolled urbanization inside the protected areas (McBain 2012; Saha *et al.* 2012). Many such examples indicate that proper flood risk assessment, which considers the sustainability of flood control projects, is required to gain benefits in the long run.

Modern flood risk management strategies and technologies have advanced through long experiences, overcoming the drawbacks of previous strategies and technologies. By sharing knowledge and experiences throughout the world, stakeholders have multiple choices of technologies to apply to flood prone communities. Globally, it is now accepted that no single strategy is enough to reduce a flood risk; however, a combination of flood risk management strategies is required in all floodplains. This approach may include land use management, structural defences and the improvement of community preparedness for floods via early warning and emergency management. However, the application of flood management measures need to comply with the local environmental, socio-economic, and institutional set up (Richards *et al.* 2008; McBain 2012; Sayers *et al.* 2012; Shah *et al.* 2012). Structural flood control measures can be extensively applied to most flood prone countries; whereas many countries have yet to implement flood sensitive land use planning, or institutionalize flood preparedness and emergency management activities. This is because the benefits of structural interventions are immediately visible to the community, while non-structural measures are not. Nevertheless, since both structural and non-structural flood management measures are emphasized in modern flood management strategies, further investigations on the proportional contribution of all measures to reduce total flood risk in flood vulnerable areas could be a useful element when choosing the better options.

Despite the immediate benefit of structural flood control measures, over the long term, an improved and sustained performance of the structural measures cannot be justified, as many areas inside large flood control projects have flooded after only a few years of their establishment. Additionally, flood protection measures attract new development in flood plains, which can create a 'moral hazard', misleading a vulnerable community from a true appreciation of the risks associated with occupying the flood plain (McBain 2012). An unexpected alteration of a flood plain, and the associated flood risk after the implementation of flood control structures, limits the performance evaluation of these structures.

Few research studies or planning efforts have been made to adopt sustainable development and integrated management approaches in flood risk management that specifically address the negative consequences of flood control projects (Brouwer and van Ek 2004; Hall *et al.* 2011; Sayers *et al.* 2012). Nevertheless, a sustainability analysis of the structural flood control projects has not been fully adopted in the planning process. Since flood risk management is recognized as a continuous adaptive management process (Hall *et al.* 2011; Sayers *et al.* 2012), 'Dynamic Sustainability' concepts, approaches that involve adaptation of interventions for achieving best possible outcome through continuous learning and problem solving, (Newman 2005; Scoones *et al.* 2007) can be adopted. Moreover, as risk perceptions and expectations of safety by stakeholders are crucial for choosing management options, a clearer understanding of the perception of flood risk and safety by present and future stakeholders could be important in achieving a greater sustainability in flood management measures. However, currently, there is little understanding of how to anticipate the types and attitudes of future stakeholders in regard to flood risk management projects implemented in

present days. Therefore, the methods of flood risk communication across present and future stakeholders and communities should be a focus of future research.

7 Conclusion

With the continuing effort required to understand flood characteristics and flood risks, several flood risk management strategies have been developed over the centuries. Nevertheless, due to the multiple causes and hydrological uncertainties associated with climatic and morphological changes, to date, flood risk assessment has remained challenging. Moreover, alterations to land use in floodplains has hindered the flood risk assessment process, as well as the performance evaluation of the previously implemented flood control projects. The potential for new risks to occur (such as pollution and drainage congestion inside the protected areas of flood control projects) are sometimes ignored in the planning process. Therefore the ultimate goal of a more sustainable flood risk management process is often not achieved.

This study recommends the development of sustainability analysis mechanisms, including 'Dynamic Sustainability' concepts, for better flood management planning. The whole lifecycle of flood control projects should be assessed in the planning stage to ensure the sustainability of the project outcome. Also, additional research is required to investigate the proportional contribution of structural and non-structural measures to reduce total flood risk that can provide a better understanding of flood risk and management options. The perception of flood risk and safety, and current risk communication methods need to be improved for both the present and future generations. Resolving the above challenges has the potential to develop better sustainable flood risk management strategies for the future.

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