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Flood risk and flood management

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Abstract

Risk management has been established as a well defined procedure for handling risks due to natural, environmental or man made hazards, of which floods are representative. Risk management has been discussed in many previous papers giving different meanings to the term—a result of the fact that risk management actually takes place on three different levels of actions: the operational level, which is associated with operating an existing system, a project planning level, which is used when a new, or a revision of an existing project is planned, and a project design level, which is embedded into the second level and describes the process of reaching an optimal solution for the project. The first two levels will be briefly described in the paper. It will be emphasized that the transition from the first to the second level is a dynamic process. As the value system of a nation changes, and as the natural boundary conditions are modified by human actions or global changes, an existing system will be found not meeting the demands of the present society, and actions on the second level are initiated. The decisions for change depend on the changes in options available for handling a flood situation, as well as on the changes in risk perception and attitudes towards risk. On the third level, the actual cost of a design are evaluated and compared with the benefits obtained from the planned project. In particular, on this level the residual risk is considered, i.e. the risk which remains even after a project is completed and fully operational.

Keywords: Flood risk; Flood management; c

1. Introduction

Flood risk management as a process has been discussed extensively, (UNDRO, 1991; Plate, 1997) without regard to the actors involved in the process. It is more useful to interpret risk management as a process which involves three different sets of actions, depending on the operators involved. The first is the set of actions which are needed to operate an existing system. It consists of four parts, as will be described briefly in the second chapter. When the system is no longer adequate to meet the needs of people—for example, because of changes in land use, increases in population, or climate change—then the next set of actions starts: the planning for a new or revised system, which is adapted to the changed conditions. The planning process leads to a decision for the new system. Embedded in this set is the third one, the process of obtaining an optimum design for and constructing a project. Many hydraulic engineers consider only the third level as part of their activity. To them, the solution to flood problems is a logical chain starting with flood studies by hydrological methods, such as extreme value analysis, selection of a design discharge, deciding on a structural system for containing the design discharge, and implementing what has been decided on—in other words, the solution to flood problems is considered a classical engineering task like many others, such as designing a highway or a sewage disposal system. In a way, this is still true for the tasks of some hydraulic engineers,

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namely those that are called to do the designing and building of a flood protection system, once it has been decided that such a system is to be built. In a modern framework of design, this task can also be very demanding, as it is required to do such a engineering job in a most efficient way and including a thorough assessment of the safety of the engineered system against failure (Plate, 2000a; Vrijling, 1989; Vrijling et al., 1995). On a higher level, however, the engineering approach must be seen as embedded in the decision process of planning for flood risk management. Not only engineers are involved in this process, but also many social groupings of a society, from political decision makers to people that are directly exposed to floods. The sequence of the three sets of actions is a result of the fact that the task of flood risk management is never done. Each generation will have to reconsider its options, and sets its own priorities according to the prevailing value system of the society. This aspect is developed in detail in the second part of the paper. It leads to the planning process as response to changes in society and environment, as described in the third part of the paper. Engineering aspects (the third set of actions) are only touched upon, with reference to earlier contributions to the subject.

2. Flood risk management for an existing system

Flood risk management in a narrow sense is the process of managing an existing flood risk situation. In a wider sense, it includes the planning of a system, which will reduce the flood risk. These two aspects of flood risk management will be considered separately, starting with the management of an existing system that consists of the processes indicated in Fig. 1. Risk management for the operation of an existing flood protection system is the sum of actions for a rational approach to flood disaster mitigation. Its purpose is the control of flood disasters, in the sense of being prepared for a flood, and to minimize its impact. It includes the process of risk analysis, which provides the basis for long term management decisions for the existing flood protection system. Continuous improvement of the system requires a reassessment of the existing risks and an evaluation of the hazards depending on the newest information available: on new data, on new theoretical developments, or on new boundary conditions, for example, due to change of land use. The hazards are to be combined with the vulnerability into the risk. The vulnerability of the persons or objects (the 'elements at risk') in an area, which is inundated if a flood of a certain magnitude occurs, is weighted with the frequency of occurrence of that flood. A good risk analysis process yields hazard or risk maps, which today are drawn by means of Geographical Information Systems (GIS) based on extensive surveys of vulnerability combined with topographic maps. Such maps serve to identify weak points of the flood defense system, or indicate a need for action, which may lead to a new project. Other weaknesses of the system become evident during extreme floods. For example, the Oder flood of 1997 has indicated (Kowalczak, 1999) that weak points contributing to flooding of a city in a flood plain not only are failures of dikes, but also seepage through the dikes and penetration of flood waters through the drainage system, i. e. through the sewerage system or water courses inside the city.

Risk analysis forms the basis for decisions on maintaining and improving the system, which is the second part of the operation of an existing system. It is a truism that a system requires continuous maintenance to be always functioning as planned, and new concepts of protection may require local improvements of the existing system. A third part of the management process is the preparedness stage, whose purpose is to provide the necessary decision support system for the case that the existing flood protection system has failed. It is evident that no technical solution to flooding is absolutely safe. Even if the system always does what it is supposed to do, it is hardly ever possible to offer protection against any conceivable flood. There is always a residual risk, due to failure of technical systems, or due to the rare flood which exceeds the design flood. The Oder river flood of 1997 (Bronstert et al. 1999; Grünewald et al., 1998) comes to mind.

It is the purpose of preparedness to reduce the residual risk through early warning systems and measures which can be taken to mitigate the effect of a flood disaster. An important step in improving an existing flood protection system is the provision of better warning systems. Obviously, the basis for a warning system has to be an effective forecasting

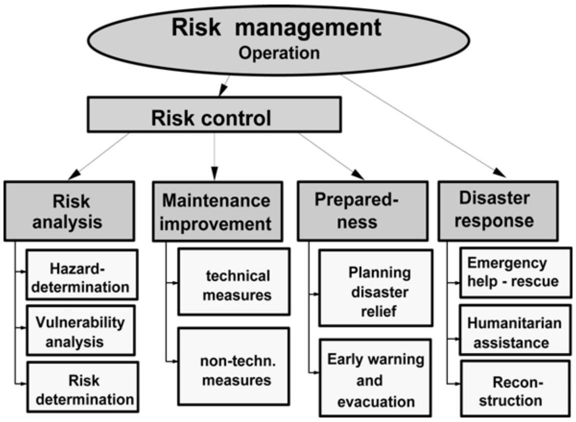

Fig. 1. Stages of operational risk management, adapted from Eikenberg (1998).

system, which permits the early identification and quantification of an imminent flood to which a population is exposed. If this is not accurately forecasted or at least estimated early enough, a warning system for effective mitigating activities cannot be constructed. Therefore, it is an important aspect that systems managers remain continuously alerted to new developments in flood forecasting technology, and to be prepared to use this technology to the fullest extent.

The final part of operational risk management is disaster relief, i.e. the set of actions to be taken when disaster has struck. It is the process of organizing humanitarian aid to the victims, and later reconstruction of damaged buildings and lifelines.

3. Flood protection as a dynamic process

Historically, flood protection underwent a number of development steps, depending on the type of flood: a flash flood obviously requires different responses than a flood which inundates the lower part of an alluvial river. Flash floods have high velocities and tremendous erosive forces, and only extremely solid structures can withstand their destructive force. The only way for escaping a flash flood used to be to get out of harms way by moving houses and other immobile belongings to grounds which are so high that no floods can reach them. Later on, banks were strengthened with rip–rap or concrete linings against erosion. The damage potential of flash floods is confined to the direct neighborhood of the river, the total damage usually is not very extensive—although due to the high velocities, the individual damage to structures or persons caught in such floods is very high. In recent times, flash floods have caused large losses of life only of people unfamiliar with the potential hazard, such as tourists, who camp in the mountain canyons. In some areas, flash floods can be avoided to some extent by flood control reservoirs. However, usually flash flood protection through flood water storage in reservoirs is a viable option only if it can be combined with other purposes, such as hydropower generation.

Very different is the response to floods in alluvial plains of large rivers. Velocities are comparatively low, and the main danger to life is from the wide lateral extent of inundated areas, as has been experienced in recent times during the floods in Mozambique in February, 2000, in which the Limpopo river flooded a large part of Mozambique south of the Zambezi river. In the earliest days, people responded to such floods by moving the location of their cities and villages out of reach of the highest flood which they experienced, or of which they had clear indications, such as deposits on old river banks along the flood plain. Typical is the situation in the upper Rhine valley between Basle and Mannheim, where one finds the old villages and cities always on high ground or on the high bank of the old river flood plain. And if an extremely rare flood was experienced, which reached even higher, then people had no choice but to live with the flood damage. In other areas, people learned to live with frequent floods: for example, in Cologne the low lying parts of the city near the Rhine used to experience regular floods and they were prepared for it. Their method of protection is called today object protection or flood proofing: protection through local measures, ranging from temporary solutions such as temporarily closing openings with sandbags or brick walls, or just by moving one's belongings to a higher level of the house, to permanent solutions, such as building houses on high ground, perhaps on artificially generated hills, as was done by farmers living on small islands off shore of Northern Germany on the North Sea.

Population pressure and lack of other farmland made people to move into the flood plain, and to protect themselves by means of dikes: already the ancient Chinese started to build dikes along their large rivers to protect farmland and villages. The Herculean tasks of dike building along the Yangtze and the Yellow river, against floods of unimaginable magnitude, united the Chinese people into a nation. No longer was the individual responsible for his own safety, for flood protection had become a national task. However, protection by means of dikes cannot be perfect, as dikes can fail, and floods can occur which are larger than design floods. In recent times, the failure of dikes caused some of the largest flood disasters in the world, with the floods on the Yangtze a very illustrative example. Table 1 (Wang, 2000) gives a summary of historical floods on the Yangtze river, which in 1998 experienced one of the largest floods of the 20th century. Through a superhuman effort, the Chinese people were able to protect the vast area of the lower Yangtze flood plain from being flooded, and managed to reduce the number of casualties to the smallest number of any comparable floods in the twentieth century—in spite of a dramatic increase in population in the affected area.

But the data of Table 1 also reveal one of the most fundamental features of rivers: in flood plains they are not stationary, but tend to shift their beds continuously. When the large rivers of the world leave their mountain confinement, they carry large amounts of sediment into the flood plain, and because of the lower velocity sediment deposits on the plain. Without interference by man, the rivers build up alluvial fans: moving across a fan shaped area over which they spread their sediments—a rather complex process which only recently has found some theoretical discussion (Parker, 1999). This is in conflict with the demands of settlers, who want to have the state of nature to remain unchanged, so that property boundaries are maintained forever. In fact, a study by the University of Bern (Hofer and Messerli, 1997) on the effects of river floods in the delta of the Brahmaputra and Ganges rivers in Bangladesh showed that people were less concerned with river floodings, which they had learned to live with, but with the shifting of the river banks during floods, which destroyed land on one side of the river and built up land without owner on the other.

The effort of keeping the large rivers of China within the boundaries set by the dikes is an extreme case of man fighting the rivers, rather than to live with them. For by confining the river between dikes, one also confined the area on which sediment could be deposited, and a gradual increase of the river bed between the dikes is unavoidable. This is illustrated by the fact that the Yangtze flood of 1998 was a flood with a recurrence interval of only 8 years. Yet in terms of stages in the middle reach between the cities of Yichang and Wuhan it was higher than the stage observed in 1954, and in many places the highest stage ever recorded. The engineer who planned the works on the upper Rhine knew the sedimentation problem of the alluvial Rhine, and he found an at least temporary solution by straightening the river: this increased the erosive capacity, and in essence moved the sediment problem downriver: since the sediment was not deposited in the upper Rhine, it had to be deposited further downstream. Fortunately, the Rhine is a small stream by comparison with the large rivers of Asia, and the sediment problem proved to be manageable. The situation in China is different: against the floods of the large rivers, in particular the Yellow river, the Chinese won many battles, but they had to suffer many setbacks when the rivers breached their dikes. In extreme cases, the river even spontaneously shifted its course, destroying all settlements in its way.

The case of the Yangtze river is not only the story of a fight of epic proportions against nature, it also is an illustration of the development of the technology of defenses against floods. Protection of the vast fertile lands of East Central China against earliest floods was sought through dikes, and when these proved ineffective, the dike system was supplemented by polders, into which water was to be stored when the flood stage exceeded critical levels. But the relentless growth of the population forced people to move into the polders: today, the polders are inhabited by many thousands of people, and during the 1998 flood, the largest flood diversion basin—the Jingjiang polder with a surface area of 920 km^2 and storage capacity of 6 billion m^3, which had been the main reason for the reduced number of losses in 1954 as compared to earlier floods of similar magnitude—was not flooded because of the opposition of the people living in the polder.

Table 1
Major floods on the Yangtze river with the highest ever observed flood in 1870. (Modern hydrologic measurements started in 1877). The recurrence interval of the 1998 event in terms of maximum discharge is about 8. The Yangtze river experienced about seven floods of approximately the same magnitude between 1896 and 1998, of which the last four of the table are examples adapted from Wang (2000)

Year	Discharge at Yichang station (m^3/sec)	Return period (years)	Inundated area (km^2)	Grand levee breaches (No.)	Death toll (persons)
1788	86,000	140	70 counties		10,000
1870	105,000	>200			30,000
1931	64,600	10	40,000	300	145,000
1935	56,900				142,000
1954	66,800	10	31,700	60	33,000
1998	63,300	8*	3210	1	2292

The different examples of adjustment to floods serve very well to illustrate that modern options for flood management are not absolute, but depend on three variable factors: the available technology, the availability of financial resources, and the perception of the urgency of the need for protection, which is embedded into the value system of a society. As these factors change with time, the options which one has to consider, also change, and new paradigms of thinking may require new solutions to old problems. When one looks at the time development of a protection system—not only against floods, but also against all kinds of other hazards—it is evident that this is a circular process, as indicated schematically in Fig. 2. A state of a river system may be considered satisfactory at a certain time, meeting both the demands on the river as a resource and for protection against floods. But new developments take place, leading to new demands on the river. Unanticipated side effects may occur, which could impair the functioning of the system. After some time, the system is considered inadequate, and people demand action to change the existing conditions.

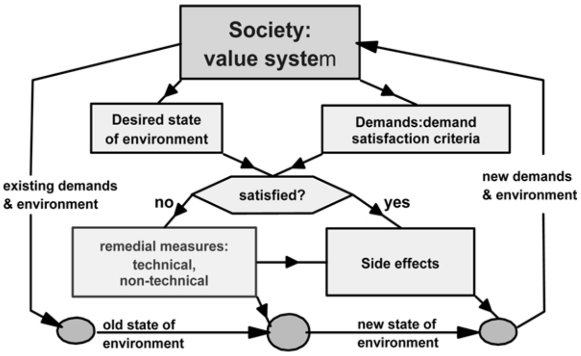

Fig. 2. The cycle of responses to changing value systems and changing environmental conditions for water management.

In this circular process, the determining factor of technology is self evident. When J. G. Tulla in the early 19th century planned his momentous correction of the Rhine river between Basle and Mannheim, he was planning a task for at least two generations, with people who would be ordered to work on the river with shovels and wheelbarrows to create the long lines of dikes along the river. In modern times, such a task would be finished in a few years, with only a few professionals, such as drivers of caterpillars and other large earth moving equipment, with modern geotechnical engineering skills guaranteeing long lasting earth dikes. As a second factor, the scientific basis for planning changes with the advance in scientific knowledge, complemented by the translation from science into engineering. Remedial measures have to be planned according to the new state of the art. Hydrologic inputs have changed, or better methods of calculation require a new evaluation of the flood potential (or the hazards).

When we look for further technological development in flood control, many new possibilities have become available through modern communication technology. Of great significance is the development of modern forecasting and early warning systems. The possibilities of remote sensing are just being recognized, and the technology for converting forecasts from mathematical models of meteorological weather situations into warning systems is being explored at many locations. Indeed, great strides have been made in forecasting and warning for large rivers, with fairly long lead times between forecast and actual occurrence (Wilke, 1998), and hydrodynamic models are available which can rapidly convert meteorological precipitation forecasts into flood forecasts (Moore and Jones, 1998; Göppert, 1998). In forecasting flash floods, which requires localizing usually randomly occurring convective storms, the success has not yet been high (Quiby and Schubiger, 1998, for an example of forecasting in the Alps). However, forecasting and warning is only one aspect of the possibilities of communication technology—it also permits the dynamic operation of flood control systems. A reservoir for flood control can be controlled on the basis of forecasting results to provide maximum protection by chopping off the peak of the flood wave. For other cases, such as on the Rhine river, series of barrages can be operated dynamically through remote control to provide maximum storage of flood waters in the retention space of the barrage system.

There is also the human influence on the system. Flood frequencies may change due to modifications of the catchment: a formerly heavily wooded rural area was cleared for agriculture, a patch of land once used for agriculture was converted into urban parking lots, or runoff is increased because agricultural heavy machinery compacts the soil. Other causes may be found through the pressure of increasing populations on the land: as an example, the rather dramatic effect of peoples encroachment on flood plains of the Yellow river in China may be cited. There, the lower part of the river has a flood plain many kilometers wide and contained between major dikes. In the course of time, farmers have started to ignore the main dikes and have moved into the flood plain area. Today more than 1.7 million people are living on and plowing 270,000 ha farmland of the lower Yellow River flood plain within the grand levees (Wang, 2000). The people built dikes along the main river channel and prevented the floodplain from being flooded, consequently sediment deposited mainly in the main channel. In the 1950s, 80–100% of sediment was deposited on the flood plain, whereas in the past 15 years 74–113% of sediment deposited in the main channel (more than 100% because of additional erosion in the middle reach). Therefore, the amount of sediment deposit in the main channel was increased, in spite of the fact that the total amount of annual sediment deposit in the lower Yellow River was reduced due to activities in the upper reaches of the river. The result was that the channel cross section decreased, and the water conveying capacity of the river channel is greatly reduced.

A governing factor in the decision process for flood control measures is the availability of funds. The financial resources for flood protection usually have to come from public funds and are in competition with other needs of society. But finances are not the only issue. Decisions for flood protection also depend on the changing value system of the society, starting with the solidarity of the non-flood endangered citizens of a country with those endangered by floods. For example, in the not so distant past the infringement on the natural environment by engineered river works usually was accepted as the price to pay for the safety from floods. However, in recent times flood protection by technical means faces serious opposition, not so much because of concern about the long range geomorphic adjustment of the river (which is bound to occur sooner or later), but because dikes and land development cut off the natural interaction of a river and its riparian border. The reduction of wetlands and the impairment of riparian border fauna and flora in many—particular in the developed—countries causes great concern of environmentalists and has led to a backlash against flood protection by dikes and reservoirs. For example, in some parts of Germany people are actually talking about removing some of the existing flood protection works. In other countries, complete removal of existing dams has been talked about as a means of giving back to nature what used to be hers (but also because some people find the failure risk of a dam unacceptable). Pristine nature is assumed to have a right of its own that needs enforcement, in order to reduce the steady decline of rare species, and restore habitats for wild life given up in the past in favor of human development.

The recognition that the adjustment process is open ended—is a transient only in the stream of development—is part of the principle of sustainable development: while revising or constructing a flood protection system to meet our needs, this principle requires us to consider that future generations may have other needs and other knowledge, and that we should not cast our solutions into immutable solidity, such as producing irremovable gigantic concrete structures, or soils that are permanently degraded, or eroded down to base rock. For a discussion of issues involving sustainable water resources management on the basis of the original Brundtland report (WCED 1987) see Jordaan et al. (1993) and ASCE (1998).

4. Flood risk management: project planning

When we look at flood protection from the point of view of a modern decision maker, flood management directed at developing a new project starts with a set of guide lines which are based on the value system of the present society. In this setting, and in countries like Switzerland or Germany, environmental protection and flood management are tasks of similar importance, and the optimum flood control system is a compromise between these two competing objectives. To illustrate this process, the case of integrated planning for flood safety and a healthy environment as part of a sustainable project is shown schematically in Fig. 3 (adapted from A. Götz, Swiss Institute for Water Resources, personal communication). The societal goal of sustainable development is converted into a set of objectives: objectives for the safety, and objectives for the preservation of natural functions. If an analysis of the existing situation is showing that existing conditions meet the objectives, then the only action required is to keep it that way, i.e. to maintain the system and to prevent intrusion of external demands that could alter the situation to the negative. For example, to prevent settlement of a flood plain, it might be necessary to set up legal barriers.

If the existing situation does not meet the objective, a process has to be initiated for improving the situation. Then the next stage of the decision process is to find the best among possible alternative plans which meet the objectives of the design, based on the degree of protection decided on by the political process. Because of the difficult nature of the decision, it is the current view that the conflicts should be discussed and resolved by involving the people affected by the measures to be taken—with the decision maker becoming a broker, aided by a team of experts, to advise the people and reach a consensus on the level of demanded flood protection—for example, against the 100 or 1000 year flood. Note that for a criterion such as the 1000 year flood there do not exist statistically significant numbers. Therefore, the procedure by means of which the level is decided is part of the decision process. Not infrequently one finds that none of the alternatives meets all the objectives. There are cases when financial, social, or political constraints make it impossible to meet all requirements. Then it is necessary to temporarily change the objectives, to make them to conform more to the present reality. In this manner, many well meaning nature preservation objectives had to be overruled, or protection objectives had to be set aside. In the final stage of the flood protection project the alternative selected is implemented.

The technical procedure for preparing the decision basis for the process of Fig. 3 is risk assessment, as shown in Fig. 4. In response to the reassessment of the flood danger the phase is initiated of project planning for an improved flood disaster mitigation system. Experts involved in risk management have to ensure that the best existing methods are used to mitigate the damages from floods: starting with a clear understanding of the causes of a potential disaster, which includes both the natural hazard of a flood, and the vulnerability of the elements at risk, which includes people as well as their properties. Risk assessment as tool for project planning yields the information required for selecting the optimum among the possible project alternatives. It forms the basis of the evaluation process of Fig. 3.

The first step in risk assessment for floods is the design of hazard maps. The same type of maps as used for operational risk management are also the foundation on which decisions for disaster mitigation are to be made. Risk assessment does, however, not stop at evaluating the existing risk. Rather the analysis process has to be repeated for each of the structural or non-structural alternatives for mitigating flood damage. Good technical solutions integrate protection of rural and urban areas, through coordinated urban storm drainage projects, stream regulation in rural and municipal areas with bridges and culverts designed to pass more than the design flood. Structures including reservoirs and dikes are usual technical options, but other possibilities adapted to the local situation also exist, such as bypass canals and polders on rivers. Risk assessment, for example, also includes examination of the option to do nothing technical but to be prepared for the flood if it strikes, i.e. to live with the situation as is and be prepared for the floods.

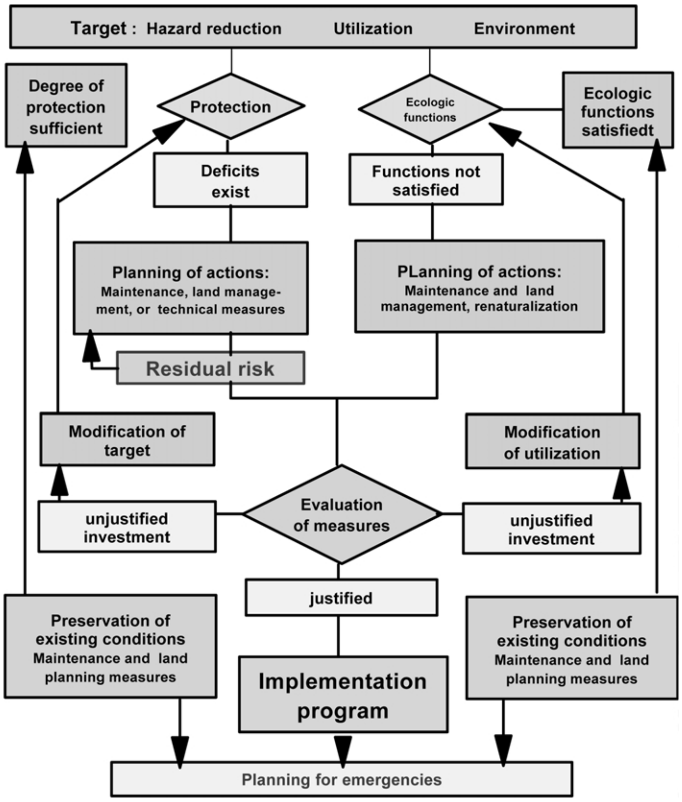

Fig. 3. Integrated project planning for considering flood safety and ecology as complementary objectives, adapted from A. Götz, personal communication (1999).

It is obvious that the process of evaluating the risk depends on the technical or non-technical solution contemplated, and therefore, the risk mitigation step is not an independent third step in series with the second, but it interacts and the two are interdependent: the technical or non-technical solution is evaluated, the new hazards determined and the decision basis is enlarged by this analysis. The outcome of each of the analysis is the risk, which is defined as:

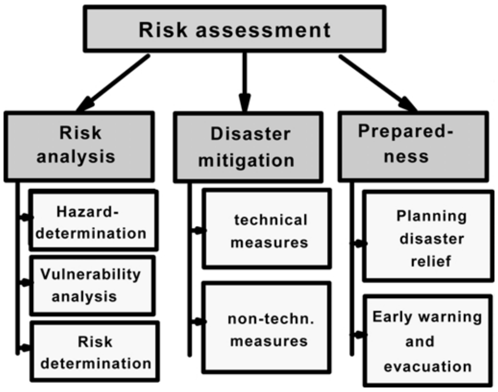

Fig. 4. Project planning as part of risk management.

$$RI(\mathbf{D}) = \int_0^\infty K(x|\mathbf{D}) f_x(x|\mathbf{D}) \mathrm{d}x \qquad (1)$$

It is based on a consequence function $K(x|\mathbf{D})$,) where x is the magnitude of the event causing the load s (for example, the water level of the flood), and $\mathbf{D}$ is the vector of decisions, (for example, for the height of a dike along a river), that influence the (usually adverse) consequences K (dropping the reference to $\mathbf{D}$ from here on) of any event x. The consequences could be the cost of replacing the damage to be expected by a flood of magnitude or level x. Obviously, the consequences depend on the decisions $\mathbf{D}$. The function $f_x(x|\mathbf{D})$ is the probability density function (pdf) of the (usually annual) occurrence of x, so that Eq. 1 is the expected value of the consequences K.

The decision which of the possible alternatives to use depends on a number of factors, among which the optimum solution in the sense of operations research is only one, albeit an important factor. The classical approach for optimizing a cost function (Crouch and Wilson, 1982) has been adapted by Freeze et al. (1990) to the case of water projects, and their analysis can easily be extend, at least formally (Plate, 2000b) to the case of flood protection systems. But there might be other compelling reasons for deciding on a particular alternative, even if it is not cost effective for flood protection. One of these reasons might be the expected loss of human lives. This is the second type of risk to be considered. For this risk, K is the number of people killed when event x occurs with n_o people affected. The use of this quantity in a decision process based on cost benefit considerations is quite critical, as it implies putting a value on the life of a human being. Therefore, it usually enters as a constraint: engineers are required to devise systems in which the probability of any human being losing his or her life is so low that it matches other risks which people are readily exposed to. The question of acceptable risks involving losses of human lives has been discussed by Vrijling et al. (1995).

5. Conclusions

The paper has been concerned with setting up a framework by means of which the different processes of flood management can be classified. It was found useful to distinguish three levels within flood risk management: the project operation level, the project design level, and the level of engineering decision making involving estimating the risk in the setting of a cost benefit analysis. The risk management process at the operational level has been described extensively in previous papers—for example in Plate (1997). Details therefore have been omitted—as have details of the third level, which is the structural design level, about which much has been published. It was an interesting exercise to identify the different processes which contribute to the three different levels, and it was particularly important to identify the changing conditions under which flood protection has been approached during different times. It was concluded that the natural environment is always changing due to natural processes such as geomorphological modifications of a flood plain, or due to human interference, such as using the flood plain for agricultural purposes and cutting the flood plain into different regions by building dikes. Under such conditions, sustainable development is difficult to achieve and the efforts, which the Chinese population is making for preventing the large rivers of China to behave like natural rivers are cited as examples of non-sustainable development. This implies that the fight against the huge floods of the Yangtze and Yellow River will never be completely won, and also the less dramatic changes of smaller rivers like the Rhine need to be constantly observed and solutions for flood control adjusted to the changing conditions.

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