Intl. J. River Basin Management Vol. 2, No. 2 (2004), pp. 101–112

Flood management options for The Netherlands

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ABSTRACT
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 and debris and pollution that accompanies them. Hence the challenge is to be prepared to manage floods and mitigate the resulting damage when floods occur. One approach to flood management is to provide space for floods when they occur and keeping that space available when they are not occurring. The challenge is finding the mix of open space and development on floodplains that maximize the net expected monetary, environmental, and social benefits derived from them. This paper discusses some floodplain management approaches being considered in The Netherlands, recently 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.

Keywords: Floodplain planning; Rhine River; modeling; flood damage mitigation management; The Netherlands.

Introduction

In mid August 2002 it rained a lot in Central Europe. 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 map in Figure 1 shows the affected rivers.

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, that flows through the provincial capital of Changsha, were near all-time highs. If the sandbag dikes had failed around the 2,800 square-kilometer (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 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, creating lakes of stagnant polluted water. In the capital of Algeria the flood toll reached 597 when muddy waters swept them 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.

Figure 1 The Rivers Danube and Elbe in Central Europe experienced their most extreme flood of record in August 2002.

Revision received

In spite of considerable study and advice over the past half century on how to plan and manage floods (Kates *et al.*, 1986; SAST, 1994; White, 1945) and in spite of increasing amounts of money being spent on flood protection, annual flood damages are increasing almost everywhere. In some years, like 2002, the damages can be quite substantial.

How can floods be managed? How can humans live with floods that some believe are becoming more frequent and more severe? This paper discusses approaches to floodplain management in The Netherlands. 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.

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. Levees (dikes) 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 national Parliament. Levees along the coasts of densely-populated and highly industrialized parts of the country are to be designed to protect from 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 this year, or in two successive years in a row. The probability of having at least one storm that exceeds the design capacity of the levee at least once in a 50-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 per 4,000 years, i.e., 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 constrain all landscape planning projects in the floodplain. Proposed river works for nature restoration, sand mining or any other purpose, need formal approval as stated in the River Act.

The condition of flood control works, levees and fairways is monitored regularly. Every 5 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. Based on that information, the design flood levels are assessed, taking into account effects of wind set-up and a freeboard margin of half a meter (20″) for overtopping of the levee crests. If pre-established flood risk level tolerances are being exceeded, actions must be taken to reduce these excess 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.

The Rhine river basin

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

The River Rhine now has a combined rainfall-snow melt 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. Climate scenarios show a temperature rise combined with a rainfall increase during winter in the basin (Kwadijk, 1993). 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 in future.

The Netherlands is at the end of the Rhine. It contains the Rhine Delta. That delta comprises more than half of The Netherlands. A river often divides into multiple branches in its delta. The River 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 2. Along the Rhine branches, flood levels are fully 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 flood plains 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, dikes have been built. As early as the mid-14th century, a nearly completely connected system of dikes arose that created the landscape of The Netherlands up to the present day. There are two dikes on each side of a floodplain: the summer dikes and the winter (flood season) dikes. These are shown in Figure 3.

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 embankments and vegetation and other obstacles in the floodplain. The relation between design discharge and design water levels is therefore not entirely fixed, but is dependent upon the width and depth of the riverbed, the height of the floodplains, and the flow resistance, and the wind and wave

Figure 2 The Rhine Branches and their floodplains in The Netherlands. The purple areas shown on the map of The Netherlands are subject to flooding and hence need dike protection.

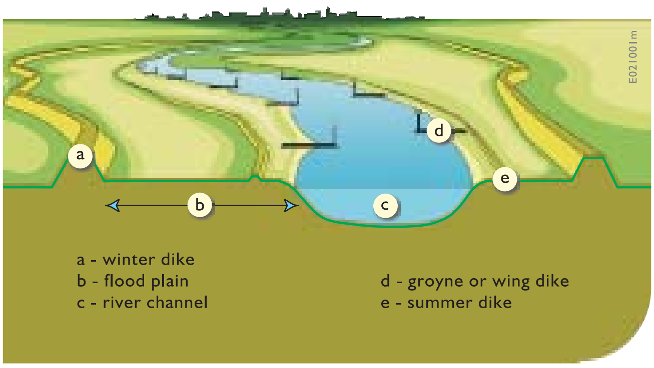

Figure 3 Two-tier dike structures and groynes for flood protection along the rivers in The Netherlands.

effects. Finally, an extra height is added to the dike to equip it with an inspection path that keeps the dike passable, and to compensate for any subsidence of the embankment. In the lower river region, the design water levels are calculated using 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 dike 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 dikes along the Rhine Branches have a protection level of 1/1250 per year (Silva *et al.*, 2001). This means that the chance that the water level in a particular year will be higher than the design water level is less than 1/1250. In the western part of The Netherlands, the protection levels are higher, namely 1/2000 up 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 also so is the difficulty of predicting a storm at sea. Floods from seawater can result in substantial casualties and economic damage due not only to getting wet, but also getting salty.

In 1995 – after a long period of relative freedom from floods – the River Rhine region witnessed a flood. That flood was not only the highest one since 1926, it was 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 dikes 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 harbors 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 dikes. At the same time, the dikes have now come to represent a sort of Achilles' heel for The Netherlands.

A large part of The Netherlands lies below the high-water level of the major rivers. The sea level currently is gradually rising as a result of climate change. This same climate change may cause the peak discharges on the Rhine and Maas to increase. In the meantime, the area protected by the dikes 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 dikes and the area outside of the dikes.

The population in the area protected by the dikes, the land use intensity, and the capital investment, have all rapidly increased. As a result, the adverse economic and emotional consequences of a flood, or even an evacuation due to flood risk, have increased substantially. Yet there is a limit on just how much more heightening and reinforcing of dikes is reasonable. The public has made it clear they do not want dike heights increased. Many in this crowded country feel too boxed in as it is. Today a more natural solution is sought.

Problems and solutions

As a result of the floods of 1993 and 1995, the design once-in-1250-year discharge that must be contained or controlled within the flood plain is now higher than it was prior to these events. As shown in Figure 4, the design discharge of the Rhine is now established at 16,000 m^3/s, an increase of 1000 m^3/s. This design discharge height determines the design height of the dikes.

Without further measures, this means higher dikes. Due to climate change, the design discharge may further increase to 18,000 m^3/s by 2050–2100. At the same time, the sea level is expected to rise, causing backwater effects in the estuaries and rivers.

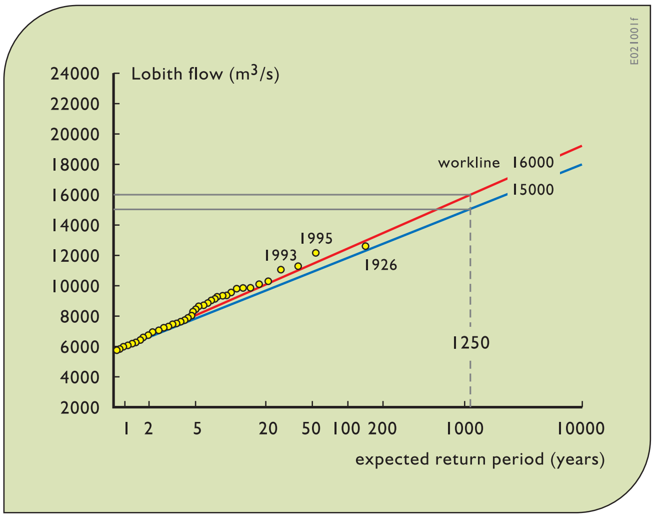

Figure 4 Re-evaluation of design flood flows for the River Rhine in The Netherlands.

Given this increase in the design water level, one could argue that the dikes should be made higher and stronger. If this is not done, the probability of floods toping the dikes will increase. However, the higher the dikes, the more severe the impacts will be once a dike fails. The dikes protect often low-lying 'polders' whose potential flooding depths already exceed several meters. If nothing is done to change the available room that exists for the Rhine river flood flow, this will lead to 20 to 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 necessitate higher dikes in order to maintain the current level of flood protection. The higher the river water level, the larger the consequences should a major flood occur that exceeds the dike capacity. But higher flood protection dikes 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 – negates the need for additional dike heightening. The only way to do that is to create more space for water to flow at existing dike levels. This means increasing the widths or depths of the rivers or their floodplains and by providing flood overflow areas outside the diked floodplain for use when the space within the dikes 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.

Managing risk

There is always the possibility that the water level along a river will exceed the design dike capacity. The desired level of safety is a matter of societal choice. If society would want complete and total safety the only way to achieve that would be to move out of the flood plain. 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 to protect to the extent they deem appropriate and to prepare 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 the adverse consequences of that flood. Minimizing the chance of getting wet is not the only possible risk reduction option. Diminishing the adverse consequences of getting wet also reduces risk. This idea in particular underlies the design of emergency overflow areas: better a controlled flood with minor damage than an uncontrolled flood with major damage.

It is technically possible to continue raising dike 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. Dike reinforcements bring with them increasingly more negative consequences for landscape, nature and cultural historical values. And as the difference in height between the water level in the river and the area protected by (behind) the dikes continues to increase, the flood risk also increases. The larger population and capital investment in the area protected by the dikes already make uncontrolled floods more drastic events than they were some 20 to 50 years ago. Moreover, the perception of safety increases as the dikes 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 for breaking this trend. Such a policy needs to:

- anticipate floods instead of only reacting to them;
- make more room for water, besides relying on technical measures such as dike heightening; and
- prevent the transfer of water problems to downstream areas by means of the succession: detain–store–discharge.

In The Netherlands this requires river widening and deepening measures to prevent new design flood flow water levels from exceeding current dike heights.

Past human interventions have resulted in (1) erosion of the low flow channel in upstream sections in reaction to maintaining the navigation channel, (2) sedimentation in the low flow channel in the downstream sections after closing off estuaries, and (3) the silting-up of flood plains due to constructing dikes and summer embankments. These processes increase the elevation of the flood plains with respect to the low flow channel. At the same time the area protected by the dikes is subsiding due to drying out and oxidation of the peat soils. All of this results in higher river levels above the surface of the land protected by (behind) the dikes than they are above the land adjacent to the river in front of the dikes.

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 (extra) water along the Rhine Branches in The Netherlands; and
- discharge (extra) 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 in Germany, of which the development of detention basins has the most promising effect on peak flows. 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. This lowers the water levels downstream of the detention areas. On the contrary, 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 flood plains, lowering of groynes or wing dikes, dredging of the low flow channel, and setting back the dikes. Some of these options are illustrated in Figures 5–7.

An important condition for such projects as illustrated in Figures 5 through 7 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. The following sections outline findings on the effectiveness of various types of measures. In all, the effects of some 700 individual projects have been assessed. Effects on peak water levels haven been determined by applying detailed 2D hydraulic models of the river.

Storage

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

Since the desired effect of a detention area occurs downstream from the area itself, a location as far upstream as 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 1,000 m^3/s from the peak flow of a flood wave lasting several days and having an 'average' shape. This in turn would require a detention area of

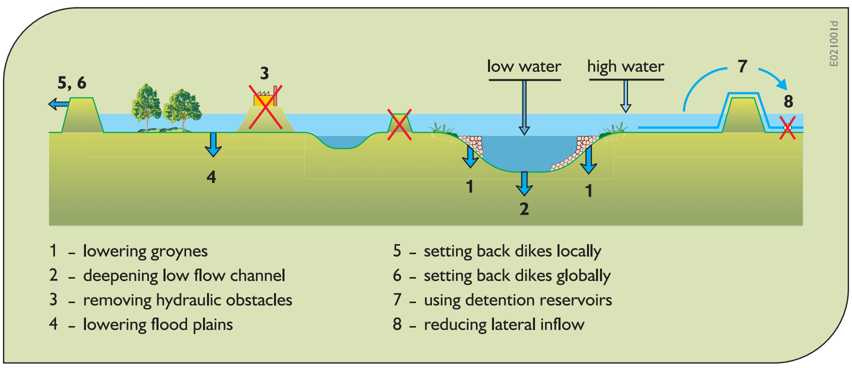

Figure 5 Alternatives to dike heightening for increasing flood flow capacity of rivers.

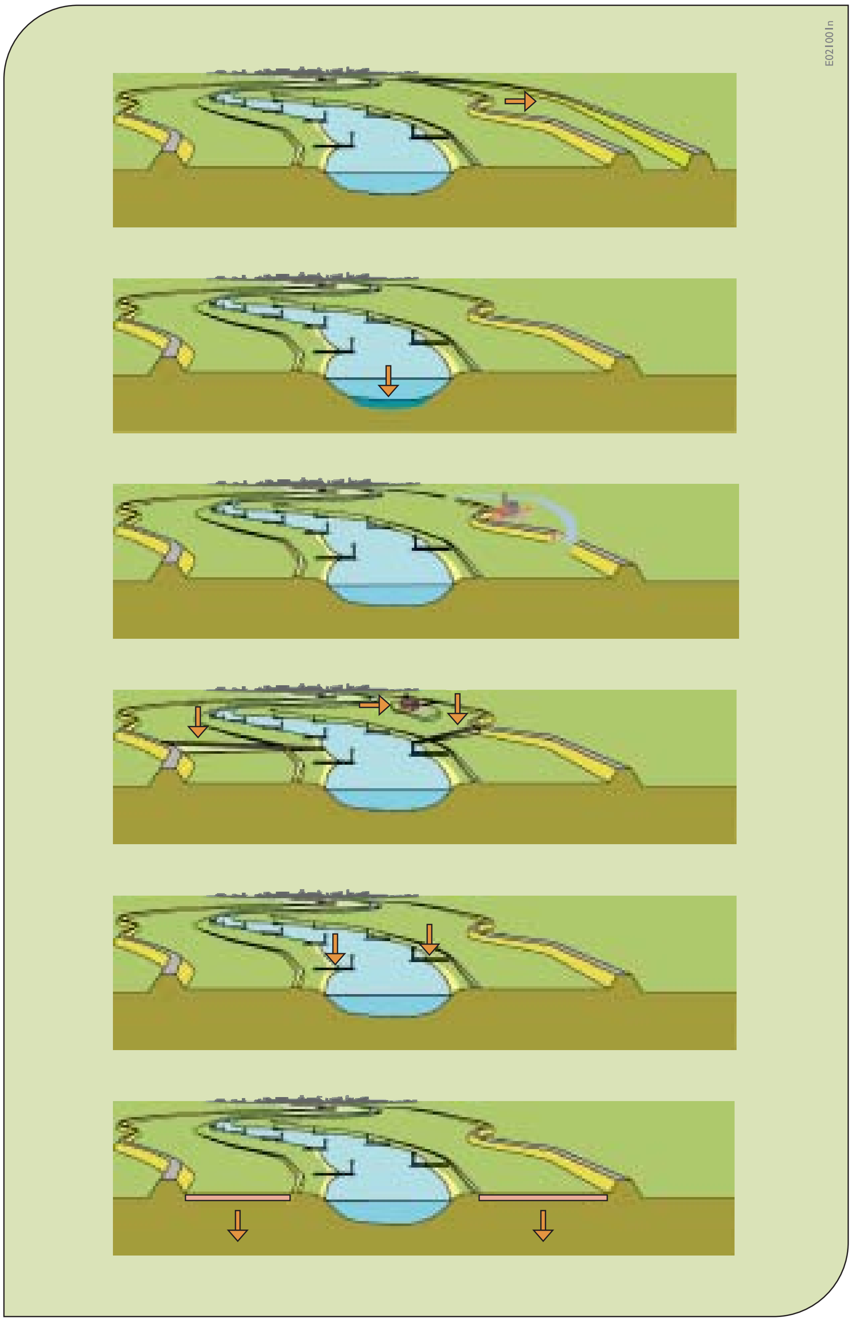

Figure 6 Alternatives to dike heightening are, from top to bottom, setting back dikes, deepening low flow channel, detention reservoirs, removal of hydraulic bottle necks, lowering groynes, and lowering floodplains.

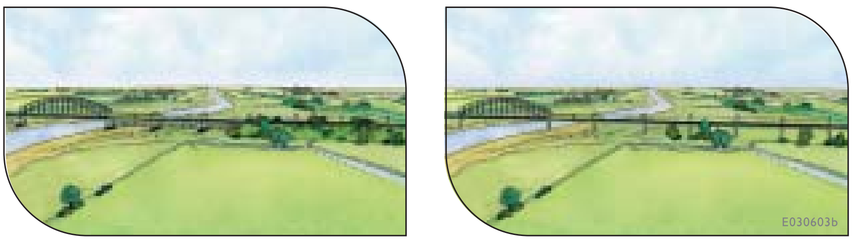

Figure 7 Bridge abutments and supporting structure, before (left) and after (right) floodway modification.

some 3,000 hectares (30 km^2) flooded to a depth of 5 meters. In areas with less depth, the surface area must be proportionately larger.

Detention areas require enclosure dikes and intakes, both of which can be extensive. Implementing detention areas also usually 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 are seldom necessary, and in this case the probability of them being needed in any year is approximately

1/500, as seen from Figure 4. This low probability can be a problem. The less often an area overflows, the more the societal pressure will be to develop it and then due to its increased economic value 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 that 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 need not have been necessary, and/or alternatively to restrict the areas' use to, for example, open recreation or nature.

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 it cannot store some of the peak flow, when the peak flow arrives, it 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. This suggests some real-time modeling for flood wave prediction or forecasting may be desirable during a flood event.

In the past, detention basins were usually filled via a fixed sill, a lowered section of the dike 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 insure a uniform overflow over a substantial length. By employing a human operated (regulated) intake, this problem may be overcome. However regulated intakes can create social problems. The residents of an area are never in favor of the idea that inundation might occur, and if some person is making it occur a conflict with the responsible organization or agency, if not the operator, is inevitable.

Discharge increasing measures

Measures taken to increase the discharge capacity of river channels 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 dikes and other obstacles on the floodplain, the hydraulic roughness of the flood plains, 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; and
- providing flood storage capacity in the areas protected by (behind) the dikes (such as setting back dikes, detention basins, etc.).

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

Alternatives to dredging include groynes or wing dikes (Figures 5 and 6). Groynes were constructed in the past to ensure that the river retained a sufficient depth without continual dredging. They also tend to prevent sand banks. Groynes 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.

Removal of the groynes would result in a decreased flow velocities and depths. 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 that option is not likely to ever be seriously considered in the Rhine River.

It appears from simulations that lowering of groyne heights can 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 flood plains and the removal of hydraulic bottlenecks can also be considered. Flood plain excavation is a measure by which the gradual height increase caused by sedimentation on flood plains may be counteracted. Floodplain excavation may be combined with clay mining, and dike reinforcement, and/or with nature development, in which farm land is returned to nature and floodplain excavation changes the flooding frequency to fit selected ecosystems. 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, nature development produces a result that is valued by many. Nature development without floodplain excavation however pushes water levels upward since rough vegetation, scrub, and wooded areas can slow down the discharge. Thus nature development 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 floodplain excavation were to be implemented along all three Rhine Branches, the costs involved would total between 3 and 4 billion euros. 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 materials.

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 Euros.

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 7), high-lying areas (Figure 8), summer embankments that are high and/or perpendicular to the flow direction, narrowing of winterbeds and other obstacles. Hydraulic bottlenecks may be identified by studying the water level slope of the river. Typically there is a direct relation with structures and a change in the water level slope.

Removing bottlenecks can decrease design flow water levels. This decrease together with its cost can be calculated. The costs of replacing bridge abutments by bridge sections (Figure 7) and the removal of ferry ramps vary from less than 2.5 million euros to more than 75 million euros for a large bridge. The costs of removing embankments and small-scale setting back of dikes (Figure 9) are usually on the order of 5 million euros 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 8) can amount to 30 million Euros, especially in those cases where contaminated lands exist.

Substantial water level reductions may be achieved with 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, the measures at the urban bottlenecks can be cost effective due to the relatively large reduction in water levels that may be achieved from their implementation.

On average, the removal of about 60 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 can vary considerably over the length of the river branches.

There are some 40 locations, not including urban bottlenecks, where large-scale setting back of dikes can lead to a substantial decrease in the water levels. Setting back of dikes 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 dikes can in fact decrease the water level up to half a meter. There are other sites where such measures produce only several centimeters worth of reduction.

Setting back of dikes cost from 5 to 100 million euros for a single setting back of a dike stretch of up to 5 kilometers in length. While rather expensive, particularly if considerable urban or industrial development is present on or just behind the dike, these measures are cost effective compared to many other hydraulic bottleneck reductions. Along the Waal and the Neder-Rijn/Lek, all of the setting back of dikes together can result in a maximum reduction of 60 cm.

Green rivers

If setting back the dike is not possible, 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 dikes where water would flow only during floods. Green rivers may be used for agricultural purposes or may be designed for nature and/or recreational areas: they are, in short, ‘green.’ This does not exclude the possibility, for example, of digging a channel or lake into such an area for the sake of recreation. How such a green river may be designed depends upon the location.

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, but it may change the discharge distribution over the three Rhine Branches.

Green rivers offer options for agriculture, water-based recreation, and nature development. This land is seldom flooded, and if it is, it usually occurs ‘off-season’ (outside the agricultural

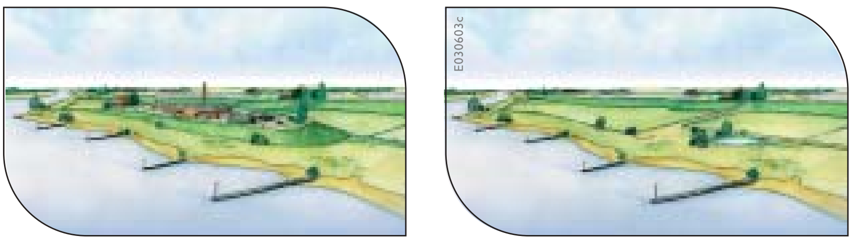

Figure 8 Removal of high lying areas on a floodplain.

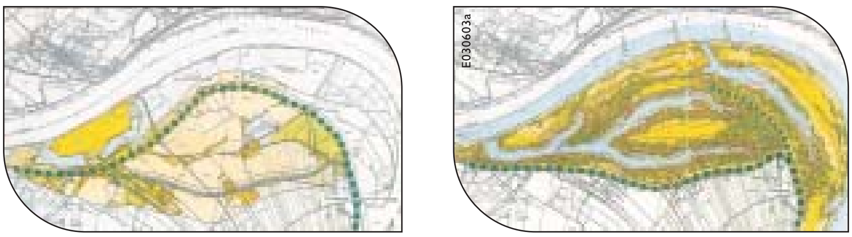

Figure 9 Opening up a narrowing by setting dikes back farther, and at the same time creating a nature area.

season). One could say that the land is temporarily loaned to the river every year, but is otherwise available 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 possibility to implement other river widening and deepening measures in future, such as flood plain 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.

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. Possibilities to do this have been examined particularly in the lower Rhine Branches region. Also new, still-to-be excavated channels are being studied with respect to their effectiveness and costs. In practically all of the cases however water is guided in an entirely different direction and this places increasing burdens on other rivers or sections situated further downstream.

The overall picture

It would appear that the large-scale setting back of dikes, construction of detention basins/green rivers, and lowering of groynes result in the most water level reduction per euro invested. The removal of hydraulic bottlenecks is more expensive as is dredging the low flow channel. Flood plain excavation is the most expensive and in this respect is the least desirable type of measure. Clearly, above findings depend on local circumstances, including the economic value of the floodplain land use and construction costs.

Additionally, some measures are only really possible in upstream sections, such as lowering of groynes and floodplain excavation, and others are more feasible downstream, such as dredging of the low flow channel. Large-scale setting back of dikes 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 should be explored.

Undoubtedly combinations of flood height reducing measures will be undertaken along the Rhine River Branches. Models will be needed to assess their overall effectiveness. This overall reduction in flood heights will not be simply the sum of their individual reductions just by themselves. 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 resulting flood wave must be taken into account.

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

Dealing with uncertainties

There are many uncertainties when predicting flood levels, and sometimes there is little one can do about them. One uncertainty involves the design discharge itself. Other uncertainties exist regarding 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 flood plains along the three branches. All these uncertain factors affect the design water levels. Hence the design water level is itself uncertain.

Secondly, we are at the mercy of changes that may occur in future and these are by definition uncertain. We know climate will change, but we do not know how quickly or to what extent. The climate models currently used all predict warming and more frequent extremes, but the variations between predictions remain rather substantial (Kwadijk, 1993). All of these issues present quite a dilemma for the manager: on the one hand, safety is so vital that the river manager should anticipate higher discharges, yet on the other hand, the speed with which situations change is very unsure. To wait around 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. These flow measurements were corrected for the effects of river engineering works in the past. The current measurement series spans the period 1901 to 1995. Previously, the period was from 1901 to 1991. An extension of only 5 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 4. The new design discharge has become 16,000 m^3/s, an increase of 1000 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 1250 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 1/1250 risk level. This can result in strange effects. For example, a plot of the annual peak flows of the Odra River catchment area in Poland from 1901 to 1985 produces a fairly straight line without any large deviations. In 1997 however, a discharge of 3300 m^3/s was measured. This flow was the largest of record. That one flood flow lead to the 'new' extrapolation line causing the 1/1250 discharge to rise from 2500 to 2600 m^3/sec. This is still far below the 3300 m^3/s discharge that actually occurred. While extreme discharges, perhaps such as that on the Odra, may be rare, they can nonetheless occur in any year.

What is clear is that any extrapolation line, such as shown in Figure 4, is uncertain. It could be higher, and it could be lower. Figure 10 shows the 90% confidence interval band of uncertainty associated with the extrapolation in Figure 4. This shows that there is a 90% chance that the design discharge on the Rhine (that is expected on average once in 1250 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 10 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 (Kwadijk, 1993), 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 dikes.

In this regard, there are thus two types of uncertainties. Firstly, what precisely would change in terms of climate, and secondly,

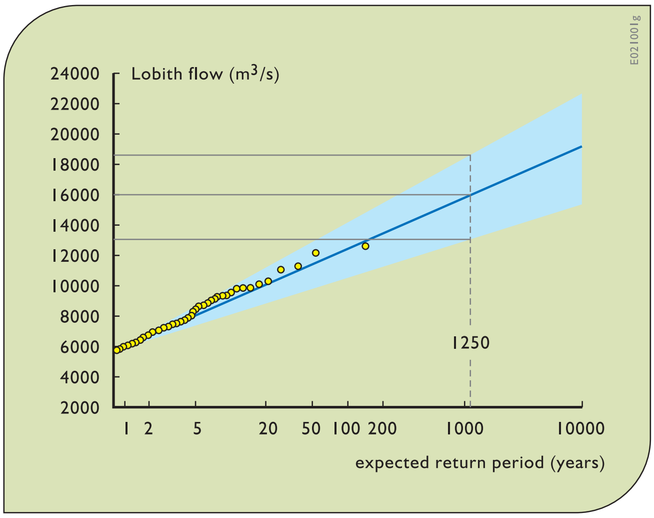

Figure 10 Range of uncertainty associated with estimated design flows of various return periods. The true design flow has a 90% chance of being within the blue band.

how the other Rhine States upstream of The Netherlands will 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 (Vis *et al.*, 2003).

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. Building temporary and emergency detention areas are other ways of increasing flexibility.

The term resilience on the contrary, 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 occur – 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 dike 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 regret by taking into account the fact that uncertainties will always exist concerning the expected discharges in rivers.

Summary

Visions for future developments on the River Rhine in and upstream of The Netherlands currently concentrate on flood mitigation and ecological restoration (Silva *et al.*, 2001). Relatively little effort is devoted to dealing with low flows including future water quality and navigation requirements.

The recent strategy in the past for flood prevention was to raise dikes (embankments) along the floodplains. Currently this strategy has met social resistance and is thus 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 the lowering of floodplains in The Netherlands to enlarge the cross section of the river. Meanwhile these floodplains are to be designed in such a manner that facilitate and promote more natural morphological and ecological processes in the floodplains.

In the upstream sections in Germany the focus is on landscape planning so that water will flow less quickly to the river. 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 used during floods.

Conclusions

In the wake of the unusually severe floods, not only on the Rhine but also in central Europe, Asia, and in the United States, an increasing consensus is emerging. Humans must provide space for floods and when they occur floods must be managed better. These are not new ideas (White, 1945). The only sustainable way to reduce the continuing cycle of increasing flood damages 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 dike 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 reasons for restoring river ecosystems.

Governments can motivate more responsible floodplain management. National governments can assume leadership and define clear roles and provide fiscal support for flood management at lower levels of government. Governments can

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

In the US, the Army Corps of Engineers flood control program 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 US, flood control projects constructed, and partly financed, by the Corps provide incentives for floodplain development. The Corps' analyses of benefits and costs have traditionally strongly favored structural flood control projects. Engineers like to build things. Many within the Corps now recognize 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 flood projects (Interagency Floodplain Management Review Committee, 1994).

In The Netherlands, a similar history 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 that country would be permanently under water. But in this country, in the US, 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, 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 on 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, 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 floodwaters, slowing and reducing downstream flows. They can protect shorelines from erosion. Wetlands 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 programs that can support a local acquisition project. For example, more than 8000 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:

1. Restore river systems and functions that improve flood management while at the same time restore the natural waterway and its ecosystems.
   a. 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.
   b. Increase wetland and riverside forest habitat within the widened river zone.
   c. Increase the use of planned floodplain flooding to reduce downstream flood peaks.
   d. Strengthen existing and properly sited levees at high risk that protect high value floodplain uses that cannot be relocated from the floodplain.
   e. Reassess the operations of reservoirs and waterworks to ensure the 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.
   f. Improve use of weather forecasting and monitoring upstream conditions to have a better "early warning system" of when a flood could be coming.
2. Manage the uses of floodplains to minimize taxpayer expense and maximize environmental health:
   a. Eliminate incentives or subsidies for development in the most dangerous parts of the floodplain. No more people should be put in harm's way.
   b. Reform floodplain mapping programs so that they accurately portray the risks and consequences of anticipated flooding. Ensure that people understand the risk of flooding where they are located.
   c. Ensure that new structures unavoidably being built in floodplains are designed to resist damage from foreseeable future floods.
   d. Educate people on 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.
   e. Endeavor to relocate the most threatened people and communities who volunteer to move to safer locations.
   f. Ensure that state and local governments responsible for floodplain land use decisions bear an increased financial responsibility for flood recovery efforts.
3. Manage the entire watershed to provide the most protection from floods in an environmentally sensitive way:
   a. Discourage development in remaining wetlands and floodplains. Wetlands and functioning floodplains act as giant sponges to absorb and slow the progress of floodwaters.
   b. Use acquisition and easement programs to restore historical wetlands and floodplain acreage and to promote functional restoration of associated river systems.
   c. Discourage clearcutting and road building in areas prone to landslides.
   d. 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 (Stelling *et al*., 1998). This includes 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. These applications can lead to a better understanding of the flood phenomena, more accurate predictions and better planning.

Acknowledgement

We gratefully acknowledge the contributions from F. Klijn and the figures prepared by E. Vennix of Delft Hydraulics based on those from Silva *et al*., 2001.

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