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Floods are always in conflict with floodplain development. No amount of structural protection will remove the risk of being damaged by flood flows and the mud, debris and pollution that accompany them. Hence the challenge is to be prepared to manage floods and mitigate the resulting damage when floods occur. In short, this means allowing space for floods when they occur and keeping that space available when they are not occurring. The challenge is to find the mix of open space and development on floodplains that maximizes the net expected monetary, environmental and social benefits derived from them. This chapter discusses some floodplain management approaches being considered in Europe and in North America, both motivated by the extreme flood events that occurred in the mid-1990s and early 2000s. Time will tell if any of these approaches are successfully implemented.

1. Introduction

Just as droughts are defined as unusual scarcities or deficits of water, floods are defined as unusual surpluses or excesses of water. The result is higher than usual water levels that extend out onto floodplains. They occur in river basins, usually as the result of a lot of rain. They occur along coastal areas, usually as the result of severe storms and occasionally as the result of earthquakes. Floods are natural events. Flood damage usually results because humans and their structures occupy the space needed to store the excessive amounts of water. When a flood comes, as it will, these objects get inundated. To the extent that structures occupy some of the space floods need, flood levels increase, thereby flooding larger areas. The occurrence of flood events is not often enough to keep reminding people that floodplains can and do get wet. Flooded buildings and sandbags, such as shown in Figure D.1, are symbolic of what happens on occasion when floodplains are used, and often beneficially used, for other activities incompatible with flood prevention.

In mid-August 2002 Central Europe received an abnormal amount of rain. Floodwaters inundated floodplains along three major rivers, claiming around 100 lives and causing over 10 billion euros of damage to property in Germany, Russia, Austria and the Czech Republic. The upper left image in Figure D.1 illustrates a small but particularly damaging part of that flood in the historic portion of Dresden, Germany. The map in Figure D.2 shows the affected rivers.

The top image in Figure D.1 shows the River Elbe (Figure D.2) flooding the historic portion of Dresden in mid-August 2002. This flood of record exceeded the highest of floods in 157 years of records. Central Europe was not the only place getting flooded in the summer of 2002. By August of that year, flooding across Asia had claimed an estimated 1,800 lives. The waters of Dongting Lake and the Xiangjiang River (Figure D.3), which flows through the provincial capital of Changsha, were near all-time highs. If the sandbag dykes (middle image of Figure D.1) had failed around the 2,800 square-kilometre (1,070 square-mile) Dongting Lake that acts as a giant overflow for the flood-prone Yangtze River, over 10 million people and 667,000 hectares (1.6 million acres) of fertile crop land would have been flooded.

In the summer of 2002, millions of people in Bangladesh, India, Nepal, Thailand and Vietnam were

Figure D.1. Scenes of flooding, the efforts made to prevent flood damage, and coping at times of high flows and water levels.

Figure D.2. The Rivers Danube and Elbe in Central Europe experienced their most extreme flood of record in August 2002.

Figure D.3. Map showing Dongting Lake, which receives excess flow from the Yangtze River in China.

displaced from their homes by flooding. At least 900 people died in eastern India, Nepal and Bangladesh just in July and August of 2002 after heavy monsoon rains triggered widespread flooding, landslides and disease. In Venezuela at least 45,000 people lost their homes in flooding in the southwestern state of Apure as rivers overflowed and created lakes of stagnant, polluted water. In Algiers, the capital of Algeria, the flood toll reached 597 lives when muddy waters swept down a main road. In India's state of Assam, thousands of homes were destroyed by floodwaters. In Cambodia, water levels on the Mekong River rose to above emergency levels in two central towns following heavy rains upstream. Floods from rain falling across southern China inundated Vietnam's northern provinces, including streets in the capital Hanoi (lower image in Figure D.1).

In spite of considerable study and advice over the past half century on how to plan and manage floods, and in spite of increasing amounts of money being spent on flood protection, annual flood damage is increasing almost everywhere. In some years, like 2002, the damage can be quite substantial.

Of the major floods that occurred in the last decade of the last century, one (in 1993) occurred on the Mississippi River and some of its tributaries in the central United States, and two (in 1993 and 1995) occurred on the Rhine River. Both rivers are major multipurpose waterways serving many different interests, including

barge transport, which is critical to the economy of the regions they flow through.

How can floods be managed? How can humans live with floods that, some believe, are becoming more frequent and more severe? This appendix discusses approaches to floodplain management in the Netherlands and in some parts of the United States. In both cases the goal is to avoid the continuing spiral of increasing costs, both for flood protection and then for flood damage recovery when the protection measures fail. (Additional information on flood modelling and risk assessment is in Chapters 7 and 11.)

2. Managing Floods in the Netherlands

Much of the land surface in the Netherlands is below sea level; thus, it is not a surprise that those who live in the Netherlands place a high priority on safety against flooding.

2.1. Flood Frequency and Protection

Levees (dykes) protect the economically important low-lying part of the Netherlands: roughly the western half of the country. The design levels of these levees are linked to the frequency of occurrence of a certain flood stage. The particular frequencies of occurrence, or risk levels, are determined by the Dutch Parliament. Translating those risks to levee heights is the job of engineers.

Levees along the coasts of densely populated and highly industrialized parts of the country are to be designed to protect against all storms whose magnitudes would be exceeded only once in 10,000 years on average. In other words, the levees could fail but only for storms that exceed that 10,000-year storm. The probability of such a failure happening in any year is 1/10,000 or 0.0001. Of course, there is no guarantee it could not happen two successive years in a row. On the basis of methods discussed in Chapter 7, the probability of having at least one storm that exceeds the design capacity of the levee at least once in a fifty-year period is 0.005. While considerably greater than the probability (0.0001) of it happening in any particular year, this is still a low probability. The Dutch are not risk prone when it pertains to floods.

For the less densely populated coastal areas, the design risk level is increased to storms expected once in 4,000 years, that is, those having a probability of 0.00025 of being exceeded in any given year. Along the Rhine and Meuse Rivers, the flood frequency is once per 1,250 years, or a probability of 0.0008 of being exceeded in any given year. These so-called design floods also constrain all landscape planning projects in the floodplain. Proposed river works for nature restoration, sand mining or any other purpose, need formal approval as laid down in the River Act.

The condition of flood control works, levees and fairways is monitored regularly. Every five years a formal report on flood safety is made. This involves re-determining the design floods using statistical analysis of river flows in the period 1900 to date. Furthermore, data regarding river cross sections and vegetation types and densities are updated. With the aid of that information, the design flood levels are assessed, taking into account effects of wind set-up and a freeboard margin of half a metre (twenty inches) for overtopping of the levee crests. If pre-established flood risk level tolerances are being exceeded, action must be taken to reduce these excessive risks.

While the principal objective is to protect places where people live, work and spend their leisure time, a secondary objective is to preserve the quality of the spatial environment, including natural as well as cultural and historical sites. The socio-economic interests of many sectors of society are considered when designing alternatives for flood risk reduction.

2.2. The Rhine River Basin

The Rhine, one of the largest rivers in Europe, extends 1,320 km through Switzerland, France, Germany and the Netherlands. It enters the Netherlands at Lobith and travels another 170 km until it reaches the North Sea. The Rhine catchment area, shown in Figure D.4, covers some 185,000 km^2, draining parts of nine countries.

The River Rhine now has a combined rainfall–snowmelt driven flow regime. The winter season shows the largest discharges originating from precipitation in the German and French parts of the basin. Summer discharges originate mainly from melting snow in the Swiss Alps when evaporation surpasses precipitation in the lowland region. Modern climate scenarios show a temperature rise combined with a rainfall increase during winter

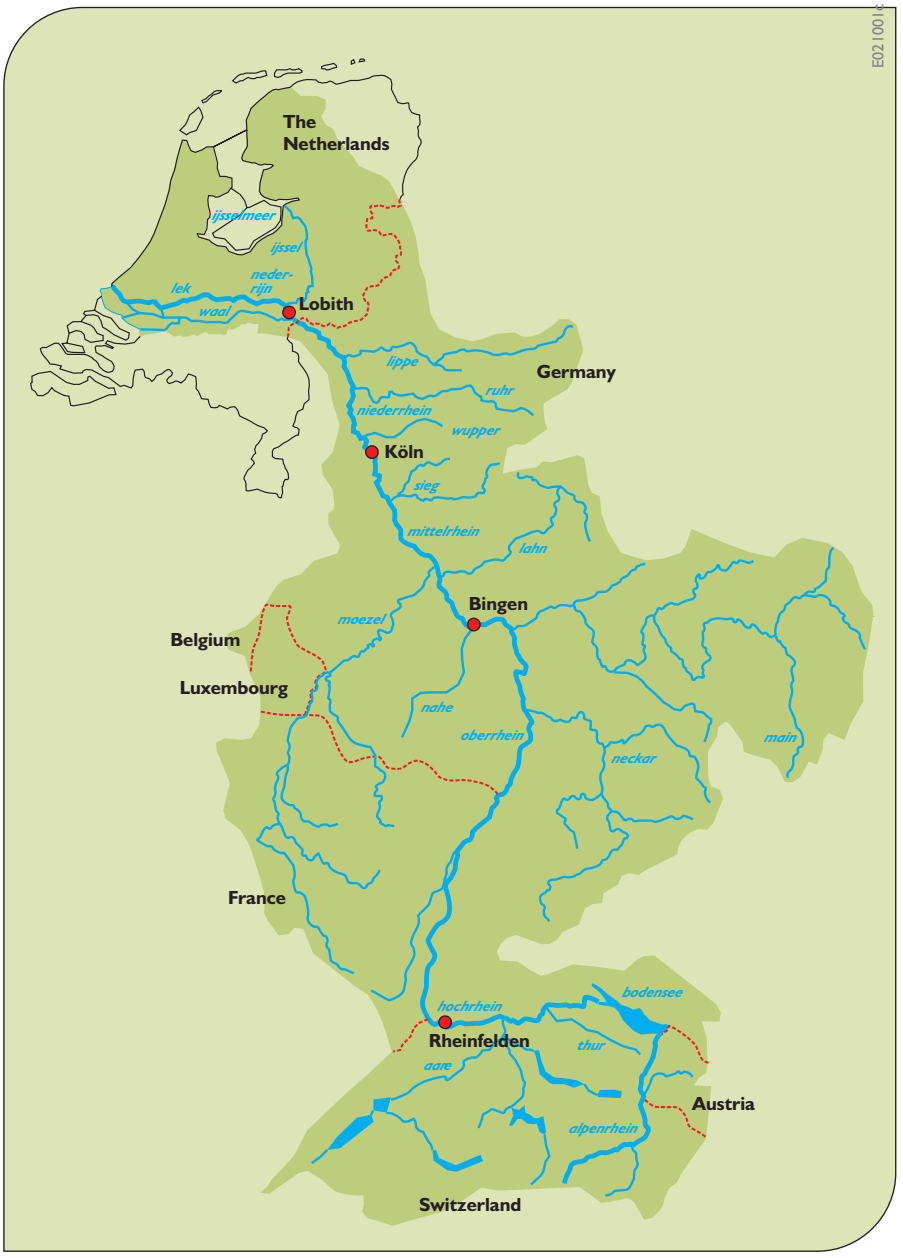

Figure D.4. River Rhine drainage basin. The river enters the Netherlands at Lobith.

in the basin. According to these scenarios the River Rhine could change from a combined snowmelt–rain-fed river into an almost completely rain-fed river. If that happens, both floods and dry spells could become more frequent.

To maintain the same flood safety standards, additional flood protection measures will be necessary. Water supplies in the future will be limited when they are most needed, and dry spells are likely to occur more often. Also, water quality may decrease due to both higher concentrations of pollutants and longer residence times of the water behind weirs. This means that preservation of water for use in dry periods could become necessary and that floodplains may be more frequently inundated.

The Netherlands is at the end of the Rhine and contains the Rhine Delta, which comprises more than half of the Netherlands (Figure D.4). A river often divides into multiple branches in its delta and the Rhine is no exception. In this case, the so-called Rhine Branches are the Waal, the Neder-Rijn/Lek and the Ijssel, as shown in Figure D.5. Along the Rhine branches, flood levels are entirely

Figure D.5. The Rhine branches and their floodplains in the Netherlands. The purple areas are subject to flooding and hence need dyke protection.

determined by the Rhine discharge. The area where the water levels are no longer determined solely by river discharge, but are also under the influence of the tidal effect of the sea, is referred to as the lower river region. In total, the low flow channel and the floodplains in the Netherlands cover an area of approximately 500 km^2.

To make and keep inhabitable that portion of the Netherlands that is below sea level, dykes have been built. As early as the mid-fourteenth century, an almost completely connected system of dykes arose that created the landscape of the Netherlands as it is today. There are two dykes on each side of a floodplain: the summer and the winter (flood season) dykes. These are shown in Figure D.6.

Design flow water levels in the river are mostly determined by the room that is present in the riverbed and by the flow resistance that the water encounters from

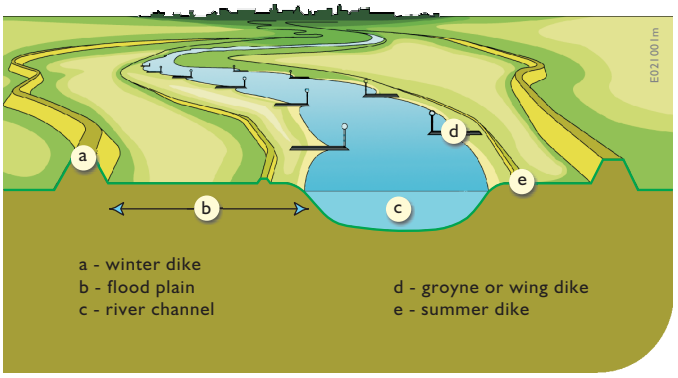

Figure D.6. Two-tier dyke structures and groynes for flood protection along the rivers in the Netherlands.

embankments and vegetation and other obstacles in the floodplain. The relation between design discharge and design water levels is therefore not entirely fixed, but depends upon the width and depth of the riverbed, the height of the floodplains, the flow resistance, and the wind and wave effects. Finally, an extra height is added to the dyke to equip it with an inspection path that keeps it passable, and to compensate for any subsidence of the embankment. In the lower river region, the design water levels are calculated with the aid of computer simulation models based on a large number of combinations of Rhine and Maas discharges, the sea level and the possible failure of the coastal flood barriers in the Rotterdam area.

The design height of a dyke is the water level whose chance of occurrence is linked to the level of protection that has been chosen for the protected regions. As already mentioned, practically all of the dykes along the Rhine Branches have a protection level of 1/1,250 per year. This means that the chance that the water level in a particular year will be higher than the design water level is less than 1/1,250. In the western part of the Netherlands, the protection levels are higher, namely 1/2,000, and rise to 1/10,000 per year for 'Central Holland,' where large cities such as Rotterdam and The Hague are located. Here, the population density and economic interests are larger, but so also is the difficulty of predicting a storm at sea. Floods from seawater can result in substantial casualties and economic damage due not only to water, but also to salt.

Two movable gates protect the entrance to the Rotterdam harbour, as shown in Figure D.7. Each gate is about as long as the Eiffel Tower is tall and contains over twice the tower's weight of steel.

In 1995 – after a long period of relative freedom from floods – the River Rhine region witnessed a flood. It was not only the highest since 1926, but also one that was long in duration. Approximately 250,000 people were evacuated for a little under a week due to the questionable stability of saturated dykes that had been exposed to long-term flooding. This flood – together with the flood of 1993 and the comparable events along the River Maas (Meuse), the second largest river in the Netherlands – motivated government agencies to give some priority to flood safety and flood risk reduction in the river regions.

Thanks in part to its location in the Rhine Delta, the Netherlands has been able to flourish economically. Rotterdam is one of the largest harbours in the world with a large and rich hinterland. Agriculture in the Netherlands has been able to profit from the rich soils that the Rhine has deposited. The economically strong position of the Netherlands is also due in part to the dykes. At the same time, the dykes have come to represent a sort of Achilles' heel for the country.

A large part of the Netherlands lies below the high-water level of the major rivers. At present, the sea level is gradually rising as a result of climate change. This same climate change, together with watershed land use changes within and upstream of the Netherlands, may cause the peak discharges on the Rhine and Maas to increase. In the meantime, the area protected by the dykes has been sinking, primarily due to subsidence and oxidation of peat, because the soil is so 'well' drained. This has increased the difference between water levels in the area protected by the dykes and the area outside of the dykes.

The population in the area protected by the dykes, the land use intensity and the capital investment have all rapidly increased. As a result, the potential adverse economic and emotional consequences of a flood, or even an evacuation due to flood risk, have increased substantially.

Figure D.7. A drawing and photograph of the waterway storm surge barrier in the closed position at Rotterdam in the Netherlands.

Yet there is a limit to just how much more heightening and reinforcing of dykes is reasonable. The public has made it clear they do not want dyke heights increased. Many feel too boxed in as it is, in this crowded country. Today a more natural solution is sought.

2.3. Problems and Solutions

As a result of the floods of 1993 and 1995, the design once-in-1,250-year discharge that must be contained or controlled within the floodplain is now higher than it was prior to these events. As shown in Figure D.8, the design discharge of the Rhine is now established at 16,000 m^3/s, an increase of 1,000 m^3/s. This design discharge height determines the design height of the dykes.

Without further measures, this means higher dykes. Due to climate change, the design discharge will most probably further increase to 18,000 m^3/s in the second half of this century. At the same time, the sea level is expected to rise, causing backwater effects in the estuaries and rivers.

Given this increase in the design water level, one could argue that the dykes should be made higher and stronger. If this is not done, the probability of floods topping the dykes will increase. However, the higher the dykes, the more severe the impacts will be once a dyke fails. The dykes often protect low-lying 'polders,' whose potential flooding depths already exceed several metres. If nothing is done to change the available room that exists for the Rhine River flood flow, this will lead to 20–30-cm higher design water levels in the short run, and up to 90-cm higher design water levels in the long run, factoring in climate change impacts. This will make higher dykes necessary in order to maintain the current level of flood protection. The higher the river water level is, the larger the consequences are, should a major flood occur that exceeds the dyke capacity. In reality, however, higher flood protection dykes are not going to be a problem, since the public has made it clear they are against that option. So, how to provide the extra protection needed to meet the design risk criteria established by the Dutch Parliament?

The challenge is to create and execute measures that – despite the higher design discharge that must be contained – avoid the need for additional dyke heightening. The only way to do that is to create more space

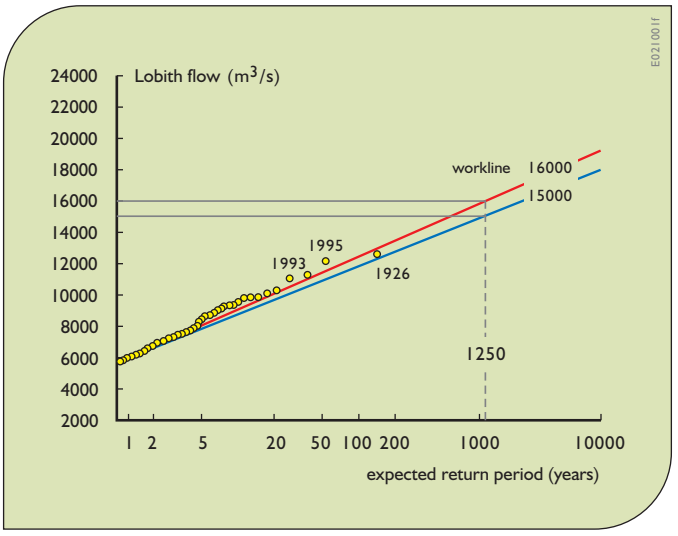

Figure D.8. Re-evaluation of design flood flows for the River Rhine in the Netherlands.

for water to flow at existing dyke levels. This means increasing the widths or depths of the rivers or their floodplains, and providing flood overflow areas outside the dyked floodplain for use when the space within the dykes is full. Specific floodplain planning and designs needed to cope with the design flow of 16,000 m^3/s are to be implemented by 2015.

2.4. Managing Risk

There is always a possibility that the water level along a river will exceed the design dyke capacity. The desired level of safety is a matter of societal choice. If society wanted complete and total safety, the only way to achieve it would be to move out of the floodplain. For natural phenomena such as wind, rain and river discharge, there are no absolute known upper limits. There are, thus, no absolute protection guarantees; a finite risk of flooding will always exist. What society can do however is protect to the extent people deem appropriate, while preparing for flood events that exceed the design capacity of any implemented protection works. Controlled flooding in emergency overflow areas is one way to manage flood events that exceed the design water levels.

The notion of flood risk considers both the chance of a flood and its adverse consequences. Minimizing the chance of inundation is not the only possible risk reduction option. Diminishing the adverse consequences

of the event also reduces risk. This idea in particular underlies the design of emergency overflow areas: it is better to have a controlled flood with minor damage than an uncontrolled flood with major damage.

It is technically possible to continue raising dyke heights, now and on into the future, just as has been done in the past. But Dutch society has made it clear that this is undesirable. Dyke reinforcements bring with them increasingly negative consequences for landscape, nature, and cultural and historical values. And as the difference in height between the water level in the river and the area protected by (behind) the dykes continues to increase, the flood risk also increases. The larger population and capital investment in the area protected by the dykes already make uncontrolled floods more drastic events than they were some twenty to fifty years ago. Moreover, the perception of safety increases as the dykes are made higher and more heavily reinforced, which leads to an increase in infrastructure investment, which leads to greater land value and hence potential loss should a flood occur, which justifies further flood protection investments, and so on.

It is for this reason that a policy is needed to break this cycle. Such a policy needs to:

- anticipate floods instead of merely reacting to them
- make more room for water, rather than relying only on technical measures such as dyke heightening
- prevent the transfer of water problems to downstream areas by means of a detain–store–discharge sequence.

This requires river-widening and deepening measures to prevent new design flood flow water levels from exceeding current dyke heights.

Past human interventions have resulted in the erosion of the low flow channel in upstream sections due to maintenance work on the navigation channel; the sedimentation in the low flow channel in the downstream sections after estuaries were closed off; and the silting-up of floodplains due to the construction of dykes and summer embankments. These processes have increased the elevation of the floodplains in relation to the low flow channel. At the same time, the area protected by the dykes has been subsiding due to drying out and oxidation of the peat soils. All of this has resulted in river levels that are higher above the surface of the land protected by (behind) the dykes than they are above the land adjacent to the river in front of the dykes.

There are several ways to maintain design water levels as design discharges increase in the Rhine:

- keep water in the catchment area upstream of the Netherlands
- store (excess) water along the Rhine Branches in the Netherlands
- discharge (excess) water via the Rhine Branches.

The first alternative attempts to ensure that the upstream precipitation does not lead to higher discharges downstream at a later time. This requires measures in the catchment area upstream of the Netherlands, namely Germany, such as changes in land use or detention. Comparable measures in the Netherlands may also help to reduce the additional flow to the Rhine Branches from tributary streams and canals.

Alternatives for storing and discharging floodwaters can be implemented in the Netherlands. The storage of river water in detention areas along the Rhine Branches leads to lower peak flows, lowering the water levels downstream of the detention areas. Conversely, measures that increase the discharge capacity of the riverbed reduce the water levels upstream of the measure. Examples include the removal of obstacles in the winter bed such as high lying areas, ferry ramps or bridge abutments, excavation of the floodplains, lowering of groynes or wing dykes, dredging of the low flow channel, and setting back the dykes. Some of these options are illustrated in Figures D.9, D.10 and D.11.

An important condition for such projects is that they must allow at least an increase in the design flow from 15,000 to 16,000 m^3/s. A further condition is that they cannot change the proportions of river flow that enter each of the Rhine Branches in the Netherlands.

2.4.1. Storage

Storage reduces discharge, and is helpful for practically the entire area downstream of the storage basin. Emergency overflow and temporary storage areas are being considered for controlled flooding in a way that limits damage. A segment of the discharge peak could be attenuated by temporarily storing it in a dyked area. After the flood peak has passed through, the temporarily stored water can be released.

Since the desired effect of a detention area occurs downstream from the area itself, a location as far upstream as

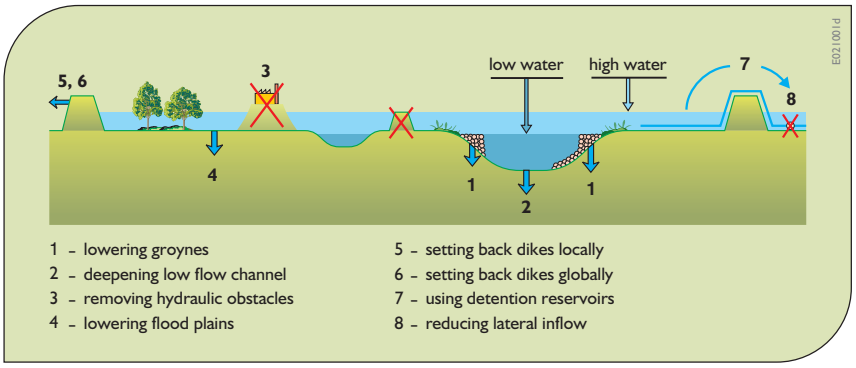

Figure D.9. Alternatives to dyke heightening for increasing flood flow capacity of rivers.

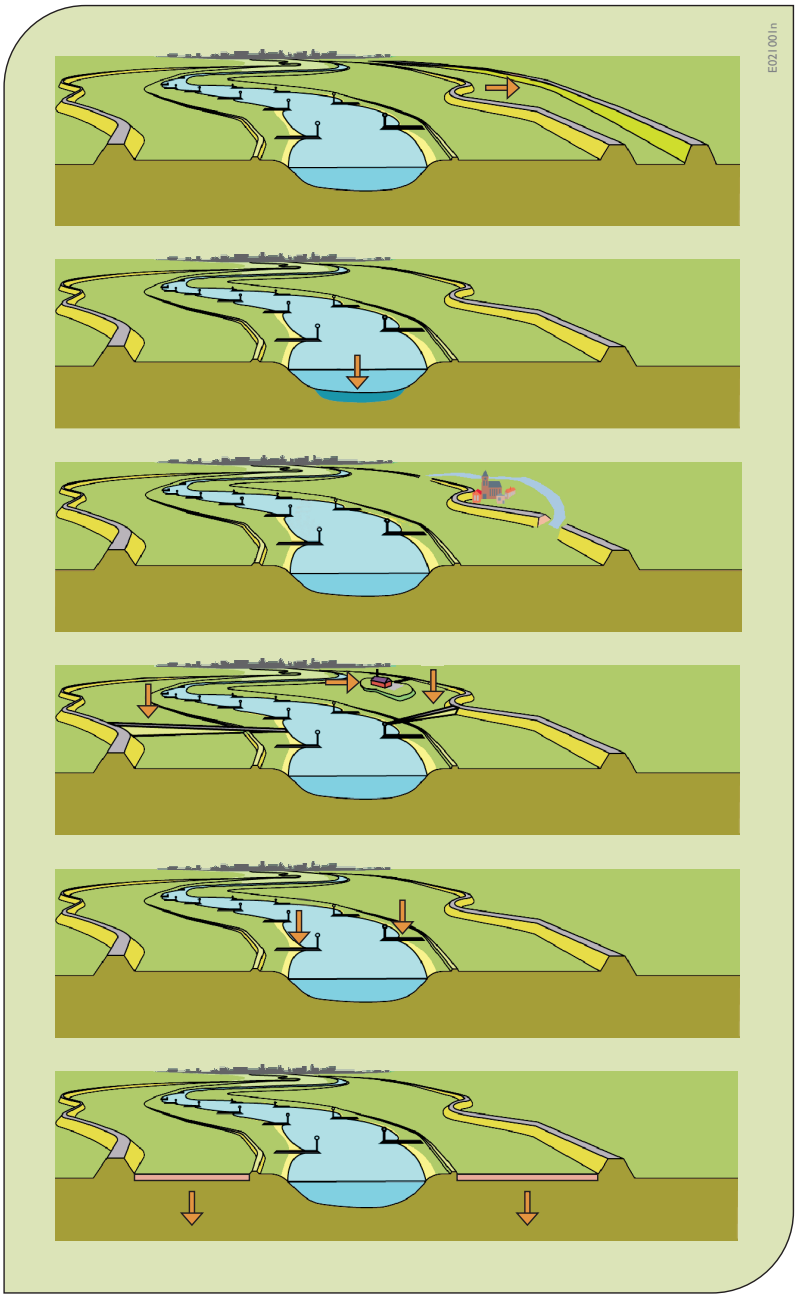

Figure D.10. Alternatives to dyke heightening are, from top to bottom, setting back dykes, deepening low flow channel, development of green rivers, removal of hydraulic bottle necks, lowering groynes, and lowering floodplains.

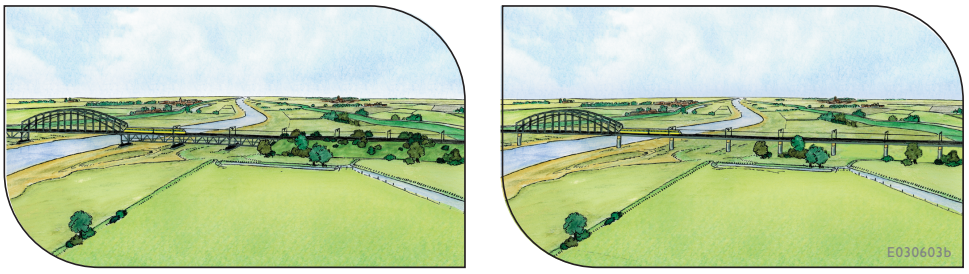

Figure D.11. Bridge abutments and supporting structure, before (left) and after (right) floodway modification.

possible is preferred. In the Netherlands, detention areas close to the German border are thus the most appealing.

The total detention (storage) capacity necessary to maintain a given flood height depends on the shape and duration (or length) of a flood wave. For example, a storage capacity of more than 150 million m^3 would be required to reduce the peak flow by 1,000 m^3/s of a flood wave lasting several days and having an 'average' shape. This in turn would require a detention area of some 3,000 hectares (30 km^2) flooded to a depth of five metres. In areas with less depth, the surface area must be proportionately larger.

Detention areas require enclosure dykes and intakes, both of which can be extensive. Implementing detention areas usually also involves landowner evacuation, and compensation for any damage occurring during occasional flooding. All of these factors add to the cost of detention measures.

Detention areas seldom need to be used, and in this case the probability of them being needed in any year is approximately 1/500, as seen from Figure D.8. This low probability can be a problem. The less often an area overflows, the more the societal pressure will be to develop it and safeguard it against flooding. After many years without floods, people may begin to think that these detention areas will never be needed for flood detention. The result: flood flow restricting activities will begin to encroach on that land. The additional flood protection provided by the detention area would then be decreased if not entirely lost. Perhaps this suggests the need to periodically let some water flow into these areas during high river flows, even when it might not have been necessary, and/or alternatively to allow it to become an open recreation area or nature reserve.

For detention areas to be effective during flood events, a reasonable amount of precision in their operation is required. They must not fill up too soon, because they run the risk of being full before the actual peak discharge has arrived. If they cannot store some of the peak flow, when it arrives, they will have no effect in lowering the maximum flood stage. A similar danger exists for a very lengthy, flattened flood wave, or when a second peak occurs soon after the first, and the detention area has not emptied.

Detention basins must also not fill up too late, because the discharge peak will already be over. All these considerations imply that accurate predictions for the timing and shape of the discharge must be available if detention basins are to be used effectively.

In the past, detention basins were usually filled via a fixed sill, a lowered section of the dyke that allows overflow to take place in a 'controlled' manner, ideally uniformly over the entire length of the sill. It is still very difficult to design a sill that will ensure a uniform overflow over a substantial length. This problem may be overcome by using a 'regulated' intake under human control. However, people have had bad experiences with regulated intakes. The residents of an area are never in favour of inundation, and if some person is making it occur a conflict with the responsible organization or agency, if not the operator, is inevitable.

2.4.2. Discharge-Increasing Measures

Measures taken to increase the discharge capacity can also reduce water levels while maintaining the same design discharge. In contrast to storage, however, increasing the discharge capacity is only advantageous for a limited river section.

With discharge-increasing measures, it is not only the height reduction but also the distance a measure covers that is important. The distance depends on factors such as the steepness of the water level slope, the location of the dykes on the floodplain, other obstacles in the area,

the hydraulic roughness of the vegetation in floodplains and so on.

There are many measures available for reducing the stage of a particular design discharge. Three major ones include:

- increasing the flow capacity in the low flow channel
- increasing the flow capacity in the floodplains
- providing flood storage capacity in the areas protected by (behind) the dykes (by, for example, setting back dykes or creating detention basins).

As mentioned earlier, sedimentation occurs in downstream sections and this makes regular dredging necessary. Dredging to deepen the low flow channel in the downstream sections can lead to a water level reduction. However, it can also accelerate erosion upstream. Thus, to maintain the desired design water level, continual dredging may be required.

Alternatives to dredging include groynes or wing dykes (Figures D.6, D.9, and D.10). Groynes were constructed in the past to ensure that the river retained a sufficient depth without continual dredging. They guide the river flow to the middle of the channel and ensure that the depth of the river is maintained for a pre-determined width. This is particularly important for navigation. They also tend to prevent sand banks.

Removal of the groynes would result in a decrease in flow velocities and the river would become shallower in places. Sandbanks might even form in the middle of the river. With few exceptions shortening or removing groynes is an option only if the shipping function of the river were to be discontinued, and of course in the River Rhine it is not.

It appears from simulations that lowering of groyne heights could contribute to a reduction varying from 5 to 15 cm in the water level on the Waal and the Ijssel. On the Neder-Rijn, the maximum reduction is 10 cm. This may not seem like much, but on the other hand, the costs of groyne lowering are relatively low; thus, this measure is relatively cost effective.

Excavation of the floodplains and the removal of hydraulic bottlenecks can also be considered. Floodplain excavation is a measure by which the gradual height increase caused by sedimentation on floodplains may be counteracted. Floodplain excavation may be combined with clay mining, and dyke reinforcement, and/or with developing nature reserves. Nature development is often a reasonable use of an excavated floodplain since excavation makes land less profitable for agriculture, particularly if the summer embankments are also removed in the process. Moreover, it appears that after excavation, such development produces a result that is valued by many. Creating nature reserves without floodplain excavation, however, pushes water levels upward since rough vegetation, scrub, and wooded areas can slow down the discharge. Thus, it requires additional excavation to compensate for the backwater effect of the vegetation.

While floodplain excavation is an effective way to reduce flood heights, it is also the most expensive measure. If it were to be implemented along all three Rhine Branches, the costs involved would total 3 to 4€ billion. Soil excavation is expensive in and of itself, but it is the necessary storage and containment of contaminated soil that substantially increases the costs. Roughly 15 to 20% of the soil on the Rhine floodplains is actually contaminated and another 40 to 50% is unusable as building material.

Storing the contaminated soil safely and locally in existing deep ponds or in sand excavation pits after usable material has been removed, so-called 'earth-swapping,' can achieve substantial cost savings, from 1 to 1.5€ billion.

The removal of hydraulic obstacles in the floodplain is another way to increase its discharge capacity without increasing its water level. Examples of hydraulic bottlenecks include ferry ramps, bridge abutments (Figure D.11), high-lying areas (Figure D.12), summer

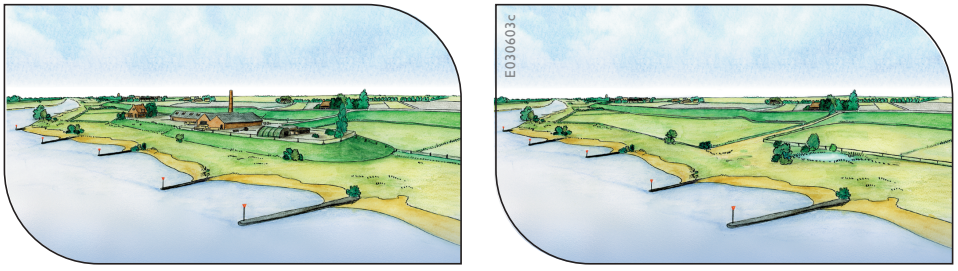

Figure D.12. Removal of high-lying areas on a floodplain.

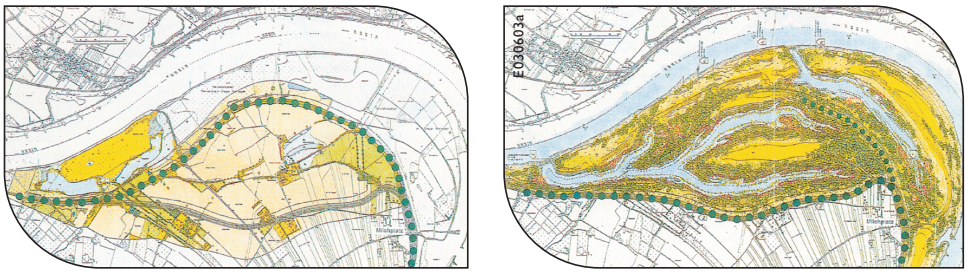

Figure D.13. Opening up a narrowing by setting dykes further back, and at the same time creating a nature reserve.

embankments that are high and/or perpendicular to the flow direction, narrowing of winterbeds (Figure D.13) and other obstacles. Hydraulic bottlenecks may be identified by studying the water level slope of the river. Typically, there is a direct relation between structures and a change in the water level slope.

Removing bottlenecks can decrease design flow water levels. This decrease can be calculated, as can its cost. The costs of replacing bridge abutments by bridge sections (Figure D.11) and the removal of ferry ramps vary from less than 2.5€ million to more than 75€ million for a large bridge. The costs of removing embankments and small-scale setting back of dykes (Figure D.13) are usually on the order of 5€ million per project, but they can run up to over 15€ million if many houses must be expropriated. The costs for removing high-lying areas (Figure D.12) can amount to 30€ million, especially in those cases where land is contaminated.

Substantial water level reductions may be achieved by widening and deepening measures at an urban bottleneck. Such measures are typically very expensive, as a sizeable area is often needed in times of flooding. Despite their high costs, these measures can be cost effective at the urban bottlenecks due to the relatively large reduction in water levels that may be achieved.

On average, the removal of about sixty bottlenecks can reduce the water level by 20 cm on the Waal and 10 cm on the Neder-Rijn/Lek and the Ijssel. However, actual water level reductions may vary considerably over the length of the river branches.

There are some forty locations, not including urban bottlenecks, where large-scale setting back of dykes can lead to a substantial decrease in the water levels. Setting back of dykes is particularly effective in situations where the winter bed is very narrow and causes backwater effects quite a distance upstream. In such a case, this decrease in the water level also continues to work relatively far upstream. Some setting back of dykes can, in fact, decrease the water level up to half a metre. There are other sites where such measures produce only several centimetres worth of reduction.

To set back a single dyke section of a few kilometres in length costs anything from 5€ million to 100€ million. While rather expensive, particularly if considerable urban or industrial development is present on or just behind the dyke, these measures are cost effective compared to many other hydraulic bottleneck reductions. Along the Waal and the Neder-Rijn/Lek, the setting back of all the dykes together could result in a maximum reduction of 60 cm.

2.4.3. Green Rivers

If it is not possible to set back a dyke, or if the effect is too small, then a so-called 'green river alternative' may be an effective way to reduce flood levels. Green rivers are floodplains between two dykes where water would flow only during floods. Green rivers may be used for agricultural purposes or may be designed for nature reserves and/or recreational areas; they are, in short, 'green.' This does not preclude the possibility of digging a channel or lake into such an area for the sake of recreation, for example. How such a green river may be designed depends upon the location. Figure D.14 shows a section of a river floodplain converted to a green river.

Green rivers can lead to significant reductions in water levels at and upstream of those locations. This means that other flood height reducing measures along these river sections may not be necessary.

Green rivers offer options for agriculture, water-based recreation and nature development. The land is seldom flooded and, if it is, this usually occurs 'off-season' (outside the agricultural season) just as it currently does in the floodplains. One could say that the land is temporarily loaned to the river every year, but is otherwise available

Figure D.14. Existing situation (left) of the Rhine floodplain near the Dutch town of Haaften, and artist's impression (right) of a green river north of the town.

for other compatible activities. There is thus a definite practical value derived from green rivers.

Additionally, these measures offer what one could refer to as a future value for river management. Efforts must be made to prevent such space from being used for incompatible residential construction, business parks, greenhouse complexes and similar land developments that would incur substantial damage, and indeed increase the flood height, should a flood occur. While this limits the land use possibilities at this moment, it offers the option to implement other river widening and deepening measures in the future, such as floodplain excavation.

Similar far-reaching measures may be taken to improve the quality of the surroundings, such as clean-ups of industrial areas and development of recreational areas.

2.4.4. Use of Existing Water Courses

Where existing canals, brooks or creek remnants run parallel to the river, these may be connected to the river channel to take on a portion of the discharge. Opportunities to do this have been examined in the lower Rhine Branches region in particular. New, still-to-be excavated channels are also being studied with respect to their effectiveness and costs. In practically all cases, however, water is guided in an entirely different direction and this places increasing burdens on other rivers or sections situated further downstream.

2.4.5. The Overall Picture

It would appear that the large-scale setting back of dykes, construction of detention basins/green rivers and lowering of groynes would result in the greatest water level reduction per euro invested. The removal of hydraulic bottlenecks obtains an average score, as does dredging the low flow channel. Floodplain excavation is the most expensive, and in this respect, the least desirable type of measure.

Some measures, such as lowering of groynes and floodplain excavation, are only really possible in upstream sections. Others, such as dredging of the low flow channel, are more feasible downstream. Large-scale setting back of dykes and green rivers relieve certain bottlenecks only, albeit with substantial carry-over upstream.

Finally, cost effectiveness is only one criterion. Sometimes floodplain excavation can involve multiple objectives; nature development and even sand and clay mining may also profit from it. The extent to which similar multiple objectives may be served by various flood capacity enhancing alternatives needs to be explored.

Combinations of flood-height-reducing measures will undoubtedly be undertaken along the Rhine River Branches. Models will be needed to assess their overall effectiveness. The overall reduction in flood heights will not be simply the sum of their individual reductions in isolation. It is not possible to simply add up the water level reducing effects of the different measures. The discharge of a river is, after all, determined by the functioning of the whole: one single bottleneck can negate the effect of a package of measures. On the other hand, some measures are synergistic; their overall effectiveness can be greater than the sum of all their individual water level reductions. For this reason, a systems view is necessary to effectively lower water levels across the entire length of the Rhine Branches. Not only the combination of measures but also the possible changes in the shape of the flood wave must be taken into account.

There are an innumerable number of alternatives that could be put together to safely contain the design flow of 16,000 m^3/s. It is a matter of preference which measures will be applied first or most often.

To handle a discharge of 18,000 m^3/s safely, it appears that large-scale measures in the dyke-protected area would be necessary, such as setting back dykes and creating detention areas and green rivers.

2.5. Dealing With Uncertainties

There are many uncertainties in predicting flood levels, and sometimes there is little one can do about them. One uncertainty involves the design discharge itself. Others

arise over the shape of the flood wave, the distribution of River Rhine flow over the three Rhine Branches, the bed level of the river and the roughness of the vegetation in the floodplains along the three branches. All these uncertain factors affect the design water levels; hence, the design water level is itself uncertain.

Moreover, we are at the mercy of changes that may occur in future and these are by definition uncertain. We know the climate will change, but we do not know how quickly or to what extent. All the climate models currently used predict warming and more frequent extremes, but the variations between predictions remain rather substantial. All of these issues present quite a dilemma for management: on the one hand, safety is so vital that the river manager has to anticipate higher discharges that must be accommodated, yet the speed with which situations may change is very unpredictable. To wait and see how new floods influence design flow risk statistics seems unacceptable. Further research can do nothing to change that.

Essentially, decisions must be made in spite of these uncertainties.

The design discharge for the Rhine is based upon an extrapolation of measurement data from the past. Previously, the period was 1901 to 1991, but this has now been extended to 1995. The extension of only four years, two of which had high discharges (namely 1993 and 1995), has caused the slope of the graph to change somewhat, as shown in Figure D.8, above. The new design discharge has become 16,000 m^3/s, an increase of 1,000 m^3/s. It appears that several floods resulting from relatively wet years can substantially influence the design discharge.

The most important reason for the large change in the design discharge is that it applies for events that occur once every 1,250 years, well beyond what has been observed during the 100 years of measurements. This means that the graph must be extrapolated beyond the measured data to estimate the design flow associated with that 1/1,250 risk level. This can result in strange effects. For example, a plot of the annual peak flows of the Oder River catchment area in Poland from 1901 to 1985 produces a fairly straight line without any large deviations. In 1997 however, a discharge of 3,300 m^3/s was measured, the largest flow on record. That one event led to the 'new' extrapolation line causing the 1/1,250

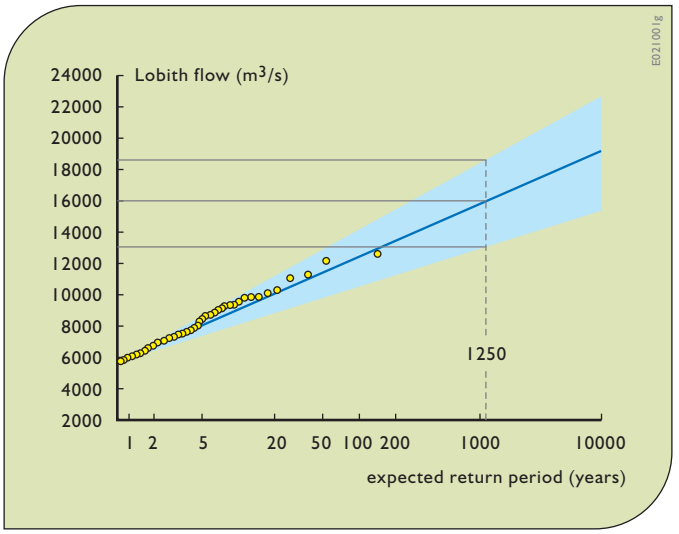

Figure D.15. Range of uncertainty associated with estimated design flows of various return periods. The true design flow has a 90% chance of being within the blue band.

discharge to rise from 2,500 to 2,600 m^3/sec. This is still far below the 3,300 m^3/s discharge that actually occurred. While extreme discharges, perhaps such as that on the Oder, may be rare, they can nonetheless occur in any year.

What is clear is that any extrapolation line, such as the one shown in Figure D.8, is uncertain. It could be higher, or it could be lower. Figure D.15 shows the 90% confidence interval band of uncertainty associated with the extrapolation in Figure D.8. This shows that there is a 90% chance that the design discharge on the Rhine (that is, expected on average once in 1,250 years) will be between 13,000 and 18,500 m^3/s. Not only the new design flow of 16,000 m^3/s but also the old design flow of 15,000 m^3/s, as well as the possible future design flow of 18,000 m^3/s, are in this range.

Figure D.15 is based on historical flow data that may not be indicative of future flows. There are various climate change scenarios, each with high and low estimates. Assuming a high estimate of a 4 °C rise in temperature in the year 2100, the design discharge on the Rhine could increase by 20%. This added to the current 16,000 m^3/s would produce a design discharge of more than 19,000 m^3/s, assuming that Germany is successful in keeping this discharge within the dykes.

In this respect, there are thus two types of uncertainties: first, what precisely would change in terms of

climate, and second, how the other Rhine States upstream of the Netherlands would react to these changes. No one today can answer that.

How can flood management proceed, given this uncertain future? The answer is: by building into any adopted management strategy both flexibility (robustness) and resilience.

Flexibility is the ability to adapt with minimal cost to a wide range of possible futures. Building in this flexibility may cost more, but may be still be desirable insurance against risks society does not want to take. Regulating the discharge distribution over the Rhine Branches could increase flexibility. So too could building temporary and emergency detention areas.

The term resilience, on the other hand, specifically involves the speed of recovery after a flood and its accompanying damage has occurred. This is achieved much more easily if the consequences of an above design level flood are not permanent, but remain limited and may be easily rectified. This requires that no uncontrolled flood should occur – one that would be accompanied by possibly extremely severe damage or even social disruption – but only controlled flooding that will cause the least amount of damage. In this manner, resilience could be 'built into' a flood safety system through disaster facilities, for example in the form of emergency spill areas or by dividing large dyke rings up into smaller sections – compartmentalizing – to limit flood damage.

It is a major challenge for river managers and also for the water and spatial-planning policy-makers to develop a strategy that will minimize future pain by taking into account the fact that there will always be uncertainties about the expected discharges in rivers.

2.6. Summary

Visions for future developments on the River Rhine in and upstream of the Netherlands currently concentrate on flood mitigation and ecological restoration. Relatively little effort is devoted to dealing with low flows that have implications for future water quality and navigation requirements.

Until recently, the strategy for flood prevention was to raise dykes (embankments) along the floodplains. Currently this strategy has met social resistance and is thought to be too inflexible to cope with an uncertain future. Alternative solutions focus on reducing water levels during floods, using retention basins along the River Rhine in Germany and lowering floodplains in the Netherlands to enlarge the cross section of the river. At the same time, these floodplains are to be designed in such a manner that more natural morphological and ecological processes in the floodplains can take place.

In the delta of the River Rhine, future adaptation visions focus on a further widening of the floodplains and the planning of 'green rivers.' These 'green rivers' will only be inundated during floods. In the upstream sections in Germany, the focus is on landscape planning so that water will flow less quickly to the river.

3. Flood Management on the Mississippi

The Mississippi River, shown in Figure D.16, is the major river of North America and the United States. It is over 3,700 km (2,300 miles) in length, flowing from the northwestern part of the state of Minnesota south to the Gulf of Mexico, just below the city of New Orleans. It drains 3.2 million km^2 (1.2 million square miles), or about 40% of the United States. The Mississippi is the sixth largest river in the world in terms of discharge. Its annual average flow rate is 14,000 m^3/s and its freshwater discharge onto the continental shelf is 580 km^3/yr. It is a significant transportation artery, and when combined with its major tributaries (the Missouri and Ohio rivers), it is the third largest river transportation system in the world.

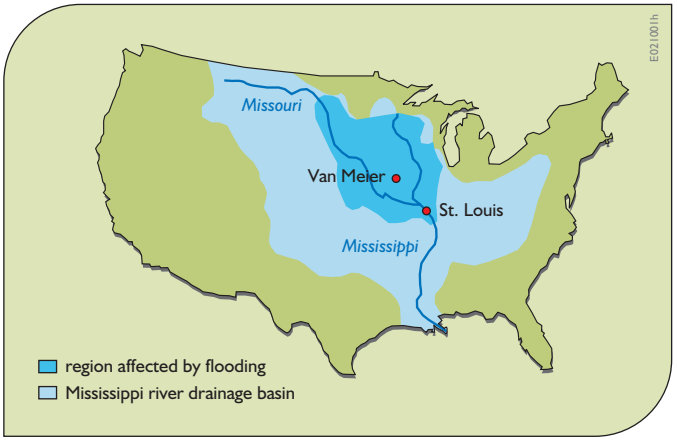

Figure D.16. Mississippi River Basin in the United States and the area affected by the 1993 flood.

Figure D.17. Confluence of Des Moines and Mississippi Rivers during the 1993 flood.

Typically the discharge at the mouth of the Mississippi River into the Gulf of Mexico varies over the seasons, with the highest flow occurring between March and May and the lowest between August and October. In August and September of 1993, however, it rained heavily. Monthly mean discharges in April and May 1993 were approximately 50% higher than their long-term monthly mean values. August and September 1993 discharges exceeded the highest of those recorded in the previous sixty-three years. The result was a flood.

The States of Minnesota, Iowa, Illinois, and Missouri were hardest hit (the darker blue area of Figure D.16). At St. Louis, the river crested at about 15 m (49.6 ft), some 6 m (over 19 ft) above flood stage. This was about two metres (more than six feet) above the old record set in 1973. The Mississippi remained over flood stage at St. Louis for over two months. Farther north, record flooding occurred on the Des Moines River, a tributary of the Mississippi (Figure D.17). At one point flooding disabled a major water plant, and Des Moines, Iowa, a city of nearly 200,000 people, was without safe drinking water.

The discharge of 35,700 m^3/s (1,070,000 ft^3/s) was the greatest ever measured during more then 130 years of data, exceeding the previous high by 26%. Flood elevations exceeded the design flood stage of 9 m (30 ft) on the St. Louis gauge for eighty consecutive days during the main portion of the flood, and for 148 days during the calendar year. The previous record was seventy-seven days above flood stage, both consecutively and annually.

The duration of flooding at high stages was unprecedented. The flood was 3 m (10 ft) or more over the design flood stage for thirty-six days, exceeded the 'fifty-year flood' stage for twenty-three days and exceeded the '100-year flood' stage for eight days. Before 1993, there had only been twelve days total in the entire period of record, dating back to 1861, when floods exceeded the design flood stage by this extent or more. The total water volume passing St. Louis from June 26 to September 13 could cover the entire State of Missouri to a depth of 0.75 m (2.5 ft). The peak discharge at St. Louis has been estimated to have a 150–200 year average recurrence interval. At some upstream stations the flood exceeded the 500-year average recurrence interval.

Transportation and industry along the Mississippi River was disrupted for months. Damage to surface and river transportation in the region was the worst ever incurred in the United States.

Over 1,000 of the 1,300 levees designed to hold back floodwaters failed, though major cities along the rivers, like St Louis, were protected from flooding by massive floodwalls. Floods displaced over 70,000 people, and damaged or destroyed nearly 50,000 homes and over 31,000 km^2 (12,000 square miles) of productive farmland. Fifty-two people died. The estimated damage was between $12 and 20 billion (1993 US dollars), depending on what is included in those estimates.

This flood provided a trigger, once again, for an evaluation of the existing flood protection schemes and procedures for managing the rivers and floodplains in the Mississippi Basin. At the same time, the future use of the rivers and floodplains, especially in the context of economic development, coupled with the improvement of ecological habitats, became important political issues.

Historically considerable attention has been given to solving problems associated with particular interests. For the Mississippi Basin, these include navigation,

hydropower generation, nature conservation and providing a certain flood safety for agricultural, industrial and urban areas. A large number of structural and non-structural measures have been implemented over the years, many of which have contributed to the economy of the region, the safety of the inhabitants and the protection of natural values. What was less strongly developed, however, was a clear, concrete and widely accepted perspective (a policy or strategy) on the long-term future water resources development in the Mississippi Basin as a whole.

Studies carried out by the Federal Interagency Floodplain Management Review Committee (known as the Galloway Committee), further supported by US Army Corps of Engineers (USACE) studies, all prompted by the flood, have contributed substantially to debates over future policies for river management. Various alternatives for floodplain management were evaluated, but detailed concrete proposals were not asked for and were not included within the scope of this floodplain management assessment.

Identifying alternative future river management strategies that could be implemented raises two questions:

- Should the river management strategy be based on a continuation of the historic practice of river engineering works, using reservoirs and levees to provide a certain flood safety level, in combination with dredging works for navigation? Or alternatively, should a future strategy focus more on the use of the floodplain and the river in such a way that environmental values are enhanced, while at the same time the potential flood damage is reduced?
- How and to what extent can the river and floodplain resources be further used by society for the development of the regional and national economy without compromising the river ecosystem?

Associated with the need for a strategy for river basin management, additional questions include:

- How can federal and state agencies be organized in such a way that river basin management can take place effectively?
- How can management and development planning be structured so that stakeholders (industry, environmental groups, farmers, urban population and others) are actively involved in the process?

3.1. General History

A sketch of some aspects of the history of water resources development in the United States may provide some context for what has happened in the Mississippi River.

For more than a century, the Federal Government has been involved in developing water projects for a variety of purposes including flood control, navigation, power generation, and irrigation and settlement of the West. Most major water projects, such as large dams and diversions, were constructed by government agencies – the Bureau of Reclamation or the U.S. Army Corps of Engineers. Traditionally, the Corps has built and maintained projects designed primarily for flood control, navigation and power generation, whereas Bureau projects were designed primarily to enhance storage capacity and provide reliable supplies of water for irrigation and some municipal and industrial uses.

The Corps operates hundreds of flood control, navigation, and multipurpose works throughout the country. While its navigational activities date back to foundation of the Federal Government, the Corps did not become involved in flood control until the mid-to-late 1800s, and then was primarily concerned only with studies and investigations. Although Congress authorized the Corps to construct levees throughout the country in 1917, the modern era of federal involvement in flood control did not get fully underway until the enactment of the Flood Control Act of 1936, when Congress declared that it was in the national interest to assist states with flood control measures and that this was a 'proper' federal activity. Prior to this time, flood control had been largely viewed as a local responsibility. In addition to its flood control responsibilities, the Corps continued to construct navigational improvements, and later expanded its activities to include construction of multipurpose water projects.

For decades, the Federal Government took a largely structural approach to flood control, floodplain management and water supply development. While the Corps was active in building dams and levees throughout the country, channelling meandering rivers and streams to move floodwaters quickly and efficiently 'out of harms way', the Bureau was building some of the largest water supply projects in the world. Thus, the Corps and the Bureau are substantially involved in the management of some of the country's largest river systems, including

the Colorado, the Columbia, the Missouri and the Mississippi.

Project construction for all types of water works expanded greatly during the 1930s and 1940s and continued rapidly until the late 1960s and early 1970s. By the late 1960s, a combination of changing national priorities and local needs, increasing construction costs and the decreasing number of prime locations for water works all contributed to a decline in new construction of major water works nationwide. Water supply for traditional off-stream uses – such as public supply, domestic, commercial, industrial and agricultural uses – was increasingly in direct competition with a growing interest in allocating water to maintain or enhance in-stream uses such as recreation, scenic enjoyment, and fisheries and wildlife habitat.

During the 1970s, construction of new projects slowed to a handful of major works, culminating in the completion of the Tellico Dam project in Tennessee and the Tennessee Tombigbee Waterway through Alabama and Mississippi. These projects pitted conservation and environmental groups, as well as some fiscal conservatives, against the traditional water resources development community. New on the scene was the National Environmental Policy Act of 1970 (NEPA), which for the first time required an assessment of the environmental effects of federal projects and provided for more public scrutiny of such projects.

In 1978, President Carter announced that future federal water policy would focus on improving water resources management, constructing only projects that were economically viable, cooperating with state and local entities, and sustaining environmental quality. The subsequent Reagan administration continued to oppose large projects, contending they were fiscally unsound. Federal water research and planning activities were also reduced during the early years of the Reagan Administration (early 1980s), which felt that states should have a greater role in carrying out such activities. Consistent with this outlook, President Reagan abolished the Water Resources Council, an umbrella agency established in 1968 to coordinate federal water policy and to assess the status of the nation's water resource and development needs.

Congress subsequently scaled back several remaining authorized projects, changed repayment and cost-share structures, and passed laws that altered project operations and water delivery programmes. For example, in 1982 Congress passed the Reclamation Reform Act, which altered the Bureau's water pricing policies for some users. The Act revised acreage limitation requirements and charges for water received to irrigate leased lands. Congress soon passed another landmark law, the Water Resources Development Act of 1986, which requires local entities to share the construction costs of water resources projects built by the Corps. This act did little to enhance comprehensive systems-wide planning but did allow projects to be built, especially if members of Congress wanted them.

Over the last decade, both the Corps and the Bureau have undertaken projects or programmes aimed at mitigating or preventing environmental degradation due in part to the construction and operation of large water projects. The agencies have pursued these actions through administrative efforts and congressional mandates, as well as in response to court actions. Currently, the Federal Government is involved in several restoration initiatives, including the Florida Everglades, the California Bay-Delta, the Mississippi Delta, Lake Ontario and St. Lawrence River, and the Columbia and Snake River Basins in the Pacific Northwest. Degradation processes in these river, lake and coastal systems have been occurring over many years.

These restoration initiatives are not without controversy. Each involves many stakeholders at the local and regional level (water users, landowners, farmers, commercial and sports fishermen, urban water suppliers and users, navigational interests, hydropower customers and providers, tourists and environmentalists), all with their own objectives and desires. At the same time, demand for traditional or new water resources projects continues – particularly for ways to augment local water supplies, maintain or improve navigation, and control or prevent floods and shoreline erosion.

Now let us turn to the Mississippi

Nature's design of the upper Mississippi was imperfect for human use. So Congress, with the help of the US Army Corps of Engineers, remade it. For over a century, the Corps has responded to Congressional requests to provide for transportation and flood control – and most recently for ecology as well – in the upper Mississippi.

Figure D.18. Barged cargo passing through a lock on the upper Mississippi River.

Figure D.19. The upper Mississippi River locks and navigation dams, known locally as pools.

Nature's upper Mississippi was often less than four feet deep. Today's canalized version handles the standard upper-Mississippi barge: 2.75 m (9 ft) deep, 10.7 m (35 ft) wide and some 60 m (195 ft) long. They are tied three across (32 m or 105 ft) and five deep (297 m or 975 ft), and pushed (not towed) by a towboat, as shown in Figure D.18. Most of the locks are 33.5 m (110 ft) wide and 183 m (600 ft) long. So a standard set of barges is divided into two lengths, each taken separately through the lock, and then re-tied. A single lock-passage takes about twenty minutes. Waiting, because of traffic, can sometimes take twenty hours. This is one of the reasons why the Corps of Engineers has been asked to build more lock capacity.

Managing floods on the upper Mississippi, to the extent possible, is done by using reservoirs and levees. They will no doubt continue to be used.

The upper Mississippi has twenty flood-control reservoirs, controlled by three Corps of Engineer Districts: St Paul (16), Rock Island (3), and St Louis (1). There are also more than a hundred smaller dams and reservoirs on upper-Mississippi tributaries for local use and not for flood control on the main river. There are no flood control reservoirs on the river; the locks and dams on the river above St. Louis control water levels primarily for transportation (Figure D.19).

The Corps-controlled reservoirs serves several purposes. At each, a permanent minimum level is kept for recreation and wildlife. In dry times, water is released to maintain minimum levels in the tributary and the river. On a tributary that can flood any time, water is released after a flood, to be ready for the next one. On a tributary with well-defined flood seasons, floodwater is held for release as needed by the tributary and the river. Hydropower is produced at some reservoirs, and provides approximately 9% of the combined energy used in the Mid-continent Area Power Pool, which includes Iowa, Minnesota, Nebraska, North Dakota, South Dakota, and portions of Illinois, Montana and Wisconsin.

Levees are used for local flood control. They reduce flooding for one area but typically cause problems elsewhere. A levee on one side causes higher floods on the other. Levees on both sides narrow the channel, causing higher floods upstream. Levees protecting portions of the fertile floodplain keep floodwaters from occupying and soaking into that natural floodplain land. This increases the flood flow downstream.

The overall plan of reservoirs and levees includes the possibility that, in extreme situations, less valuable areas will be flooded to reduce the risk of losses in more valuable ones. According to the basic plan for the upper Mississippi, submitted to Congress by the Corps in 1940:

> The reservoir system proposed is not of sufficient capacity to completely control floods in the upper Mississippi River.... The best method of operation of reservoirs ... often requires that reservoirs be emptied as rapidly as practicable after a flood has passed in order to be in readiness for a possible second large flood in the same season.... Large discharges might be superimposed upon the crest of a major flood at some point downstream.

Hydrological regimes in watersheds have been changed significantly by the construction of dams, levees and channels. Drainage systems and other land use changes have influenced the runoff pattern. Watershed alterations promoted human welfare, and policy-makers saw opportunities to use water development as an engine for economic prosperity. The achievements were impressive: improved safety against floods, expanded navigation on the rivers, availability of floodplains for agricultural and commercial uses, production of hydroelectric power and other benefits.

However, as in many rivers that are highly controlled, the floodplains of the upper Mississippi, Illinois and Missouri Rivers have been reduced in size by the construction of levees. The remaining floodplains have slowly been rising due to silt deposition. River runoff has increased due to the loss of upland cover in the basin. The construction of wing dykes has made the low flow channel narrower and deeper. Plants and animal species have slowly disappeared. Wetland areas have decreased gradually as land was converted to agricultural use. However, even today the upper Mississippi, Illinois and Missouri Rivers still contain extensive and important ecological and landscape values. Figure D.20 illustrates land cover changes over a century at two sites along the upper Mississippi.

Comparison of the land-cover/land use data between 1891 and 1989 in the dammed portion of the upper Mississippi River showed that open water and marsh habitats generally increased, mostly at the expense of forest and agriculture (upper images in Figure D.20). Where river dykes have been built, wetland and woody areas tended to be converted to agricultural areas over the same period (lower images in Figure D.20).

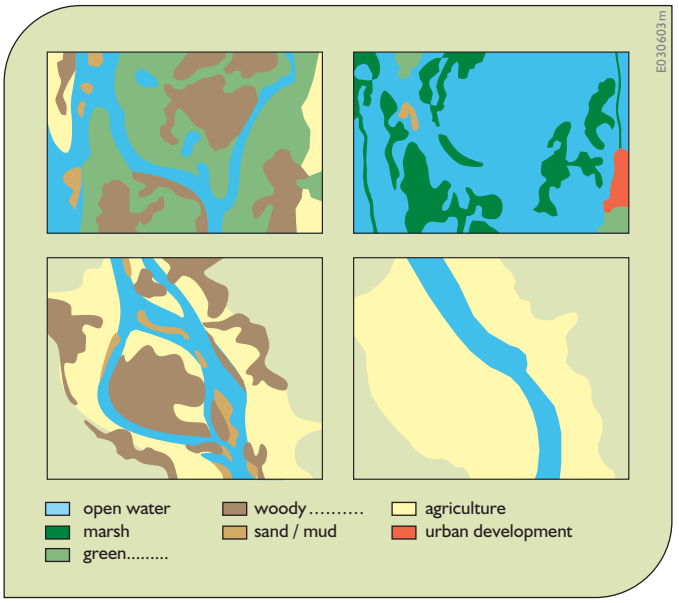

Figure D.20. Land-cover/land use comparisons at two sites on the upper Mississippi. The left-hand images depict land uses in 1891 and the right-hand images show the land uses at the same sites nearly 100 years later (Wlosinski et al., 2002.).

In all, nearly 2,000 km (1,240 miles) of levees now isolate more than 400,000 ha (988,000 acres) from the river during all but the highest discharge rates. Wing dams and levees, along with other changes to the watershed, have also had a major effect on habitats by changing the relationship between discharge and water-surface elevations. Wing dams have narrowed and deepened the main channel so that water elevations at low discharges are now lower than they were historically. Levees restrict flows and result in higher water elevations during high discharges. Water surface elevations at relatively low discharges (1,700 m^3/s or 60,000 ft^3/s) have dropped about 2.4 m (8.0 ft) over the recorded 133-year period at St. Louis, Missouri, 0.5 m (1.5 ft) over the 52-year record at Chester, Illinois, and 1.5 m (5.0 ft) over the 60-year record at Thebes, Illinois. Water-surface elevations at relatively high discharges (22,000 m^3/s or 780,000 ft^3/s), however, have risen about 2.7 m (9 ft) over the record period at St. Louis, 1.5 m (5.0 ft) at Chester, and 1.1 m (3.6 ft) at Thebes.

In the upper Mississippi Basin, protection levels against flooding vary, largely depending on the use of the floodplain. Major urban areas are generally protected by levees that are strong and high enough to withhold a

flood like the 1993 flood. Many small towns and agricultural areas, however, are protected by 50-year levees, and many of these were overtopped or failed in 1993.

The 1993 flood reminded everyone of how damaging a river can be. The damage caused by this 1993 flood was substantial but was less than it might have been without the upstream flood control works (reservoirs and levees), upland soil conservation measures, terraces and ponds. Yet those flood damage reduction measures were not sufficient. The issue addressed by Gilbert White (1945) over a half century ago, the issue today, and no doubt the issue on into the future is how to effectively reduce the threat of future flood damage while supporting continued economic development in the affected areas.

A variety of options are available to reduce flood risks. Many are similar to those being considered in the Netherlands. They include raising or strengthening levees, relocating or setting back levees, dredging the main and/or side channels, and lowering floodplains. These may have major or minor effects, be expensive or relatively inexpensive, be in line or out of line with the current regulations or policies, and be more or less socially acceptable. For sustainable protection against flooding, measures in the upstream and downstream part of the river need to be considered together as a single system.

3.2. Other Considerations

The Mississippi is an important waterway for inland navigation, and the region's economy depends on the inexpensive transport of its bulk commodities. Much of the transport of goods to and from the Midwest states is by barge through an extensive lock and dam system. Periodic dredging is necessary at several locations on the river to maintain the navigation system.

Safe, speedy and cheap navigation demand a channel of adequate depth and width, and locks large enough to accommodate the fifteen-barge tows (Figure D.18). For such tows, the length of the present locks on the upper Mississippi River and Illinois is limiting, and often causes considerable delays, as mentioned above. Furthermore, the continued growth of commercial and recreational traffic is approaching maximum lock capacities. The width of the navigation channel is insufficient for two-way navigation at many locations. This further delays navigation and adds to transportation costs. However, reliability and low cost still make inland navigation a competitive means of transport. Other positive attributes of inland navigation are the relatively low energy consumption and the large transport capacity with few nuisance and safety problems. Air pollution by navigation per ton of cargo is far less than that produced per ton by trucks, or even by rail transport.

Agriculture and industry compete for space on the floodplain. Agriculture is the leading commercial user of the floodplains along the rivers in the upper Mississippi Basin. About 70% of the total 2.4 million ha (6 million acres) of floodplain is used for agricultural production. Due to the fertile soils, the yield in well-drained floodplains is usually substantially higher than in the upland areas.

A small but highly valuable portion of the floodplain, mainly in the direct vicinity of towns, is occupied by industries. Floodplains well protected by levees offer industry the advantage of immediate access to inland water transport to bring in raw materials and transport finished products, and immediate access to cooling and process water.

Nature also competes for space on the floodplain. Large wetland areas used to exist in the basin. These are unique links between land and water. Some are almost continuously under water, whereas others may be flooded for only a short period. This results in a variety of wetlands and their specific habitat types and functions. Through these special conditions, wetlands are among the most biologically productive natural ecosystems in the world.

In addition to being vital to the survival of various animals and plants, including threatened and endangered species, wetlands play a role in the reduction of peak water levels during smaller flood events (occuring every few years) because of their capability to store floodwater and release it slowly. For large events like the 1993 flood, the effect of wetlands on high water levels is much less because wetlands are usually saturated by rainfall or already flooded in an earlier stage.

From the mid-1800s the wetland areas were gradually decreased mainly to reduce the incidence of malaria and other waterborne diseases. Wetlands were converted to agricultural land and to a lesser extent to residential and industrial uses. Currently, wetlands account for about 10% of the floodplain in the upper Mississippi Basin.

Wetlands, storage lakes and the river itself provide considerable opportunities for recreation. Popular activities are hunting, fishing, camping, boating, sightseeing and bird watching. River-related recreation is important for the economy of local communities. The locks and dams provide many recreation lakes and the opportunity for boating, skiing, fishing and hunting.

Floodplains along the rivers also contain numerous archaeological and historic sites. These sites include historic architectural and engineering features and structures, and resources of traditional cultural or heritage significance to Native Americans and other social or cultural groups. Examples are forts, quarries, potteries and burial sites. Construction activities in and along the river, streambank erosion and extreme floods all can adversely affect these values.

Some of these multiple uses of the floodplain are compatible with flood management and obviously others are not. Yet all must be considered when developing a flood management plan.

The river itself is a source of water for municipal and industrial use: drinking water, processing and cooling water, and irrigation. The number of people who obtain drinking water from the river and its tributaries is quite large, yet the amount of water extracted for these purposes is relatively small when compared with the river discharge. As long as the flow withdrawn for water uses (after proper treatment) is returned to the rivers, this water use can be considered of minor importance in the overall water balance of the rivers. The export of water to other basins (diverting Missouri water all the way to Denver, for example) is another matter.

3.3. Interactions Among User Groups

Just as there are multiple purposes for the upper Mississippi River water and floodplain, some of which are complementary and others of which conflict, the same is true of the different user groups or stakeholders.

Table D.1 provides a rough indication of the ranges of some of the potentially more conflict-causing interactions. The table's columns are the activities that affect the activities shown in the rows. Scores of +1 and +2 indicate complementarities and positive interactions, 0 is neutral and –1 and –2 are competing or negative interactions. Participatory planning can help to push these relative numbers towards the positive side of the ranges, representing fewer conflicts and more positive interactions.

There are other important uses of water that are not mentioned in Table D.1 because the interactions are obvious and straightforward. Supplying municipal and domestic public water systems is one. Hydropower is another.

Some of the categories of conflict indicated in Table D.1 create serious problems in the upper Mississippi Basin. Some of the potential positive interactions are only weakly developed. The sharpest conflicts appear to be those between environmentalists and agriculturalists, and with those who would develop industrial sites through flood control and increased river shipping, but are constrained by legislation limiting land development in the floodplain.

A significant number of farmers consider environmental concerns by-and-large as expressions of urban outsiders, who have somehow gained the right to criticize the farmers' activities on their own land. In some cases, environmental regulations are viewed as threats to farm livelihood. Furthermore, when the reasons for regulation involve the preservation of animal or plant species that seem either insignificant or even nuisances to the agricultural community, the regulations are perceived to be both insulting and injurious. Whatever the pros and cons of the regulations, when the conflict of interests has reached the stage that some of the parties feel threatened, willing compliance with regulations drops and conflict resolution becomes far more difficult.

Table D.1 indicates only direct interactions. Indirect interactions are not listed, although they may also be very important. For instance, the effect of industrial development in or near the floodplain on river ecology is scored at 0 to –2 because industrial effects may vary between environmentally neutral, moderately polluting to so badly polluting that they destroy habitats. Industry is rarely directly complementary or positive to environmental concerns in floodplains. However, if the commitment is made to use some of the revenues generated by industrial development, through taxes or other means, to enhance environmental conditions (e.g. using some funds to establish conservation areas) then the indirect effects of the industrial development on the environment may be positive (score +1). Such indirect effects can be important in negotiations among user groups.

Table D.1. Interactions among potentially conflicting river activities.

	scoring the effects of						
	flood control structures	agriculture in the floodplain	industry in or near floodplain	shipping channel dredging	river based recreation	historical and cultural preservation	environmental protection
on flood control		+ 1 to − 1	0	+ 1 to − 1	0 to − 1	+ 1 to − 1	+ 1 to − 2
on floodplain agriculture	+ 2 to + 1		0 to − 1	+ 2 to + 1	0 to − 1	+ 1 to − 1	+ 1 to − 2
on industry in or near floodplain	+ 2	+ 1 to 0		+ 2 to + 1	0	0 to − 1	0 to − 2
on river navigation	− 1 to + 1	0	+ 1 to 0		0 to − 2	0	0 to − 1
on river-based recreation	+ 1 to − 1	0 to − 1	0 to − 2	0 to − 1		+ 1 to − 1	+ 2 to + 1
on historical & cultural property	+ 2 to − 2	0 to − 1	0 to − 2	0 to − 1	+ 1 to 0		+ 2 to 0
on condition of river ecology	0 to − 2	+ 1 to − 1	0 to − 2	0 to − 1	+ 1 to − 1	+ 2 to 0	

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+ 2 = necessary, or highly complementary and positive effects
+ 1 = generally positive
0 = neutral: no particular advantage nor conflict (small interaction)
− 1 = implementation of one means a restriction or damage to the other
− 2 = mutually exclusive thus completely in competition, or highly damaging

There are serious conflicts over the degree and extent of flood control that should be provided and the ways this should be done. There are various possibilities between two extremes: those who feel that flood protection levels should be raised significantly, primarily by increasing the heights of levees all along the river; and those who believe that development in the floodplain should be actively discouraged, and existing uses that restrict flood flows should be reduced. Arguments for the first option are largely that economic development in the region, particularly farming and industry, will be greatly served by protection from floods. The arguments for the second approach are primarily that floodplain protection and compensation for flood damage are very expensive, and that there is no compelling reason for the nation to subsidize floodplain development when alternative sites for agriculture and industry exist outside the floodplain. Floodplain protection measures are also frequently not environmentally friendly. Decreased floodplain development allows a return to more natural conditions.

Both arguments are valid. In some cases, flood control measures are complementary to environmental interests, particularly when the measures involve setting back levees, lowering floodplains or making parallel, unregulated channels or levees that protect or encourage the re-establishment of certain kinds of habitat. In general, however, environmental interests favour less engineering and lower rather than higher levees. River dredging is highly controversial. This puts environmental groups in strong conflict with those advocating floodplain development.

Negotiating conflicts between different interest groups requires extensive data collection and expert analyses of the impacts of different measures to control flooding. The results of the analyses need to be presented in ways that are accessible and understandable to stakeholders and decision-makers, and there should be a process that encourages debate, negotiation and compromises among stakeholders.

3.4. Creating a Flood Management Strategy

The current (2004) approach to river management on the upper and middle Mississippi River is not as integrated or as well balanced as it could be. This situation is not unique to this river and some of the reasons for it could be eliminated if policies that restrict comprehensive integrated approaches were changed. The 1993 flood in the upper Mississippi River Basin focused national attention on this problem, at least for a while. The concern it aroused presented an opportunity for reassessment and the creation of an integrated water resources management strategy. One of the conclusions of the Galloway Committee (1994) was: '*The United States has a rare opportunity to make a change in floodplain management. It should not be missed*'. Many of the recommendations made by this Committee have yet to be seriously considered. It seems, once again, that the concerns generated by the flood and identified by the committee are fading from national attention. What began as a useful debate following the 1993 flood seems to be dissipating without many substantial decisions that will make it easier to manage or mitigate the damage when the next flood occurs.

An argument could be made that the resources offered by the river could be used considerably more intensively than they are now without compromising the river's ecological integrity. The basin's potential for increased economic and ecological benefits is not fully developed. A more active management of ecological values, including using options for ecological restoration, can serve environmental protection and at the same time allow sustainable economic development. Active management of both economic and ecological values requires some compromises, but can also provide some important gains.

The economic advantage the river offers to the communities along it and to the region could and should be increased along with its ecological benefits. Navigation could be increased, even from an environmental point of view, given the relatively low air pollution and high safety levels of river freight compared with trucking and even rail. River transport of containerized cargo in addition to bulk agricultural products, agro-chemicals, coal and steel could be stimulated. There is potential to develop additional river ports and inter-modal transport facilities. Such development would enhance the economies of the communities along the river.

Similarly, the use of the river and the riverbanks for recreation (boating, fishing, hunting) could be increased. This would benefit local economies and could lead to the provision of guarantees for environmental conservation. Increased river-related recreation helps support environmental integrity since a high-quality environment is a necessary condition for this activity.

An integrated water management strategy would address flood management issues and uncertainties such as how levees influence upstream flood stages, how raising or setting back levees affect water levels elsewhere, how floodplain vegetation (particularly trees) influences flood stages, and so on. In addition, the flood safety levels for different land uses on the floodplain would be selected. The Galloway Report (1994) emphasized flexibility and variations in flood protection levels. Questions remain as to what levels of flood protection are appropriate for urban areas/industrial sites and agricultural lands, and how agreements on such levels are to be reached.

3.5. The Role of the Government and NGOs

State and federal agencies are major players in water resources management in this as in most major river basins in the United States. Without their leadership, not much planning or management takes place or is implemented. Yet there are limits as to what any particular agency can do. Thus, it is absolutely necessary for them to work together with each other and with private non-governmental organizations (NGOs and other stakeholder groups) if any approximation of an integrated water management plan or strategy is to be developed. If institutional change can facilitate that process, such change should be considered. Independent river basin commissions representing all stakeholders and taking responsibility for integrated river management can be effective, assuming their recommendations are sought

and would be seriously considered in the higher-level political decision-making process.

Present regulations regarding benefit–cost analysis need to be revised to allow more types of values to be considered alongside monetary values. The nation's interest in the economic development of the upper Mississippi, Illinois and Missouri River Basins is not reflected in the restricted way future benefits are calculated in the benefit–cost considerations required for federal investment plans in the river and floodplains. The omission of any estimates of the growth of future economic benefits can undervalue economic development. Since environmental benefits are not easily translated into monetary terms, they tend not to be fully considered. The economic benefits derived from natural well-functioning ecosystems that help to justify environmental protection are not made explicit either. The manner in which future benefits are included in the benefit–cost calculation should be consistent for different types of projects.

A balanced river-basin development plan for the upper Mississippi, Illinois and Missouri River Basins, to be drafted interactively with wide participation by all parties concerned, would improve understanding of the complex interrelationships between environmental protection, resource use, and river and floodplain development. Such a development plan would not be static, but would serve as a foundation to be revised on a regular basis in line with new developments and insights. In such an adaptive way, the plan could enhance the effective as well as efficient use of the river resources.

4. Flood Risk Reduction

There are two types of structural alternatives for flood risk reduction. One is flood storage capacity in reservoirs designed to reduce downstream peak flood flows. The other is channel enhancement and/or flood-proofing works that will contain peak flood flows and reduce damage. This section introduces methods of modelling both these alternatives for inclusion in either benefit–cost or cost-effectiveness analyses. The latter analyses apply to situations in which a significant portion of the flood control benefits cannot be expressed in monetary terms and the aim is to provide a specified level of flood protection at minimum cost.

The discussion will first focus on the estimation of flood storage capacity in a single reservoir upstream of a potential flood damage site. This analysis will then be expanded to include downstream channel capacity improvements. Each of the modelling methods discussed will be appropriate for inclusion in multipurpose river basin planning (optimization) models having longer time-step durations than those required to predict flood peak flows.

4.1. Reservoir Flood Storage Capacity

In addition to the active storage capacities in a reservoir, some capacity may be allocated for the temporary storage of flood flows during certain periods in the year. Flood flows usually occur over time intervals lasting from a few hours up to a few days or weeks. Computational limitations make it impractical to include such short time durations in many of our multipurpose planning models. If we modelled these short durations, flood routing equations would have to be included in the model; a simple mass balance would not be sufficient. Nevertheless, there are ways of including unknown flood storage capacity variables within longer-period optimization models. These capacities can be determined on the basis of economic efficiency within benefit–cost analyses, or they can be based on constraints specifying maximum flood risk protection levels.

Consider a potential flood damage site along a river. A flood control reservoir can be built upstream of that site. The question is how much flood storage capacity, if any, should it contain. For various assumed capacities, simulation models can be used to predict the impact on the downstream flood peaks. These hydraulic simulation models must include flood routing procedures from the reservoir to the downstream potential damage site and the flood control operating policy at the reservoir. For various downstream flood peaks, economic flood damages can be estimated. To calculate the expected annual damage associated with any upstream reservoir capacity, the probability of various damage levels being exceeded in any year needs to be calculated.

The likelihood of a flood peak of a given magnitude or greater is often defined by its expected return period. How many years would one expect to wait, on average, to observe another flood equal to or greater than some

specified magnitude? This is the reciprocal of the probability of observing such a flood in any given year. A T-year flood has a probability of being equalled or exceeded in any year of $1/T$. This is the probability that could be calculated by adding up the number of years an annual flood of a given or greater magnitude is observed, say in 1,000 or 10,000 years, divided by 1,000 or 10,000 respectively. A one-hundred year flood or greater has a probability of 1/100 or 0.01 of occurring in any given year. Assuming annual floods are independent, if a 100-year flood occurs this year, the probability that a flood of that magnitude or greater occurring next year remains 1/100 or 0.01.

If PQ is the random annual peak flood flow and PQ_T is a particular peak flood flow having a return period of T years, then by definition the probability of an actual flood of PQ equalling or exceeding PQ_T is $1/T$;

$$\Pr[PQ \geq PQ_T] = 1/T \tag{D.1}$$

The higher the return period (i.e. the more severe the flood), the lower the probability that a flood of that magnitude or greater will occur. Equation D.1 is plotted in Figure D.21.

The exceedance probability distribution shown in Figure D.21 is simply 1 minus the cumulative distribution function $F_{PQ}(\cdot)$ of annual peak flood flows. The area under the function is the mean annual peak flood flow, E[PQ].

The expected annual flood damage at a potential flood damage site can be estimated from an exceedance probability distribution of peak flood flows at that site together with a flow or stage damage function. The peak flow exceedance distribution at any potential damage site will be a function of the upstream reservoir flood storage capacity K_f and the reservoir operating policy.

The probability that flood damage of FD_T associated with a flood of return period T will be exceeded is precisely the same as the probability that the peak flow PQ_T that causes the damage will be exceeded. Letting FD be a random flood damage variable, its probability of exceedance is

$$\Pr[FD \geq FD_T] = 1/T \tag{D.2}$$

The area under this exceedance probability distribution is the expected annual flood damage, $E[FD]$;

$$E[FD] = \int_0^\infty \Pr[FD \geq FD_T] \mathrm{d}FD_T \tag{D.3}$$

This computational process is illustrated graphically in Figure D.22. The analysis requires three input functions that are shown in quadrants (a), (b), and (c). The dashed-line rectangles define point values on the three input functions in quadrants (a), (b), and (c) and the corresponding probabilities of exceeding a given level of damages in the lower right quadrant (d). The distribution in quadrant (d) is defined by the intersections of these dashed-line rectangles. This distribution defines the probability of equalling or exceeding a specified level of damage in any given year. The (shaded) area under the derived function is the annual expected damage, $E[FD]$.

The relationships between flood stage and damage, and flood stage and peak flow, defined in quadrants (a) and (b) of Figure D.22, must be known. These do not depend on the flood storage capacity in an upstream reservoir. The information in quadrant (c) is similar to that shown in Figure D.21 defining the exceedance probabilities of each peak flow. Unlike the other three functions, this distribution depends on the upstream flood storage capacity and flood flow release policy. This peak flow probability of exceedance distribution is determined by simulating the annual floods entering the upstream reservoir in the years of record.

The difference between the expected annual flood damage without any upstream flood storage capacity and the expected annual flood damage associated with a flood storage capacity of K_f is the expected annual flood damage reduction. This is illustrated in Figure D.23.

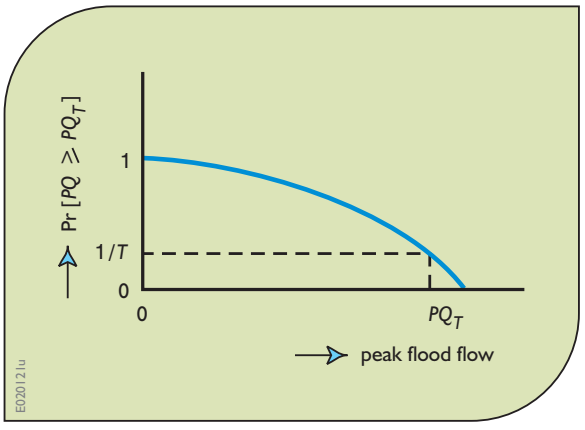

Figure D.21. Probability of annual peak flood flows being exceeded.

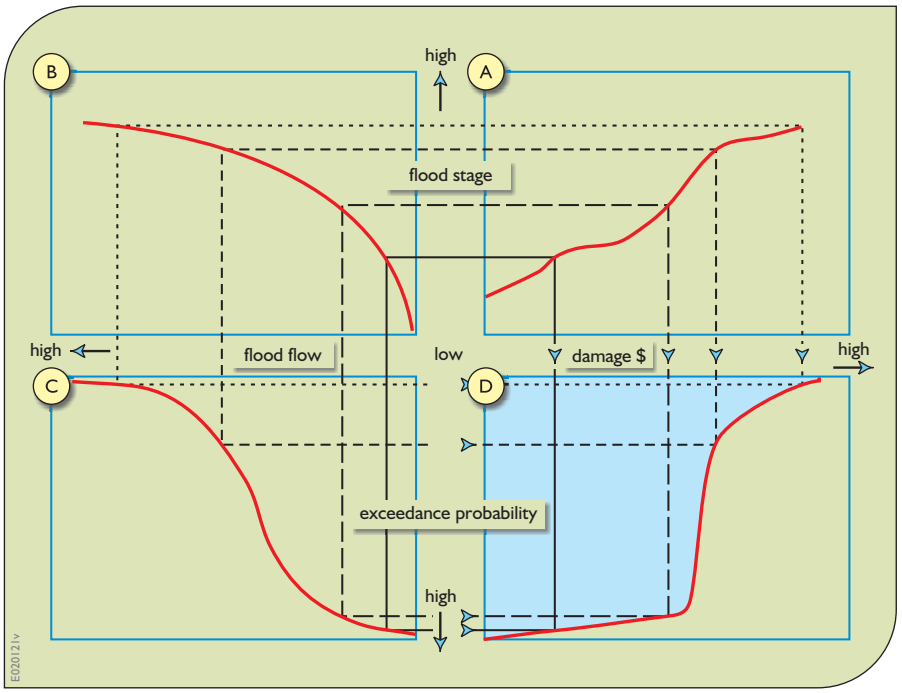

Figure D.22. Calculation of the expected annual flood damage shown as the shaded area in quadrant (d) derived from the expected stage-damage function (a), the expected stage-flow relation (b), and the expected probability of exceeding an annual peak flow (c).

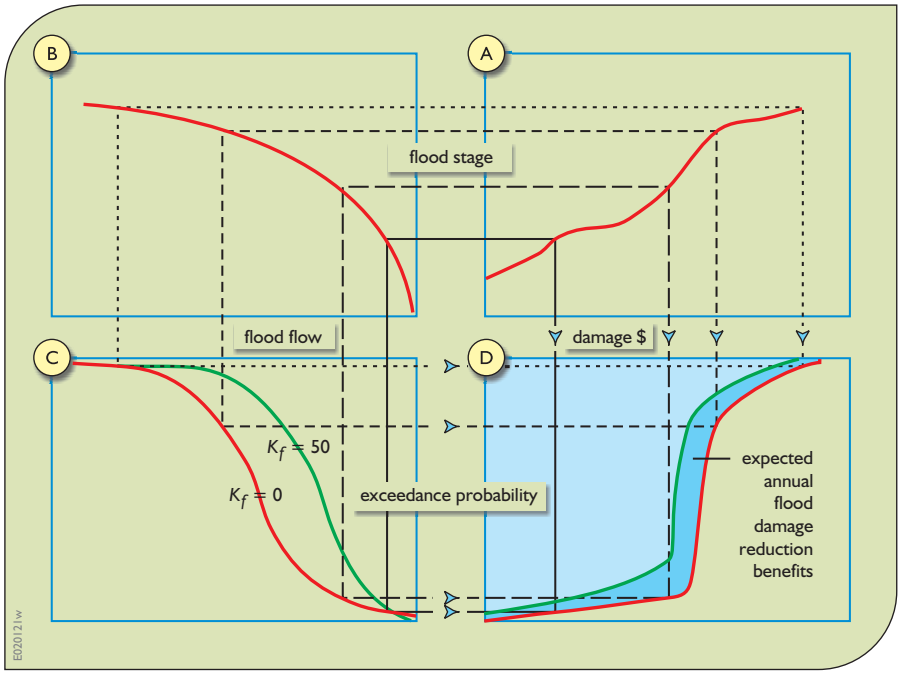

Figure D.23. Calculation of expected annual flood damage reduction benefits, shown as the darkened portion of quadrant (d), associated with a specified reservoir flood storage capacity.

Knowing the expected annual damage reduction associated with various flood storage capacities, K_f, permits the definition of a flood damage reduction function, $B_f(K_f)$.

If the reservoir is a single-purpose flood control reservoir, the eventual tradeoff is between the expected flood reduction benefits, $B_f(K_f)$, and the annual costs, $C(K_f)$, of that upstream reservoir capacity. The particular reservoir flood storage capacity that maximizes the net benefits, $B_f(K_f) - C(K_f)$, may be appropriate from a national economic efficiency perspective but may not be

best from a local perspective. Those occupying the potential damage site may prefer a specified level of protection from the reservoir storage capacity, rather than the protection that maximizes expected annual net benefits, $B_f(K_f) - C(K_f)$.

If the upstream reservoir is to serve multiple purposes, say for water supply, hydropower and recreation as well as for flood control, the expected flood reduction benefit function just derived could be a component in the overall objective function for that reservoir.

Total reservoir capacity K will equal the sum of dead storage capacity K_d, active storage capacity K_a and flood storage capacity K_f, assuming they are the same in each period t. In some cases they may vary over the year. If the required active storage capacity can occupy the flood storage zone when flood protection is not needed, the total reservoir capacity K will be the dead storage, K_d, plus the maximum of either 1) the actual storage volume and flood storage capacity in the flood season or 2) the actual storage volume in non-flood season.

$K \geq K_d + S_t + K_f$ for all periods t in flood season plus the following period (that represents the end of the flood season) (D.4)

$K \geq K_d + S_t$ for all remaining periods t (D.5)

In the above equations, the dead storage capacity, K_d, is a known variable. It is included in the capacity Equations D.4 and D.5, assuming that the active storage capacity is greater than zero. Clearly, if the active storage capacity were zero, there would be no need for dead storage.

4.2. Channel Capacity

The unregulated natural peak flow of a particular design flood at a potential flood damage site can be reduced by upstream reservoir flood storage capacity, or it can be contained within the channel at the potential damage site by levees and other channel-capacity improvements. In this section, the possibility of levees or dykes and other channel capacity or flood-proofing improvements at a downstream potential damage site will be considered. The approach used will provide a means of estimating combinations of flood control storage capacity in upstream reservoirs and downstream channel capacity improvements that together will provide a pre-specified level of flood protection at the downstream potential damage site.

Let QN_T be the unregulated natural peak flow in the flood season having a return period of T years. Assume that this peak flood flow is the design flood for which protection is desired. To protect from this design peak flow, a portion QS of the peak flow may be reduced by upstream flood storage capacity. The remainder of the peak flow QR must be contained within the channel. Hence, if the potential damage site s is to be protected from a peak flow of QN_T, the peak flow reductions due to upstream storage, QS, and channel improvements, QR, must at least equal to that peak flow;

$$QN_T \leq QS + QR \tag{D.6}$$

The extent to which a specified upstream reservoir flood storage capacity reduces the design peak flow at the downstream potential damage site can be obtained by routing the design flood through the reservoir and the channel between the reservoir and the downstream site. Doing this for a number of reservoir flood storage capacities permits the definition of a peak flow reduction function, $f_T(K_f)$:

$$QS = f_T(K_f) \tag{D.7}$$

This function is dependent on the relative locations of the reservoir and the downstream potential damage site, on the characteristics and length of the channel between the reservoir and downstream site, on the reservoir flood control operating policy, and on the magnitude of the peak flood flow.

An objective function for evaluating these two structural flood control measures should include the cost of reservoir flood storage capacity, $\text{Cost}_K(K_f)$, and the cost of channel capacity improvements, $\text{Cost}_R(QR)$, required to contain a flood flow of QR. For a single-purpose, single-damage site, single-reservoir flood control problem, the minimum total cost required to protect the potential damage site from a design flood peak of QN_T, may be obtained by solving the model:

$$\text{minimize } \text{Cost}_K(K_f) + \text{Cost}_R(QR) \tag{D.8}$$

subject to

$$QN_T \leq f_T(K_f) + QR \tag{D.9}$$

Equations D.8 and D.9 assume that a decision will be made to provide protection from a design flood QN_T of return period T; it is only a question of how to provide the required protection.

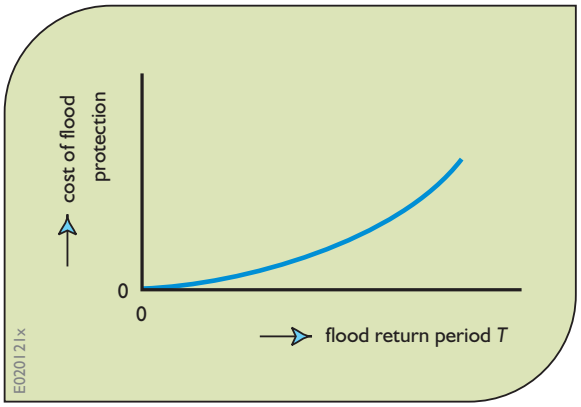

Figure D.24. Tradeoff between minimum cost of flood protection and flood risk, as expressed by the expected return period.

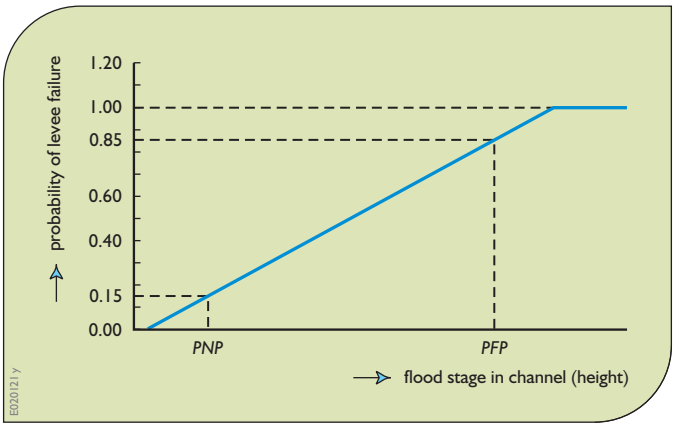

Figure D.25. Assumed cumulative probability distribution of levee failure expressed as function of flood stage in river channel.

Solving Equations D.8 and D.9 for peak flows QN_T of various return periods T will identify the risk–cost tradeoff. This tradeoff function might look like what is shown in Figure D.24.

4.3. Estimating Risk of Levee Failures

Levees are built to reduce the likelihood of flooding on the floodplain. Flood flows prevented from flowing over a floodplain due to a levee will have relatively little effect on users of the floodplain, unless of course the levee fails to contain the flow. If any of the flow in the stream or river channel passes over, through or under the levee and onto the floodplain, the levee is said to fail. This can result from flood events that exceed (overtop) the design capacity of the levee, or from various types of geo-structural weaknesses. The probability of levee failure along a river reach is in part a function of the levee height, the probability distribution of flood flows in the stream or river channel and the probability of geo-structural failure. The latter depends in part on how well the levee and its foundation were constructed. Some levees are purposely designed to 'fail' at certain sites at certain flood stages to reduce the likelihood of more substantial failures and flood damage further downstream.

The probability of levee failure given the flood stage (height) in the stream or river channel is often modelled using two flood stages. The US Army Corps of Engineers calls the lower stage the probable non-failure point, *PNP*, and the higher stage the probable failure point, *PFP* (USACE, 1991). At the *PNP*, the probability of failure is assumed to be 15%. Similarly, the probability of failure at the *PFP* is assumed to be 85%. A straight-line distribution between these two points is also assumed, as shown in Figure D.25. Of course, these points and distributions are at best only guesses, as not many, if any, data will exist to base them on at any given site.

To estimate the risk of a flood in the floodplain protected by a levee due to overtopping or geo-structural levee failure, the relationships between flood flows and flood stages in the channel and on the floodplain must be defined.

Assuming no geo-structural levee failure, the flood stage in the floodplain protected by a levee is a function of the flow in the stream or river channel, the cross-sectional area of the channel between the levees on either side, the channel slope and roughness, and the levee height. If floodwaters enter the floodplain, the resulting water level or stage in the floodplain will depend on the topological characteristics of the floodplain. Figure D.26 illustrates the relationship between the flood stage in the channel and the flood stage in the floodplain, assuming no geo-structural failure of the levee. Obviously once the flood begins overtopping the levee, the flood stage in the floodplain begins to increase. Once the flood flow is of sufficient magnitude that its stage without the levee is the same as that with the levee, the existence of a levee has only a negligible impact on the flood stage.

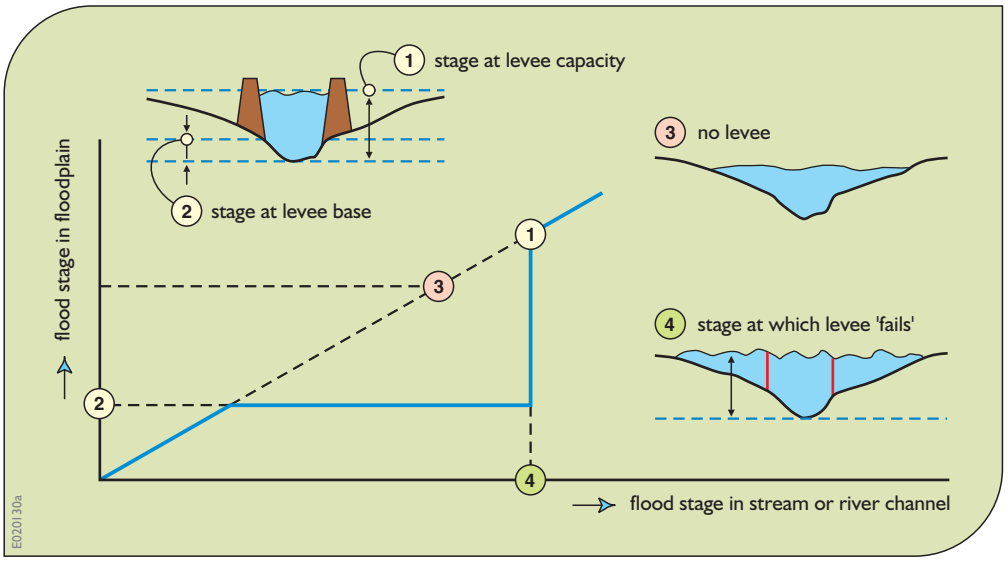

Figure D.26. Influence of a levee on the flood stage in floodplain compared to stream or river flood stage. The channel flood stage where the curve is vertical is the stage at which the levee fails due to overtopping or from geo-structural causes.

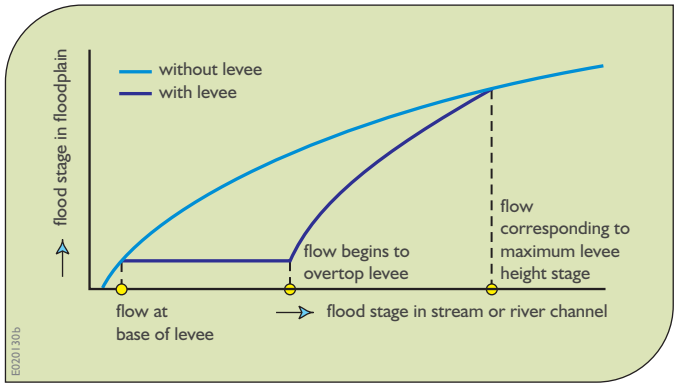

Figure D.27. Relationship between flood flow and flood stage in a floodplain with and without flood levees, again assuming no geo-structural levee failure.

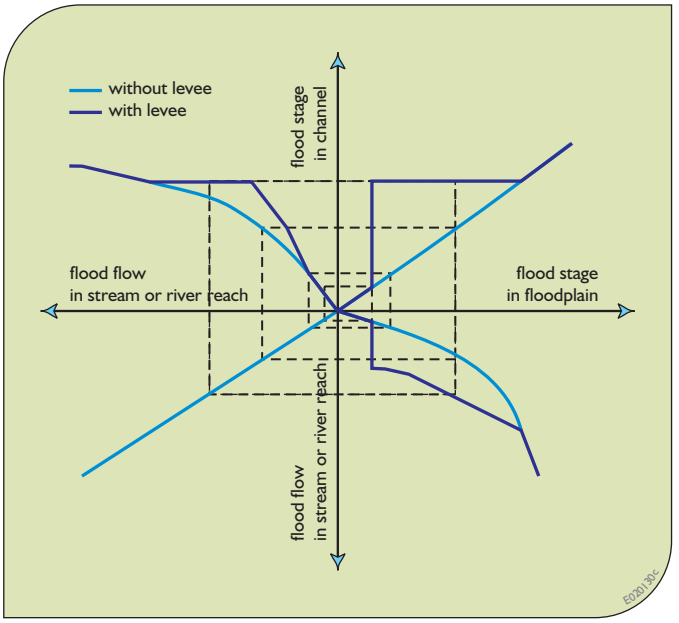

Figure D.28. Deriving the relation (shown in the upper left quadrant) between flood flow and flood stage in the channel.

Figure D.27 illustrates the relationship between flood flow and flood stage in a floodplain with and without flood levees, again assuming no geo-structural levee failure.

Combining Figures D.26 and D.27 defines the relationship between reach flow and channel stage. This is illustrated in the upper-left quadrant of Figure D.28.

Combining the relationship between flood flow and flood stage in the channel (upper-left quadrant of Figure D.28) with the probability distribution of levee failure (Figure D.25) and the probability distribution of annual peak flows being equalled or exceeded (Figure D.21), provides an estimate of the expected probability of levee failure. Figure D.29 illustrates this process of calculating the expected probability of levee failure in any year from overtopping and/or geo-structural failure. This expected probability is shown as the blue shaded area in the lower-right quadrant of the figure.

The channel flood stage function, $S(q)$, of peak flow q shown in the upper-left quadrant of Figure D.29 is obtained from the upper-left quadrant of Figure D.28. The probability of levee failure, $PLF(S)$, a function of

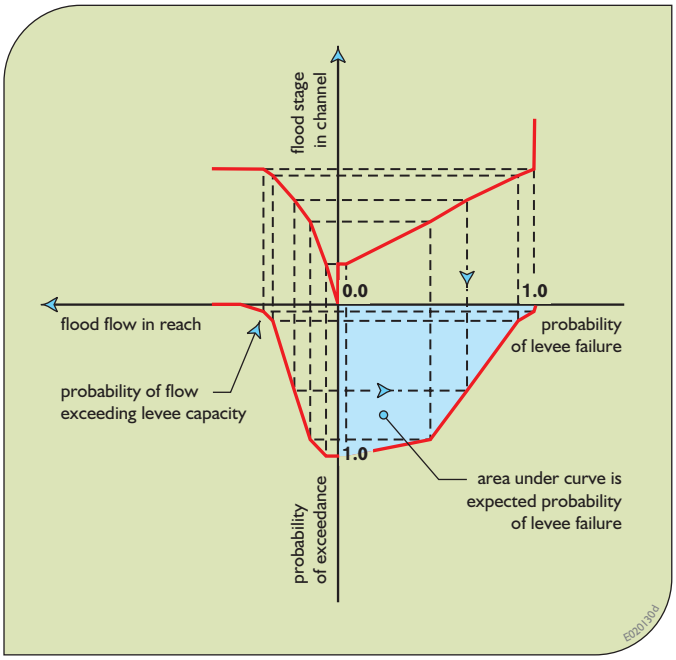

Figure D.29. Derivation of the probability of exceeding a given probability of levee failure, shown in lower right quadrant. The shaded area enclosed by this probability distribution is the annual expected probability of levee failure.

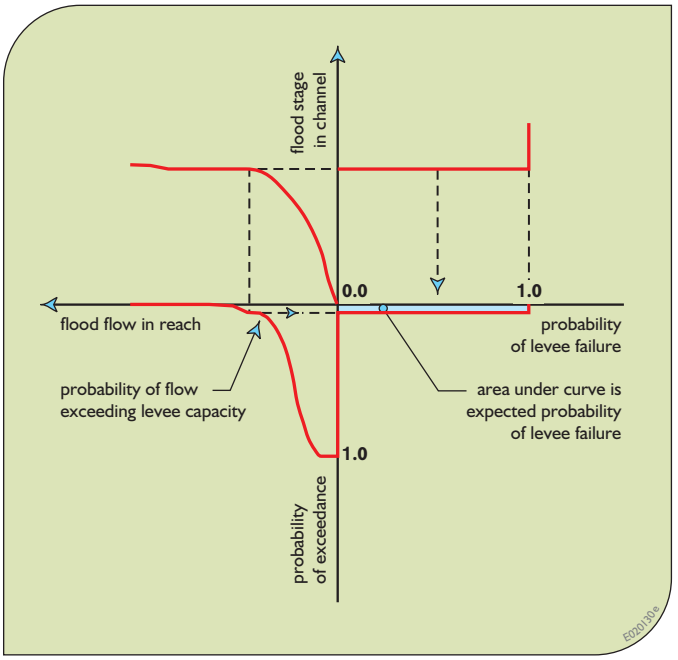

Figure D.30. Calculation of annual probability of equalling or exceeding any specified probability of levee overtopping, shown in the lower right quadrant. The shaded area in this quadrant is the expected probability of levee overtopping, assuming there is no geo-structural failure.

flood stage, $S(q)$, shown in the upper-right quadrant is the same as in Figure D.25. The annual peak flow exceedance probability distribution, $F_Q(q)$, (or its inverse $Q(p)$) in the lower-left quadrant is the same as Figure D.30 or that in the lower-left quadrant (c) of Figure D.22. The exceedance probability function in the lower-right quadrant of Figure D.29 is derived from each of the other three functions, as indicated by the arrows, in the same manner as described in Figure D.22.

In mathematical terms, the annual expected probability of levee failure, E[*PLF*], found in the lower-right quadrant of Figure D.29, equals

$$\mathrm{E}[PLF] = \int_0^\infty PLF[S(q)]f(q)\mathrm{d}q = \int_0^1 PLF[S(Q(p))]\mathrm{d}p$$
$$= \int_0^1 PLF'(p)\mathrm{d}p \qquad \text{(D.10)}$$

where $PLF'(p)$ is the probability of levee failure associated with a flood stage of $S(q)$ having an exceedance probability of p.

Note that if the failure of the levee was only due to channel flood stages exceeding the levee height (i.e. if the probability of geo-structural failure were zero), the expected probability of levee failure would be simply the probability of exceeding a channel flow whose stage equals the levee height, as defined in the lower-left quadrant of Figure D.29. This is shown in Figure D.30.

Referring to Figure D.30, if the levee height is increased, the horizontal part of the curve in the upper-right quadrant would rise, as would the horizontal part of the curve in the upper-left quadrant as it shifts to the left. Hence, given the same probability distribution as defined in the lower-left quadrant, the expected probability of exceeding an increased levee capacity would decrease, as it should.

4.4. Annual Expected Damage From Levee Failure

A similar analysis can provide an estimate of the expected annual floodplain damage for a stream or river reach. Consider, for example, a parcel of land on a floodplain at some location i. If an economic efficiency objective were to guide the development and use of this parcel, then the owner would want to maximize the net annual economic benefits derived from its use, B_i, less the annual (non-flood damage) costs, C_i, and the expected annual

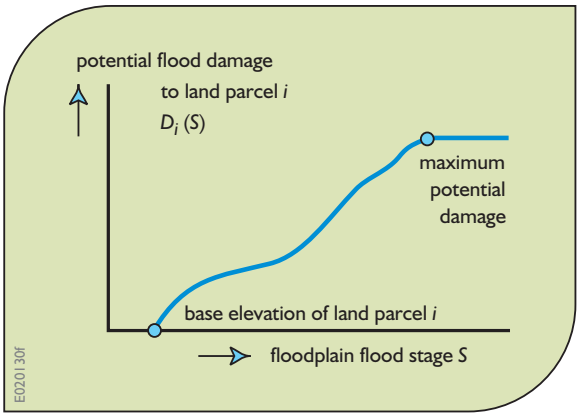

Figure D.31. An example function defining the damages that will occur given any flood stage *S* to a parcel of land *l*.

flood damage, EAD_i. The issue of concern here is the estimation of the expected annual flood damage.

The degree of damage at location i resulting from a flood will depend in part on the depth of flooding at that location and a host of other factors (flood duration, velocity of and debris in flood flow, time of year and so on). Assume that the flood damage at location i is a function of primarily the flood stage, S, at that location. Denote this potential damage function as $D_i(S)$. Such a function is illustrated in Figure D.31.

Integrating the product of the annual exceedance probability of flood stage, $F_s(S)$, and the potential damages, $D_i(S)$, over all stages S will yield the annual expected damages, $E[D_i]$, for land parcel i;

$$E[D_i] = \int D_i(S)F_s(S)\mathrm{d}s \qquad \text{(D.11)}$$

The sum of the expected damage estimates over all the parcels of land i on the floodplain is the total expected damage that one can expect each year, on average, on the floodplain.

$$EAD = \sum_i E[D_i] \qquad \text{(D.12)}$$

Alternatively, the annual expected flood damage could be based on a calculated probability of exceeding a specified flood damage, as shown in Figure D.22. For this method, the potential flood damages, $D_i(S)$, are determined for various stages S and then summed over all land parcels i for each of those stage values S to obtain the total potential damage function, $D(S)$, for the entire floodplain, defined as a function of flood stage S:

$$D(S) = \sum_i D_i(S) \qquad \text{(D.13)}$$

This is the function shown in quadrant (a) in Figure D.22.

Levee failure probabilities, $PLF'(p)$, based on the exceedance probability p of peak flows, or stages, as defined in Figure D.29 can be included in calculations of expected annual damage. Expressing the damage function, $D(S)$, as a function, $D'(p)$, of the stage exceedance probability p and multiplying this flood damage function $D'(p)$ times the probability of levee failure, $PLF'(p)$ defines the joint exceedance probability of expected annual damages. Integrating over all values of p yields the expected annual flood damage, EAD:

$$EAD = \int_0^1 D'(p)PLF'(p)\mathrm{d}p \qquad \text{(D.14)}$$

Note that the floodplain damage and probability of levee failure functions in Equation D.14 both increase with increasing flows or stages, but as peak flows or stages increase, their exceedance probabilities decrease. Hence, with increasing p the damage and levee failure probability functions decrease. The effect of levees on the expected annual flood damage, EAD, is shown in Figure D.32. The 'without levee' function in the lower right quadrant of Figure D.28, is $D'(p)$. The 'with levee' function is the product of $D'(p)$ and $PLF'(p)$. If the probability of levee failure, $PLF'(p)$ function were as shown in Figure D.28, (that is, if it were 1.0 for values of p below some overtopping stage associated with an exceedance probability p^*, and 0 for values of p greater than p^*), then the function would appear as shown 'with levee, overtop only' in Figure D.32.

4.4.1. Risk-Based Analyses

Risk-based analyses attempt to identify the uncertainty associated with each of the inputs used to identify the appropriate capacity of various flood risk reduction measures. There are numerous sources of uncertainty associated with each of the functions shown in quadrants (a), (b) and (c) in Figure D.21. This uncertainty translates into uncertainty associated with estimates of flood risk probabilities and expected annual flood damage reductions obtained from reservoir flood storage capacities and channel improvements.

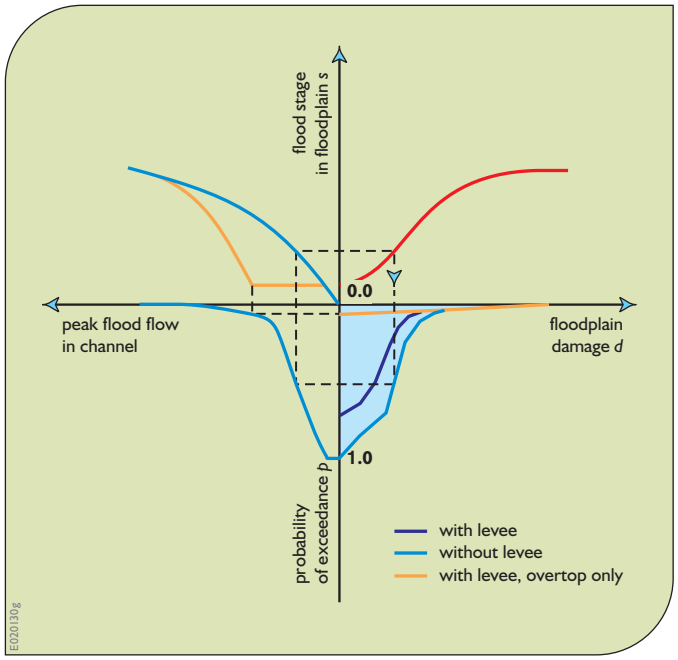

Figure D.32. Calculation of expected annual flood damage taking into account probability of levee failure.

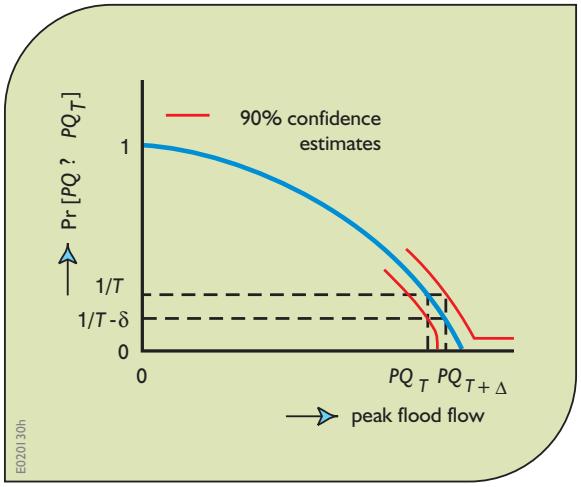

Figure D.33. Portion of peak flow probability of exceedance function showing contours containing 90% of the uncertainty associated with this distribution. To be 90% certain of protection from a peak flow of PQ_T, protection is needed from the higher peak flow, $PQ_{T+\Delta}$ expected once every $T + \Delta$ years, i.e. with an annual probability of $1/(T + \delta)$ or $(1/T) - \delta$ of being equalled or exceeded.

Going to the substantial effort and cost of quantifying these uncertainties, which themselves will be surely be uncertain, does provide additional information. The design of any flood protection plan can be adjusted to reflect the attitudes of stakeholders toward the uncertainty associated with specified flood peak return periods or equivalently their probabilities of occurring in any given year.

For example, assume a probability distribution capturing the uncertainty about the expected probability of exceedance of the peak flows at the potential damage site (as shown in Figure D.22) is defined from a risk-based analysis. Figure D.33 shows that exceedance function together with its 90% confidence bands near the higher flood peak return periods. To be, say, 90% sure that protection is provided for the T-year return period flow, PQ_T, one may have to design for an equivalent expected $T + \Delta$ year return period flow, $PQ_{T+\Delta}$; that is, the flow having a $(1/T) - \delta$ expected probability of being exceeded. Conversely, protection from the expected $T + \Delta$ year peak flood flow will provide 90% assurance of protection from flows that will occur less than once in T years on average.

If society wanted to eliminate flood damage it could do so, but at a high cost. It would require either costly flood control structures or the elimination of economic activities on floodplains. Both reduce expected economic returns from the floodplain, and hence, are not likely to be undertaken. There will always be a risk of flood damage. Analyses such as those just presented help identify the risks. They can be reduced and managed but not eliminated. Finding the best levels of flood protection and flood risk, together with risk insurance or subsidies (illustrated in Figure D.34) is the challenge for public and private agencies alike. Flood risk management is as much concerned with good things not happening on floodplains as with bad things happening on them.

5. Decision Support and Prediction

To assist decision-makers in evaluating alternative solutions for problems encountered in integrated river management, and in communicating these solutions and their consequences to the public, interactive computer-based decision support systems (DSS) can be of considerable help. A DSS could consist of up-to-date river and floodplain information (using geographic information systems and database managers) and dynamic river

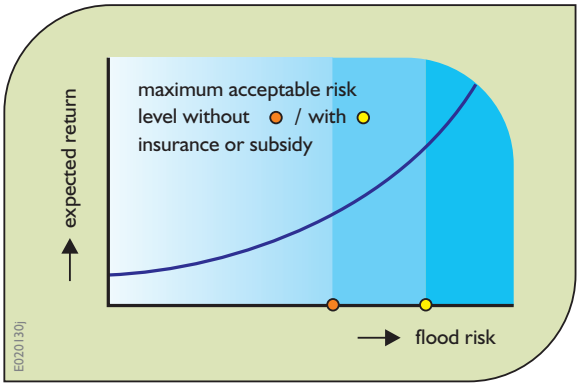

Figure D.34. Relationship between expected economic return from floodplain use and risk of flooding. The lowest flood risk does not always mean the best risk, and what risk is acceptable may depend on the amount of insurance or subsidy provided when flood damage occurs.

models of the complete river network. It could be used to simulate flooding scenarios in which water managers and stakeholders could be involved in deciding what to do and noting the impacts or consequences. Periodic simulation exercises such as this could serve as a reminder to the public, especially during dry years, that floods can and will occur, and some may have to be allowed to overflow levees and cause damage.

5.1. Floodplain Modelling

Efforts to identify improved flood management policies are almost always based on predictions, admittedly uncertain, of the impacts of specific structural or non-structural measures. These impact predictions come from models and their databases. Modelling and the communication of model results to interested property owners, government planners and insurance companies are becoming increasingly important components of flood management.

In providing the desired information, one must deal with uncertainties. Flood studies imply extrapolation of model parameters and boundary data to situations that have never been recorded. This raises the question of the reliability of current procedures of model calibration. The quality of model results depends to a large extent on available data and their relevance for future planning. Two-dimensional (2D) models require accurate digital terrain models (DTM). The cost of collecting data of sufficient accuracy for flood studies has decreased significantly through the use of airborne laser altimetry. Moreover, research has started to provide floodplain roughness data through complementary analysis of laser altimetry data. Laser altimetry techniques are now also applied to the recording of flood levels, which can further support the calibration of flood simulation models. The new data collection techniques are also complemented by hydraulic laboratory investigations, such as the derivation of laws and parameters describing flow resistance resulting from various classes of vegetation.

New data collection techniques also show a distinct change in the type of data underlying model development and model use. In general, there is a tendency to move from the collection of point data to spatially-distributed data. Whereas design flood hydrographs used to form the basis for flood control studies, the rainfall radar data, together with river catchment models, allow the use of design storm patterns. The development of 2D models based upon digital terrain models and roughness maps is becoming easier and more cost-effective than the development of 1D models based upon point information of cross sections measured at selected intervals along the river axis.

This does not mean that the traditional 1D modelling of flood events will be fully replaced by 2D model applications. Although the development of an accurate 2D model supported by the new data collection and processing techniques is becoming easier and cheaper for many studies, 2D models require more computer time, and this is not going to change within a decade. Flood management planning and risk assessments typically require the simulation of many floodplain management alternatives over large numbers of probabilistic or stochastic events.

Both 1D and 2D models can be used together as appropriate. They can be integrated in many applications to provide local refinement of the description, in particular the flooding of normally dry land. A 2D model can be used as a support tool for the development of accurate and extrapolatable 1D models through the transfer of discharge conveyance and storage functions.

The shift from a policy of protecting as much agricultural, industrial and urban land as possible by constructing dykes or levees close to the main river, to one of creating, if possible, green rivers and larger floodplains or areas with lower protection against flooding results in a need to understand and predict the

flood flows and heights resulting from such measures. This requires data on the local topography and flow resistance.

The hydraulic roughness of floodplains can be assessed with the aid of maps showing vegetation or land use classes. Such habitat or land use compositions can be related to flow roughness descriptions. Assessments of roughness values associated with each vegetation class are usually based upon a combination of hydraulic laboratory experiments and expert judgement. The spatial distribution of vegetation or land use classes subsequently leads to the assignment of roughness values at the grid cells of 2D models. Flow resistance for each vegetation class can be constant or expressed as a function of stage (flood height).

The 2D models incorporating these floodplain roughness parameters can be used to assist in the calibration of 1D models. Both types of model can then be used for a variety of water management studies and policy analyses.

The link between vegetation or land use classes and roughness provides a description of the energy losses as a function of the flow-blocking area in a specific region. This provides a more accurate description of the losses as a function of the water level. Flow through reed fields, for example, meets a high resistance as long as the vegetation is not overtopped or bent-over and lying on the bottom. Other, more dense vegetation may even create laminar flow before overtopping takes place. After drowning, its flow resistance reduces significantly. A relation between vegetation or land use and flow resistance also allows for the introduction of seasonal variations in flow resistance.

One software product developed at WL | Delft Hydraulics is the so-called Delft-1D2D system. This is currently in use for the simulation of large numbers of scenarios of flooding resulting from potential dyke breaches. The approach followed in this software provides many possibilities for the integrated simulation of river floods, tidal flow and urban storms.

5.2. Integrated 1D–2D Modelling

There are various ways in which one can couple hydrological and hydraulic system simulation models. These include:

- Sequential coupling of data flows if one process is completely independent of another process, for example, from a rainfall–runoff module to a channel flow module.
- On-line explicit coupling at a selected frequency in time, such as the link between a surface water flow module and a water quality module. Such coupling works well if the mutual dependence of processes described by the individual modules is not important: for example, if the time scale of one process is quite different from the time scale of the other process. If process time scales are similar, constraints in time stepping may have to be satisfied.
- On-line implicit coupling of modules. This approach requires not only the exchange of data between various modules but also the exchange of complete sets of equations, which are to be solved simultaneously.

The WL | Delft Hydraulics' general 0D, 1D and partly 2D modelling system called SOBEK is designed to integrate processes, such as rainfall–runoff; river, channel and pipe flow; water quality and morphology. The hydrodynamic part handles sub- and supercritical flows, including transitions such as hydraulic jumps and tidal bores.

This approach to integration offers a range of modelling options. In an urban drainage model, one can combine pipe flow, river flow, tidal flow, street flow, and flow over parks and parking places, for example (Bishop and Catalano, 2001). Another example is dam break analysis that allows for any suitable combination of 1D and 2D flow, including zones with supercritical flow. Finally, the creation of retention storage in flood control is modelled more realistically than on the basis of a combined 0D and 1D schematization by itself.

The 1D2D integration can be illustrated by examining alternative flood scenarios for the Geldersche Vallei in the centre of the Netherlands (Figure D.35). The area modelled measures approximately 35 × 20 km, schematized with a 2D grid of 100 × 100 m and coupled to a 1D schematization of the principal waterways and road culverts in the area. The model study had the objective of assessing flood damage and establishing evacuation plans for a number of flood scenarios. The most severe situation is caused by a possible breach in the Grebbedijk, protecting the area from floods conveyed along the Lower Rhine.

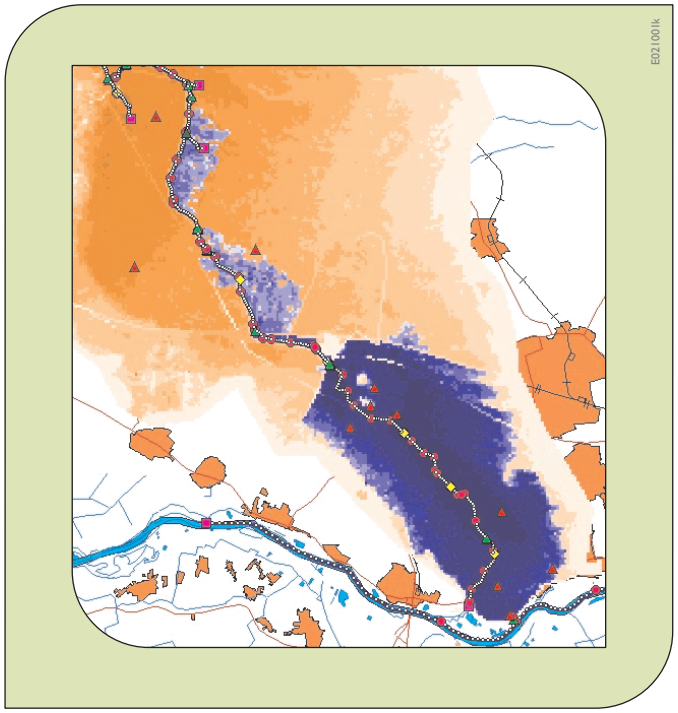

Figure D.35. Coupled 1D2D SOBEK model of the Geldersche Valley in the Netherlands.

The coupled model also allows for the extension of the 2D model along the Lower Rhine. This river has been schematized in 1D over a length of 19 km, with the breach coupled a few kilometres downstream of the upstream boundary of the Lower Rhine branch. The flow through the breach significantly influences water levels upstream, and consequently the discharges generated through it. It is here that another advantage of implicit coupling shows up. Inclusion of the Lower Rhine into the 2D model would have given only approximately a 3 to 10 grid-point resolution over its width, which is not sufficient to model its flow satisfactorily. Another and often principal advantage of 1D and 2D coupling is that the grid cells of the 2D model part can generally be significantly larger than when pure 2D modelling is applied. Apart from the flexibility in schematization, this usually also leads to considerable savings in simulation times.

6. Conclusions

In the wake of the unusually severe floods on the River Rhine and on the upper Mississippi River in the early and mid-1990s and the equally severe floods in many parts of the world since then, including those in Central Europe and in Asia that occurred in 2002 and 2004, an increasing consensus is emerging. Humans must provide space for floods where and when they occur, and floods must be managed better. This is not a new idea. The only sustainable way to reduce the continuing cycle of increasing flood damage and increasing flood protection costs is to restore the natural floodplains that contain the river's floodwaters. Floods have become a reason to restore rivers rather than dam or dyke them. Many who have traditionally advocated structural solutions to flood protection are increasingly embracing the idea that rivers need to be given space to flood. Flood protection has joined clean drinking water and recreation as a reason for restoring river ecosystems.

Governments can motivate more responsible floodplain management. National governments can assume leadership, define clear roles and provide fiscal support for flood management at lower levels. As happened in the upper Mississippi River Basin, governments can

- provide relocation aid and buyout funding for those living in floodplains
- stop disaster relief payments and subsidized flood insurance for those who continue to live or develop in flood prone areas
- make flood insurance mandatory where offered, and have the premiums reflect flood risks
- enforce building code requirements on floodplains.

In the United States, the Army Corps of Engineers Flood Control Programme has had a major influence on floodplain development. Many now might claim it to be a negative influence, but the Corps did what Congress, and the public, asked them to do. Hundreds of dams and thousands of miles of Corps levees and floodwalls were built for flood protection. The result, of course, was to encourage further development in flood-prone areas. Existing Corps projects continue to influence the management of most major rivers and their floodplains, including those of the Mississippi, Missouri, Ohio and Columbia River Basins. Although local government is ultimately responsible for decisions regarding land use in the United States, flood control projects constructed by the Corps provide incentives for floodplain development.

The Corps' analyses of benefits and costs have traditionally strongly favoured structural flood control projects. Engineers like to build things. Many within the Corps now recognize that their regulations and incentives need to be changed to enable them to take a more balanced view and allow non-structural flood control projects to compete with structural ones.

In the Netherlands, a similar story can be told. There is an expression the Dutch like to say: 'God made the Earth, but the Dutch made the Netherlands.' Without structures, much of the country would be permanently under water. But here, as in the United States and in most of the rest of the world where floods occur, flood management needs to become a part of integrated water and land management. Multiple uses, multiple sectors of the economy, and the interests of multiple stakeholders need to be considered when developing comprehensive land use and water management plans and policies.

Options available to local governments for floodplain management include land use zoning. Land zoning should be based on comprehensive land use plans that define a vision of how a community should be developed (and where development should not occur). Through these plans, uses of the land can be tailored to match the land's economic benefits as well as its hazards. For example, flood hazard areas can be reserved for parks, golf courses, backyards, wildlife refuges, natural areas or similar uses that are compatible with the natural flooding process.

Open space preservation should not be limited to floodplains, because some sites in the watershed (but outside the floodplain) may be crucial to controlling runoff that adds to the flood problem. Areas that need to be preserved in a natural state should be listed in land use and capital improvement plans.

Zoning and open space preservation are ways to keep damage-prone development out of hazardous or sensitive areas. Floodplain development regulations can include construction standards governing what can and cannot be built in the floodplain. They can serve to help protect buildings, roads and other projects from flood damage, and prevent development from aggravating the flood problem. The three most common types of floodplain regulations are subdivision ordinances, building codes, and 'stand-alone' floodplain ordinances.

Several measures can help reduce runoff of stormwater and snowmelt throughout the watershed. Retention and detention regulations, usually part of a subdivision ordinance, require developers to build retention or detention basins to minimize the increases in runoff caused by new impervious surfaces and new drainage systems. Best management practices (BMPs) reduce polluted runoff entering waterways. Pollutants in runoff may include lawn fertilizers, pesticides, farm chemicals, and oils from street surfaces and industrial areas.

Wetlands filter runoff and adjacent surface waters to protect the quality of lakes, bays and rivers, and protect many of our sources of drinking water. They can store large amounts of floodwater, slowing and reducing downstream flows. They can protect shorelines from erosion. They also serve as a source of many commercially and recreationally valuable species of fish, shellfish and wildlife.

Moving a flood-prone building to higher ground is the surest and safest way to reduce its risk from flooding. Acquisition of flood-prone property is undertaken by a government agency, so the cost is not borne by the property owner. After any structures are removed, the land is usually converted to public use, such as a park, or allowed to revert to natural conditions. There are a variety of funding programmes that can support a local acquisition project. For example, more than 8,000 homes were acquired or relocated by the US Government after the 1993 Mississippi Flood.

Based on lessons learned from floods and flood protection efforts throughout the world, the following principles are suggested:

- Restore river systems and functions that improve flood management, while at the same time restoring the natural waterway and its ecosystems:
  - Restore to a meaningful extent the historic capacity of rivers and their floodplains to better accommodate floodwaters by setting back levees to widen the floodway of the river channel.
  - Increase wetland and riverside forest habitat within the widened river zone.
  - Increase the use of planned floodplain flooding to reduce downstream flood peaks.

  - Strengthen existing and properly sited levees at high risk that protect high value floodplain uses that cannot be relocated from the floodplain.
  - Re-assess the operations of reservoirs and waterworks to ensure efficient, reliable and prudent use of flood control space. In some cases, dams and waterworks need to be structurally modified to improve their ability to release water to avoid downstream flooding.
  - Improve use of weather forecasting and monitoring upstream conditions so as to have a better 'early warning system' of when a flood could be coming.

- Manage the uses of floodplains to minimize taxpayer expense and maximize environmental health:
  - Eliminate incentives or subsidies for development in the most dangerous parts of the floodplain. No more people should be put in harm's way.
  - Reform floodplain mapping programmes so that they accurately portray the risks and consequences of anticipated flooding. Ensure that people understand the risk of flooding where they are located.
  - Ensure that new structures that have to be built in floodplains are designed to resist damage from foreseeable future floods.
  - Educate people in the risks of living, working or farming in areas prone to floods, and make sure they are willing to bear the appropriate financial responsibility for such use.
  - Endeavour to relocate the most threatened people and communities who volunteer to move to safer locations.
  - Ensure that state and local governments responsible for floodplain land use decisions bear an increased financial responsibility for flood recovery efforts.

- Manage the entire watershed to provide the most protection from floods in an environmentally sensitive way:
  - Discourage development in remaining wetlands and floodplains. Wetlands and functioning floodplains act as giant sponges to absorb and slow the progress of floodwaters.
  - Use acquisition and easement programmes to restore historical wetlands and floodplain acreage and to promote the functional restoration of associated river systems.
  - Discourage clearcutting and road building in areas prone to landslides.
  - Where possible, replace non-native hillside annual vegetation with native perennials to improve rainwater absorption and reduce hillside erosion.

Newly developed technologies are facilitating the development of models for studying the propagation of floods through floodplains, coastal zones and urban areas. They include the use of airborne laser altimetry to provide cheaper and more accurate digital terrain models. In addition, the technology is being used for an efficient assignment of flow resistance parameters to flood models. It also offers further support to model calibration by monitoring water levels during the passage of flood waves.

The descriptive capabilities of flood models have been extended significantly through the implicit coupling of 1D and 2D schematizations. Integrated 1D–2D surface and subsurface modelling can be applied to floodplain and urban flooding investigations. These applications can lead to a better understanding of the flood phenomena, more accurate predictions and better planning.

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