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FLOODS - ARE WE PREPARED?

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Abstract

Flooding in the USA and elsewhere, as well as issues related to climate change, have again alerted politicians and scientists to the dangers that floods pose. This article, written by international river experts from several countries, is aimed at giving readers an insight into what engineers are currently doing to understand the underpinning science, to improve hydrodynamic flow models and to develop better flood risk management procedures. It reviews fluvial flooding from a European perspective, describes recent R&D studies in the UK, China & Japan and highlights the need for more international collaboration.

Introduction

Flood disasters account for about a third of all natural disasters (i.e. floods, earthquakes or storms) world-wide, but are responsible for over half the deaths *(1)*. Thousands of lives have been lost directly or indirectly from flooding in many countries *(2, 3)*, and damage costs have been significant (e.g. Mississippi basin, 1993; New Orleans, 2005). Specific reviews for different regions are available: global review *(1-3)*, Asia *(4)*, Europe *(5)*, UK *(6-8)*, China *(9)* and Japan *(10)*. The United Nations (UN) has also highlighted why people are at risk, and what can be done to mitigate flood disasters in the future *(2)*.

Even with the most advanced 3-D models *(11, 12)*, and the best of turbulence science *(13, 14)*, rivers are difficult to model, either at a reach or river basin scale, although much progress has been made *(15, 16)*. This article is aimed at giving readers an insight into the underpinning science behind river flood hydraulics and hydrodynamic flow models.

River basin management considers flooding from the governing meteorological conditions and the point of impact of rainfall on the land to the discharge of the flood to the sea *(17)*. It recognises, evaluates and takes into account the human dimension as well as the technical and economic cases for intervention, and the environmental impact of these *(18)*.

Flooding - a European perspective

Since 1990 the European and international media have commented on notable incidents almost every year. For example, in France 42 people died in 1992 during the flash flooding in Vaison-la-Romaine (see Fig. 1); basin wide floods caused widespread disruption and losses in the Rhine and Meuse basins in 1992, 1993 and 1995; and exceptional flooding struck the Po in 1994. In 1997 severe localised flash floods and basin-wide floods on several major river systems occurred, causing loss of life, distress and disruption. That year started with flash flooding in Athens and then in July exceptional rainfall in the Czech Republic and Poland caused catastrophic flooding on the Oder river killing over 100 people and laying waste vast areas of the countryside. Again, in early November, flash floods occurred, this time in Spain and Portugal with over 20 people losing their lives.

Figure 1 Vaison-la-Romaine flood in which 38 people died and £180m worth of damage was caused (22 September 1992)

In early April 1998 a nearly stationary band of rain caused extensive flooding over central regions of the UK, with thousands of people affected, some without warning. The winter of 2000-01 was the wettest on record (for over 250 years), caused the worst flooding in many regions, and led the government to commission an independent review *(7, 8)*.

Between 1998 and 2002, European countries suffered over 100 major floods, including the catastrophic floods in the Danube and Elbe basins in 2002. These floods caused about 700 fatalities, the displacement of about half a million people and at least €25 billion ($30 billion) of economic losses *(18)*. In the summer of 2004 dramatic pictures were seen worldwide of the rescue by helicopter of about 100 people from a flash flood at Boscastle (UK) where many riverside buildings were destroyed (see Fig 2). In the summer of 2005 there was widespread flooding in river basins in Bulgaria, France, Germany and Romania.

As a result, the European Environment Ministers produced "*Best practices on flood prevention, protection and mitigation*" (2003), followed by a Commission Communication (2004), and an Action Programme (2006). The Programme, now under development, includes: legislative proposals for a new Directive requiring flood risk management plans, research and information exchange activities and funding possibilities for the proposed actions. The Action Programme and the Directive now being drafted recognise the importance of research in improving knowledge and understanding of flood risks

Figure 2 Flood damage at Boscastle, UK, August 2004 (Courtesy HR Wallingford)

Flooding – national perspectives and strategic planning initiatives from the UK, China & Japan

A perspective on flooding from the UK

In the UK, the government has taken a long-term strategic view of flooding through the Foresight programme (www.foresight.gov.uk), which highlights various drivers and scenarios. The aim was to produce a long-term vision up to the year 2100 for the future of flood and coastal defence, which took into account the many uncertainties, but which is nevertheless robust, and which can be used to inform policy. It was managed by the chief scientist to the government and worked through the UK government Cabinet Office *(19)*.

In 2001, the economic value of national UK assets at risk from flooding and coastal erosion were estimated at ~ \$350 billion, the potential annual damage (without defences) at about \$4.7 billion, and the annual average damage at around \$1 billion *(20)*. Following the floods in the Autumn of 2000/01, these figures were revised upwards. It is now estimated that up to 5 million people in the UK (~ 10% of the population) are at risk from flooding, and that the annual average damage is around \$1.4 billion. Since the potential annual average losses are now estimated to be some \$5.8 billion, flood risk reduction measures have reduced the potential losses by \$4.4 billion, based on average annual expenditure of \$900 million.

A perspective on flooding from China

In China, the annual mean flood losses (1950-1980) accounted for approximately 20 billion RMB (\$2.3 billion). However, they approached 80 billion RMB (\$9.3 billion) in 1991, passed 100 billion (\$11.7 billion) in 1994, exceeded 200 billion (\$23.3 billion) in 1996 and reached 248.4 billion (\$41.5 billion) in 1998. Damages amounted to 1% - 4% of the nation's total GNP during the 1990s, about 10 to 20 times higher than equivalent percentages for developed countries such as the USA and Japan *(21)*. Due to the special geographical location and climate conditions, China is a country with frequent floods. When combined with the pressure of a large population and relatively high utilization of flood detention areas, China suffers disproportionately from severe flood disasters *(9)*.

Since the floods in the Yangtze River (1998), the Chinese government has proposed a series of policies and measures for flood mitigation: transforming land back into forests, demolishing polder fields, transforming farmland back into lakes, employing laid-off labourers for rehabilitation, relocating people to form new townships, reinforcing key levees and dredging river beds. In addition, positive fiscal policies have been adopted during 1998 to 2002, increasing the total financial input for water infrastructure from the central government by 3-4 times the average of past decades. The improvement in flood defences and safety for the riparian people also improved the socio-economic development of the areas that used to be at risk *(22)*. However, flood control works in 60% of cities and 50% of seawalls have not yet achieved the planned standards *(23)*.

A perspective on flooding from Japan

In Japan, 50% of the population and 75% of assets are located on flood-risk districts, corresponding to 10% of the national land area. Over the last 50 years, the number of dead, missing persons and damaged houses due to floods has decreased, largely as a result of implementing flood control measures (e.g. levees and storage reservoirs). However, a number of flood disasters still occur because many cities with high concentrations of population still suffer from inundation. Furthermore, the effects of climate change have also become noticeable, with heavy rainfall of over 100 mm an hour, or 500 mm in a day, increasing. In 2004, there were 10 landfalls of big typhoons onto Japan, and rainfall and river discharge records were broken at many points. The total loss of life reached over 200.

The annual average flood losses in Japan during the last decade were about \$5.0 billion. Since 1990, the "flood damage density", that is the amount of flood losses per inundation area, has increased significantly and a figure of \$60 million/km^2 was recorded in 1998 *(10)*. In 2000 heavy rainfall, caused by an autumn rain front, attacked Nagoya city, with a population of 2 million. Almost half the city area was inundated, due to levee breaks and the shortage of drainage capacity (*24)*, causing total losses of \$7.0 billion. It is now recognized that many large cities carry the same risk. If the levees of the main river in Tokyo are broken, the total losses are estimated to be \$280 billion *(25)*. Countermeasures for flood disasters in concentrated urban areas and methods of dealing with floods above design values are two key issues to address.

Why is the modelling of flooding rivers so difficult?

There are many causes for floods, both natural and anthropogenic, as well as many types of flooding, e.g. urban, alluvial and coastal. From a river basin perspective (17), since one of the main causes of flooding is that due to rivers, the modelling of flooding rivers is described herein. The various processes at work in a river flowing overbank *(26, 27*) are shown schematically in Fig. 3. The shape of the cross section generates anisotropic turbulence and longitudinal secondary flows (shown in the main river channel), and these interact with the planform vorticity (shown at the interface between the floodplain and main channel). Fig. 4 shows the plan form vorticity at the free surface of a laboratory channel with one floodplain, for a relative depth of 0.18. The same flow structure may be observed at full scale in Fig. 5, for the 600 m wide Tone river in Japan. However at higher discharges, the planform vorticity weakens and the streamwise vorticity may become dominant at the floodplain edge, masking the planform vorticity (17). Although longitudinal secondary flows are generally weak in straight channels, they greatly influence the distribution of boundary shear stress *(28)*. In meandering channels the flow structures are more complex *(29)*

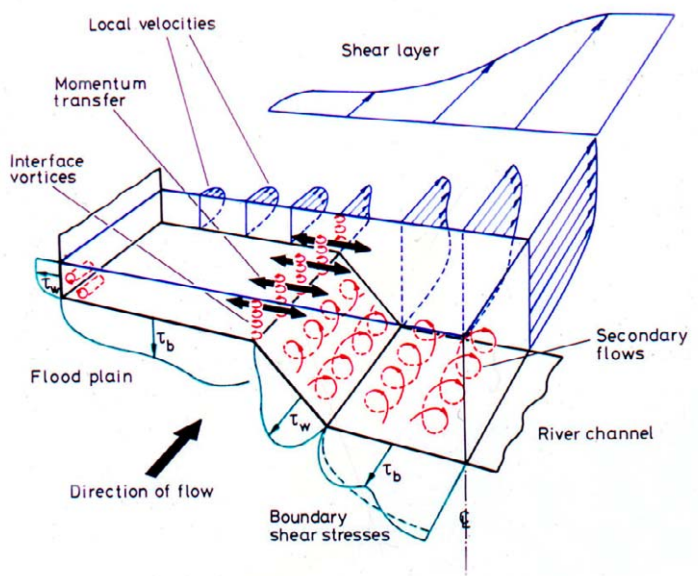

Figure 3 Flow structures in a straight two-stage channel (after Knight & Shiono, 1996)

Engineers traditionally use the Reynolds Averaged Navier-Stokes equations (RANS) or URANS in unsteady flow. The Navier-Stokes equations (NS), which describe laminar flow and were formulated in 1845, have still not been solved and pose one of the outstanding mathematical problems this century. Indeed, the Clay Mathematics Institute of Cambridge, Massachusetts, have offered $1.0 million for a solution. Furthermore, since turbulence has not yet been precisely defined *(14)*, the level of turbulence closure, i.e. degree of complexity admitted in several governing equations, has to be chosen carefully. Empirical coefficients also have to be selected, based on calibration for flows other than in rivers and in some cases not amenable to experimental scrutiny *(13)*. In addition to the turbulence, various coherent structures may also be present *(30)*. The engineer has thus to blend pragmatically theoretical and empirical knowledge in order to simulate the river at all.

One example of this, already seen in Figs 4 & 5, is the formation of large coherent unsteady planform vortices that often form at the edge of a floodplain. Since planform vorticity is *a priori* excluded from all Reynolds averaged Navier-Stokes (RANS) equation models, but is known to be present in most overbank flows (31-33), it behoves those using RANS based 3-D models to limit their application. Thus even simulating flows in straight prismatic channels is not straightforward. When to this are added the complexity of the longitudinal variation of cross-sectional shape, reach averaging of energy, vegetation and sediment, it is not surprising that the best estimates the river engineer makes are prone to uncertainty. Large eddy simulation (LES) and direct numerical simulation (DNS) are likewise still fundamentally limited by lack of suitable data for validation.

Figure 4 Visualization of planform vorticity in a straight two-stage channel, (H-h)/H = 0.180 (after Ikeda, Sano, Fukumoto & Kawamura, 2006).

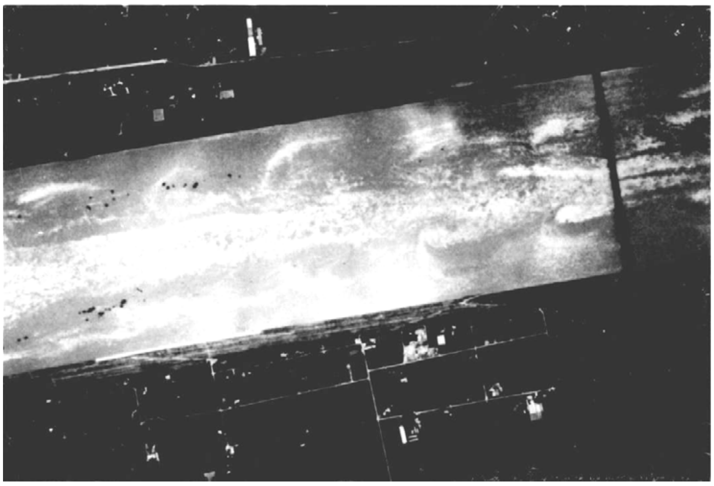

Figure 5 Horizontal vortices observed in Tone River during the 1981 flood. The flow is from right to left (Courtesy, Ministry of Construction of Japan).

Flooding - national R&D initiatives from the UK, China & Japan

UK initiatives

The two government agencies responsible for flood risk management, the Environment Agency (EA) and the Department of Food and Rural Affairs (Defra), joined forces in 1998 to develop a joint program of research, with the aim of improving delivery to practitioners *(34)*. R&D expenditure by Defra and the EA is around \$4.7 million, i.e. ~0.6% of capital expenditure.

The UK Research Councils also support R&D work. For example, the Engineering & Physical Sciences Research Council (EPSRC) supported '*strategic*' research on flooding for over a decade (1986-96), notably that in the Flood Channel Facility (FCF). This FCF programme (~\$7 million) involved teams from 10 UK and European universities looking at fundamental hydraulic and sediment issues in overbank flow. Recent '*targeted*' research (2002-04) on 'Reducing uncertainty in river flood conveyance', funded by the EA & Defra (~\$0.9 million), was then aimed at 'parachuting down' some of this '*strategic research*' on 3-D fluid mechanics into a usable form for practitioners. Modelling software to simulate dominant 3-D effects in simpler 1-D & 2-D depth-averaged river models is now available (See www.river-conveyance.net for further details). Individual universities have now put much of their own and the FCF data on to the web (www.flowdata.bham.ac.uk) for general use. The sharing of expensively acquired data from large-scale national experimental programs is strongly recommended as a way engineers can enhance each others work and increase the pool of data that modellers can use to validate models. Two more recent initiatives by two UK Research Councils (EPSRC & NERC) have just begun: a 'Flood Risk Management Research Consortium' (www.floodrisk.org.uk) and a study 'Flood Risk from Extreme Events' (www.nerc.ac.uk/funding/thematics/free/index.shtml), both running to 2010.

Chinese initiatives

China has implemented the National Basic Research Program (also called the 973 Program) to increase its investment in fundamental research, including research related to flooding. For example, the Ministry of Science and Technology (www.most.gov.cn) has supported two '*strategic*' projects: "Evolving Law and Maintaining Mechanism of Renewable Capacity of Water Resources in Yellow River Basin" (35 million RMB ($4.1 million), 1999-2004), and "Mechanism of Runoff-Sediment Yield and Transport Processes and their Interaction with Environmental Changes in the Yangtze River Basin" (29 million RMB, ($3.4 million), 2003-2008). The two projects involved teams from 5 universities and 6 research institutes in China. In addition, the National Natural Science Foundation of China (www.nsfc.gov.cn) and Ministry of Water Resources also have provided more than 10 million RMB ($1.2 million) to undertake basic research on flooding. The Government passed new floodplain zoning and land use control legislation in 1998, and in the wake of the 1998 floods a new flood management policy was announced. That policy emphasizes the need to move towards natural resource management in the long-term, and signals a shift from strong dependence on structural measures for reducing flood damage to a more balanced approach using both structural and non-structural measures *(21)*. However, it is likely that structural flood control measures will continue to be important *(35)*.

In 1980 the Chinese Hydraulic Engineering Society (CHES) initiated the International Symposium on River Sedimentation (ISRS) as a triennial event and obtained sponsorship from UNESCO. Nine symposia of this series have been successfully convened, five of which were held in China, including the Ninth, which was at the site of the spectacular Three Gorges Project TGP) in Yichang, in 2004 (www.irtces.org/isshhu/9ISRS.htm).

Individual universities also play a key role in fluvial research. The State Key Laboratory of Hydraulics (SKLH) at Sichuan University, Chengdu, established in the early 1950s, focuses on many aspects of flood hydraulics, river processes, river and reservoir morphology, development of numerical models, and physical model studies. The latter include flume experiments and scale models of river training, reservoirs and hydropower works. The CRS-1 series of numerical river models, developed by SKLH, has been used to determine water and sediment routing in rivers as well as the effects of human activities. The model was verified rigorously using laboratory and field data from over 100 rivers in SW China. It predicts sediment deposition and capacity recovery of reservoirs, and is useful in designing bank protection for flood control dykes *(36)*.

Japanese initiatives

Most major rivers in Japan are composed of a main channel and floodplains enclosed by high levees in downstream areas of the alluvial plain. Flow structures and resistance characteristics of such compound channels have therefore been studied vigorously *(37)*. In recent years, large areas of the floodplains have become wooded, because of main channel degradation, thus aggravating the risk of flooding by overtopping of the levees. High grade levees are therefore needed to delay breaching and to give time for evacuation *(10)*. After several severe flood disasters in cities with high concentrations of population, it is now recognised that it is not possible to prevent flood disasters by river control alone and comprehensive flood management measures have to be considered. For example, the River Bureau of M.L.I.T submitted an act to the Diet in 2003, with the following contents *(10)*:

1) Prefectural governor, mayor and sewerage administrator to make a comprehensive joint plan for flood disaster prevention.
2) M.L.I.T. to announce to residents those areas likely to be inundated.
3) House developers must build rainfall storage facilities in recently inundated areas.
4) Local government must designate both a refuge route and a refuge place (hazard map).

M.L.I.T. established an Urgent Action Plan for Measures against Flood Disaster in 2005, recognising that it is necessary to predict an inundation process not only by an embankment failure but also by drainage deficiency. Flood simulation techniques have been developed for river basins, including city areas *(38)*, and are used extensively for predicting the inundation areas of many hazardous cities in Japan. In the last 30 years, 14 subway stations and 7 underground malls have suffered inundation damage. Large-scale modelling tests on the inundation into underground space have been conducted by the Disaster Prevention Research Institute of Kyoto University *(39)*.

Flooding – International collaborative R&D initiatives from Europe

The European Commission (EC) Research Directorate General (formerly DG XII) has funded research on many issues in the science and management of flooding since the early 1980s. The number and scope of the projects has increased in the past decade, driven partly by the need to address the real and apparently increasing needs of the citizens of Europe for protection from floods (see Table 1). This research has been set mostly within a broader programme of science on understanding natural hazards and hydrogeological risks. In all, 100 projects have been funded through a variety of specific programmes and mechanisms with a total Commission funding in excess of €90 million ($109 million); access to summary information on most of these projects is possible through the EC research server http://www.CORDIS.lu, in book form *(40)* and via the links given in Table 2.

These projects cover a diversity of topics, ranging from remote sensing of weather conditions, climate impact on floods and paleo-flood assessment, socio-economic factors in flood management, hydrological and hydrodynamic model integration, debris and sediment movement in high energy rivers and exploitation of Telematics in managing flood risk.

Table 1 EC funded research project related to flood risks

Framework Programme	Project Start Dates	Number of Projects
FP2 and earlier	1990 and earlier	9
FP3	1991 to 1994	19
FP4	1995 to 1998	34
FP5	1999 to 2003	38

Table 2 Links to project reports

Project	Link
RIBAMOD	http://www.hrwallingford.co.uk/projects/RIBAMOD/index.html
RIPARIUS	http://www.nwl.ac.uk/ih/www/research/briparius.html
MITCH	http://www.hrwallingford.co.uk/Mitch/default.htm
University of Birmingham	http://www.actif-ec.net/library/review_EU_flood_projects.pdf

The findings for projects in FP3 and FP4 are well documented in the end-of-project reports of the FP4 and FP5 Concerted Actions: RIBAMOD, RIPARIUS and MITCH. The UB report identifies 100 flood related projects from CORDIS and also includes some statistics on the participation in the EC research on flood risks, showing that four countries (Italy, France, the UK and Germany) account for over half the partners in all the projects and nearly three quarters of the project co-ordinators. This concentration of research activity appears to follow approximately the extent of the flood problems in these countries. Two exemplary flood projects from the 5th and 6th Framework are now briefly summarised.

European research, 5th Framework - Investigation of Extreme Flood Processes (IMPACT)

The IMPACT project (http://www.samui.co.uk/impact-project/) addressed the assessment and reduction of risks from extreme flooding caused by rare natural events or the failure of dams and flood defence structures. IMPACT involved directly 11 institutes from different countries, with additional collaboration from 4 other countries including Canada and the US. The work programme was divided into five main areas, addressing issues raised by the earlier FP4 CADAM Concerted Action on: breach formation, flood propagation, sediment movement, modelling uncertainty and geophysical investigation techniques. All areas were drawn together through an assessment of modelling uncertainty and a demonstration of modelling capabilities through a case study application.

The nature of extreme flood events means that little reliable data exist through which processes may be understood and models validated. Consequently, a common approach adopted within many of the research tasks was to undertake field and laboratory work, to collate reliable data sets through which model performance might be assessed and subsequent development undertaken. To ensure that model performance was as objective as possible, many of the benchmark tests were undertaken 'blind'. Full results of the research work are available via www.impact-project.net and details of the benchmark tests will be published in a special issue of the Journal of Hydraulic Research in 2006.

European research, 6th Framework – An Integrated Project: FLOODsite

The 5-year FLOODsite project (http://www.floodsite.net) is the largest ever EC research project in the area of flood management, and was commissioned in March 2004. The Community grant to the FLOODsite consortium's €14 M ($16.9 million) budget is just under €10 M ($12.1 million). Other funding is coming to project partners from national sources. The project consortium (led by HR Wallingford) involves over 30 of Europe's leading institutes and universities. The project is interdisciplinary, integrating expertise from across the physical, environmental and social sciences. FLOODsite will deliver:

- An integrated, European, methodology for flood risk analysis and management.
- Consistency of approach to the causes, impacts and management of flooding from rivers, estuaries and the sea.
- Techniques and knowledge to support integrated flood risk management in practice covering pre-event planning, event management and post event recovery.
- Dissemination of this knowledge to the broader community.
- Networking and integration with other EC national and international research.

Conclusions

Engineers are uniquely placed to deal with the issue of river basin management. The public, like some politicians, generally have short memories, and a 'complacency cycle' with respect to flood events often sets in, as illustrated in Fig. 6. The expenditure on flood related R&D also tends to be cyclical *(38)*, and in a world of increasing risk there needs to be recognition of the issues outlined in this article. Some of the key issues are:

- A need to develop strong national programmes in flood risk management.

- A need to fund R&D on flooding at a consistent level, based either on a percentage of annual expenditure on flood defence works or on infrastructure assets at risk.
- A need to improve the science base by improved hydrometry, full scale measurements, and post project/flood appraisals.
- A need to improve the sharing of flood related data, modelling expertise and simulation results, as each river basin in the world is unique.

A need for greater international collaboration in all aspects of river engineering, as demonstrated by the Fluvial Hydraulics Section of the International Association of Hydraulic Engineering and Research (IAHR) (15, 16 & 41), the EU (17, 40), the World Association for Sedimentation and Erosion Research (WASER) (42) and other bodies.

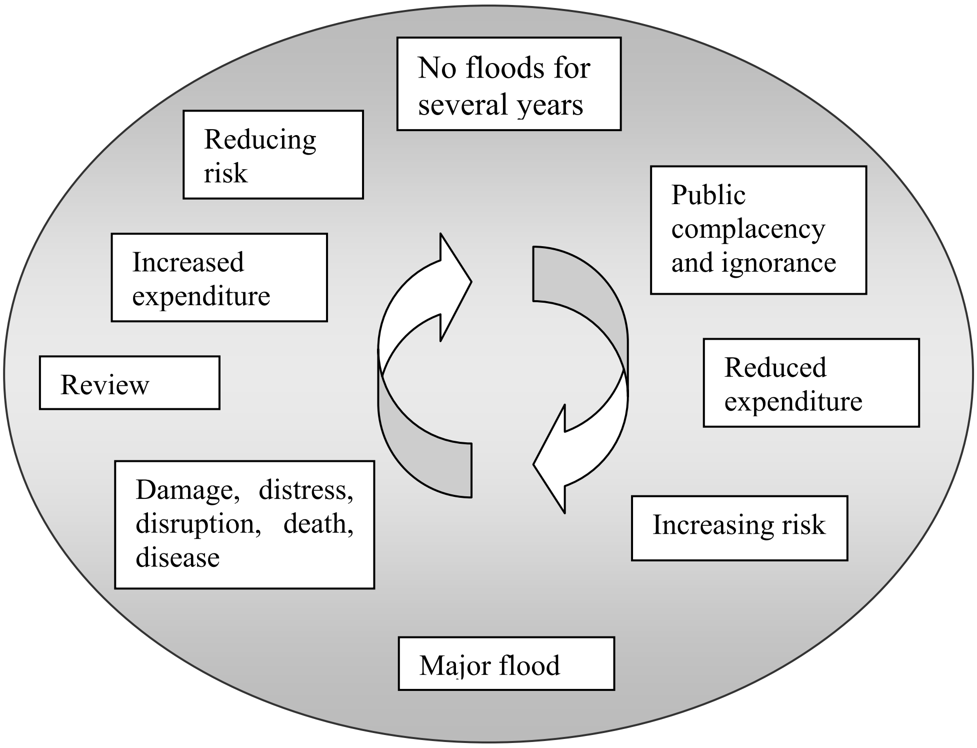

Figure 6 Hypothetical Risk – Expenditure Cycle (Samuels, 2005)

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