RESILIENCE AND FLOOD RISK MANAGEMENT

A SYSTEMS APPROACH APPLIED TO LOWLAND RIVERS
Cover: Flooding of a village in the Netherlands (Rijkswaterstaat – Meetkundige Dienst)
RESILIENCE AND FLOOD RISK MANAGEMENT
A SYSTEMS APPROACH APPLIED TO LOWLAND RIVERS

PROEFSCHRIFT

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1. Introduction
Floods still cause lots of damage and many casualties although people have tried to reduce flood impacts for many centuries. Flood impacts may even increase in the future due to population growth and climate change. In order to reduce flood impacts, current flood risk management strategies need to be reconsidered.

In the Netherlands, policy makers propose to increase the resilience of systems, since scientists expect resilient systems to be able to cope better with disturbances such as flood waves. In the policy documents on water management, however, ‘resilience’ and ‘resilient water systems’ are not clearly defined. ‘Resilience’ has a positive connotation although it is difficult to explain what the positive aspects of resilient systems for water management are exactly.

In this thesis this positive connotation of resilience was verified for the flood risk management of lowland rivers. The objective was to establish whether applying the resilience concept facilitates the development of comprehensive strategies for flood risk management of large lowland river systems.

To study the potential benefits resulting from the application of the resilience concept, first the following main questions were addressed:

- Which definition of resilience is useful and applicable in the context of flood risk management of lowland river systems?
- Which indicators can be used to make the resilience concept quantifiable in this context?

Secondly, three case studies were carried out on the lowland parts of respectively the Rhine, Meuse and Mekong rivers in which the following questions were addressed:

- How resilient are the studied systems?
- How can their resilience be increased or what do resilience strategies look like for these systems?
- What are the advantages and disadvantages of resilience strategies?
- Would the same strategies have been found without applying the concept of resilience?

2. Resilience in flood risk management
In order to be able to apply resilience on flood risk management, first flood risk management and resilience are defined and secondly the understanding of both is combined into a definition of resilience in the context of flood risk management. Flood risk management is understood in this thesis as all activities that enable a region to cope with flood waves. Flood
risk management strategies should enable a region to function normally at present and in the future despite disturbances by flood waves. Flood risk management strategies should thus enhance the sustainable development of a region. Sustainable development is interpreted as improving the socio-economic development without deteriorating nature values, taking into account uncertainties and dynamics within the system and in the disturbances. To assess the contribution of flood risk management strategies to this aim, evaluation criteria were developed.

The concept of resilience as used in water management was derived from ecology. In ecology the concept of resilience and the related concept of resistance are used to describe a system’s ability to cope with disturbances and to persist without huge irreversible changes in their most important characteristics.

Since resilience is a system’s property, it was applied to flood risk management by adopting a systems approach and by then studying the reaction of lowland river systems to flood waves. Lowland river systems are defined by the physical and socio-economic characteristics of the lowland river itself and the corresponding flood-prone area. Resistance is defined as the ability of this system to prevent floods, while resilience is defined as the ability of the system to recover from floods. The resistance of the system thus determines which flood waves can still flow through the river without causing floods, while the resilience determines the ease of the system to recover from flood impacts.

3. Quantifying resilience
To make the concept more tangible, resilience needed to be quantified. Therefore, indicators were developed which provide insight into the system’s resilience. Because the concepts of resilience and resistance reflect the reaction of a system to flood waves, indicators should relate to the different aspects that describe a system’s reaction to flood waves. These aspects are (1) the amplitude of the reaction, (2) the graduality of the increase of reaction with increasing disturbances and (3) the recovery rate. The resilience of a system is larger when the amplitudes are smaller, the graduality is larger or the recovery rate is higher. Whether the system reacts or not, depends on the resistance of the system. The resistance is indicated by the reaction threshold, which is the largest disturbance which does not provoke a reaction. In the context of flood risk management this threshold is defined as the recurrence time of the design discharge or as the highest discharge which is not expected to cause floods.

The amplitude of the reaction is defined as the magnitude of the reaction to a disturbance, which is equal to the severity of the direct flood impacts resulting from a flood wave. As indicator for the whole range of amplitudes related to the whole regime of flood waves the Expected Annual Damage (EAD) and the Expected Annual Number of Casualties (EANC) were selected. A disadvantage of these indicators is that they are not only sensitive to the magnitude of the reactions, but also to their probabilities. This explains why in case of rare floods, the EAD may be very low, but the resilience is not necessarily high. For that reason, the indicators for the other aspects have to be considered together with the EAD and EANC. In systems with rare but severe floods, after all, not only the amplitude but also the graduality will be low, which points towards a resistant system.
The *graduality* of the reaction is defined as the increase of the reaction with increasingly severe flood waves. This aspect is quantified by comparing the relative increase of discharge in percentages by the corresponding relative increase of damage. The indicator has a value between zero and one. It is close to zero when a small discharge increase causes the damage to increase sharply, and it is one when discharge increases linearly with damage.

The *recovery rate* of the reaction is indicated by the recovery capacity of the system. It is related to physical, economic and social characteristics of the system that influence the recovery rate. The physical characteristics of the system determine how fast the area dries out. The economic characteristics reflect the availability of funds for reconstruction and expected support from non-flooded areas. The social characteristics which could enhance recovery are the functioning of social networks, the preparedness of the inhabitants and organisations in the system, and the human capital of the inhabitants (their health and skills). The recovery capacity analysis is qualitative and results in a score between one and ten.

The indicators were first tested on hypothetical systems in order to evaluate whether their values are in accordance with expectations. The tests showed that the indicators distinguish between different physical layouts and land use types.

Because each indicator separately reflects only one aspect of the reaction of a system to flood waves, the resilience of a system can only be assessed by considering the whole set of indicators. Since the three indicators are neither aggregated nor prioritized, ranking systems according to their degree of resilience is only possible when the ranking of all the different resilience indicators is the same.

4. Application of the resilience concept and indicators in three case studies
In order to evaluate the applicability of the resilience indicators and to assess the benefits resulting from applying resilience in flood risk management, three case studies were carried out, namely on the lowland parts of the Rhine, Meuse and Mekong Rivers.

4.1 Rhine
The lower Rhine case study focussed on measuring the resilience of the current system and on evaluating different resilience-oriented strategies for long-term flood risk management. The lowland part of the Rhine River stretches from about Bonn (Germany) to Gorinchem (The Netherlands) and includes both the river itself and the corresponding flood-prone area. The current resilience of this system was assessed by calculating the flood impacts of representative flood waves with the help of hydrodynamic and damage models.

The reaction of the current Rhine system to the discharge regime was found to be as follows: most flood waves will not result in any reaction, but if an extreme flood wave occurs, damage is enormous. The system can, however, rapidly recover from the flood impacts thanks to the high level of welfare and organisation in the Netherlands. This reaction is reflected by the indicator values: the current system was found to have a low amplitude, caused by the low flood frequency, a low graduality and a high recovery rate. The resistance of the current system appeared to be high because floods are rare.
If the current strategy is continued in the future, the resilience of the system will decrease, because the amplitude will increase significantly while the graduality remains low. It is possible to increase the resilience of the system by implementing flood risk management strategies that increase flood probability differentiation in such a way that more vulnerable areas have lower flood probabilities and the less vulnerable areas have higher flood probabilities. Different strategies were studied: a compartmentalization strategy, three variants of a green river strategy (‘floodway’) and the so-called River-and-Land strategy. The results showed that these strategies reduce the amplitude and increase the graduality by flood probability differentiation, land use adaptations and measures to prevent the flooding of cities and other vulnerable areas. The evaluation of the strategies revealed that the resilience strategies require higher investment costs than continuing the current strategy does. However, they result in lower flood impacts, they improve nature values and land scenery and have positive effects on the sensitivity to unexpected events. The strategies which resulted in the most resilient systems (River-and Land strategy and two variants of the green river strategy) negatively affect economic opportunities. The other resilience strategies did not significantly affect these opportunities.

4.2 Meuse
The Meuse case study was dedicated to the changes in the resilience of the Meuse system in time. The case study area includes the river and flood-prone area between Eijsden and Mook situated in Belgium and the Netherlands. The values for the resilience indicators were calculated for the Meuse system as it was in 1900, 1993, and 2000, and as it is expected to be in 2015 and 2100. The values for 1993, 2000 and 2015 were calculated by using hydrodynamic and damage modules. From these values, the scores for 1900 and 2100 were derived. They have a more indicative value. The results showed that mainly the graduality and amplitude have changed in the past and are expected to change further in the future. In 1900 the amplitude was low and graduality high. Between 1900 and 1993 the graduality decreased and the amplitude increased, mainly due to economic growth and reduction of the flood-prone area. Between 1993 and 2015 the amplitude is expected to decrease due to measures that reduce the flood frequency of villages and cities, but also the graduality is expected to decrease. If no further measures are taken in the future, the amplitude will increase due to climate change and economic growth. The recovery rate increased slightly between 1900 and 1993 and remained unchanged since then. Since the increase in recovery rate is only little, while the graduality and amplitude indicator values deteriorated, it was concluded that the resilience of the system decreased between 1900 and 1993. It will probably decrease again between 2015 and 2100. The results showed that in between 1993 and 2015 the reaction of the system does change significantly. However, it is difficult to conclude whether the system is becoming more or less resilient in that period, since the different indicators do not point in the same direction.

4.3 Mekong
The lowland river part of the Mekong is situated in Cambodia between Kratie and the Vietnamese-Cambodian border. In this case study the current resilience of the system was determined and the influence of three strategies was assessed: continuation of the current strategy, a resilience and a resistance strategy. In order to calculate the resilience indicators the current socio-economic system and its relationships with the flood regime were studied, extreme value analyses and flood wave volume analyses were carried out, flood patterns were
calculated with the help of a hydrodynamic model, and a damage model was developed to assess flood impacts. To be able to develop sensible strategies the developments in the region which are expected to occur in the future were studied as well.

Since floods and society are strongly related in the lowland part of the Mekong, the systems approach which is required in order to be able to apply resilience proved to be very useful here. Agriculture and fisheries, transport and the way people build their houses and construct roads are all adapted to the frequent floods. Agriculture is that much adapted that it has become dependent on the floods. The current resilience of the Mekong River was expected to be very high, because the whole country seems to be adapted to the annual floods. Although the graduality was found to be very high indeed, the amplitude proved to be high also and the recovery rate low. The high amplitude is caused by frequent severe flood damages and the low recovery rate by relative poverty. The resilience of the system is expected to change in the future. Population growth, socio-economic development and climate change are expected to cause an increase of both the amplitude and recovery rate.

When developing flood risk management strategies, the complex relationships between agriculture, fisheries and floods must be considered. The Mekong case study included a resilience strategy based on flood forecasting, flood regulation and agricultural development. This strategy significantly increases resilience: the resulting amplitude is lower than when the current strategy is continued and the recovery rate is similar. Next to the current strategy and the resilience strategy, also a resistance strategy was studied. This resistance strategy consists of the construction of embankments which prevent discharges with a probability larger than 1/100 a year to cause floods. This strategy results in a decrease of the amplitude, graduality and recovery rate. The evaluation of the strategies showed that the resilience strategy scores well on socio-economic development, on natural and land scenery values and on coping with unexpected events. The resistance strategy, however, scores higher on reducing flood impacts. Because the resilience strategy can be implemented stepwise and differs less from the current strategy, it seems more feasible than the resistance strategy.

### 4.4 Comparison of the case study areas

Apart from comparing different flood risk management strategies for one area, the indicators were also used to compare different systems. The Rhine system is the most resistant, because the highest flood wave which is not expected to cause floods has a very high recurrence time. The Meuse system is more resilient than the Mekong system, because its recovery rate is much higher while the amplitude and graduality are comparable. In the future, the resilience of all systems is expected to decline because of climate change and economic growth. Because the systems are different, different strategies will be required, if it is intended to increase the system’s resilience. Resilience-oriented strategies seem more feasible for the Mekong than for the Rhine system, because the measures included in the resilience strategy for the Mekong are comparable with the currently applied measures there and because changes are made more easily in the Mekong system.

### 5. Discussion and conclusions

This research succeeded in defining and quantifying resilience in the context of flood risk management. Resilience and resistance are both system characteristics that express a system’s ability to cope with disturbances. These concepts are therefore applied to flood risk
management by adopting a systems approach and studying the systems ability to cope with flood waves. The resistance of a system determines which discharges can pass through the system without causing floods, while a system’s resilience determines the ease of the recovery from flood impacts when floods do occur. The selected indicators for resilience proved to be applicable to very different systems. They are reproducible and reveal the reaction of systems to flood waves.

The application of the concept of resilience on flood risk management proved to be useful, because it enforces a system’s approach and the study of the reaction of the system as a whole to flood waves. It therefore provides knowledge on the relationships between floods and society and flood risk management and society. It also results in knowledge on the flood risk of the system, the recovery capacity and the graduality. The obtained knowledge facilitates the development of comprehensive tailor-made strategies for flood risk management, as was found in the case studies.

Resilience strategies have both positive and negative effects. The positive connotation that resilience has thus needs nuance. Resilience strategies for currently resistant systems are costly and they do not enhance socio-economic opportunities. However, resilience strategies may be preferable when natural values and the coping with the effects of unexpected events are valued high or when floods have important positive impacts. In systems with a presently low resistance, at the other hand, resistance strategies are costly. Whether a change towards a more resilient or more resistant strategy is preferable depends on societal preferences and thus differs for each lowland river system.
SAMENVATTING

1. Inleiding
Overstromingen veroorzaken nog steeds veel schade en kosten nog steeds veel mensenlevens, ook al proberen mensen al eeuwenlang de gevolgen van overstromingen te beperken. Door klimaatverandering en bevolkingsgroei kunnen de gevolgen van overstromingen in de toekomst zelfs nog verder toenemen. Om de gevolgen van overstromingen te reduceren zouden de huidige strategieën voor het beheer van overstromingsrisico’s heroverwogen moeten worden.

Nederlandse beleidsmakers hebben voorgesteld om overstromingsrisicobeheer te richten op het vergroten van de veerkracht van systemen, omdat veerkrachtige systemen volgens wetenschappers beter geschikt zijn om verstoringen zoals hoogwatergolven op te vangen. Echter, in beleidsdocumenten zijn de begrippen ‘veerkracht’ en ‘veerkrachtige watersystemen’ niet helder gedefinieerd. De term ‘veerkracht’ heeft een positieve klank, maar het is moeilijk vast te stellen wat de positieve aspecten van veerkrachtige systemen voor waterbeheer precies zijn.

In dit proefschrift wordt die positieve klank van veerkracht geverifieerd in de context van ‘overstromingsrisicobeheer’ van laaglandrivieren. Doel van het onderzoek is om te bepalen of het toepassen van het veerkrachtconcept positief bijdraagt aan het ontwikkelen van strategieën voor het reduceren van overstromingsrisico’s van laaglandriviersystemen.

Om de mogelijke voordelen van het toepassen van het veerkrachtconcept te bepalen, zijn eerst de volgende vragen beantwoord:
1. Welke definitie van veerkracht is nuttig en toepasbaar in de context van overstromingsrisicobeheer van laaglandrivieren?
2. Welke indicatoren kunnen worden gebruikt om veerkracht te kwantificeren?

Vervolgens zijn drie case studies uitgevoerd naar respectievelijk het laagland deel van de Rijn, Maas en de Mekong, waarin onderstaande onderzoeksvragen aan de orde gesteld zijn:
1. Hoe veerkrachtig zijn de bestudeerde systemen?
2. Hoe kan de veerkracht van de systemen vergroot worden en hoe zien veerkrachtige strategieën voor deze systemen eruit?
3. Wat zijn de voor- en nadelen van veerkrachtstrategieën?
4. Zouden dezelfde strategieën gevonden zijn zonder het gebruik van het concept veerkracht?
2. Veerkracht in overstromingsrisicobeheer

Om veerkracht te kunnen toepassen in de context van ‘overstromingsrisicobeheer’ zijn eerst deze context en het begrip veerkracht gedefinieerd. Vervolgens zijn de begrippen gecombineerd. ‘Overstromingsrisicobeheer’ is gedefinieerd als de combinatie van alle maatregelen die samen een gebied in staat stellen om hoogwatergolven op te vangen. Strategieën voor overstromingsrisicobeheer hebben tot doel om een regio normaal te laten functioneren, nu en in de toekomst, ook al wordt het systeem af en toe bedreigd door een hoogwatergolf. Overstromingsrisicobeheer zou dus duurzame ontwikkeling moeten bevorderen. Duurzame ontwikkeling is hier geïnterpreteerd als het bevorderen van socio-economische ontwikkeling zonder dat de natuurwaarde verslechtert, rekening houdend met onzekerheden en dynamiek in het systeem en in de verstoringen die op het systeem inwerken. Om de bijdrage van strategieën aan duurzame ontwikkeling te kunnen beoordelen, zijn evaluatiecriteria ontwikkeld.

Het concept ‘veerkracht’, zoals gebruikt in overstromingsrisicobeheer, is afkomstig uit de ecologie. In de ecologie beschrijft het begrip ‘veerkracht’ samen met het daaraan gerelateerde begrip ‘weerstand’ het vermogen van een systeem om verstoringen op te vangen en te blijven voortbestaan zonder dat de belangrijkste kenmerken van het systeem veranderen.

Omdat veerkracht een systeemeigenschap is, is het toegepast in de context van overstromingsrisicobeheer door een systeembenadering te volgen en de reactie van laaglandriviersystemen op hoogwatergolven te bestuderen. Laaglandriviersystemen zijn hierbij gedefinieerd als het geheel van fysische en socio-economische eigenschappen van zowel de laaglandrivier zelf als het door overstromingen bedreigde gebied. Weerstand is gedefinieerd als het vermogen van dit systeem om overstromingen te voorkomen, terwijl veerkracht gedefinieerd is als het vermogen van het systeem om te herstellen van de gevolgen van overstromingen. De weerstand van het systeem bepaalt dus welke hoogwatergolven door de rivier afgevoerd kunnen worden zonder overstromingen te veroorzaken, terwijl de veerkracht van het systeem bepaalt hoe gemakkelijk het systeem herstelt van de gevolgen van overstromingen.

3. Het kwantificeren van veerkracht

Om het veerkrachtcconcept concreet te maken moet het gekwantificeerd worden. Daarom zijn indicatoren ontwikkeld waarmee inzicht kan worden verkregen in de veerkracht van laaglandriviersystemen. Omdat de veerkracht en weerstand de reactie van een systeem op verstoringen weerspiegelen zijn indicatoren ontwikkeld voor de verschillende aspecten die samen een dergelijke reactie beschrijven. Deze aspecten zijn (1) de amplitude van de reactie, (2) de geleidelijkheid van de toename van de reactie met toenemende verstoringen en (3) de herstelsnelheid. De veerkracht van een systeem is groter wanneer de amplitudes kleiner zijn, en de geleidelijkheid of de herstelsnelheid groter zijn. Of er een reactie optreedt, hangt af van de weerstand van het systeem. De indicator voor de weerstand is de reactiedempelwaarde, de grootste verstoring die naar verwachting niet leidt tot een reactie. In de context van overstromingsrisicobeheer is deze dempelwaarde gekwantificeerd als de herhalingstijd van de ontwerpaflvoer of de hoogste afvoer die naar verwachting niet leidt tot een overstroming.

De amplitude van de reactie is gedefinieerd als de grootte van een reactie op een verstoring. In de context van overstromingsrisicobeheer is dit de directe overstromingsschade. Als
indicatoren voor de amplitudes horend bij een heel regime van hoogwatergolven zijn de jaarlijkse verwachte schade en het jaarlijks verwachte aantal slachtoffers gekozen. Een nadeel van deze indicatoren is dat ze niet alleen gevoelig zijn voor de grootte van de reacties, maar ook voor de kansen op deze reacties. In het geval van erg zeldzame overstromingen kan de jaarlijks verwachte schade laag zijn, terwijl de veerkracht niet noodzakelijkerwijs hoog is. Om die reden moeten de indicatoren voor de amplitude in samenhang met de indicatoren van de andere aspecten bekeken worden. In systemen met zeldzame maar catastrofale overstromingen zal de amplitude wel laag kunnen zijn, maar zal de geleidelijkheid ook laag zijn, wat wijst op een systeem met een hoge weerstand.

De geleidelijkheid van de reactie is gedefinieerd als de toename van de reactie bij toenemende hoogwatergolven. Dit aspect wordt gekwantificeerd door de procentuele toename van de afvoer te vergelijken met de procentuele toename van de schade. De indicator heeft een waarde tussen nul en één. De waarde ligt dicht bij nul wanneer een kleine afvoertoename leidt tot een zeer sterke toename van de schade. De waarde is één wanneer de schade evenredig toeneemt met de afvoer.

Een indicatie van de herstelsnelheid van het systeem wordt verkregen door de herstelcapaciteit van het systeem te bepalen. De herstelcapaciteit is afhankelijk van fysische, economische en sociale kenmerken van het systeem. De fysische eigenschappen van het systeem bepalen hoe lang het duurt voordat het systeem opdroogt. De economische eigenschappen bepalen of er voldoende geld is voor een snel herstel en of er hulp uit andere gebieden verwacht mag worden. Sociale eigenschappen die het herstel bevorderen zijn ondermeer het functioneren van sociale netwerken, de voorbereiding op overstromingen en de gezondheid en vaardigheden van de inwoners. De analyse van de herstelcapaciteit is kwalitatief en resulteert in een score die ligt tussen de 1 en de 10.

De indicatoren zijn eerst toegepast op hypothetische systemen om te testen of ze zich naar verwachting gedragen. De resultaten van de test toonden aan dat de indicatoren geschikt zijn om verschillende systemen te kunnen onderscheiden op basis van hun veerkracht. Zowel verschillen in fysische eigenschappen als in landgebruik leiden tot andere indicatorwaardes.

Omdat iedere indicator slechts één aspect van de reactie van een systeem op hoogwatergolven weergeeft, kan de veerkracht van een systeem alleen bepaald worden door de set van indicatoren in zijn totaliteit te beschouwen. Doordat de drie indicatoren niet samengevoegd worden tot één, is het alleen mogelijk om systemen te ordenen naar hun veerkracht als de rangschikking voor alle indicatoren afzonderlijk dezelfde is.

4. Toepassing van de veerkrachtdefinitie en indicatoren in drie casestudies
Om de toepasbaarheid van de veerkrachtindicatoren te testen en de voordelen van het toepassen van veerkracht op overstromingsrisicobeheer te bepalen zijn drie casestudies uitgevoerd: één voor het laaglanddeel van de Rijn, één voor de Maas en één voor de Mekong.

4.1 Rijn
De casestudie naar het laaglanddeel van de Rijn richtte zich op het meten van de veerkracht van het huidige systeem en het evalueren van verschillende veerkrachtstrategieën. Het laaglanddeel van de Rijn ligt grofweg tussen Bonn (Duitsland) en Gorinchem (Nederland) en
omvat behalve de rivier ook het door overstromingen bedreigde gebied. De huidige veerkracht van dit systeem is bepaald door de gevolgen van representatieve hoogwatergolven te berekenen met hydrodynamische modellen en schademodellen.

De resulterende waardes voor de verschillende indicatoren beschreven de volgende reactie van het huidige systeem op het afvoerregime: de meeste hoogwatergolven zullen niet tot een reactie leiden, maar als er een extreme afvoergolf optreedt, is de schade enorm. Het systeem kan deze schade echter snel weer te boven komen dankzij de grote welvaart en de hoge organisatiegraad in Nederland. Deze reactie is weerspiegeld in de scores van de verschillende indicatoren: Het huidige systeem heeft een lage amplitude veroorzaakt door de lage overstromingskans, een lage geleidelijkheid en een hoge herstelsnelheid. Uit de lage overstromingsfrequentie is af te leiden dat de weerstand van het huidige systeem hoog is.

Als de huidige strategie voortgezet wordt in de toekomst, zal de veerkracht van het systeem afnemen omdat de amplitude significant zal stijgen terwijl de geleidelijkheid laag blijft. Het is mogelijk om de veerkracht van het systeem te vergroten door strategieën toe te passen die de overstromingskansen van verschillende deelgebieden binnen het systeem differentiëren, zodat de overstromingskansen van de gebieden met een hoge potentiële schade lager worden, en die van de overige gebieden hoger. De veerkrachtstrategieën ‘compartimentering’, verschillende varianten van groene rivieren en de ‘RivierenLand strategie’ zijn bestudeerd. Deze strategieën blijken de amplitude te verlagen en de geleidelijkheid te vergroten. De veerkrachtstrategieën vragen hogere investeringskosten dan voortzetten van de huidige strategie doet. Ze leiden echter wel tot een afname van de overstromingsschade en een vergroting van de natuurwaarde en zij hebben een positief effect op de gevoeligheid van het systeem voor onverwachte gebeurtenissen. De strategieën die leiden tot de meest veerkrachtige systemen (de RivierenLand strategie en twee varianten van de groene rivierenstrategie) beïnvloeden de economische mogelijkheden van het gebied negatief. De overige veerkrachtstrategieën hebben nauwelijks invloed op de economische mogelijkheden.

4.2 Maas
Samenvatting

de veerkracht van het systeem af nam tussen 1900 en 1993 en dat deze naar verwachting
niet in dezelfde richting wijzen, is het niet duidelijk of het systeem meer of minder veerkracht
wordt in die periode.

4.3 Mekong
Het laaglanddeel van de Mekong ligt in Cambodja tussen Kratie en de Vietnamse -
Cambodjaanse grens. De casestudie richtte zich op de veerkracht van het huidige
laaglandsysteem en de verkenning van drie strategieën voor overstromingsrisicobeheer,
namelijk continuering van de huidige strategie, een veerkrachtstrategie en een
weerstandstrategie. Om de veerkrachtindicatoren te kunnen berekenen zijn het huidige socio-
 economische systeem en de relaties tussen dit systeem en het afvoerregime bestudeerd, zijn er
extreme waardenanalyses en een analyse van afvoervolumes uitgevoerd, overstromings-
patronen berekend met behulp van een hydrodynamisch model en is er een schademodel
ontwikkeld om de overstroomingsschade te berekenen. Om realistische strategieën te
ontwikkelen zijn ook de verwachte ontwikkelingen in het systeem en in het afvoerregime
bestudeerd.

Juist voor dit systeem bleek de systeembenadering erg nuttig te zijn, omdat de maatschappij
en het afvoerregime sterk gerelateerd zijn. De landbouw en de visserij, de constructie van
huizen en wegen en het transport zijn allemaal aangepast aan de frequentie overstromingen.
Landbouw is in een zodanige hoge mate aangepast aan de jaarlijkse overstromingen dat zij
zelfs afhankelijk is van deze overstromingen. Bij aanvang van de casestudie was verwacht dat
de huidige veerkracht van de Mekong erg hoog zou zijn, omdat het hele land aangepast lijkt te
zijn aan de jaarlijkse overstromingen. Hoewel de geleidelijkheid inderdaad hoog is, is de
amplitude ook hoog en de herstelsnelheid laag. De hoge amplitude wordt veroorzaakt doordat
relatief frequent overstromingen veel schade veroorzaken en de lage herstelsnelheid door
armoede. De veerkracht van het systeem verandert waarschijnlijk in de toekomst. Bevolkingsgroei,
sociaal-economische ontwikkelingen en klimaatverandering leiden naar
verwachting tot een toename van zowel de amplitude als de herstelsnelheid.

Bij het ontwerpen van strategieën voor overstromingsrisicobeheer moet rekening gehouden
worden met de complexe relaties tussen landbouw, visserij en overstromingen. In de Mekong
case is een veerkrachtstrategie verkend die gebaseerd is op hoogwatervoorspelling,
overstromingsregulatie en agrarische ontwikkeling. Deze strategie leidt tot een significante
toename van de veerkracht: de resulterende amplitude is lager dan wanneer de huidige
strategie wordt voortgezet in de toekomst en de herstelsnelheid blijft vergelijkbaar. Er is ook
een weerstandsstrategie bestudeerd, bestaande uit de constructie van dijken met een
ontwerphoogte gebaseerd op de eens per honderd jaar afvoer. De resultaten toonden aan dat
de weerstandsstrategie leidt tot een afname van de amplitude, geleidelijkheid en de
herstelsnelheid. De evaluatie van de strategieën liet zien dat de veerkrachtstrategie goed
scoort op sociaal-economische ontwikkeling, natuur- en landschapswaarde en op het omgaan
met onzekere gebeurtenissen. De weerstandsstrategie scoorde echter beter op het verlagen van
de gevolgen van overstromingen. Omdat de veerkrachtstrategie stapsgewijs geïmplementeerd
can worden en minder verschilt van de huidige strategie, ligt deze meer voor de hand dan de
weerstandsstrategie.
4.4 Vergelijking van de casestudies
Behalve voor het vergelijken van verschillende strategieën voor één gebied, zijn de indicatoren ook gebruikt om verschillende systemen onderling te vergelijken. De Rijn heeft de hoogste weerstand, omdat de hoogste afvoergolf die geen overstromingen veroorzaakt, een erg hoge herhalingsintervallen heeft. Het Maassysteem is veerkrachtiger dan het Mekongsysteem, omdat de herstelsnelheid van de Maas veel hoger is, terwijl de amplitude en geleidelijkheid vergelijkbaar zijn. In de toekomst zal de veerkracht van alle systemen naar verwachting afnemen door klimaatverwachting en economische groei. Omdat de systemen op dit moment zo sterk verschillen, zijn ook verschillende strategieën vereist indien getracht wordt de veerkracht van de systemen te vergroten. De veerkrachtstrategieën voor de Mekong lijken gemakkelijk te realiseren dan die voor de Rijn, omdat de maatregelen in de veerkrachtstrategie voor de Mekong passen bij de huidige economische ontwikkelingen en omdat het gemakkelijker lijkt veranderingen door te voeren in het Mekongsysteem dan in het Rijnsysteem.

5. Discussie en conclusies
Dit onderzoek heeft een bruikbare definitie van veerkracht opgeleverd, alsmede indicatoren om veerkracht te kunnen kwantificeren. Veerkracht en weerstand zijn beide systeemeigenschappen die het vermogen van een systeem om om te gaan met verstoringen uitdrukken. Deze concepten zijn daarom toegepast op overstromingsrisicobeheer door een systeembenadering te volgen en het vermogen van de systemen om hoogwatergolven op te vangen te onderzoeken. De weerstand van een systeem bepaalt welke afvoeren weerstaan kunnen worden zonder dat ze tot overstromingen leiden, terwijl de veerkracht het vermogen van een systeem om gemakkelijk van overstromingen te herstellen aangeeft. De gekozen indicatoren voor veerkracht bleken toepasbaar te zijn op zeer verschillende systemen. Ze zijn reproduceerbaar en geven de reactie van systemen op hoogwatergolven goed weer.

Het gebruik van het concept veerkracht voor overstromingsrisicobeheer bleek nuttig, omdat het een systeembenadering vereist waarbij de reactie van het gehele systeem op afvoergolven wordt bestudeerd. Deze benadering leidt tot kennis over de relaties tussen overstromingen en de maatschappij en tussen overstromingsrisicobeheer en de maatschappij. Het leidt ook tot kennis van het overstromingsrisico van het systeem, de geleidelijkheid van de reactietoename bij toenemende afvoeren en de herstelcapaciteit van het systeem. Al deze kennis draagt bij aan het vinden van strategieën die goed passen bij de maatschappij in kwestie, zoals gebleken is in de casestudies.

1 Introduction

1.1 Background

Flooding of lowland rivers has been very important for human societies. Famous ancient civilizations, such as those along the Nile River in Egypt, along the Chinese rivers and in Mesopotamia, all depended on lowland river floods. The annually returning flood water and the deposition of sediments enabled large agricultural productions in the floodplains, which sustained societal development. However, with increasing population and intensifying land use the floods became increasingly less welcome. The positive effects of floods became less relevant, while the floods caused more inconvenience and larger disasters.

Although peak discharges will continue to occur in the future, they do not necessarily have to turn into disasters. Flood risk management strategies attempt to prevent peak discharges from causing disasters by implementing a combination of measures that enables a region to cope with flood waves.

Motivations to reconsider flood risk management

During the last decades flood disasters have become more frequent and have increased in magnitude of damage, despite centuries of experience with flood management (Berz, 2001; Parker, 2000; Susman et al., 1983; Takeuchi, 2002). This increase is due to a combination of climate change, population growth and unsustainable development (Kundzewicz, 2000). Apparently, there is a lack of ability or a lack of knowledge to reduce the damage caused by floods. If it is intended to reduce this damage, research on flood risk management must be intensified and solutions implemented.

Not only the increased severity of flood disasters during the last decades, but also climate change and population growth which may further increase flood damage in the future (Kundzewicz, 2000), and technological developments and changes in social preferences are reasons to reconsider different options for flood risk management of lowland rivers. An example of a changed value of society which influences the selection of flood risk management strategies is acceptance of floods. Whereas people accepted floods as acts of God or Nature in the past, nowadays people’s opinion in many western countries is that ‘the state’s efforts should protect the inhabitants from floods’ (Commissie Waterbeheer 21e eeuw, 2000; Penning-Rossell & Fordham, 1994). Technological developments widen the range of possible measures. Anticipation and flood regulation, e.g. by opening an inlet structure and using a detention area, has become easier than it was in the past. This is an example of a development which may change societal preferences for a certain flood risk management strategy (Hooijer et al., 2002).
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Current flood risk management
Currently, managers of lowland rivers have a wide variety of measures for flood risk management to choose from. In the past, when development levels were low, society had no other option than to adapt to nature and to floods. When the development level increased, also the need and the possibilities for flood control increased. Since advantages of floods decreased and disadvantages increased with increasing population, urbanisation and industrialisation, people started to construct embankments to protect their investments from flooding (Rossi et al., 1994). In the nineteen sixties, however, the appreciation of embankments changed, and non-structural measures, such as warning systems based on real-time flood forecasting techniques, floodplain zoning to restrict occupancy of the plain to certain uses, local flood proofing and flood insurance programs started to receive more attention (Rossi et al., 1994; White, 1974). To date, embankments can be found along many lowland rivers. However, there are also areas where people have adapted to annual floods or where other strategies are followed.

The commonly applied flood risk management strategy aiming at raising and strengthening embankments has next to many advantages also some disadvantages (Changnon, 1998; Kundzewicz, 2000; Linnerooth-Bayer & Amendola, 2003; Vis et al., 2001). One of the most important disadvantages of the current strategy is that if an embankment fails, a sudden and uncontrolled flood will occur in an area that was assumed to be protected from floods. In contrast to natural lowland rivers along which floods occur frequently and water levels rise gradually, along rivers with embankments floods are rare. However, when they happen water levels may rise fast which may take the inhabitants by surprise. In the wide floodplains most people do not live along the river and do not see the river water level rising. Although flood risk managers know that safety is guaranteed only for discharges lower than the discharge for which the embankments are designed, the inhabitants may not realise that they live in a flood-prone area and that floods may occur. The inhabitants and local governments may not be well-prepared for floods (Kundzewicz, 2000; Vis et al., 2001). This disadvantage, however, might be outweighed by the many advantages of the strategy.

Search for alternative strategies
The strategies adopted in the past may be continued into the future, but as explained above, there are also reasons to consider other possible strategies. Policy makers and researchers are studying which strategies for flood risk management would be preferable in the future (Changnon, 1998; Evans et al., 2004; Linnerooth-Bayer & Amendola, 2003; Szlávik & Rátky, 2000; Vis et al., 2001). In their policy and research documents new ideas, approaches and visions appeared, often expressed by concepts that seem to have turned into buzzwords. In the Netherlands, for example, next to safety, new policies for water management strive for sustainability by trying to create healthy natural ecosystems and resilient water systems, by letting water control land use planning instead of the other way around and by creating more room for the rivers (Commissie Waterbeheer 21e eeuw, 2000; Min. VROM and V&W, 1997; Min. V&W, 1999; Mostert, 2003; Silva et al., 2000). Likewise, many other countries search for a good strategy for the future (Galloway, 2000; Williams, 1994; United Nations International Strategy for Disaster Reduction, 2002). Current research and recently developed policies seem thereby to move away from flood protection by raising or strengthening the embankments towards adjusting the floodplains (Wiering & Driessen, 2001).
In order to find and evaluate alternative strategies for the future that correspond with the general ideas of policy makers, integrative research on long-term strategies for flood risk management is needed. Many studies focus on a particular aspect of flood risk management of river management, such as flood probabilities in different areas (TAW, 2000), the design of flood defences (Voortman, 2002), breach growth in sand embankments (Visser, 1998), potential flood impacts (Tapsell et al., 1998), or the evaluation of a certain type of measures (Commissie Noodoverloopgebieden, 2002; Eijgenraam, 2003; Holst et al., 2003). These studies do provide valuable insights in different aspects of flood risk management. However, they do not aim to evaluate the existing strategies or to generate new strategies for flood risk management of lowland rivers. Other studies do so, but are focused on a certain area only (RWS-DWW, 2001; Vis et al., 2001). Therefore, additional integrative research for lowland rivers in general is needed (Samuels, 1999).

**Resilience in flood risk management**

To improve flood risk management in the future, Dutch policy makers suggest making water systems more resilient (Min. V&W, 1999). However, they do not define what they mean by ‘resilient water systems’. Resilient systems are expected to be able to cope better with unexpected events (Silva et al., 2000). ‘Resilience’ thus has a positive connotation (Remmelzwaal & Vroon, 2000), although it may be difficult to explain what exactly the positive aspects are.

‘Resilience’ is frequently used in different scientific disciplines and in spoken language (De Bruijn et al., in press). It is usually associated with recovery from an unpleasant situation caused by a disturbance, back to the pre-disturbed situation (Remmelzwaal & Vroon, 2000). Companies that almost go bankrupt but recover are called resilient and patients in hospitals that recover quickly are considered resilient as well. In all these meanings, resilience has a positive connotation.

Resilience, as used in water management, seems to be derived from the scientific discipline of ‘systems ecology’ (Klijn & Marchand, 2000). In ecology the behaviour and persistence of ecosystems are studied by considering the reaction of these systems to disturbances. This reaction reflects the system’s resilience and resistance. Together, the system properties resilience and resistance determine a system’s capability to cope with disturbances and thus its persistence (see a.o. Begon et al., 1996). Because flood waves may be considered as disturbances, the application of the resilience concept in flood risk management was considered (Klijn & Marchand, 2000). Studying resilience may result in a new way of looking at flood risk management. This new way of looking might result in better, more integrated strategies. It is, however, not sure yet whether the resilience concept is applicable to flood risk management of lowland rivers.

The concept of resilience has been defined earlier in the context of water management, and its definition in the context of flood risk management has been explored before. In the USA resilience is used as a quantifiable criterion for the performance of reservoirs, water supply systems, and other regulated systems (see a.o. Hashimoto et al., 1982). Klijn & Marchand (2000) and Remmelzwaal & Vroon (2000) have explored definitions for the concept of resilience for flood risk management of large diked rivers in the Netherlands. However, a
definition that is applicable in flood risk management of both diked and undiked lowland rivers is still lacking.

The meaning of resilience in flood risk management has thus remained vague. Nevertheless, it is common belief that it is something positive. In order to study whether this positive connotation of resilience is right, it is thus necessary to define resilience clearly in the context of flood risk management. If the resilience concept is applicable to flood risk management, then potential benefits resulting from applying the concept must be studied and strategies for flood risk management that increase resilience need to be evaluated. Will applying resilience result in a different view on flood risk management and/or will it help to find comprehensive strategies for the future and stop the trend of increasing flood damages?

1.2 OBJECTIVE AND RESEARCH QUESTIONS

The objective of this research is to investigate whether applying the resilience concept is useful for flood risk management of lowland river systems. The concept of resilience is considered useful when applying the concept facilitates strategy development or results in strategies that differ from strategies that are currently applied or considered. The main question addressed in this thesis is therefore:

Does applying the resilience concept facilitate the development of strategies for flood risk management?

This main question can be answered by addressing the following subquestions:

1. Which definition of the resilience concept is useful and applicable for the flood risk management of lowland rivers?
   a. What is resilience and how is resilience defined in systems theory? What does the concept indicate?
   b. What does flood risk management involve? What does it aim at and how can a flood risk management strategy be evaluated?
   c. How can resilience be defined in the context of flood risk management?
2. Which indicators can be used to make the resilience concept operational and quantifiable in flood risk management?
3. How resilient are different flood risk management systems and what are advantages and disadvantages of resilience strategies?
   a. How resilient are existing systems?
   b. How can resilience be increased or what are characteristics of resilience strategies for these systems?
   c. What are the advantages and disadvantages of resilience strategies?
   d. Do the resilience strategies differ from the current strategies used for flood risk management?
   e. What are differences in resilience between different river systems?
1.3 Definitions and Focus of the Research

This research focuses on flood risks along lowland rivers. Floods along other river types, lakes or sea floods are not considered. Lowland rivers are rivers that have a relatively low gradient, a slow water level rise and fall, and flow through a relatively flat area. They have large floodplains which in natural conditions would become regularly flooded. Floods can be defined as inundations of areas that are usually dry (Hooijer et al., 2002). Lowland floods are clearly different from other types of floods and, therefore, they will have their own kind of strategies and measures. Lowland river floods are more predictable than flash floods and sea floods, because the discharge of lowland rivers usually changes gradually. This gives people time to react. Furthermore, in rivers a certain limited volume of water is available for flooding, while in seas the volume is almost infinite. Flooding at one location along a river, therefore, may increase safety downstream. Another difference is that floods of lowland rivers normally threaten vast areas, which is not the case for flash floods. The areas are often densely populated.

The area of interest of this study includes both the river and the adjacent flood-prone area and comprehends the physical as well as the socio-economic characteristics of that area. The research uses a systems approach which assumes that the socio-economic system, that is the system in which people act, and the physical system that includes the natural and man-made structures, together form one system. The systems approach will be elaborated in chapter two.

Flood risk management aims at improving or maintaining the capacity of a region to cope with flood waves. The term 'flood risk management' is used here to emphasize that not only flood probabilities but also flood impacts are considered and that not only the river system but also the socio-economic system can be managed. Flood risk management may involve flood control, flood abatement, and flood alleviation measures. This will also be elaborated in chapter two.

In this research flood risk is defined as the expected yearly flood impact. This is calculated as the summation of the products of the probabilities of all potential flooding events and their corresponding impacts (Hooijer et al., 2002).

1.4 Research Set-up

The research consists of two parts: the development of a theoretical framework and the testing of the framework in case studies. To develop the theoretical framework, firstly, relevant literature on the meaning of the resilience concept was studied. Next, discussions with flood risk managers and a literature review on flood risk management and flood impact assessment were carried out. Confronting the resulting understanding of resilience with the obtained knowledge on flood risk management led to a definition of resilience in the context of flood risk management of lowland rivers. This definition was translated into resilience indicators, which were tested on hypothetical river systems.

The theoretical framework was tested in three case studies, which gave insight in flood risk management strategies, the applicability of the resilience concept on the different systems and
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the advantages and disadvantages of resilience oriented strategies. These case studies resulted in conclusions on the relevance of resilience for flood risk management for the specific case study areas and in general.

The three case studies are:

1. The lower Rhine River (Germany and the Netherlands). For this system the current resilience was calculated and different flood risk management strategies were developed and evaluated.
2. The undiked part of the Meuse River (the Netherlands and Belgium). This case study focused on the development of flood risks and resilience in time.
3. The Lower Mekong River (Cambodia). This river basin is still quite natural but is changing rapidly, which makes it an interesting case. It also provides an example of flood risk management in a developing country. The current resilience was studied and a resilience strategy for the future was developed and evaluated.

The three case studies cover areas threatened by different discharge regimes. They have different physical and socio-economic characteristics and different flood risk management strategies. The same approach was used for all three case studies. First, the discharge regime and the socio-economic and physical characteristics of the region were analysed to get insight into the effects of floods and the potential effects of measures to reduce flood risk. Secondly, the current resilience of the region was assessed. Thirdly, new strategies to increase resilience were developed and evaluated. In the case study on the Meuse River no resilience strategies were developed, but instead developments over time were studied by determining the resilience of the region at different moments in the past, at present and in the future.

1.5 OUTLINE OF THIS THESIS

The outline of the thesis is summarized in figure 1.1. Chapter 1 introduces the research subject, the research questions and approach.

Chapter two and three discuss the theories used in the thesis. Chapter two explores the concept of resilience and describes in more detail what flood risk management is and where it aims at. This chapter then combines the flood risk management and resilience theories into a definition of resilience in the context of flood risk management. Chapter three discusses indicators to quantify the concept of resilience and illustrates these indicators by applying them on hypothetical river systems.

Chapter 4, 5, 6, 7 and 8 describe the case studies on the Lower Rhine River, the undiked part of the Meuse River and the lower Mekong River. Chapter 4 describes the current resilience of the Rhine, while in chapter 5 strategies to increase resilience of the Rhine are developed and evaluated. In chapter 6 the Meuse case study answers the question: ‘How resilient is the Meuse River currently and how did the resilience change over time?’ Chapter 7 studies the current resilience of the Lower Mekong River and defines and evaluates a resilience and a resistance strategy for this river. In chapter 8 the systems considered in the case studies are compared.
Finally, in chapter 9 the results of the thesis are discussed and conclusions and recommendations are presented.

**Figure 1.1 Thesis outline**
Resilience in the context of flood risk management

2 RESILIENCE IN THE CONTEXT OF FLOOD RISK MANAGEMENT

In order to study whether the resilience concept is useful to flood risk management, resilience must be clearly defined and its meaning in relation to flood risk management must be understood. This chapter starts with a literature review on the resilience concept and continues with a discussion on flood risk management. The understanding of both is then combined into a definition of resilience in the context of flood risk management.

2.1 THE RESILIENCE AND RESISTANCE CONCEPTS

Review of the resilience and resistance concepts
The use of the resilience concept in water management was derived from ecology (Klijn & Marchand, 2000). The central question in systems ecology addressed in the ’70s and ’80s was how to explain the apparent stability or persistence of complex ecosystems. In this context, Holling (1973) introduced the concept of ‘resilient systems’. Holling states that the most essential feature of ecosystems is that they recover from disturbances. This recovery means that the principal characteristics of the system are restored, not that the exact same situation returns.

Nowadays, two different resilience definitions are used that will be discussed here by having a look at a system’s reactions to disturbances. The reaction of a system with a static equilibrium to a disturbance may be one of the following:

1. The system does not react at all;
2. The system reacts but returns to the equilibrium situation;
3. The system reacts and turns into another stable situation;
4. The system does not return to any stable situation.

In the first case, no reaction is visible. In the second case the system reacts, but the system state stays in the domain of attraction of the equilibrium. The domain of attraction of an equilibrium is the collection of all initial states from which the system tends towards the equilibrium as time progresses. The system in the second case will therefore return to the equilibrium state. In the third case the disturbance causes the system to flip suddenly and unexpectedly to another equilibrium situation. An example of this situation is a shallow lake that is disturbed by a huge inflow of nutrients. It turns suddenly from a state with a high number of game fish, effective grazing upon phytoplankton and low incidences of algal blooms into a ‘pathological’ state in which there are few game fish, less grazing, no macrophytes and extensive and frequent algal blooms (Carpenter & Cottingham, 1997). This

1 Parts of this chapter are based on De Bruijn (2004a).
transition is rapid and is not easily reversed. Both situations are stable in a certain domain. In
the fourth case the system does not become stable anymore.

These four cases involve a static equilibrium. In reality, however, systems are rarely static,
but instead they develop and change continuously. They will, therefore, not have a certain
equilibrium state to which they return. However, natural systems must have some stability
and stabilizing processes to recover from disturbances and to persist (Holling, 2000). Holling
(2000) concludes that the essence of persistence is the seeming paradox of change and
stability inherent in developing systems. Elements taken from stability theories can thus be
very useful to study resilience and the resilient behaviour of dynamic ecosystems. If a
developing system is disturbed, the same four types of reaction apply, but the system does not
return to the former equilibrium state, but to the pre-disturbed pattern of development.

Against this background, resilience has been defined in two ways:

1. Resilience is the ability of a system to maintain its most important processes and
   characteristics when subjected to disturbances (Holling, 1973).
2. Resilience is the ability of a system to return to its equilibrium after a reaction to a
disturbance (Begon et al., 1996; Jørgensen, 1992; Pérez-Españo & Arreguín-Sánchez,
   1999).

In the first definition, resilience is measured as the magnitude of disturbance that can be
absorbed before the system redefines its structure by changing the variables and processes
that control behaviour (Holling, 1973). According to this definition the system in the
previously discussed cases 1 and 2 have sufficient resilience to deal with the disturbance. A
system with a small domain of attraction that can change dramatically by small disturbances
(see case 3 above) is considered not resilient (Coller, 1997). This definition has been used to
describe the dynamics of a variety of ecosystems, including freshwater rivers (Fiering, 1982),
freshwater lakes (Capenter and Cottingham, 1997), forests (Ludwig et al., 1978) etc.
(Gunderson, 1999).

The second definition is based on the assumption that systems operate at or near a global
equilibrium where they will return to (Begon et al., 1996; Jørgensen, 1992; Ludwig et al.,
1997). According to this definition only the system in the previously discussed case 2 applies
resilience to deal with the disturbance. The system in case 1 does not need resilience since it
does not react to the disturbance. The users of this definition measure resilience as the return
time of a system to its equilibrium (Kwa & Ringelberg, 1984; O’Neill et al., 1986; Pérez-
España & Arreguín-Sánchez, 1999). O’Neill et al. (1986) adds that to measure resilience both
the time needed to return to the equilibrium and the deviation of the equilibrium after a
disturbance should be measured. He quantifies resilience as the sum of the squared deviations
from the equilibrium.

Holling (1973), the author of the first definition above, introduced the concept of resilience in
addition to existing concepts within the systems approach in order to emphasize that systems
are not stable and do not return to a stable equilibrium. This stability is, however, assumed in
the second definition above. Therefore, Holling (1973) used this second definition of
resilience for stability and not for resilience. The users of the second definition, however,
consider both resilience and resistance as characteristics that make a system stable. A resilient
system reacts on a disturbance and then recovers (see case 2 above); a resistant system does not show any reaction at all (see case 1 above). A tree species could, for example, survive fires by having fire-resistant bark (exhibiting resistance), or alternatively it could burn down and regenerate from seeds with fire-induced germination (exhibiting resilience). In very dynamic environments, such as coasts and natural floodplains, resilient species dominate, whereas in stable environments, as rainforests and coral reefs, more resistant species will be found. According to the second definition of resilience and resistance, the first definition (the one from Holling (1973)) covers both resilience and resistance and is rather a definition of stability or persistence.

Use of the resilience and resistance concepts in this thesis
In this thesis Holling’s (1973) definition of resilience is used for ‘persistence’. ‘Persistence’ then includes both stable systems and evolving systems. The persistence of a system depends on its ability to cope with disturbances and thus on its resilience and resistance. The resilience concept is defined in this thesis according to the second definition above: Resilience is the ability of a system to recover from a response to a disturbance. Similarly, resistance can then be defined as the ability of a system to withstand disturbances without reacting at all. In the resilience definition ‘recovery’ does not mean that the exact same system state has to return, but only that the negative impacts of the disturbance have passed. In that way the fact that most systems are dynamic and do not return to a stable equilibrium is incorporated.

An extra aspect included in the definition of resilience used in this thesis, is that resilient systems are supposed to react proportionately to increasing disturbances. This graduality of the increase of reaction with increasing disturbances is related to how easy a sudden change in the system can occur. In this thesis, systems that show a surprisingly more severe reaction to a slightly increased disturbance are considered less resilient than systems from which the reaction to increasing disturbances increases gradually. It is expected that the systems with a low ‘graduality’ recover more slowly and with more difficulties than systems with a high ‘graduality’.

The definition found here can be applied to all kind of systems. In section 2.3.2 it will be applied to flood risk management systems.

The aspects that describe reactions to disturbances
The reactions of systems to disturbances reflect the system’s resilience and resistance. By studying the reactions insight into the system’s resilience and resistance can thus be obtained. Two main features of a system’s reaction are represented in figure 2.1 as the behaviour of one hypothetical state variable reacting to sudden disturbances with negligible duration. The system in figure 2.1a has sufficient resistance to cope with small disturbances, while it has resilience to recover from larger disturbances. The maximum disturbance that causes no reaction is indicated by the ‘reaction threshold’. The reaction amplitude (A) and the recovery rate (the angle indicated in figure 2.1a) together describe the reaction to the disturbance. The reaction amplitude is a measure for the magnitude of the reaction to the disturbance. The recovery rate is the speed with which a system recovers from its reaction to a disturbance.

In order to understand the behaviour of a system it is not sufficient to study its reaction to a single disturbance. Instead, the system’s response to the whole possible range of disturbance
magnitudes should be studied. Figure 2.1b shows the reaction amplitude of three hypothetical systems given the whole range of disturbance magnitudes. From this figure a third reaction aspect, the graduality of the reaction increase with increasing disturbance magnitudes can be derived. The steeper the slope of the curve that represents the relationship between the disturbance magnitude and the corresponding reaction amplitude is, the less gradual the reaction. Instinctively, a gradual response that is proportionate to the disturbance is expected. A sudden discontinuity in the disturbance-response relationship is usually unexpected and may therefore be undesirable.

In conclusion: A system’s reaction to a disturbance depends on its resistance and resilience. The resistance of a system determines which disturbances a system can withstand without reacting; its resilience determines the response to and recovery from more extreme disturbances. The system’s reactions can be described by the amplitudes of the reactions to the disturbances, by the recovery rates from the reactions and by the graduality of the increase of reaction with increasing disturbance magnitudes.

2.2 Flood Risk Management

2.2.1 Definition of Flood Risk Management

In this thesis flood risk management is defined as all activities that aim at maintaining or improving the capability of a region to cope with flood waves. Flood waves are discharge waves flowing down a river with a peak discharge level, a duration and a volume. A flood is defined here as the inundation of an area that is usually dry (Hooijer et al., 2002). Risk is
Resilience in the context of flood risk management

defined as a function of flood probabilities and flood impacts. It can be quantified by the expected annual damage.

Flood risk management comprehends flood control, flood alleviation and flood abatement (Table 2.1). Flood abatement aims at the prevention of the occurrence of peak flows (Parker, 2000). Flood abatement measures include water retention and land use change in the upper reaches and erosion prevention. This type of measures is normally not feasible for large lowland rivers; it is especially effective for small river catchments with higher flood frequencies. Flood control comprehends all activities that aim at preventing inundations. Flood control measures such as embankments focus on and are situated along the river system. In contrast, flood alleviation comprehends all activities that aim at flood impact reduction. Flood alleviation measures mainly focus on the flood-prone area. Examples are land zoning, water proofing, mounds, land use change and land use regulations (Parker, 2000).

Table 2.1 Overview of flood risk management

<table>
<thead>
<tr>
<th>Measures</th>
<th>FLOOD ABATEMENT</th>
<th>FLOOD CONTROL</th>
<th>FLOOD ALLEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim</td>
<td>Prevent flood waves</td>
<td>Prevent inundations</td>
<td>Reduce / distribute flood impacts</td>
</tr>
<tr>
<td>Types</td>
<td>Structural</td>
<td>Structural</td>
<td>Non-structural measures</td>
</tr>
<tr>
<td>Examples</td>
<td>Reforestation, soil &amp; water conservation</td>
<td>Embankments, detention areas</td>
<td>Flood-proofing, land zoning, flood warning, insurance</td>
</tr>
</tbody>
</table>

Flood risk management implies two main types of measures that are distinguished by their aim: structural and non-structural measures. The aim of structural measures is to modify the flood pattern, while non-structural measures aim at reduction of the flood impacts (Parker, 2000). Examples of structural measures are reservoirs, levees, embankments, new flood-related channels, and increasing infiltration capacity in the catchment. Non-structural measures lower flood damages by planning and regulating the way of floodplain use, floodproofing, enhancing preparedness, educating and warning the inhabitants, or by redistributing flood damages in time and space by insurance, flood relief and other financial instruments.

2.2.2 FLOOD RISK MANAGEMENT AS A SERVICE TO THE REGION

As described in the previous section, flood risk management aims at enabling a society to cope with flood waves. This definition of flood risk management does neither give any indication of why flood waves have to be coped with nor when and to what extent flood risk management is necessary nor does it describe how flood waves should be coped with. There are numerous strategies possible. In order to find the best strategy the broader context in which flood risk management occurs should be considered.

Sustainable development

Flood risk management in a region is clearly related to the characteristics and developments in the region (Hall et al., 2003). Flood risk management is not primarily about floods but
about the region that may suffer from floods. Flood risk management must enable a society to cope with flood waves in such a way that the region’s welfare can grow or is maintained in the future. This is reached when flood risk management strengthens the sustainable development of the region where floods may happen. In regions where devastating floods occur sustainable development is hampered (Handmer, 2000; Loucks, 2000). ‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED, 1987). The WCED (1987) also stresses that sustainability not only requires equity between generations, but also within one generation. This means that in order to increase sustainability the benefits and costs of different strategies for flood risk management should be distributed fairly among different groups. Since we do not know what future generations may want and need, equity between generations is usually translated into 'keeping options open for future generations' and into maintaining natural resources. However, this does not mean that water resources cannot be developed and should remain completely natural (Loucks, 2000). Present societies need to develop and change their environment. The issue is, therefore, how to reach a development in which a larger welfare can be reached without causing severe environmental degradation or flood disasters, and without increasing inequity between current generations.

Several attempts have been made to make the vague ‘sustainable development’ concept more tangible by distinguishing different elements that are covered by its definition (ASCE & UNESCO, 1998; Blowers, 1993; Callens & Tyceta; 1999; Hooijer et al., 2002; Parker, 2000). Important elements are the socio-economic dimension (the need to develop to reduce inter- and intra-generational equity), an environmental dimension (acknowledgement that our continued existence depends on the health of the biosphere) and the focus on dynamics. The first element, socio-economic development, refers to cultural, social and economic improvement or progress (which is not necessarily ‘economic growth’). The second element is the one of seeking ecological sustainability. This is the part of sustainable development most discussions focus on. It is concerned with the prevention of consumption of non-renewable resources and the production of harmful emissions; it is about maintaining ecosystems and biodiversity. It is, as the WCED (1987) clearly explains, strongly related to socio-economic development. The third element, which actually lies above the other two elements, is the focus on dynamics. We must realize that all systems are dynamic and that coping with changes and the potential effect of uncertain disturbances is important for sustainable development.

The aim of flood risk management to support sustainable development can thus be defined as enhancing socio-economic development, while at the same time sustaining the ecology in the region, and both in a context of unexpected changes and disturbances. These unexpected changes and disturbances may, for example, be changes in the world economy, changes in societal preferences, climate change and sudden extreme discharges.

**How to find measures that enhance sustainable development?**

In order to find measures which enhance sustainable development the discharge regime and the physical and socio-economic characteristics of the region involved must be considered (Table 2.2). The discharge regime characteristics, such as the season when floods may occur and the variability and predictability of the discharge, affect the potential damage and the efficiency of flood forecasting systems and other measures. The physical characteristics such as elevation differences, soil and geological properties and sediment transport in the river
Resilience in the context of flood risk management

influence the feasibility of flood risk management measures such as land zoning and the effectiveness of embankments. *Socio-economic characteristics* of a region determine for example:

- Whether change to another strategy is possible (change is easier in less densely developed areas (Green, 2003a));
- Whether investment costs and maintenance costs for expensive structural measures can be afforded;
- The priorities of society: e.g. the importance of nature values of a river, and the price that society is willing to pay for flood prevention;
- The positive impacts of floods (e.g. the importance of agriculture to society);
- The positive effects of measures.

A flood risk management strategy that enhances sustainable development can thus only be found by an integrated approach in which the discharge regime and the physical and socio-economic characteristics of the region involved are considered.

Table 2.2 Examples of flood risk management strategies in regions with different physical and social characteristics and discharge regimes

<table>
<thead>
<tr>
<th>Region</th>
<th>Physical characteristics</th>
<th>Social characteristics</th>
<th>Discharge regime</th>
<th>Strategy /Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon (Brasil)</td>
<td>Flat area, large flood-prone area, swamps</td>
<td>Natural rain forest, extremely low population density, no urbanisation</td>
<td>Rain forest</td>
<td>Adaptation: natural landscape, houses on poles, floods are considered positive</td>
</tr>
<tr>
<td>Mekong (Cambodia)</td>
<td>Flat area, large flood-prone area, stable channels</td>
<td>Low, but fast increasing population density, poverty, agriculture, fisheries</td>
<td>Monsoon</td>
<td>Adaptation: Houses on poles, adapted agriculture, shelters, transport by boats, fisheries</td>
</tr>
<tr>
<td>Ganges Brahmaputra (Bangladesh)</td>
<td>Flat, large flood-prone area, unstable channels, much sediment transport</td>
<td>High population density, poverty, agriculture, water used for irrigation, fisheries</td>
<td>Monsoon</td>
<td>Adaptation and flood control: adapted houses and agriculture, shelters, embankments and bypasses</td>
</tr>
<tr>
<td>Lower Mississippi (USA)</td>
<td>Valley, flood-prone area is small part of total area, stable river channels</td>
<td>Low population density, high welfare level</td>
<td>Temperate climate</td>
<td>Flood control: Embankments (1/100), reservoirs, land zoning, insurance</td>
</tr>
<tr>
<td>Thames (upstream of London, UK)</td>
<td>Hills, small part of the area is flood-prone</td>
<td>High welfare level, densely populated, urbanised area</td>
<td>Temperate climate</td>
<td>Flood control based on cost-benefit analysis, insurance, flood warning</td>
</tr>
<tr>
<td>Lower Rhine (Germany – The Netherlands)</td>
<td>Flat area, stabilized river channels, large flood-prone area</td>
<td>High population density, high welfare level</td>
<td>Slow rising winter peaks</td>
<td>Flood control: High embankments (1/1250), flood forecasting</td>
</tr>
</tbody>
</table>
Chapter 2

2.2.3 EVALUATION CRITERIA FOR FLOOD RISK MANAGEMENT STRATEGIES

This section discusses and defines the criteria which will be used to evaluate strategies in the case studies in the next chapters. These criteria will help answering the research question on the advantages and disadvantages of resilience strategies (see research question 3c Chapter 1). The evaluation criteria are based on the aim of flood risk management as discussed in the previous section: a comprehensive flood risk management strategy supports and strengthens sustainable development of the region involved. This includes the three aspects: enhancing socio-economic development, sustaining the ecology in the region and enabling the system to cope with unexpected changes and disturbances. In order to evaluate different strategies, criteria that reflect these three aspects of sustainable development are defined:

1. The socio-economic impacts of the strategy;
2. The effects on nature and land scenery;
3. Sensitivity of the strategy for unexpected events and changes.

These three main groups can be divided into sub-criteria (Table 2.3). The sub-criteria are based on the ones that Vis et al. (2000) used to evaluate flood risk management strategies for the lower Rhine Basin. However, they are adapted to allow the use of these criteria for other basins, such as the Mekong Basin. The main groups are evaluated only qualitatively, while sub-criteria can be quantified if sufficient information is available. The sub-criteria should preferably be independent, although this is almost impossible to achieve. The economic opportunities of different land use functions, for example, are influenced by the flood impacts and vice versa. The quantification of the criteria will be done in such a way that they are as independent as possible.

**Socio-economic impacts of the strategy**

For socio-economic development the following sub-criteria are used:

- Socio-economic flood impacts;
- Investment costs and costs of maintenance of the measures in the strategy;
- Effects on and opportunities for important land use functions;
- Effect on equity.

The *socio-economic flood impacts* are quantified by three parameters: the total flood risk, the expected average number of affected persons per year and recovery capacity. The flood risk consists of both the direct and indirect flood impacts at a certain moment in time (e.g. 2050). The risk and the resulting average number of casualties are estimated as indicated in equation 2.1. The recovery capacity is expressed qualitatively as a number between 1 and 10. Since recovery is also relevant for the quantification of resilience, the determination of this number will be discussed in chapter three.

\[
R = \int_{0}^{1} PD(P)dP \quad \text{(Eq. 2.1)}
\]

With: \(R = \text{Average annual impact ($/yr or number of casualties/yr)}, D = \text{flood impact corresponding with a certain probability ($ or number of casualties), } P = \text{annual probability}\)
The costs include both maintenance and investment costs of the measures within the strategy. They are calculated as a net present value assuming a certain lifetime for the measures.

The effects on and opportunities for important land use functions are assessed qualitatively. Which land use function is important differs per region. In the Mekong system, for example, fisheries in the floodplains is very important, while in the Rhine system opportunities for trade and industry are more relevant.

Equity is included in the analysis only, if relevant effects on equity are expected. If a flood risk management strategy causes the difference between rich and poor to increase or decrease, then this criterion is relevant. If strategies do not affect this difference at all, the criterion can be neglected. To estimate this criterion one must ask who benefits from the strategy and who has to pay for it. It is assessed qualitatively based on a comparison of the current situation and the situation which is expected to occur after the strategy that is being evaluated has been implemented.

The effects on nature and land scenery
The second group of criteria is quantified by assessing the effect on nature and on land scenery (Vis et al., 2001). The effect on nature is estimated qualitatively by using a Delphi technique or by comparing the current situation with the expected future situation. Land scenery is assessed by considering the preservation of cultural heritage values and scenic quality. It is quantified relatively and qualitatively.

Sensitivity of the strategy to unexpected events and changes
The sensitivity of strategies to unexpected events and changes is related to uncertainties and their effect on decisions and outcomes of decisions. To decide on which strategy to follow in flood risk management, managers will ask questions that cannot be answered because many characteristics of the current system are unknown and the future is even more uncertain. Since uncertainties are important, this section briefly discusses kinds of uncertainties and factors which are considered when assessing the sensitivity of strategies to uncertainties.

Uncertainty exists where something is unknown (Keynes, 1973). Uncertainty may result from imprecise knowledge i.e. where the probabilities and magnitude of either the hazards and or their associated consequences are uncertain. Even when there is precise knowledge of these components there is still uncertainty because outcomes are determined probabilistically meaning that it is still unknown if and when they will occur (Willows & Connel, 2003).

There are many different kinds of uncertainty. They can be classified according to the source of uncertainty and the way they present themselves. Sources of uncertainty are lack of knowledge and natural variability (Van Asselt & Rotmans, 2000) and they can present themselves as technical or statistical uncertainties, methodological uncertainties and fundamental uncertainties (Van Asselt & Rotmans, 2000). Technical or statistical uncertainties are uncertainties that surround a variable when its state at any one point is unknown, but the probability distribution that characterizes that variable is known (Hilborn, 1987). An example is the uncertainty on whether you may win a lottery. Methodological uncertainties occur when the relationship between parameters and/or the processes are not understood. These uncertainties are often neglected, but they are relevant, for example, when
models are being used. Models are obviously just a simplified representation of reality and include thus uncertain understandings. *Fundamental uncertainties* arise on subjects where we cannot know anything about because they never occurred before.

Whether uncertainties are important in flood risk management depends on the influence they have on decisions. *Decision uncertainty is doubt* on what choice to make (Green, 2003b). It may arise from lack of knowledge on the options available, on the consequences of the options, on the future state of the system, or on the decision criteria (Green, 2003b). For decision making it is only useful to reduce uncertainties if it changes the ranking of alternative options. If the ranking of alternatives is certain, despite many aspects being uncertain, still a decision can be taken (Green, 2003b).

One of the most important uncertainties in flood risk management is variability in nature. If flood waves always occurred on the same time and with the same magnitude, they would be better manageable. However, nobody knows if and when certain discharge waves will occur. Other aspects that are uncertain to some degree are: the division of water over different river branches, stage-discharge relationships for extreme discharges, embankment stability, the magnitude of flood impacts, behaviour of the inhabitants and the effects of measures. Next to the uncertainties in the current system, there are even more uncertainties on how the system will behave in the future. Land use will change, societal preferences may change and probably the climate and the river system will change also (De Bruijn *et al.*, in press).

Not all uncertainties can be avoided or solved. However, decisions have to be taken. Important questions for flood risk managers are: ‘What decisions should be taken, given all uncertainties?’, ‘What might go wrong and under what circumstances may this go wrong?’, ‘What are the consequences and how can these consequences be attenuated?’. A lot of research on the potential consequences of uncertainties and on ways to cope with uncertainties is carried out (Burn, 1999; Commissie Noodoverloopgebieden, 2002; Van Asselt & Rotmans, 2000; Van Mierlo *et al.*, 2003).

Flood risk managers may try to manage their system in such a way that these unexpected disturbances and changes can be better coped with. Systems that are able to cope with disturbances are called *robust* and those that can be adapted to all kind of circumstances are *flexible*. Not only a system can be robust and flexible, but also a flood risk management strategy.

In this thesis the sensitivity of the strategy to uncertainties is evaluated by studying the response to unexpected events in the current situation and to changes in the future. Unexpected events are events which are not considered in the design of the strategy. The sensitivity of the system to unexpected events in the current situation, defined as the system’s robustness, is studied by questioning what happens when the disturbance on the system is different than anticipated, when the hydraulic system behaviour is different than expected, when a process or a structure is not functioning as intended or when the inhabitants do not respond as expected. To test this sensitivity the following types of questions are addressed:

- On the disturbance: What would happen if the discharge wave is much wider than usually?
Resilience in the context of flood risk management

- On hydraulic system behaviour: What happens when the distribution over the branches is different from what is expected?
- On organisational & technical issues: What is the result of the non-functioning of an inlet structure, embankment, or another structure, a monitoring system or a warning system? What if a structure fails? What happens if important people who have to put processes in work cannot be reached?
- On behaviour of inhabitants: What if people get caught in traffic jams, or what if inhabitants of detention areas prevent flooding of that area?

The sensitivity of a strategy to changes in the future is assessed by quantifying the strategy’s flexibility. Flexibility is defined as the ability to prevent future regrets (Vis et al., 2001). A flood risk management strategy is thus flexible when it remains a good strategy in a large range of changed circumstances or when it can be adapted to changing circumstances. These circumstances are, for example, changed economic interests, and changed societal preferences and values. Questions asked to assess flexibility are:
- Is it possible to phase measures and investments with changing circumstances and conditions?
- Is it possible to undo measures without irreversible effects and without capital losses resulting from investments that cannot be recovered?

<table>
<thead>
<tr>
<th>Main criteria</th>
<th>Sub-criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socio-economy</td>
<td>Socio-economic flood impacts:</td>
</tr>
<tr>
<td></td>
<td>Flood risk</td>
</tr>
<tr>
<td></td>
<td>Expected annual number of affected persons</td>
</tr>
<tr>
<td></td>
<td>Recovery capacity</td>
</tr>
<tr>
<td></td>
<td>Costs of strategy: Investment &amp; maintenance costs</td>
</tr>
<tr>
<td></td>
<td>Economic opportunities for relevant land use</td>
</tr>
<tr>
<td></td>
<td>Equity</td>
</tr>
<tr>
<td>Nature &amp; land scenery</td>
<td>Nature</td>
</tr>
<tr>
<td></td>
<td>Land scenery</td>
</tr>
<tr>
<td>Sensitivity of the</td>
<td>Robustness to unexpected events</td>
</tr>
<tr>
<td>strategy to unexpected events and changes</td>
<td>Flexibility for future changes: phasing of measures, possibility to undo measures</td>
</tr>
</tbody>
</table>

2.3 Resilience and resistance in flood risk management

In section 2.1 the resilience concept was discussed and defined and in the previous section an overview of flood risk management was presented. In this section these two are combined into a definition of resilience in the context of flood risk management.
2.3.1 THE SYSTEMS APPROACH IN FLOOD RISK MANAGEMENT

Section 2.1 explained that resilience is a system’s characteristic. Consequently, a systems approach, similar to the one used in ecology must be adopted in order to be able to apply resilience in the context of flood risk management, and the system relevant for flood risk management must be defined. The system boundaries can be defined by considering where flood risk management focuses on, thus for what area and what objects and which people measures and strategies are being designed.

In this thesis a flood risk management system is defined geographically as the combination of the lowland river and the adjacent flood-prone area. The upper boundary of the system is located in the river reach where the river turns into a lowland river (see chapter 1) and the lower boundary is located in the reach where the sea influence on the river becomes important. Flood waves from the upper river enter this system as an external force. Conceptually, the system comprises both the socio-economic and physical aspects of the area (Figure 2.2). These aspects include, for example, land use, institutional aspects, political system, population characteristics, the presence of embankments, elevation differences and soil characteristics. Flood risk management aims at maintaining or increasing the capability of this system to cope with flood waves.

For practical reasons, the flood risk management system is geographically limited to the area threatened by floods. However, the socio-economic situation of this area strongly relies on a larger socio-economic context at regional, national or even global scale. Therefore, although the area threatened by floods is the focal system, relationships with other areas are taken into account when these other areas suffer indirect flood impacts or influence the recovery rate.

In order to develop flood risk management strategies that enhance sustainable development an integrated approach is required (see section 2.2.2). The systems approach as defined in this section is an example of such an integrated approach. This approach incorporates the discharge regime and the socio-economic and physical characteristics of the region involved.

Figure 2.2 A flood risk management system, consisting of the physical and socio-economic characteristics of the flood-prone area, is subjected to flood waves coming from the upper river
2.3.2 Definition of resilience and resistance of flood risk management systems

The reaction of a flood risk management system on disturbances depends on its resilience and resistance. Resilience has been defined in section 2.1 as the ability of a system to recover from the response to a disturbance. In this section the resilience of flood risk management systems is defined by discussing what ‘disturbance’, ‘response’ and ‘recovery’ mean in the context of flood risk management.

A flood risk management system is disturbed by flood waves generated upstream in the catchment area outside the focal system. These flood waves, which are variable and uncertain, can be considered as disturbances.

The system can respond in different ways to the flood waves entering the system. The flood wave can result in no reaction at all: in a system with sufficiently high embankments flood waves will not change anything in the socio-economic system. However, flood waves may also cause an inundation resulting in social and economic disruption. Society may suffer from flood damage to properties, the need for evacuations, emotional shock, and the destruction of monuments and ecosystems.

The recovery of society from this disruption is the return to a normal situation and normal development pattern. This means that at least the economic, social and physical development should be similar to the development before the flood or comparable to the development in areas that were not flooded. Damage has to be repaired, companies must reach their normal production level again and emotions must have been overcome.

Summarizing, for lowland rivers the resilience of a flood risk management system to flood waves can be defined as the ability of the system to recover from floods in the area. In contrast, the resistance of the system can be defined as its ability to let discharge waves pass without causing floods. In other words, in resilient flood risk management systems floods may occur, but their impacts will be rapidly recovered from, while in resistant systems discharge waves will not result in floods.

The aspects that describe a system’s reactions to disturbances: the reaction threshold, amplitude of the reaction, graduality of the increase of reaction with increasingly severe flood waves and recovery rate (see section 2.1), can also be applied to flood risk management systems. The reaction threshold is equal to the maximum discharge which is not expected to cause floods in the system.

The amplitude or magnitude of the reaction is equal to the economic, social, psychological and ecological impact of floods. It depends on the following parameters:

- Hydraulic parameters that are related to the flood event such as the maximum water depth, stream velocity, area flooded, duration of flooding and sediment carried;
- Socio-economic parameters that determine the corresponding damage such as the land use and the preparedness to floods;
- Ecological parameters such as the types of ecosystems, the presence of refugee locations and the connectivity with other ecosystems.
The graduality, relates to the increase of flood impacts with increasing flood waves. The graduality depends on the same parameters as the reaction amplitude, but is also strongly influenced by the physiography of the area and the flood defence infrastructure of embankments, outlets, weirs, bypasses, detention areas etc., and their operational management.

The recovery rate indicates how fast a system returns to its former state or former development pattern or to a development pattern comparable to systems that were not disturbed. It is not necessary that exactly the same state is achieved, as long as the most important characteristics return. After all, people may try to improve their situation during the recovery process, which may result in a system that is better prepared to future floods or with better living conditions. The duration of the recovery period depends on the magnitude of the damage itself and the context in which the damage occurs. Because the magnitude of the reaction is already described by the amplitude aspect, the recovery rate does not cover that aspect. Important factors that determine the recovery rate are the duration of flooding, the possibility to find funds to recover, the ability to earn an income during and after a flood, the spreading of effects to other areas, management and corruption in an area, health and equity. A sound assessment of the recovery rate requires the collaboration of social scientists and engineers.

### 2.3.3 Resilience and Resistance Strategies in Flood Risk Management

As explained in section 2.2 people can change the reaction of a flood risk management system to flood waves by implementing flood risk management strategies. Decision makers may choose measures which enhance the resilience or the resistance of the system, or both, in order to make the system able to cope with flood waves. Resilience strategies for flood risk management are defined as strategies that increase the system property ‘resilience’ and resistance strategies as strategies that enlarge a system’s resistance.

Resilience strategies can be characterised in general as strategies that allow floods, but aim at minimizing flood impacts, maximizing graduality of the increase of flood impacts with increasing discharges, and maximizing recovery rates, for all possible flood waves. They aim at increasing the capability of a system to recover from flood impacts. In contrast, resistance strategies can be defined as strategies which prevent that flood waves below a certain threshold cause floods. Resistance strategies thus try to increase the highest discharge which is not expected to cause floods. Resilience strategies try to direct floods to the less vulnerable areas, to limit the flood extent by compartmentalisation or to lower flood impacts by, for example, measures such as flood-proofing and land use regulations. They can also focus on the increase of the recovery rate by, for example, insurances and enhancing preparedness. In resilience strategies the whole discharge regime is considered, while in a resistance strategy attention may be focus on one single design discharge.

The two strategies apply different combinations of measures, although the same measures may be used in both resilience and resistance strategies. The measures used in a resilience strategy may change the flood probabilities or the impacts for specific locations within the system. They comprise both structural and non-structural measures. The flood probability can
be changed by, for example, decreasing the protection of nature areas, or increasing that of cities, while flood impacts may be reduced by e.g. raising flood risk awareness and changing land use. Both types of measures may increase the resilience of the system as a whole, since expected damages are lowered, recovery is enhanced and the reaction to flood waves may become more gradual. In resistance strategies, in contrast, flood protection by means of structural measures dominates. Both strategies can also be combined.

2.3.4 THE RELATIONSHIP BETWEEN RESILIENCE AND IMPORTANT RELATED CONCEPTS

Resilience is often confused with vulnerability and adaptability. To avoid confusion, the definitions used for these concepts in this thesis are explained and the relationships between those concepts and resilience are discussed. The aim of this section is to explain that the concept of resilience can be a useful addition to the already existing concepts, since it is clearly different from the already existing concepts as it corresponds with a systems approach.

Resilience and adaptability

Resilience, as defined in this chapter, relates to short-term disturbances, resulting from variability. However, resilience has also been used to express the ability of a system to adapt to long-term changes (Green et al., 2000; McFadden, 2001). To avoid confusion, a system’s ability to cope with or to adapt to sudden permanent changes or gradual long-term trends is called adaptability here. In contrast to short-term disturbances, these long-term changes and trends are not temporary and will not pass after a while (Figure 2.3). They can occur either in the system itself or in the external disturbances and they may affect the average value of a parameter, the extremes or both. Examples of such changes are: population increase, climate change and changes in societal preferences. When applied to flood risk management strategies, the adaptability of the system can be understood as the flexibility of the strategy as explained in section 2.2.3.

Figure 2.3 The difference between temporal variability, a trend and a change: the figure shows a change in the mean value of the parameter x, a trend, variability and the combined result
**Resilience in relation to vulnerability**

Vulnerability, and the related concepts risk and hazard are widely used in flood risk management. A hazard is the trigger to a disaster while the concept of vulnerability determines whether or in what circumstances such a hazard will result in a disaster. The concept of ‘hazard’ can be used as a qualitative characterisation of disturbances in different categories or alternatively it can be used in a quantitative way in which it equals, for example, discharge probabilities. *Risk* is often defined as a combination of hazard and vulnerability (Gilard & Givone, 1997). In such definitions hazard reflects the flood probability, while vulnerability reflects the corresponding flood impacts.

Apart from potential flood impacts, the definition of vulnerability has been used to describe other flood related aspects as well (De Bruijn et al., in press). The concept of vulnerability is used both as a quantitative and a qualitative concept; it is used in relation to both disturbances that have a short duration and for trends (e.g. sea level rise (Nicholls & Klein, 2000)) and it is even used without identifying the disturbance type or hazard. Furthermore, it is applied to all kind of objects (Alcantara-Ayala, 2002), on communities and persons (Blakie et al., 1994; Cannon, 2000) and on systems (Nicholls & Klein, 2000). Blakie et al. (1994) define vulnerability as a combination of factors that determine the degree to which someone’s life and livelihood is potentially affected by a disturbance or change in nature or in society. This vulnerability of people depends on the political, economic and social context they live in. Different components within this vulnerability concept are the potential impacts which a hazard may have and the recovery capacity to overcome those impacts (see section 3.3). Vulnerability as used by social scientists as Blakie et al. (1994) cannot be used to calculate flood risks, because it is not possible to link vulnerability defined in that way to a quantified hazard with a certain probability.

Although the concepts of vulnerability and resilience have similarities, they are used differently. Resilience, together with resistance describes *how* a system reacts to a disturbance, while vulnerability relates to *why* a (socio-economic) system responds in a given way. The origin of the two concepts is also different. The resilience concept is derived from stability theories and theories on system dynamics, while the vulnerability concept is mainly used in social science. The central issue in the concept of resilience is the reaction of the system to flood waves, while in the concept of vulnerability people and their livelihoods are the central issue. Vulnerability relates to a hypothetical non-quantified hazard and depends mainly on the characteristics of the flood-prone area. Furthermore, the presence of embankments and other structures for flood control is very relevant in the analysis of a system’s resilience or resistance, while in vulnerability analysis this presence may be excluded.

Resilience is thus not a synonym for vulnerability. By using resilience and resistance concepts the reactions of systems to peak discharges can be studied. By adopting this approach, other strategies *may* be found. The concept of vulnerability is important because it represents the social science’s knowledge on why people’s life is affected by floods and on the importance of floods to people’s life. It may help studying, for example, whether people are poor because of the floods or alternatively, do suffer from floods because they are poor. Therefore, both concepts are valuable in studies on flood risk management.
2.4 Reflection

This chapter defined flood risk management and resilience and combined the two in a definition of resilience in the context of flood risk management. This section summarizes the core notions and links them to the next chapters.

Flood risk management is no aim in itself, it should serve a region to function normally and develop in a sustainable way, despite disturbances by flood waves. How flood waves can be coped with adequately, depends on the socio-economic situation, physical situation and the river’s discharge regime. Therefore, an integrated approach which addresses all these aspects is needed to develop flood risk management strategies. Strategies for flood risk management can be evaluated by using criteria that relate to the effect of the strategies on different elements of sustainable development.

Resilience is a system’s characteristic that represents the ability of a system to recover from its reaction to a disturbance. By defining flood risk management systems the resilience and resistance concepts can be applied to flood risk management. In this thesis, the system for which flood risk management strategies must be developed consists of the lowland river and the socio-economic and physical aspects of the adjacent flood-prone area. The upstream boundary of this system is where the river changes from an upland river into a lowland river and the downstream boundary where the sea-influence becomes dominant. This system has a certain degree of resilience and resistance to cope with uncertain variable flood waves. The resistance of the system determines which flood waves can still be discharged through the river without causing floods, while the resilience determines the ability of the system to recover from floods. The smaller its reaction to floods, the faster the recovery from this reaction and the more gradual the reactions increase with increasing flood waves, the larger is the resilience of the system.

Flood risk management strategies may aim at increasing the system’s resistance, resilience or both. Resistance oriented strategies include measures that enable a certain design discharge to pass without causing floods. In resilience oriented strategies floods are allowed to occur, but recovery from the flood impacts should be fast and reaction increase with increasing discharges should be gradual. This type of strategy uses both non-structural and structural measures while resistance strategies mainly use structural measures.

In the next chapter the meaning of resilience will be further clarified by defining indicators to quantify resilience.
3 QUANTIFYING RESILIENCE

3.1 INTRODUCTION

Resilience has been quantified before. Hashimoto et al. (1982) introduced resilience in water management as a criterion for the operation and design of water supply systems. Other scientists adopted this idea and used resilience to characterise regional droughts (e.g. Correia et al., 1986), to measure the performance of water distribution systems (Zongxue et al., 1998), to characterise reservoir operation rules (e.g. Burn et al., 1991; Moy et al., 1986) and to quantify sustainability of water resource systems (ASCE & UNESCO, 1998). In these applications resilience is defined as the statistical probability to reach a satisfactory state in the next time step, given an unsatisfactory state in the present time step or as the reciprocal of the average duration of an unsatisfactory state. These applications focus on the state of the water system only, without considering the water uses and users. The consequences of the unsatisfactory states for the water users are thus not included in this definition of resilience. For example, for a reservoir an unsatisfactory state could be 'not fulfilling the water demand', and thus is the resilience of a reservoir the duration of such periods of unsatisfactory delivery. The system state is considered satisfactory, when the demand is met again. The consequences of this water shortage (the crop may have died already) and recovery from that consequence (e.g., planting new crop) are not included in this definition of resilience. This means that the definition of the systems is relatively simple. (Still, determining resilience of these systems is difficult, as is described in Maier et al. (2001)). If these definitions for resilience are used, resilience can be derived from recorded water discharges or water levels.

Quantifying resilience as the opposite of the average duration of an unsatisfactory state is only possible in relatively simple systems with clearly defined states. A flood risk management system is much more complex than a reservoir of which the state can be expressed by only one parameter: its water level. Assessing the recovery time of a flood risk management strategy for the future is thus more difficult. Because responses and recoveries are not easily measured, indicators for resilience have to be found.

Currently, there are no indicators available to quantify the resilience of flood risk management systems in all respects. Although different attempts to define indicators and to quantify resilience have been made already (Klijn & Marchand, 2000; Termes et al., 1999), none of these seems totally adequate. Therefore, this chapter aims at defining and quantifying new or additional indicators for resilience of flood risk management systems against flood waves.

2 Parts of this chapter have been published (De Bruijn, 2004b)
As chapter two explained, resilience and resistance reflect the reaction of flood risk management systems to flood waves. Therefore, indicators that quantify this reaction must be found. The reaction of a system can be described by the amplitude of the reaction, the graduality of the increase of reaction with increasingly severe flood waves and recovery rate (see chapter 2). The reaction threshold indicates the maximum discharge which is not expected to cause a reaction. In our search for resilience indicators, these aspects will be studied.

Section 3.2 presents an overview of possible reactions of flood risk management systems to flood waves by describing flood impacts and recovery from those impacts. Section 3.3 discusses indicator requirements and gives an overview of existing indicators. Section 3.4 proposes new indicators for resilience. Finally, in section 3.5 the behaviour of the newly proposed indicators is evaluated by applying them on hypothetical river systems. In section 3.6 the core findings are summarized.

3.2 REVIEW OF FLOOD IMPACTS AND RECOVERY

3.2.1 FLOOD IMPACTS

Flood impacts can be summarized as all the effects a flood has on its environment starting from the moment the water inundates dry land until full recovery has occurred. There is a wide variety of positive and negative flood impacts, such as: increased fertility of agricultural land, damage to houses and other buildings, loss of life, loss of jobs or income, disruption of the network of social contacts, and interruption of normal access to education, health and food services. All these different flood impacts can be categorised based on (Parker et al., 1987; Parker, 2000; Penning-Rowsell & Chatterton, 1977):

- Whether the effect is positive or negative;
- The link with the flood (direct and indirect damage);
- The location where damage occurs (primary, secondary and flood-induced damage);
- The possibility to express the damage in monetary values (tangible/intangible).

Regular floods usually bring benefits to Riverside communities. In the case of regular normal floods, the local economy and ecology are well adapted to the 'flood pulse'. In regularly flooded inhabited areas agriculture is often important. Agriculture not only uses water but may also benefit from the nutrients in the sediments that are deposited during floods. Furthermore, 'normal' floods also help preserve areas of floodplain marsh and swamp; they may increase the biodiversity of floodplains and replenish lakes and ponds, which in turn, support irrigation or fish farming. Other possible advantages of floods are the recharge of shallow aquifers that supply households with drinking water and the flushing of salt from the surface of areas thereby increasing soil fertility.

Also disastrous floods can have positive impacts on some people. For example, competing companies outside the flooded area may have the opportunity to increase their production and sales, farmers outside the area may enjoy the increased prices of the agricultural products and companies that sell construction materials see their sales going up. Although these benefits
may reduce the total economic flood damage, they do not alleviate the flood impacts for people in the flooded area. In the remainder of this section only negative flood impacts will be discussed.

Based on the link with the flood, direct and indirect flood impacts can be distinguished (Table 3.1). Direct flood impacts are caused by the destructive force of the water, while indirect flood impacts are impacts that result from interruption of economic and social activities (Parker et al., 1987). Examples of indirect impacts are production losses of agriculture and industry, loss of income for trade companies, shops and hotels, extra costs for transport due to flooded roads, disruption of family activities and emergency and evacuation costs.

A second distinction can be made between primary, secondary and flood-induced flood impacts depending on the location where damage has occurred. Primary flood impacts are impacts which occur in the flooded area, secondary impacts occur in other areas (e.g. loss of income of companies that sell to or buy from companies in the flooded area). Flood-induced impacts are induced by a (threatening) flood but cannot be attributed a certain area (e.g. evacuation costs or extra costs of information services).

Thirdly, tangible and intangible damage can be distinguished. Tangible damage is damage that can be expressed in monetary values, while intangible damage is damage that cannot easily be translated to an amount of money. Examples of intangible damage are damage to monuments, emotional loss of personal belongings, casualties, health and psychological damage (fear, shock, sleeplessness). Except damage to human society also damage to ecosystems might occur. This intangible damage depends on the proximity of other aquatic ecosystems in upstream reaches and tributary streams or in less-damaged relict patches. However, in natural floodplain ecosystems floods are valuable and essential.

The purpose of a damage assessment determines which damage types are relevant. Damage to small companies is counted in small-scale studies, while at regional level such damage may be unimportant due to economic transfers. Non-flooded companies in the region may have taken over production resulting in no production losses at that level. Damage to individual households, businesses or industrial plants is called ‘financial damage’, while the macro-economic effects for a country or region are indicated by the term ‘economic damage’.

Table 3.1 Negative flood impact categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Tangible</th>
<th>Intangible</th>
</tr>
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<tbody>
<tr>
<td>Primary</td>
<td>Direct: Capital loss (houses, crops, cars, factory buildings)</td>
<td>Victims, ecosystems, pollution, monuments, culture loss</td>
</tr>
<tr>
<td></td>
<td>Indirect: Production losses, income loss</td>
<td>Social disruption, emotional damage</td>
</tr>
<tr>
<td>Secondary</td>
<td>Production losses outside the flooded area, unemployment, migration, inflation</td>
<td>Emotional damage, damage to ecosystems outside the flooded area</td>
</tr>
<tr>
<td>Induced</td>
<td>Costs for relief aid</td>
<td>Evacuation stress</td>
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3.2.2 RECOVERY FROM FLOOD IMPACTS

In order to understand the ability of a system to cope with certain flood impacts, the recovery from flood impacts needs to be understood. Knowledge on recovery is essential for the quantification of resilience (see chapter 2). This section defines recovery, explains what should recover, within which period recovery should happen and when we call a system recovered. Also some examples of studies on recovery from historic events are discussed. Finally, a literature review of different frameworks that represent understandings of the recovery process is presented.

The definition of recovery in this thesis

This research studies recovery of the flood risk management system, which includes socio-economic and physical characteristics. However, especially the recovery of the socio-economic characteristics is considered important. Recovery is defined here as the return of the system from a situation in which adverse flood impacts are clearly present to a situation in which the adverse impacts of floods have been overcome. Flood risk management systems are dynamic and change in time also when no floods occur. Therefore, recovery is not defined as the return to a former situation (see chapter 2).

The time period within which recovery takes place must be a period that is relevant for society. The time-scale used is, therefore, a couple of years to at maximum the lifetime of a person. The rate of recovery is not equally distributed within a flood risk management system. Communities may recover rapidly, whereas individual households in those communities may never recover (Quarantelli, 1999). Here, we are primarily interested in the recovery of whole systems, but if clear differences between different social groups occur, these will be taken into account.

A community is considered recovered, when the main characteristics that describe welfare and human live are back to normal or even improved. These characteristics and their relevance to a community will differ in time and with cultural background. Examples of such characteristics are: the area that is dry land, living standards, employment and income levels, food status, education level, and general aspects of live such as mortality, birth, crime rates, health, alcoholism and migration. Systems that do not recover from flood impacts show permanent deterioration of the living conditions of the inhabitants. Recovery of the deaths is not possible. However, this study focuses on recovery at the level of flood risk management systems and not on the level of individuals.

It is difficult to study the recovery of systems from historic floods. Since floods along lowland rivers do normally not occur in isolated areas, it is mostly impossible to distinguish flood impacts from impacts of other events and trends such as population growth, financial crises, civil wars and diseases (Alberla-Bertrand, 1993).

Webb et al. (2000) studied recovery after the 1993 floods along the Mississippi River. They used surveys in different communities in the period 1995-1998 and found that 18% of the companies in the flooded area were doing better than before the floods, 12% were doing worse and 70% did not notice much difference. Webb et al. (2000) showed that larger companies recovered more easily than small companies. However, it is possible that also in
the absence of floods larger companies survive competition easier than small companies. They also concluded that the severity of physical damage did not determine recovery rate. Instead, recovery rate depended mostly on the recovery of neighbourhoods, critical infrastructural systems and communities surrounding the company.

Other examples of studies on recovery time relate to health effects of floods in England and Wales (Tapsell et al., 2002; Tapsell et al., 2003; RPA/FHRC, 2004). Tapsell et al. (2003) showed that floods still have significant health effects even after 4.5 years. RPA/FHRC (2004) used a combination of a qualitative and quantitative study, which included a survey of over 1000 persons in the UK, who were flooded or at risk from floods. Both the qualitative in-depth study and the quantitative study showed that a majority of people suffered from physical health effects a few weeks after the flood and that even several years after the floods the majority still suffered from emotional and psychological effects. People still check river water levels on rainy days, have sleeping problems, suffer from stress and are anxious. RPA/FHRC (2004) studied many factors that are supposed to explain which people are more vulnerable to health effects than others such as the fact whether they were single parents, immigrants, had prior health problems, were non-English speaking persons, elderly, financial deprived etc. However, not one variable could explain the results and by combining different variables no clear explanations were found either. There seemed to be a relation with gender, flood event severity and age: the persons above 65 seemed to be less vulnerable psychologically, and women seemed to be more vulnerable. Furthermore, a strong relation between stress of the affected persons and treatment by insurance companies and builders was found. The research clearly showed that recovery is complex and that the recovery process differs for each person and family.

Understanding recovery
In literature on coping with disasters and recovery from disasters, two main visions can be distinguished. In the first one disasters and recovery from those disasters are seen as isolated phenomena, while in the second one both the disaster and the recovery afterwards are seen as part of ongoing societal processes. These two visions are presented in this section. Because the second one is important for the remainder of the chapter, it is discussed more intensively.

The first vision in which disasters are considered as isolated phenomena with more or less well-marked beginnings and ends was popular in the eighties (see amongst others Bolin, 1982; Drabek, 1986; Friesma et al., 1979; LaPlante 1988; Rubin et al., 1985). These authors generally describe the recovery process in sequential phases:

- Emergency phase: a period of high consensus in community, altruistic behaviour aimed at preventing or reducing human suffering;
- Restoration phase: a period in which actions are undertaken to return to the pre-disaster situation;
- Development phase: in this phase plans are implemented to improve the situation to prevent or mitigate the effects of new floods.

Although the context can be different, these phases are supposed to occur everywhere. This approach is used for planning relief and aid. It does not aim at explaining differences in recovery rate or at understanding recovery rates. This model is widely employed by researchers, but it is not universally accepted. In farming villages in the third world, recovery
may be interrupted by periods in which there is a high demand for agricultural labour (Cuny, 1983). Recovery at family level involves more phases: emotional recovery, housing recovery, and quality of life recovery (Bolin, 1982). Furthermore, recovery is complex and does not follow an orderly pattern, which is overlooked in this approach. A community might appear to be recovering but it could contain many families that are not recovering and may never do so.

In the 1990ties a new vision on disasters and recovery became popular. In this second vision disasters are no longer seen as events that suddenly interrupt society, but as a part of already ongoing societal processes. This means that by studying society already some information on the possibility that floods or other hazards could result in disasters, and on recovery from those disasters can be obtained.

In this approach the concept of vulnerability is important. Vulnerability to floods depends on susceptibility to negative flood impacts and recovery from those impacts. Literature on vulnerability and vulnerability assessments can thus be used as a source of information on recovery. Vulnerability literature often focuses on household level. Recovery of a household depends among others on the pre-flood financial situation: ‘Was the household just surviving or did it have financial reserves?’ Different households with the same composition and financial state may still recover differently due to e.g. a different ability of earning an income during and after the flood. Even if all economic conditions are equal, then differences due to prior health and stress and due to personality, skills, education and being part of a social network may still cause differences in recovery rate.

Many researchers have tried to clarify all these factors and to develop a framework that represents their understanding of vulnerability processes. Two important frameworks for understanding and reducing vulnerability to disasters were developed in the late 1980s and early 1990s. The first one is the Capacities and Vulnerabilities Analysis (Anderson & Woodrow 1989/1998) and the second one is the Pressure and Release/Access Models (Blaikie et al., 1994). Recently, the Sustainable Livelihood (SL) approach has become popular (Twigg, 2001). The vulnerability frameworks and the SL approach are briefly discussed here. The models primarily are tools for explaining vulnerability, not for measuring it.

The basis of the Capacities and Vulnerability Analysis (CVA) framework is a simple matrix for viewing people’s vulnerabilities and capacities in three broad interrelated areas (Anderson & Woodrow, 1999):

- Physical/material: This area includes factors as climate, environment, health, skills and labour, infrastructure, housing, finance and technologies. These factors determine what made the people affected by disaster physically vulnerable: was it their economic activities (e.g. farmers cannot plant because of floods), geographic location or poverty/lack of resources?
- Social/organizational: This area includes formal political structures and informal systems through which people get things done. To explore this aspect the question: ‘What was the social structure before the disaster and how well served it the people when disaster struck?’ has to be answered.
- Motivational/attitudinal: This area contains factors that describe how people in society view themselves and their ability to affect their environment.
CVA does not provide indicators of vulnerabilities and capacities. It is just an overarching framework.

The Pressure and Release/Access Models (Blaikie et al., 1994) are even more conceptual than CVA. The first component, PAR, proposes a progression of vulnerability with three main levels:

- Root causes: The root causes are the most remote influences such as economic, demographic and political process within society. They reflect the distribution of power in a society and are connected to the functioning and power of the state. These causes form the context in which disasters occur.
- Dynamic pressures: These pressures channel the root causes into particular forms of insecurity that has to be considered in relation to the types of hazards facing vulnerable people. These include reduced access to resources as a result of the way regional or global pressures work through on local level. Examples of this reduced access are: lack of local institutions, press freedom, local markets, rapid population growth, debt repayment schedules and deforestation.
- Unsafe conditions: The specific forms in which a population’s vulnerability is expressed in time and space in conjunction with a hazard. Examples are: dangerous locations, fragile local economy, special groups at risk and lack of disaster preparedness.

The second linked component is the Access Model that attempts to show how unsafe conditions arise in relation to the economic and political processes that allocate assets, income and other resources in society. Access involves the ability of an individual, family, group, class or community to use resources to secure a livelihood. For a comprehensive overview of this framework reference is made to Blaikie et al. (1994).

The Sustainable Livelihood Approach starts from a developmental point of view and puts livelihoods at the centre of discussion. A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future (DFID 1999/2000). The livelihoods approach is holistic, recognizing that there is a multitude of actors, influences, livelihood strategies and outcomes. It also recognizes that livelihoods and the forces that influence them are dynamic. It tries to bridge the gap between micro- and macro-level factors and actions. The SL framework of DFID defines a vulnerability context in which people live their lives and livelihood assets that they possess and transforming structures & processes. These three together and the interactions between them force people to chose certain livelihood strategies that lead to livelihood outcomes (Twigg, 2001). The DFID (1999-2000) model breaks assets (capital) into five categories:

1. Human Capital: Skill, knowledge, ability to labour, good health;
2. Social Capital: The social resources upon which people draw in pursuit of livelihood objectives (e.g. networks and connections, membership of groups, relationships of trust);
3. Natural Capital: The natural resource stocks from which resource flows and services are derived;
4. Physical Capital: The basic infrastructure and producer goods needed to support livelihoods. Infrastructure components include affordable transport, secure shelter, adequate water supplies and sanitation, access to information. Producer goods are the tools and equipment that people use to function more productively;

5. Financial Capital: Savings and credit, inflow of money other than earned income.

These frameworks make clear that the recovery rate of a society depends on many factors, which are categorised differently in the different frameworks. The context in which the floods occur is important. This context is incorporated in the PAR model (Blaikie et al., 1994), in the social/organizational factors of the CVA approach and in the ‘vulnerability context’ of the SL approach. Furthermore, the pre-flood financial situation of the households and the way the income generating activity is affected by floods determines recovery rate (see Physical/material factors of the CVA method; Access model of Blaikie et al., (1994); and Capitals and livelihood strategies of the SL approach). Not only finances, but also health, abilities and skills of individual households are relevant (see Motivational/attitudinal factors of the CVA method; Capital of the SL approach; the access model of Blaikie et al. (1994)). Furthermore, a relevant physical factor (CVA approach) for flood recovery is flood duration. However, these frameworks do not indicate how vulnerability or recovery can be measured or quantified. They also do not indicate whether the different capitals and other factors and processes are of the same importance or can be substituted by each other or whether a household needs all types of capital. The understanding of recovery incorporated in these frameworks is used to develop indicators in section 3.4.

3.3 TOWARDS INDICATORS

3.3.1 INDICATOR REQUIREMENTS

Quantifying resilience of complex dynamic flood risk management systems requires the use of indicators. A direct measurement of flood impacts and recovery rates is usually impossible, because the necessary data lack and because it is not quite clear what to measure (see section 3.1).

Indicators give a summary of a very complex behaviour of a system or of the effects of a strategy or plan. In general, indicators should be meaningful, understandable, quantifiable and unambiguous. Specifically for the quantification of resilience of flood risk management systems, we defined the following requirements:

- The resilience indicators must be applicable in all lowland rivers: in regulated and natural rivers, in ‘developed’ as well as in developing countries, and on regional and (supra) national scale. Therefore, their applicability should not be limited to specific lowland river types such as canalised rivers, or to specific countries such as the Netherlands.
- All measures and changes in a system that affect the reaction of the system to flood waves should influence the value of the indicators, no matter whether they influence overall flood impacts, the graduality of the reaction to increasing flood waves, or recovery from floods.
The indicators should allow the ex-ante evaluation of different strategies for flood risk management. Therefore, they should not require measured data on flood impacts, but should be able to rely on synthetic data or estimates as well.

These requirements will be used in the next section to evaluate existing indicators.

### 3.3.2 Existing Resilience Indicators for Flood Risk Management

Several attempts to find indicators for resilience in the context of flood risk management of the lowland rivers in the Netherlands have already been made (Klijn & Marchand, 2000; Remmelzwaal & Vroon, 2000; Termes et al., 1999). In order to understand them it must be known that the Netherlands’ rivers are characterised by two important discharge capacities:

- **Bankfull discharge**, which is the discharge capacity of the main channel. This main channel is separated from the remaining river bed by low embankments. This bankfull discharge capacity is exceeded one or more times every winter.
- **Design discharge**, which is the discharge for which the primary embankments of the river bed are designed. This design discharge of the Dutch rivers is the discharge with an annual probability of 1/1250.

The proposed indicators for resilience for the Netherlands’ rivers and the adjacent flood-prone area are:

1. The slope close to the design discharge of the curve that represents the relationship between the discharge and the water level in the river branches (Klijn & Marchand, 2000).
2. The area flooded when the design discharge passes in proportion to the area of the main channel during bankfull discharge (Klijn & Marchand, 2000; Termes et al., 1999).
3. The water level at design discharge minus the height of the protected area (Termes et al., 1999).

These indicators are all based on the assumptions that resilience is a function of the damage that occurs and that damage is primarily a function of the water level in the river. The higher the water level in the river, the higher the damage will be when an embankment breaks. When damage is higher, recovery will last longer and therefore, resilience is assumed to be lower. In the Netherlands, where these indicators were designed, these assumptions may be valid. However, they are very simplified, as is already indicated by the authors. Not only damage, but also graduality of the reaction to increasing flood waves and recovery rate describe the reaction to flood waves of a system. Furthermore, damage does not only depend on the water level in the river, but also on land use, warning time, preparedness of the inhabitants, and many other factors. If the indicators mentioned above are used, measures influencing other aspects than water depth in the river are not reflected by changing indicator values. Another disadvantage of these indicators is that they can only be used for diked rivers with a certain design discharge. Moreover, these indicators do not consider discharges above the design discharge that are supposed to cause floods in the Netherlands. Therefore, new or additional indicators are required.
3.4 NEW INDICATORS FOR RESILIENCE AND RESISTANCE

3.4.1 REACTION INDICATORS AS RESILIENCE INDICATORS

As explained in the introduction of this chapter, resilience and resistance reflect the reaction of a system to disturbances. For an adequate and comprehensive quantification of resilience, therefore, indicators are required for all three aspects that describe a system’s reaction to floods: amplitude of the reaction, graduality of the increase of reaction with increasing discharges and recovery rate from flood impacts. The indicators that describe these aspects are thus reaction indicators: they describe the system’s reaction. However, since the reaction of the system reveals the system’s resilience and resistance, these indicators indicate also the system’s resilience. They will, therefore, be referred to as resilience indicators in the text. The newly proposed indicators are discussed in the following subsections.

The resistance of the system is described by the reaction threshold. It can be quantified by the recurrence time of the highest discharge that is not expected to cause floods within the system. An approximation of this discharge for diked rivers is the design discharge.

3.4.2 AMPLITUDE OF THE REACTION OF THE SYSTEM TO FLOOD WAVES

The amplitude of the reaction to flood waves indicates the magnitude of the expected impact resulting from a certain flood wave immediately after a flood has occurred (see chapter 2). This section first provides a brief overview of methods to quantify primary direct tangible and intangible flood impacts. Next, the proposed indicators are discussed.

Methods to quantify primary direct tangible damage

Primary impacts are included in most damage assessments. A frequently used method to estimate these impacts is the unit loss model method (Parker et al., 1987; Vrisou van Eck et al., 1999; WL | Delft Hydraulics, 1999). In this method, also called micro-scale damage assessment, the potential damage per unit is determined by using relationships between flood parameters such as flood depth and the damage for these units. The units are, for example, land use types or properties (Penning-Rossell & Green, 2000). Unit loss models require detailed information of land-use units, ground floor heights and flood levels of floods of different magnitude (Penning-Rossell & Green, 2000). Next to primary direct and indirect damage, the method can also be used to calculate the potential number of casualties or the number of people at risk. Because the unit-loss method requires much detailed data and addresses mainly direct damage, it is less suitable for modelling the impact of extensive floods with a large impact. Unit loss models cannot adequately address the linkage effects within an economy; these need to be addressed at macro level.

Factors that determine primary damage on micro scale are:

- Physical factors such as: maximum flood depth and flow velocity, rate of water depth rise, flood duration, sediment carried, wind, temperature, season, water quality;
• Socio-economic factors such as: number of inhabitants, land use or economic value of the area, warning period in advance of the flooding; preparation of the people and experience with floods; behaviour of people;
• Ecological factors such as: type of ecosystems, shelters/availability of higher locations.

Usually, not all these factors are incorporated in a damage assessment. In the Standard Dutch Damage Module, for example, (Vrisou van Eck et al., 1999), the maximum flood depth, flow velocity, the occurrence of extra wind waves due to storm, and the land use are incorporated. The ecological factors are neglected. Preparation, behaviour of people, season and temperature are all incorporated indirectly by assuming values that are generally valid in the Netherlands.

Assessment of intangible impacts
Intangible impacts are by definition very difficult to quantify, because they are subjective. The importance of these impacts is subject of much discussion. To quantify intangible impacts different methods exist, such as the Hedonic Price Method, the Contingent Value Method and the 'Indicator Method'.

The Hedonic Price Method presumes that land and property markets incorporate the existence of site-related natural hazards, such as floods, which is expressed in reduced prices. All individually born effects of flooding can be approximated as the difference between the value of flood-prone properties and that of the comparable flood free properties. In this way the prices of land and property incorporate both tangible and intangible factors. This approach has been applied in a few academic earthquake studies (Brookshire et al., 1985) but no application of the method for floods is known.

The non-property based approach attempts to directly measure the effects of flooding and the benefits from flood damage reduction through survey, or direct elicitation of a bid of the non-market commodity. This method is also called the Contingent Value Method (CVM) and is based on the 'willingness to pay' principle. Although the approach has been widely used in the area of outdoor recreation and the environment, it has very limited application for flooding (Thunburg, 1988).

There are also methods that use indicators to quantify the intangible damage. For example, Waterloopkundig Laboratorium (1994b) assumes that the flood impacts on the well-being of people correlate with the severity of the material damage. This might be correct when different floods in one area and one time period are compared, but for a comparison of different systems or floods in different decades this relationship will not hold. After all, the loss of a house will not necessarily be twice as terrible when the house was twice as expensive. Other examples of relationships are relationships between the number of affected persons or the number of casualties and total suffering. These numbers can all be measured. However, these numbers still require a weighing method when they need to be compared with tangible damage.

For this research a method that relates peak discharge levels or flood wave magnitudes with intangible impact severity is needed. Since the Hedonic Price Method and the Contingent
Value Method do not provide such relationships they are not applicable in this research. Therefore, the indicator method is used. In this research only intangible damage such as stress, grieve, fear and other personal stress is incorporated. The severity of this type of stress is assumed to correlate with the number of affected people and the number of casualties in the flooded area. Other intangible damage types, such as damage to ecosystems and to monuments are neglected.

**Proposed indicators**

To describe the severity of the reaction of a system to a whole regime of flood waves by only one number, the *expected annual damage (EAD)* is proposed. In the EAD the amplitudes or flood impacts resulting from ‘all’ flood waves can be summed by using their probability as weighing criterion. A disadvantage of the use of the EAD as indicator for the amplitude is related to the fact that the EAD is not only affected by flood impacts, but also by flood probabilities. The EAD will decrease when flood probabilities of the system as a whole are reduced. This reduction of flood probabilities, however, does not result in an increase of the system’s resilience. Therefore, it is necessary to consider this indicator together with the indicators for the other aspects of reactions when the resilience of a system or a strategy is assessed. It is very unlikely that a strategy may be found which reduces flood probabilities of the system, without affecting the graduality of the increase of reaction with increasing discharges. Consequently, confusion can be avoided by studying both aspects together.

In order to calculate the expected annual damage the relationship between all possible flood waves, their probabilities of occurrence and the corresponding impacts must be determined. However, as knowledge on flood wave probabilities often lacks, discharge level probabilities combined with a sensible wave form may have to be used instead of flood wave probabilities. Also relationships between waveforms and peak levels can be used, but they are very uncertain and show a large variety (WL | Delft Hydraulics, 2000). Another difficulty in the consideration of all possible flood waves is that the maximum possible discharge is mostly not known. To be able to compare different river systems the considered flood wave range is limited to the discharges between the highest discharge with zero damage and the once in 10,000 years discharge. These boundaries include the most relevant flood waves.

Based on the information above three indicators for amplitude are proposed: the expected annual tangible damage (equation 3.1) the expected annual number of affected persons and the expected annual number of casualties (equation 3.2 and 3.3). ‘Casualty’ refers here to someone who has died due to a flood.

\[
EAD = \int_{P(D=0)}^{P(D=0)} PD(P) dP \quad \text{(Eq. 3.1)}
\]

\[
EANAP = \int_{P(D=0)}^{P(D=0)} PA(P) dP \quad \text{(Eq. 3.2)}
\]

\[
EANC = \int_{P(D=0)}^{P(D=0)} PC(P) dP \quad \text{(Eq. 3.3)}
\]
Quantifying resilience

With:

EAD = expected average damage per year ($/year)
EANAP = expected average number of affected persons per year (number/year)
EANC = expected average number of casualties per year (number/year)
P = annual flood probability
D(P) = expected damage as function of probability ($)
A(P) = number of affected persons as function of probability (number of persons)
C(P) = number of casualties as function of probability (number of casualties)

These indicators for the amplitude imply an unambiguous relationship between flood waves and the resulting impacts. As explained in the beginning of this section, there are, however, apart from the magnitude of the flood wave different other factors which also determine flood damage. Examples are the season when the flood occurs, water quality, temperature, land use and experience with floods. In this research these factors are considered in the system’s analysis and in the assessment of the damage that is expected to result from certain flood waves (see the case studies in chapter 4 to 7). However, some factors, such as whether an embankment breaches during day or night time, the rainfall pattern which may influence the distribution of crops over an area, the presence of storm during a flood, and the coincidence of floods with special events (national holidays, elections) make the relationship between flood waves and the resulting impacts ambiguous. By trying to consider averages and by studying the whole flood regime, however, the impact of those factors is expected to be small. This assumption will have to be reconsidered in the case studies in chapters 4 to 7.

3.4.3 Graduality

The second aspect, graduality, indicates the damage increase with increasingly large flood waves. This increase is not constant, but shows discontinuities where a small discharge increase causes a large increase in damage. This happens, for example, when an embankment breaks. The slope of the discharge-damage relationship can be regarded as an indicator for graduality. However, since the slope of this curve will not be uniform it is difficult to characterise it with only one number. The minimum value will always be zero (if the water depth increases but damage does not) and the maximum will approach infinity (if the damage increases enormously, due to an extremely small discharge increase). The maximum and minimum slopes are therefore not representative for the whole discharge regime. The average slope is determined only by the maximum damage and does not contain any information on graduality of the curve. Furthermore, the resulting value for the slope depends on the absolute level of damage and discharge, which means that different rivers are not easily compared. To overcome these disadvantages different indicators that quantify the graduality of the discharge-damage relationship were evaluated as described in the textbox below.

Based on the evaluation described in the textbox below the indicator as expressed in equation 3.4 was selected. To calculate the graduality as defined in equation 3.4, first the damages and discharges are expressed as a percentage of their range. For example, if discharges between 5,000 and 20,000 m$^3$/s are considered, a discharge of 15,000 m$^3$/s has a relative value of 67%. By using percentages, different river systems become comparable. Secondly, the whole
discharge regime is discretised into small ranges (e.g. discharge with a recurrence time of 1 to 5 years, recurrence time of 5 to 25 years, from 25 to 100 years, etc.). The indicator is not very sensitive to the chosen ranges as long as they are chosen in such a way that important discontinuities, for example, discharges which are expected to cause an embankment breach, are incorporated. Thirdly, the relative increase in discharge in the range considered is compared with the relative increase in damage and the results are summed. The maximum total difference lies around 200 and occurs when the discharge increases with 100 % and no damage increase occurs and damage increases with 100 % while the discharge increases only very little. The sum of the differences is thus divided by 200, to obtain a value between 0 and 1. Figure 3.1 shows two curves made in the progress of calculating the graduality. They are based on the curves in figure 2.1. In the right-hand side picture the dots corresponding with the resistant system lie clearly further from the diagonal than the dots corresponding with the resilient system.

Graduality = \[1 - \frac{\sum_{n=1}^{N} |\Delta Q_n' - \Delta D_n'|}{200}\] (Eq. 3.4)

With:

\[\Delta Q_n' = Q_n' - Q_{n-1}' = \frac{100*(Q_n - Q_{\min})}{Q_{\max} - Q_{\min}} - \frac{100*(Q_{n-1} - Q_{\min})}{Q_{\max} - Q_{\min}}\]

\[\Delta D_n' = D_n' - D_{n-1}' = \frac{100*(D_n - D_{\min})}{D_{\max} - D_{\min}} - \frac{100*(D_{n-1} - D_{\min})}{D_{\max} - D_{\min}}\]

\(Q'\) = relative discharge (%), \(Q\) = discharge (m³/s),
\(Q_{\max} = Q (P = 1/10000), Q_{\min} = \) once a year discharge
\(D'\) = relative damage (%), \(D\) = damage (M€) as a function of \(Q\), \(D_{\max} = D(Q_{\max}), D_{\min} = 0\)
\(n\) = ranking number of the discharge level

Figure 3.1 Discharge and damage increase in percentages (left) and the relative damage and discharge increase per step (right) (The graduality of the resistance curve is 0, of the resilience curve 0.91 and of the combination 0.7)
The resilience indicator for graduality

Four different options for the graduality indicator were studied:
1. The slope \(\frac{dD}{dQ}\) \((D = \text{damage and } Q = \text{discharge level})\);
2. The width of the discharge range in which most damage increase occurs;
3. The adapted Gini-coefficient;
4. The average difference of the increase rate of damage and discharge.

The first three are discussed in this textbox, the fourth in the main text.

1. Slope: \(dD/dQ\)

The slope \(dD/dQ\) is difficult to express by only one number because it is not uniform (see main text). The slope of a certain part of the curve, e.g. from \(T= 10\) to \(T = 100\) years could be used. However, this is a very arbitrary choice.

2. The part of the discharge range in which most damage increase occurs

To calculate this indicator the damage is calculated in percentages:

\[
\text{Graduality} = \frac{\text{Discharge range in which 50\% of the damage increase occurs (25\% to 75\%)}}{\text{Total discharge range}}
\]

The indicator is intuitively correct: The wider the discharge range in which most damage increase occurs, the more gradual the damage increase probably is. In diked systems where embankments break when they are overtopped, the value for this indicator will be very small. If damage increases gradually with discharge, the value for the indicator will be much higher. A disadvantage of the indicator is that the choice for the thresholds of 25\% of the maximal damage and 75\% of the maximal damage is arbitrary.

3. Adapted Gini coefficient

The Gini-coefficient is an indicator for income equity used by the CIA (2004). This coefficient gives an indication of the deviation of a curve, which occurs when all inhabitants of a country have an equal income. If one person earns all income, the coefficient is one and when everybody earns exactly the same, the coefficient has the value zero. This Gini-coefficient can be adapted to make it applicable for the measurement of graduality. The discharges and damages should then be expressed in percentages. When the relative increase of damage occurs linearly with the relative increase of discharges the slope of the curve will be 45 degrees and the graduality coefficient 1. This is called the ideal slope since it does not contain sudden discontinuities that might cause disasters. All deviations from this slope give an indication of graduality. If all damage would occur in the last 1\% of the discharges considered, the graduality is zero. A problem with this indicator is that if the system does not react to low discharges, then also the deviation of the higher values will be affected.

\[
Q' = \frac{100* (Q - Q_{\text{min}})}{Q_{\text{max}} - Q_{\text{min}}} \quad D' = \frac{100* (D - D_{\text{min}})}{D_{\text{max}} - D_{\text{min}}}
\]

With:
- \(G = \text{graduality} (-)\),
- \(Q = \text{discharge (m3/s)}\), \(Q_{\text{max}} = Q\) where \(P = 1/10000\), \(Q_{\text{min}} = \text{the once a year discharge}\),
- \(D = \text{damage (M€) as a function of } Q\), \(D_{\text{max}} = D(Q_{\text{max}}), D_{\text{min}} = D(Q_{\text{min}})\)
- \(Q' = \text{relative discharge (\%)}\), \(D' = \text{relative damage (\%)}\)
3.4.4 RECOVERY RATE

The third aspect, recovery rate, describes the rate of return from a state where flood impacts are visible to a normal state. This normal state or situation is comparable with or even ‘better’ than a situation that would have been there, if no floods had occurred. Because differences in recovery rate will occur between different social groups and different locations and because the recovery rate also depends on relations with neighbouring areas, recovery rate is difficult to quantify (see section 3.2).

Primary indirect and secondary flood impacts

Recovery rate is associated with the speed of reconstruction and with the occurrence and duration of indirect and secondary impacts. Therefore, it would be logical to try to calculate indirect and secondary impacts in order to determine recovery rate. Indirect and secondary economic flood losses can be assessed with input-output models, regional econometric models and statistics-based approaches.

Input-output models consider the economy as a network of series of connected activities or nodes between which flow goods, people and information. Each activity must have inputs of materials, labour and so on to function. In turn each activity produces goods, services and waste products. These inputs and outputs are conveyed to and from all nodes of activity along linkages, which are themselves specialised. These comprise, for example, roads, power lines and telecommunication lines (Parker et al., 1987). A flood may either cut and interrupt some of these linkages or affect one or more of the facilities which house the activities or both. The extent of the consequences of such an interruption is determined by the dependence of the remaining linkages and facilities on the interrupted ones. If there is enough redundancy and transferability in the network, the consequences will be small (Cochrane, 1981; Islam, 2000; Higgings, 1981; Parker et al., 1987; Pate, 1980a, Pate, 1980b, Rose, 1982). Floods will first cause a decrease of production due to damage to facilities. This decrease in production leads to a decline in investment and thus in a further decrease of production. This is called a multiplier effect. The recovery activities, on the other hand, increase expenditure on materials for repair and restoration and thus enhance the level of output and investment, which have positive multiplier effects (Islam, 2000).

Next to input-output models also regional econometric models can be used to study the long-term effects of disasters Ellson et al., 1984; Kwashima & Kanoh, 1990; Higgings & Robinson, 1982). Econometric models contain a set of equations, which relate economic indicators such as: population, employment, income, and industrial production. To be able to estimate flood impacts these models need to be supply-side-oriented and not demand-oriented, which is more common. Furthermore, they should be spatially disaggregated. Most importantly, the model must be made in such a way that the assumptions on which it is based are still valid during and after a flood.

A third method to assess flood impacts is by studying trends in time series data over a reasonably long period (Parker, 2000). Data that can be used are GNP, indebtedness, balance of trade (projected changes in exports, tourism and services and also in imports and payments for external services), average household income, inflation and employment levels (ECLAC,
1991; Jones & Chang, 1995). The comparison of data should be one of with and without a disaster and not before and after a disaster, which may involve some difficulties.

The first two methods (input-output and regional econometric models) are neither standardised nor widely applied (Blaikie et al., 1994; Cochrane, 1974; Du Plessis & Viljoen, 1999; Ellson et al., 1984; Islam, 2000; Jones & Chang, 1995; Olsen et al., 1998; Parker et al., 1987; Parker, 2000). The models are difficult to develop and require huge efforts to keep them up to date. The greater the impact of a flood on the economic system, the more difficult the analysis of secondary aspects is, since the effects will be non-marginal and may affect the assumptions underlying the models (Green, 2003c). Besides, the models must be validated with the help of real data and, therefore, they are not applicable to systems without recent floods and for strategies that involve significant changes in the system. The third method (studying time series) is not useful in this research, because in most countries GDP, employment levels, migration and other relevant data are highly variable and not only determined by disasters but also by politics, wars, economic recessions and certain dramatic events (e.g. the death of Ghandi in India and the terrorist attacks of 11-9-2001 globally). Furthermore, these economic indicators are mostly not determined on the scale of the flooded area, because this area forms no separate economic system. This method can only be used to assess impacts of past floods and not to assess potential flood impacts resulting from new strategies. Therefore, these methods are considered not useful to quantify recovery rate in this research.

Assessment of the recovery capacity
Instead of measuring recovery or estimating secondary flood impacts, the recovery capacity of a system is assessed here by studying general system properties that influence recovery rate. This is a qualitative approach that enables the incorporation of many system characteristics without very detailed social and economic studies. However, it does allow available studies to be used. Recovery capacity assessment can be considered part of vulnerability assessments as carried out in social science (see section 3.2.3). Vulnerability depends on the susceptibility to negative flood impacts and the recovery rate. Because the potential direct effect of the flood wave (the primary damage) is already incorporated in the amplitude aspect, this research uses only those vulnerability factors that determine recovery rate and not those that describe a system’s susceptibility for negative flood impacts. In this research recovery rate is assessed based on knowledge of the already existing frameworks CVA, the Pressure and Release/Access model and the sustainable livelihood approach (see section 3.3.2). Based on this knowledge a simplified qualitative framework was developed that enables the assessment of a system’s recovery capacity. The higher the recovery capacity, the faster a system will recover.

The recovery capacity of a flood risk management system is assumed to depend on physical, economic and social factors (Figure 3.2). The division between the three groups has similarities with the capitals as described in the vulnerability frameworks and SL approach in section 3.2.
Chapter 3

Figure 3.2 Factors that determine recovery capacity

The physical factors determine after how much time the floodwater will be gone and when the usually dry area is not inundated anymore. In a sloping environment water will flow out by gravity. In a polder, a part of the water may have to be pumped out of the area. This will cost more time and money (Table 3.2).

<table>
<thead>
<tr>
<th>Value</th>
<th>Very low (1/2)</th>
<th>Low (3/4)</th>
<th>Medium (5/6)</th>
<th>High (7/8)</th>
<th>Very high (9/10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood duration</td>
<td>Not drying again</td>
<td>&gt; than 3 months</td>
<td>2 to 3 months</td>
<td>1 to 2 months</td>
<td>Less than 1 to 1.5 month</td>
</tr>
<tr>
<td>Relief</td>
<td>Very low area, no outlet structure, river bed &gt; ground level</td>
<td>Much water has to be pumped out by emergency pumps</td>
<td>A part of the water will flow out by gravity, part has to be pumped out</td>
<td>Much water is flowing out of the area by gravity</td>
<td>Flooding is beneficial / small flooded area / outflow by gravity</td>
</tr>
</tbody>
</table>

The economic factors determine the ability to get hold of enough money for repair and reconstruction, and of returning to pre-disaster or even improved living conditions, as well as to prevent further spreading of effects (Table 3.3). People with less income, savings or insurance or with high debts are less capable of recovery (Anderson & Woodrow, 1989; Buckle et al., 2001; Blaikie et al., 1994; Penning-Rowsell & Fordham, 1994). If assets required to generate income are gone, they have to be replaced quickly. The purchase of new replacing cattle, tools, or seedlings or other essential assets is clearly easier for families with savings or insurance. Links with other areas determine the access and speed of assistance, aid funds and the spreading of flood impacts (Du Plessis & Viljoen, 1999; Penning-Rowsell & Fordham, 1994). To estimate spreading of secondary impacts the crucial lines and facilities have to be analysed. Crucial lines for transport, electricity, telephone lines or water supply, do not only cause spreading of effects, they are also essential for a fast recovery of households and companies in the flooded area (Webb et al., 2000). If a community can be reached by multiple roads or if boats are quickly available, help can be expected quicker than if the community is only accessible by one flood-prone road. Since in the latter case people in the
flooded community have difficulties at going to work, recovery will be hampered. In Manila, for example, floods may result in the absence of public transport, which makes people unable to go to their jobs in other parts of the city (Zoleta-Nantes, 2000). In western countries, most companies cannot function at all without electricity and telephones which indicates the relevance of these lines to recovery.

Table 3.3 Economic factors that influence recovery

<table>
<thead>
<tr>
<th>Value</th>
<th>Very low (1/2)</th>
<th>Low (3/4)</th>
<th>Medium (5/6)</th>
<th>High (7/8)</th>
<th>Very high (9/10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial situation before flood: Income level/debts/savings, effect flood on income</td>
<td>Nutrition status bad, debts high, not survivable on long term, no insurance</td>
<td>Nutrition OK, high debt, no sufficient savings, just surviving, no insurance</td>
<td>Life OK before flood, payable debt, insufficient savings, income affected only during floods, no insurance</td>
<td>Nutrition OK, savings for part of reconstruction, payable debts, income after flood, insurance or governmental aid</td>
<td>Sufficient savings for fast recovery, income not affected, insurance or governmental aid</td>
</tr>
<tr>
<td>Aid from other areas</td>
<td>No aid expected</td>
<td>Aid for some basic needs is expected</td>
<td>Aid for part of reconstruction is expected</td>
<td>Funds to restore majority of assets arrive quickly</td>
<td>Aid arrives quickly and covers all restoration costs</td>
</tr>
<tr>
<td>Spreading of impacts to other areas</td>
<td>Spreading of effects unavoidable</td>
<td>Spreading of effects occurs</td>
<td>Effects in non-flooded areas occur but effects are not significant</td>
<td>No spreading (links are damaged, but quickly repaired)</td>
<td>No spreading, links to other regions are intact or not relevant</td>
</tr>
</tbody>
</table>

Social factors that determine the ability to organize reconstruction and get access to funds and information are first of all related to the context in which the flood occurs (Table 3.4). Examples of such factors are: political structure, trust in the government, and equity in society (Parker, 2000). A cohesive society will be able to recover more quickly, whereas a community where there is little inter-group contact will be less likely to be able to cope (Anderson & Woodrow 1989; Blaikie et al., 1994; Penning-Roswell & Fordham, 1994). Winchester (2000) shows how rich large land owners in the Andra Padresh region in India in the period 1978-1985 recovered quickly from floods and were not affected on the long term, while their poor landless neighbours did not even recover. Winchester described that the richer people organised themselves in groups, they formed alliances with banks, irrigation district managers and politicians and had access to funds, influenced regulations and investments in the region and received flood damage compensations. Their poor landless neighbours were not organised, did receive less information, could not get loans and became poorer due to the floods. This example shows the relevance of unity, social structures, and the importance of being part of such a network. Processes that (temporarily) disturb social structure and unity and bring people in dangerous situations and thus hamper recovery are other disasters and war (Parker, 2000). The Nile flood in 1988 in Khartoum in Sudan is an example of a case in which war aggravated flood impacts and reduced recovery rate. Those most severely affected were the millions who were already refugees from civil war and famine in the south of Sudan. Many of these refugees had settled in low-lying flood prone
lands around the city where they were highly vulnerable to epidemic disease and to flooding. They were less organised than they were before they were refugees and they did not have the right connections to achieve fast help and assistance (Abu Sin & Damvies, 1991).

A second group of social factors is related to awareness, preparedness and efficient emergency management. These factors not only reduce flood impacts but also increase recovery rate, because they prevent shock, casualties, panic and reduce stress. Information on what to do and where to go, where to apply for help, a clear distribution of responsibilities, and good cooperation between different organizations and stakeholders enhances recovery.

The third group of social factors that influence recovery are the individual factors (also called human capital), e.g. health and education level or skills. Among healthy persons epidemics and diseases will less easily occur and they can more easily arrange and execute reconstruction activities. People who can read and understand bureaucratic procedures recover more quickly. Skilled people find alternative employment more easily (Anderson & Woodrow, 1998; Blaikie et al., 1994; Buckle et al., 2001; Penning-Rossvell & Fordham, 1994). Potentially vulnerable groups are single-parent families, disabled people, elderly people and children, and minorities, tourists or travellers. Furthermore, personality and attitude influence the recovery rate of individuals (Anderson & Woodrow 1989/1998; Blaikie et al., 1994; Buckle et al., 2001).

Table 3.4 The social factors that influence recovery

<table>
<thead>
<tr>
<th>Value</th>
<th>Very low (1/2)</th>
<th>Low (3/4)</th>
<th>Medium (5/6)</th>
<th>High (7/8)</th>
<th>Very high (9/10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social Capital:</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Socio-political system,</td>
<td></td>
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</tr>
<tr>
<td>equity*, unity, access to</td>
<td></td>
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<tr>
<td>services, strength of</td>
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</tr>
<tr>
<td>social structures</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>No trust in government,</td>
<td></td>
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<tr>
<td>corruption high, equity &gt;</td>
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<tr>
<td>55, access only for elite,</td>
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<tr>
<td>low level of social</td>
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<td>structures</td>
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<tr>
<td>Little trust in government,</td>
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<tr>
<td>corruption, equity &gt; 45,</td>
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<tr>
<td>no unity, low level of</td>
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<td>social structures</td>
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<td>Trust in government,</td>
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<tr>
<td>low level of corruption,</td>
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<tr>
<td>equity &gt; 40, social</td>
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<tr>
<td>organisations exist</td>
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<tr>
<td>Trust in government,</td>
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<tr>
<td>corruption low, equity &gt;</td>
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<tr>
<td>35, majority has access to</td>
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<td>services, high level of</td>
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<td>organisation</td>
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<tr>
<td>Preparation to and</td>
<td></td>
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<tr>
<td>awareness of flood risks,</td>
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<tr>
<td>emergency management</td>
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<tr>
<td>People and government did</td>
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<tr>
<td>not know flood threat, no</td>
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<tr>
<td>warning system</td>
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<tr>
<td>No emergency plan, no</td>
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<tr>
<td>warnings, no knowledge on</td>
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<tr>
<td>what to do</td>
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<tr>
<td>Flood threat is known,</td>
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<tr>
<td>there is an emergency</td>
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<td>procedure or warning</td>
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<tr>
<td>system</td>
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<tr>
<td>Emergency procedure is</td>
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<tr>
<td>known to local authorities,</td>
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<tr>
<td>warning system, people</td>
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<tr>
<td>know what to do</td>
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<tr>
<td>People adapted to floods,</td>
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<tr>
<td>people know exactly what</td>
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<td>to do and no panic occurs</td>
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<td>Human capital: Education</td>
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<td>% Healthy</td>
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<tr>
<td>&lt; 50% can read and write</td>
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<td>&lt; 70% can read &amp; write</td>
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<tr>
<td>&lt; 55% healthy</td>
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<td>&lt; 80% can read &amp; write</td>
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<td>&lt; 70% healthy</td>
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<tr>
<td>&gt; 80% can read &amp; write</td>
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<td>&gt; 80 % healthy</td>
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<tr>
<td>&gt;90% finished secondary</td>
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<tr>
<td>school</td>
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<td></td>
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<tr>
<td>&gt; 80% healthy</td>
<td></td>
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</tbody>
</table>

*Equity can be measured by the Gini coefficient, which is a number between 0 and 100, where 0 means perfect equity (everyone has the same income) and 100 means perfect inequity (one person has all the income, everyone else has nothing) (CIA, 2004)
Quantifying resilience

Quantifying recovery in a comprehensive way is difficult and probably even impossible. Here, a rather simplified qualitative approach is chosen in which the factors described in the recovery framework are given marks between 1 and 10 and then averaged. This means that they are considered to be of the same importance. The physical factors can be expressed as a period of time. The different economic factors are combined into three composite indices (Table 3.3). The social factors are arranged in three groups, namely human capital, preparedness and social capital (Table 3.4). Except health and education, which seem quite different for different areas and contexts and may influence recovery speed significantly (Tapsell et al., 2003), the personal factors are neglected in the analysis. Elderly, disabled persons and children are thus not studied separately. As a start it is assumed that these persons are present in all communities and that these groups do not influence differences in recovery speed of different systems and different strategies. In order to get the indication of the overall recovery capacity the physical, economic and social factors are averaged.

3.5 THE RESILIENCE INDICATORS EVALUATED FOR DIFFERENT HYPOTHETICAL RIVER SYSTEMS

3.5.1 APPROACH

To evaluate the behaviour of the proposed resilience indicators they were applied to hypothetical river systems. In order to study how different flood protection systems and land use influence the values of the indicators, four different physical layouts (Figure 3.3) were combined with three different land use configurations.

Layout of the hypothetical systems

The four physical layouts are:

1. A large polder surrounded by embankments designed for a discharge wave with a probability of 1/1000 per year.
2. A polder surrounded by embankments with secondary embankments parallel to the river, dividing the polder into four compartments. The embankment along the river is designed for a discharge of 1/50 per year. The levels of the secondary embankments are based on river water levels corresponding with discharges with a probability of 1/100, 1/500 and 1/1000 per year.
3. A polder surrounded by embankments with secondary embankments perpendicular to the river. The secondary embankments divide the polder in four equally large compartments. The levels of the embankments correspond with river water levels with a probability of exceedence of respectively 1/50, 1/100, 1/500 and 1/1000 a year.
4. A natural valley sloping towards the river. Natural levees along the river limit the flood frequency of the lower part of the valley to about once a year.
**Land use and socio-economic characteristics**

All physical layouts were combined with three different land use configurations: random land use, a ‘wisely’ planned land use and an ‘unwisely’ planned land use. ‘Wisely’ was considered here from the viewpoint of preventing flood damage. In all three configurations 25% of the area is occupied by woods, 25% by pasture, 25% by arable land and 25% by residential area. In the wisely planned configuration the residential area is located where flood depths and flood frequencies are lowest and pasture where flood depths and frequencies are highest. In the unwisely planned configurations, in contrast, the residential areas are located at the most dangerous locations and pasture at the safest locations. In the random land use configuration an equal percentage of all land use types is present at all locations.

In the large polder the locations of wisely and unwisely planned land use was derived from the maximum water depths. Both, in the layout with embankments parallel to the river and in the natural valley land use is zoned parallel to the river. In the layout with embankments perpendicular to the river, the land use is zoned perpendicular to the river, with the safest location being the most downstream compartment.

Socio-economically, the hypothetical systems are similar to the Netherlands. Floods are not supposed to significantly affect the income of the inhabitants. Companies are not expected to go bankrupt after flooding. People that cannot reach their work are supposed to be paid normally. Floods happen only in wintertime and do not damage crops.

**Flood modelling**

The floods were simulated with the 2D flooding model Delft-FLS (Stelling et al., 1998). The flood modelling requires a digital elevation model, roughness data and boundary conditions. The slope of both the river and the polder is assumed to be $10^{-4}$. The river bed is set at 5 m below ground level and is 400 m wide. The natural valley was assumed to have an elevation of 5 m to 45 m above the riverbed, with natural levees of 2 m high along the river. The dimension of the polder areas considered is about 12.5 km * 50 km. The total area is 60512 ha. For this simple hypothetical study, roughness coefficients (cf. Nikuradse) were used of respectively 0.066 m for the river and 0.3 m for the entire flood-prone area independent of the land use type. This resulted in an overestimation of the flow velocities in the forest and the
residential area. In order to prevent that the resulting water levels are influenced by the downstream boundary condition, the river was extended downstream.

The river’s discharge regime was assumed to show only one flood wave a year. The assumed discharge probability function is similar to that of the Waal River (one of three Rhine River branches) and the waveform is the standard waveform for the Rhine River at Lobith (after Klooster & Duits, 1999) (Figure 3.4). Peak level and waveform are related (WL | Delft Hydraulics, 2000). For these hypothetical situations the form of other peaks are generated by scaling the waveform of 10,000 m$^3$/s with a discharge factor.

The flood waves with a frequency between once every year and once in 10,000 years were considered. According to figure 3.4, the discharge with a frequency of 1/10,000 a year amounts to about 12,000 m$^3$/s, but the precise magnitude of such a rare discharge is very uncertain. The sensitivity of the resulting indicator values to the magnitude of this once in 10,000 years discharge was tested by varying this maximum discharge between 11,000 and 13,000 m$^3$/s.

![Figure 3.4 Wave form (left) and discharge as function of return time (right)](image)

**Flood impact assessment**

To assess the flood damages a simplified model based on the Standard Damage Module (Vrisou van Eck *et al.*, 1999) was used. The damage at a certain location with a certain land use type is calculated as the product of the maximum damage for the land use type concerned and a damage factor which varies between zero and one depending on water depth (Table 3.5). The total damage was calculated as the sum of the damages at all locations (equation 3.5). Total damage mainly depends on damage to residential areas, which is highest of all land use types (Table 3.6).

\[
\text{Damage} = \sum_{c,l} (\alpha_{c,l} \cdot A_{c,l} \cdot D_{\text{max},l}) \quad (\text{Eq. 3.5})
\]

With:

- $\alpha_{c,l}$ = Damage factors as function of the land use (l) and the water depth class (c)
- $A_{c,l}$ = Area of a certain land use type (l) and water depth class (c)
- $D_{\text{max},l}$ = Maximum damage as function of the land use (l)
Table 3.5 Damage factors for different land use types, random land use and the number of casualties

<table>
<thead>
<tr>
<th>Water depth (m)</th>
<th>Residential area</th>
<th>Other land use</th>
<th>Random land use</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.01 - 0.25</td>
<td>0.025</td>
<td>0.05</td>
<td>0.025</td>
<td>0</td>
</tr>
<tr>
<td>0.25 - 0.5</td>
<td>0.05</td>
<td>0.25</td>
<td>0.051</td>
<td>0</td>
</tr>
<tr>
<td>0.5 – 1</td>
<td>0.19</td>
<td>0.6</td>
<td>0.192</td>
<td>0</td>
</tr>
<tr>
<td>1 – 3</td>
<td>0.22</td>
<td>0.85</td>
<td>0.224</td>
<td>0.1</td>
</tr>
<tr>
<td>3 – 5</td>
<td>0.9</td>
<td>1</td>
<td>0.901</td>
<td>0.5</td>
</tr>
<tr>
<td>5 – 10</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.6 Maximum damage per land use type (€/m$^2$)

<table>
<thead>
<tr>
<th>Land use</th>
<th>Residential area</th>
<th>Grassland</th>
<th>Woods</th>
<th>Arable land</th>
<th>Random</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage</td>
<td>567</td>
<td>1.6</td>
<td>0.09</td>
<td>1.6</td>
<td>143</td>
</tr>
</tbody>
</table>

The number of casualties and the number of affected persons were calculated by assuming that:

- The residential area is 15128 ha (25% of 60512 ha);
- The average area per house is 200 m$^2$;
- Every household consists of 2.1 persons (as is the case in the Netherlands). This results in 1.6 million inhabitants;
- Early warning and adequate evacuation schemes limit the maximum number of casualties to one per thousand affected inhabitants;
- The actual number of casualties is determined by multiplying the maximum damage with a damage factor that varies between zero and one depending on water depth (Table 3.5).

This is, of course, a substantial simplification. The factor-water depth relationship in table 3.5 is hypothetical. In reality the number of casualties depends on evacuation, storm, the rate of water level rise, temperature and the timing of floods (day or night) (see section 3.3).

3.5.2 THE RESULTING FLOOD PATTERNS AND DAMAGES

The resulting flood patterns for all four physical layouts are discussed below. The large polder is flooded about once in 1000 years. Then, the water flows parallel to the river from east to west. At the downstream end water depths become greatest because the embankment prevents that water flows out (Figure 3.3).

In the layout with embankments parallel to the river, the flood probability is 1/50. Discharge waves with a frequency lower than 1/500 per year also overtop the second embankment and about once in 600 years even the third embankment is overtopped, resulting in the flooding of the third compartment. The fourth compartment remains dry.
In the layout with *embankments perpendicular to the river*, the flood probability of the first compartment is also 1/50. Discharges exceeding 10,000 m³/s (frequency of 1/1000 a year) also flood the second compartment and discharges of 11,500 m³/s (frequency of 1/6000 a year) flood three compartments. The last compartment is only flooded when a discharge of 13,000 m³/s (frequency lower than 1/10,000 a year) occurs. The differences between flood frequency and design levels of the embankments are caused by the reduction of river water levels due to floods in the upstream compartments.

In the *valley* the flood frequency is once a year. The flooded area is usually limited to the area adjacent to the river, but increases gradually with increasing discharges.

The resulting damages and number of affected persons (Tables 3.7 and 3.8) indicate that floods in the large polder are rare. However, if this polder becomes flooded, damages are very high. A comparison of all the different physical layouts, each with wisely planned land use, shows that the maximum damages in the large polder are about 15 to 25 times higher than in the compartmentalised polders and about 90 times higher than in the natural valley. Different land use configurations result in large differences in total damage.

The resulting number of casualties is small in all systems with a wisely planned land use (Table 3.9). When land use is unwisely planned more casualties occur. Since both tangible damage and casualties primarily occur in residential areas, the trends in casualties correspond with those in tangible damage.

Table 3.7 Damages (M€) for the four different physical layouts and the three land use configurations given different maximum discharges (in m³/s) (R = random land use configuration, W = wisely planned, U = unwisely planned land use)

<table>
<thead>
<tr>
<th>Q_{peak}</th>
<th>1. No compartment</th>
<th>2. Parallel</th>
<th>3. Perpendicular</th>
<th>4. Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>4200</td>
<td>R</td>
<td>W</td>
<td>U</td>
<td>R</td>
</tr>
<tr>
<td>5000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6000</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
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<td>8200</td>
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</tr>
<tr>
<td>12000</td>
<td>15032</td>
<td>6620</td>
<td>19091</td>
<td>37970</td>
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</tbody>
</table>
### Chapter 3

Table 3.8 Number of affected persons (in thousands) for the four different physical layouts and the three land use configurations given different flood waves (R = random land use configuration, W = wisely planned, U = unwisely planned land use)

<table>
<thead>
<tr>
<th>Q&lt;sub&gt;peak&lt;/sub&gt;</th>
<th>1. No compartment</th>
<th>2. Parallel</th>
<th>3. Perpendicular</th>
<th>4. Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q&lt;sub&gt;peak&lt;/sub&gt;</td>
<td>R W U</td>
<td>R W U</td>
<td>R W U</td>
<td>R W U</td>
</tr>
<tr>
<td>4200</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>5000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>129 0</td>
</tr>
<tr>
<td>6000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>156 0</td>
</tr>
<tr>
<td>7000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>182 0</td>
</tr>
<tr>
<td>7500</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>182 0</td>
</tr>
<tr>
<td>8000</td>
<td>0 0 0</td>
<td>406 0</td>
<td>1562 0</td>
<td>182 0</td>
</tr>
<tr>
<td>8100</td>
<td>0 0 0</td>
<td>408 0</td>
<td>1562 0</td>
<td>182 0</td>
</tr>
<tr>
<td>8200</td>
<td>0 0 0</td>
<td>409 0</td>
<td>1562 0</td>
<td>182 0</td>
</tr>
<tr>
<td>9000</td>
<td>0 0 0</td>
<td>417 0</td>
<td>1562 0</td>
<td>208 0</td>
</tr>
<tr>
<td>9400</td>
<td>0 0 0</td>
<td>505 0</td>
<td>1562 0</td>
<td>208 0</td>
</tr>
<tr>
<td>9500</td>
<td>0 0 0</td>
<td>543 0</td>
<td>1562 0</td>
<td>208 0</td>
</tr>
<tr>
<td>10000</td>
<td>0 0 0</td>
<td>717 0</td>
<td>1562 0</td>
<td>208 0</td>
</tr>
<tr>
<td>10078</td>
<td>0 0 0</td>
<td>739 0</td>
<td>1562 0</td>
<td>267 0</td>
</tr>
<tr>
<td>11000</td>
<td>1541 1323 1588</td>
<td>811 0</td>
<td>1562 0</td>
<td>234 0</td>
</tr>
<tr>
<td>11500</td>
<td>1585 1484 1588</td>
<td>892 0</td>
<td>1562 0</td>
<td>234 0</td>
</tr>
<tr>
<td>12000</td>
<td>1602 1540 1588</td>
<td>1052 0</td>
<td>1562 0</td>
<td>234 0</td>
</tr>
</tbody>
</table>

Table 3.9 Number of casualties for the four different physical layouts and the three land use configurations given different flood waves (R = random land use configuration, W = wisely planned, U = unwisely planned land use)

<table>
<thead>
<tr>
<th>Q&lt;sub&gt;peak&lt;/sub&gt;</th>
<th>1. No compartment</th>
<th>2. Parallel</th>
<th>3. Perpendicular</th>
<th>4. Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q&lt;sub&gt;peak&lt;/sub&gt;</td>
<td>R W U</td>
<td>R W U</td>
<td>R W U</td>
<td>R W U</td>
</tr>
<tr>
<td>4200</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>5000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>5 0 0</td>
</tr>
<tr>
<td>6000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>8 0 0</td>
</tr>
<tr>
<td>7000</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>23 0 0</td>
</tr>
<tr>
<td>7500</td>
<td>0 0 0</td>
<td>5 0 21</td>
<td>0 0 0</td>
<td>36 0 0</td>
</tr>
<tr>
<td>8000</td>
<td>0 0 0</td>
<td>8 0 33</td>
<td>0 0 0</td>
<td>36 0 0</td>
</tr>
<tr>
<td>8100</td>
<td>0 0 0</td>
<td>11 0 44</td>
<td>0 0 0</td>
<td>36 0 0</td>
</tr>
<tr>
<td>8200</td>
<td>0 0 0</td>
<td>92 0 369</td>
<td>0 0 0</td>
<td>36 0 153</td>
</tr>
<tr>
<td>9000</td>
<td>0 0 0</td>
<td>161 0 640</td>
<td>0 0 0</td>
<td>36 0 153</td>
</tr>
<tr>
<td>9400</td>
<td>0 0 0</td>
<td>171 0 666</td>
<td>0 0 0</td>
<td>49 0 187</td>
</tr>
<tr>
<td>9500</td>
<td>0 0 0</td>
<td>232 0 744</td>
<td>0 0 0</td>
<td>49 0 187</td>
</tr>
<tr>
<td>10000</td>
<td>0 0 0</td>
<td>245 0 750</td>
<td>0 0 0</td>
<td>49 0 187</td>
</tr>
<tr>
<td>10078</td>
<td>14 0 56 405 0</td>
<td>496 0</td>
<td>1025 0</td>
<td>58 0 221</td>
</tr>
<tr>
<td>11000</td>
<td>37 0 146 469 0</td>
<td>622 0</td>
<td>1050 86 0</td>
<td>291 0</td>
</tr>
<tr>
<td>12000</td>
<td>54 0 159 522 0</td>
<td>797 0</td>
<td>1076 86 0</td>
<td>292 0</td>
</tr>
</tbody>
</table>
3.5.3 Resulting Indicator Values

Amplitude
The amplitude aspect is quantified by the expected annual damage (EAD) (see equation 3.1). Equation 3.1 can be approximated by equation 3.6, in which the amplitude is the sum of the damages multiplied by the probabilities of the discharges from which the damage resulted. Thus, both frequent discharges with low damages and rare discharges with high damages influence the indicator value.

\[
EAD = \sum_{n=Q_{i}}^{Q_{n}} \left[ (0.5 \times (D(Q)_n + D(Q)_{n+1})) \times (P(Q_n) - P(Q_{n+1})) \right] \quad \text{(Eq. 3.6)}
\]

With: \(EAD\) = Expected annual damage, \(D\) = damage, \(Q_{1}\) to \(Q_{n}\) = Discharges with recurrence times between one and 10,000 years.

The resulting indicator values of the different flood risk management systems differ substantially (Table 3.10). All natural valley systems have a high EAD due to the high frequency of floods. The EAD is lowest for the large uncompartmentalized polders (physical layout 1) with their low flood frequency. The amplitude is thus sensitive to the physical layout of the system, because this layout determines the extent of the flooded area and the flood probability.

Systems with wisely planned land use have a much lower EAD than the same systems with unwisely planned or random land use. The difference varies from a factor 9 for the large polder (physical layout 1) to about a factor 400 for the layout with compartments parallel to the river. This proves that the amplitude is sensitive to damage mitigation measures through land use planning. It also shows that wise planning of land use is more important in the compartmentalised polders than in the large uncompartmentalized one.

Table 3.10 The expected annual damage (M€/year) for the four different physical layouts, the three different land use configurations (R = random, W = wisely planned, U = unwisely planned) and for different maximum discharges (m³/s). (The maximum discharge is the discharge with a probability of 1/10000 per year).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q max</td>
<td>R</td>
<td>W</td>
<td>U</td>
<td>R</td>
</tr>
<tr>
<td>11000</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>108</td>
</tr>
<tr>
<td>12000</td>
<td>4</td>
<td>1</td>
<td>8</td>
<td>110</td>
</tr>
<tr>
<td>13000</td>
<td>5</td>
<td>2</td>
<td>10</td>
<td>111</td>
</tr>
</tbody>
</table>

To explore the behaviour of the EAD, its sensitivity for the maximum discharge (the discharge corresponding with a recurrence time of 10000 years) was studied. It was found that the EAD of systems with a high flood frequency (the valley) is not sensitive to the level of the maximum discharge considered (Table 3.10). For these systems the contribution of the damage resulting from these rare extreme discharges to the EAD is relatively small compared
to the damage contributions of the more frequent discharges. However, in systems with a low flood frequency the extreme discharges are the only discharges that contribute to the amplitude. These systems are therefore more sensitive to the level of the maximum discharge considered. In the systems with secondary embankments perpendicular to the river and a wisely planned land use, the safest compartment becomes flooded when the discharge reaches 13,000 m$^3$/s. Consequently, considering a maximum discharge of 13,000 m$^3$/s instead of 12,000 m$^3$/s results in a significantly higher EAD, namely 4 instead of 1 M€/year. The sensitivity of the EAD to the maximum discharge considered thus clearly depends on the type of system considered. In general, the value of the indicator will change, however the order of magnitude will not. The ranking of the systems according to their amplitude does not change either.

Table 3.11 The expected annual number of affected persons (EANAP) (*1000) and expected annual number of casualties (EANC) for four different physical layouts and three different land use types (R = random, W = wisely planned, U = unwisely planned)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>W</td>
<td>U</td>
<td>R</td>
</tr>
<tr>
<td>EANAP</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>EANC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

The expected average numbers of affected persons and casualties per year are calculated in the same way as the EAD.

Table 3.11 shows that the expected average number of affected persons and casualties per year is zero to one for all systems with a wisely planned land use configuration. In systems where land use is planned unwisely or randomly more people die due to floods. A comparison of the different physical layouts all with random land use patterns shows that the expected average numbers of casualties and affected persons are highest in the natural valley (8 killed and 143000 affected) and lowest in the uncompartmentalized polder area (no death and 1000 affected). The differences between the systems have similar explanations as the differences in EAD.

**Graduality**

Figure 3.5 gives a first impression of damage increase with increasing discharges for different systems. In figure 3.5 the results of the natural valley are much closer to the diagonal which represents the line for which the graduality is equal to 1, than the results for the uncompartmentalized polder area are. The land use configuration has less influence on the graduality than the physical layout has. Most systems with randomly configured land use patterns show a higher graduality than comparable systems with other land use patterns (Table 3.12). However, of all systems consisting of a natural valley the one with wisely planned land use has the highest graduality. The graduality of the uncompartmentalized polder systems (physical layout 1) is lowest and graduality of the valleys is highest.
Table 3.12 Graduality of the different systems (-) for different maximum discharges (m$^3$/s) (R = random, W = wisely planned, U = unwisely planned)

<table>
<thead>
<tr>
<th>Qmax</th>
<th>R</th>
<th>W</th>
<th>U</th>
<th>R</th>
<th>W</th>
<th>U</th>
<th>R</th>
<th>W</th>
<th>U</th>
<th>R</th>
<th>W</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>11000</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.50</td>
<td>0.40</td>
<td>0.44</td>
<td>0.41</td>
<td>0.40</td>
<td>0.37</td>
<td>0.60</td>
<td>0.71</td>
<td>0.57</td>
</tr>
<tr>
<td>12000</td>
<td>0.24</td>
<td>0.24</td>
<td>0.20</td>
<td>0.56</td>
<td>0.42</td>
<td>0.51</td>
<td>0.46</td>
<td>0.40</td>
<td>0.34</td>
<td>0.59</td>
<td>0.69</td>
<td>0.59</td>
</tr>
<tr>
<td>13000</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.60</td>
<td>0.46</td>
<td>0.55</td>
<td>0.51</td>
<td>0.17</td>
<td>0.33</td>
<td>0.55</td>
<td>0.65</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Figure 3.5 The damage as a function of the discharge for the systems with a random land use configuration and different physical layouts (1 = polder without compartments, 2 = polder with secondary embankments parallel to river, 3 = polder with secondary embankments perpendicular to river, 4 = natural valley)

Table 3.12 also shows the sensitivity of the graduality for the maximum discharge considered. In the polder systems without secondary embankments (physical layout 1) the flood frequency is so low that a lower maximum discharge means that all damage happens in even a smaller part of the discharge range. This results in a lower graduality. For the same reason the graduality is higher when a higher maximum discharge is considered. In the polder systems with secondary embankments parallel to the river (physical layout 2) the maximum discharge has less influence. For the polder system with embankments perpendicular to the river (physical layout 3) the maximum discharge considered is important. When the maximum discharge considered is 13,000 m$^3$/s instead of 12,000 m$^3$/s the safest compartment becomes flooded, which means that the maximum damage increases. This sudden damage increase lowers the graduality enormously, especially for the system with wisely planned land use where the residential area is situated in this safest compartment. In the natural valley the sensitivity of the graduality for the maximum discharge is relatively small.
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The resulting values for the graduality of the intangible damage assuming a maximum discharge of 12,000 m$^3$/s are presented in table 3.13. The graduality of the increase of the number affected persons and casualties with increasingly severe flood waves is highest for the natural valley, than for the polders with secondary embankments and it is lowest in the polder without secondary embankments. This sequence is comparable with the graduality of the tangible damage increase. When no affected persons or no casualties occur, no graduality can be determined.

![Figure 3.6](image-url) Relative damage increase as a function of relative discharge increase for the uncompartmentalized polder area and the natural valley both with a wisely planned land use

Table 3.13 Graduality of the intangible damage increase (R = random, W= wisely planned, U = unwisely planned)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>W</td>
<td>U</td>
<td>R</td>
</tr>
<tr>
<td>Casualties</td>
<td>0.24</td>
<td>-</td>
<td>0.24</td>
<td>0.50</td>
</tr>
<tr>
<td>Affected persons</td>
<td>0.16</td>
<td>0.22</td>
<td>0.12</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The differences between the graduality of the intangible damage of the different systems are comparable with these differences for the tangible damage. However, the graduality of the number of affected persons reacts different, because this number does not depend on the water depth, but on the extent of the flooded area only.

**Recovery rate**
In order to get an indication of the system’s recovery rate, the recovery capacity of the systems was evaluated. The physical factors, economic factors and social factors that
Quantifying resilience

Influence recovery capacity are discussed below. The socio-economic context was assumed to be comparable with the Netherlands.

In the flat polder systems embankments prevent the flow of water back into the river, while the natural valley dries quickly because of its sloping geography and low embankments. The duration of the floods is estimated at about 7 to 8 weeks for the polder areas and 3 weeks for the natural valley. Consequently, the physical factors that determine the recovery rate of the natural valley score a 9 and those of the polder systems a 6.

In the hypothetical systems the income level is high, people have sufficient savings to repair damage and the government will also compensate part of the damage. Relationships with other areas will help the area to recover. Spreading of effects to other areas is not expected. Therefore, the economic factors that influence recovery of all systems score a 9 (Table 3.3 and 3.14).

The social factors are divided in three groups: organisational factors that determine access to information and funds for different groups, preparedness and human capital. Just like the people in the Netherlands, the inhabitants of all hypothetical systems have a high level of education and skills. Over 80% is healthy. The organisational level is high and there are no separated groups that will be excluded from funds, help or information. Income equity is also high. The Gini index, which indicates equity, is estimated at 33 as in the Netherlands (CIA, 2004). Communication between government and inhabitants and between different areas is excellent. Therefore, all systems score nines on the categories: social structure and human capital (Table 3.4 and 3.14).

For preparation however, different values are scored. In the polder system without secondary embankments flood frequencies are so low that people have forgotten about floods. The government has repeatedly spread the message that the area is safe. Therefore, floods cause shocks and panic. The inhabitants blame the government and wait for the government to help them recover. This system scores a 2 to 3 on preparation. In the polder systems with secondary embankments and wisely planned land use people see the embankments and know that they are supposed to limit the flooded area and thus that floods may occur. Land use has been adapted to the floods. Therefore, they are not shocked but instead act effectively in order to recover quickly. These systems score a 8 on preparation. The systems with secondary embankments and an unwisely or random planned land use are less prepared for floods. These systems score a 4 on preparation. The people in the natural valley have to cope with floods almost every year. Therefore, they are not surprised at all and know exactly what to do. This system also scores a 9 for preparation.

Table 3.14 Capacity to recover (scale 1-10) (R = random, W= wisely planned, U = unwisely planned)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td>R</td>
<td>W</td>
<td>U</td>
<td>R</td>
</tr>
<tr>
<td>Physical</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Economic</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Social</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>
Chapter 3

The overall recovery capacity is high (Table 3.14). The results show that the recovery capacity is sensitive to land use and to physical layout. Of course, these results depend on how the hypothetical systems are described. By describing realistic hypothetical systems, as is done in this case study, understanding of the relevance of certain characteristics for the indicators has been obtained. In next chapters the recovery capacity of real case study areas will be analysed.

Resistance

The resistance of the system is indicated by the reaction threshold which is quantified as the recurrence time of the highest discharge which is not expected to cause floods. The reaction threshold of the first system without compartments is 1000, the resistance of the second and third system with compartments is 50 and the resistance of the natural valley is lowest. That area floods almost every year.

3.5.4 DISCUSSION OF THE RESULTS OF THE HYPOTHETICAL CASE STUDY

The study of hypothetical systems was carried out to evaluate whether the behaviour of the indicators is conform expectation and conform our ideas on resilience. The case study has resulted in more insight into the sensitivities and the value of the indicators for very different systems. The studied systems score differently on the different indicators. The valley systems score high on graduality and recovery rate, the polder systems without compartments score well on amplitude (Table 3.15). The compartmentalized polder areas score in between. Looking at all indicators one may conclude that the system with compartment embankments parallel to the river and a wisely planned land use and the wisely planned natural valley are the most resilient systems. The polder systems without compartments have the highest resistance. These systems have a very high reaction threshold, a low amplitude and a low graduality. The exact figures depend on the chosen embankment levels and discharge regime.

The indicator values are all explainable. Graduality is expected to be higher in natural valleys and low in diked systems and resilience is expected to be higher for systems where land use and physical lay-out match in such a way that damages are reduced. Natural river valleys may have been expected to be resilient. However, in this case study they score well on only two of the three aspects. The EAD of the natural valleys is high, because of their high flood frequency. The frequent floods cause too much damage in this natural valley. Resilience would have been higher, if the land use was adapted to these frequent floods. Resilience of those areas is therefore not as high as expected.

The EAD, one of the indicators used to assess the system’s resilience, is very low for the uncompartmentalized systems. This low value is caused by the system’s high reaction threshold and thus by its high resistance. The low flood probabilities which are reflected in the high reaction threshold, also result in low values for graduality. This system is thus not very resilient, but very resistant. It is thus very important to consider all indicators together when assessing the resilience of systems.

The case study is also used to consider whether all indicators are required. To quantify the amplitude three indicators have been defined and tested: the expected annual damage (EAD), the average number of affected persons per year and the average number of casualties per
Quantifying resilience

year. Since all three indicators for the amplitude show similar behaviour, they are not all required. The average yearly damage suffices to represent the effects of all kind of measures that lower water depths, flood frequencies or change the vulnerability. Furthermore, the number of casualties has to be assessed because casualties may be the motivation for a certain flood risk management strategy. However, the average number of affected persons is less important. This number does not provide much additional information, because it shows the same effects as the tangible amplitude. For the *graduality* of the increase in reaction with increasingly severe flood waves also three indicators were calculated based on the increase of damage, number of people affected and killed with increasing discharge. By only considering the damage increase with increasing discharge already a good overview of the reaction can be obtained. The effects on the number of casualties can be seen from the amplitude indicator. The *recovery rate* is estimated by assigning marks to recovery capacities. This indicator provides insight in coping capacity of a society with the consequences of floods.

Table 3.15 Overview of the resilience of the studied systems (maximum discharge 12,000 m³/s) (R = random, W= wisely planned, EAD = Expected Annual Damage, EANC = Expected Annual Number of Casualties, (Unwisely planned land use is not presented here))

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>EAD</td>
<td>R 4 W 1 110 1 90 1</td>
<td>R 4 W 1 0 0 0 0</td>
<td>R 4 W 8 0 0 0</td>
<td>R 4 W 21 0 0 0</td>
</tr>
<tr>
<td>Amplitude</td>
<td>EANC</td>
<td>0 0 1 0 1 0 1 0 8 0</td>
<td>0 0 1 0 1 0 1 0 8 0</td>
<td>0 0 1 0 1 0 1 0 8 0</td>
<td>0 0 1 0 1 0 1 0 8 0</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality</td>
<td>0.24 0.24 0.56 0.42 0.46 0.40 0.59 0.69</td>
<td>0.24 0.24 0.56 0.42 0.46 0.40 0.59 0.69</td>
<td>0.24 0.24 0.56 0.42 0.46 0.40 0.59 0.69</td>
<td>0.24 0.24 0.56 0.42 0.46 0.40 0.59 0.69</td>
</tr>
<tr>
<td>Recovery</td>
<td>Recovery cap.</td>
<td>7 7 7 8 7 8 9 9</td>
<td>7 7 7 8 7 8 9 9</td>
<td>7 7 7 8 7 8 9 9</td>
<td>7 7 7 8 7 8 9 9</td>
</tr>
</tbody>
</table>

The remaining indicators are summarized in table 3.15. They are sensitive to the effects of all kinds of measures, whether they lower flood probabilities, damages, increase graduality, or enhance recovery. These indicators can be assessed for systems where no flood data is available, and they are not restricted to specific types of lowland river systems. Together they give insight into the reaction of the system on flood waves and thus indicate the system’s resilience and resistance.

### 3.6 Reflection

The concept of resilience can only become an applicable concept in flood risk management when it can be well-defined and made quantifiable. Measuring resilience directly is not possible, because it is not clear what to measure and mostly there is a lack of data. Therefore, indicators must be used to quantify resilience.

The resilience of a system can be quantified by studying the three aspects that describe a system’s reaction to peak discharges: amplitude of the reaction, graduality of the increase of reaction with increasing peak discharges and recovery rate. It was demonstrated that this can be done in a satisfactory way by means of four indicators. Together, these indicators give an overview of the reaction of a flood risk management system to flood waves. The amplitude covers the severity of flood impacts and can be quantified as the expected average damage...
and the expected average number of casualties per year. The graduality shows the discontinuities in the discharge-damage relationship, which point at thresholds and the possible occurrence of disasters. The recovery rate is estimated by means of a recovery capacity analysis of the system, which is a fairly qualitative approach. The reaction threshold of a system, defined as the recurrence time of the highest discharge which is not expected to cause floods within the system, indicates the system’s resistance. With these indicators the resilience of different systems and strategies can be established as was illustrated by quantifying the resilience of hypothetical systems.

By quantifying the three aspects that describe a system’s reaction to flood waves, an indication of the system’s resilience is obtained. Each indicator separately reflects only one aspect of the reaction of a system to flood waves. Therefore, the resilience of a system can only be assessed by considering the whole set of indicators. If, for example, the EAD of a system is small, the resilience is not necessarily high. If also the graduality is small and the reaction threshold high, the resistance of the system is high and the low amplitude is caused by low flood probabilities and not by small reactions.

The question on how resilient the systems are or how to integrate the different indicators has not been answered yet. The integration of the EAD and EANC could be performed by assuming a monetary value for a human life. This value will differ per country and may even differ per person. Such an approach often meets with opposition. The integration of the amplitude, graduality and recovery rate and their weighing is not possible without the loss of the essential information expressed by these indicators. Clearly, systems which score high on all three aspects are resilient and systems with a high amplitude, low graduality and low recovery are not resilient. Deciding on systems that score well on one aspect and low on another is more difficult. However, there may be no need to express resilience by one number only. The indicators clearly show that:

- in order to increase the resilience of the uncompartmentalized polder areas, particularly the graduality should be increased because the other aspects already score well;
- In the valleys the land use should be adapted in order to lower the amplitude.

The indicators clearly show which aspect of the reaction hampers fast recovery: or the reaction amplitudes are too large, or the graduality is too small or the recovery rate is too small. That may be sufficient.
4 CURRENT RESILIENCE OF THE FLOOD RISK MANAGEMENT SYSTEM OF THE LOWER RHINE RIVER

4.1 INTRODUCTION AND SYSTEM DELINEATION

This chapter studies the current resilience of the lower Rhine River by applying the resilience concept as defined in chapter two and quantifying resilience with the indicators discussed in chapter three. Chapter five discusses strategies for flood risk management of the Rhine River.

The Lower Rhine River was selected as a case study area for two main reasons. Firstly, water policy makers have already proposed a long-term vision for the Lower Rhine River, which embraces an increase of its resilience (Min V&W, 1999). In this policy resilience is not clearly defined. Resilience is commonly associated with ideas such as more room for natural processes in rivers and less reliance on structures such as dikes (Klijn & Marchand, 2000; Min. V&W, 1999; Remmelzwaal & Vroon, 2000). Since resilience is such a popular concept in Dutch water policies, a case on the lower Rhine River seems inevitable. Secondly, the long history of flood risk management in the Netherlands and the importance of flood risk management to the country make a case study on the most important river of the Netherlands

Figure 4.1 The area in the Netherlands threatened by floods

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3 Part of this chapter have been published as De Bruijn (2002a &b); Vis et al. (2003)
interesting. Two third of the Netherlands needs and has artificial protection against floods from the sea and the major rivers (Figure 4.1). In this area millions of people live and large industries have settled.

This case study focuses on the lowland river stretch of the Rhine River (Figure 4.2, Figure 4.4). The River Rhine originates in the Alps in Switzerland and flows via France, Germany, and the Netherlands into the North Sea. At Bonn the Rhine flows into a wide plain and becomes a lowland river. Downstream of Gorinchem and Schoonhoven the water levels are significantly influenced by tides. The lowland flood risk management system studied in this chapter is thus geographically limited to the section between Bonn and Gorinchem/Schoonhoven and the corresponding flood-prone area. Since the flood risk management system is part of the larger socio-economic system of the Netherlands, the socio-economic characteristics of the Netherlands are considered in order to understand the recovery of the flood risk management system from floods.

Figure 4.2 Rough indication of the situation of the flood risk management system in the total catchment of the Rhine River (the system is indicated with the black lined polygon)

To assess the current resilience of the Lower Rhine River, the following questions were addressed:

- What are the present characteristics of the discharge regime and the flood risk management system of the Lower Rhine River? (Section 4.2)
- What are the potential flood impacts? (Section 4.3)
- How resilient is the current system to flood waves? (Section 4.4)
4.2 CHARACTERISTICS OF THE DISCHARGE REGIME AND THE SYSTEM

4.2.1 THE DISCHARGE REGIME

This section discusses the characteristics of the discharge regime in order to get an overview of the flood waves that enter the flood risk management system. Floods normally occur in winter or spring. In summer the discharges are low, while in winter and spring snow melt and a small storage capacity of the soil result in flood waves.

The upstream boundary of the system is located near Bonn. However, since a long range of discharge data of the Rhine at Lobith near the Dutch-German border is available, data of Lobith was used to characterise the discharge regime. The average discharge at Lobith is around 2,300 m$^3$/s (Middelkoop, 1998). Parts of the floodplains in the Netherlands and Germany are flooded when the discharge at Lobith rises above 5,000 to 7,000 m$^3$/s. This happens once a year on average. The discharge probability function at Lobith is presented in Figure 4.3. The discharge at Lobith with a probability of 1/1250 per year, used in the Netherlands as the design discharge, is estimated as 16,000 m$^3$/s with a 95% reliability interval of about 13,000 to 19,000 m$^3$/s (Van de Langemheen & Berger, 2001). The discharge probability function is uncertain because it is based on a range of recorded discharges of only about 100 years.

![Figure 4.3](image_url) The discharge for the Rhine River at Lobith as function of the recurrence time (years) (without incorporating a physical maximum)

Lammersen (2004) estimated the physical maximum of the discharge that presently can reach Lobith at about 15,500 m$^3$/s. This figure was found with combined hydrologic and hydraulic modelling in which artificial rainfall data was used generated by statistical analyses on historic rainfall data. In this analysis it was assumed that historic rainfall data is representative for the current climate. Furthermore, it was assumed that floods in Germany occur at several locations. If floods occur along the Upper Rhine, but not along the lowland part of the Rhine in Germany, the discharge which would reach Lobith is about 17,000 m$^3$/s. Lammersen (2004) also made estimations for peak discharges and for the physical maximum discharge in
2020. If, in 2020 rainfall events could result in a discharge of 17,800 m$^3$/s at Andernach (near Bonn), then discharges of about 17,200 and 16,600 m$^3$/s are expected to reach respectively Rees and Lobith, even if floods in Germany occur. All these figures do not incorporate emergency measures, such as sand bags, which may increase the discharge capacity of the river in Germany (Lammersen, 2004). The physical maximum discharge capacity is expected to be around 17,000 to 19,000 m$^3$/s near Rees in 2020. It is not clear what physical maximum is valid for Bonn, the upstream boundary of the case study area.

4.2.2 The physical characteristics of the system

In Germany, the lowland part of the River Rhine consists of one channel flowing through an alluvial plain. Just downstream of the border between Germany and the Netherlands the Rhine River bifurcates in the Waal River flowing to the west, and the Pannerdens Canal flowing to the North (Figure 4.4). The Pannerdens Canal bifurcates near Arnhem in the Nederrijn River that flows to the west (farther downstream called the Lek) and the IJssel River, flowing to the north. The Waal River is the largest branch and transports about two thirds of the Rhine discharge. It has a high economic value, due to the fact that it is the major shipping way from Rotterdam to the Ruhr industrial area in Germany. The much smaller Nederrijn has been canalised. The smallest branch, the IJssel River, flows near Kampen into the IJssel Lake.

The lower Rhine River is characterised by a typical division in a main channel, embankments, a floodplain and high dikes to protect the area surrounding the river from flooding (Figure 4.5). The dikes and other structures in the Netherlands are designed to allow a safe passage of a flood wave with a probability of 1/1250 per year. To establish the design height of dikes, water levels corresponding to this probability are increased with the expected maximum increase in water level by wind and waves or, when this increase is smaller than 50 cm, with 50 cm to account for uncertainties. In Germany the design discharge corresponds with a discharge with a probability of 1/500 per year. Since the Germans add one meter extra height to the dikes to count for uncertainties, the resulting dike levels in both countries are comparable.

The area surrounding the Rhine River consists in coastal lowland and reclaimed land (polders) with some hills in the east and in the centre. To prevent a large area being flooded at once, secondary dikes have been constructed that divide the area in so-called dike rings. A dike ring is an area surrounded by dikes or naturally higher grounds. The dike rings differ in size, economic value at risk and population density. For example, the Betuwe (Figure 4.4) is a large dike ring with a high economic value at risk. If a flood occurs, the emptying of the dike rings may take several weeks or months. A large part of the water will flow back into the river by gravity, the remainder has to be discharged through the normal drainage systems.
Current resilience of the flood risk management system of the lower Rhine River

Figure 4.4 The Lower Rhine River and the area threatened by floods from the Lower Rhine River (in grey)

Figure 4.5 Typical cross section of the Rhine River (source: Silva et al., 2000)

Hydraulic system behaviour

In order to assess flood risks it is necessary to know the impacts of discharges that flow into the system. This requires knowledge on flow and flood patterns. Current methods to determine flood risks study each dike ring individually (DWW, 2003b). Flood probabilities for an individual dike ring are determined by evaluating the failure probability of each dike section and each failure mechanism separately. The probabilities of failure caused by each failure mechanism for each dike section are summed in order to assess the failure probability of each dike ring by using the correlation between those probabilities. In this procedure the hydraulic interaction between the different dike rings is neglected. This hydraulic system behaviour must, however, be considered when it is intended to assess the system’s resilience.
Hydraulic system behaviour determines the effects of a flood in a certain sub-area on flood probabilities in other sub-areas within the system. Hydraulic system behaviour is only relevant when interactions between different parts in the system are possible. In general, system behaviour will lower the flood probabilities of downstream dike rings as a flood upstream may lower flood probability of these areas. However, when floods may cause shortcuts to other river branches, system behaviour may also increase flood probabilities of downstream dike rings. For example, if a breach in the right embankment of the Rhine River near Rees occurs, water may flow directly to the IJssel River, thereby increasing the load on the IJssel dikes.

The influence of a flood on downstream flood probabilities depends on the effect of the inflow into the flooded area on the level and volume of the flood wave that continues flowing in downstream direction. The volume of water that flows into the flooded area depends on the form of the upstream flood wave and the storage volume in the flooded area. If the flooded area is small compared to the volume of water in a flood wave, the area may become filled up before the peak of the wave has passed. If this happens, the effect on the flood wave in the river will be small and downstream flood probabilities will not be reduced much. Another breach downstream may then occur as well. Also the rate of breach growth or the rate of opening of an inlet affects the inflow into an area and therefore also the level and volume of the flood wave continuing in downstream direction. Whether an upstream flood reduces downstream flood probabilities depends furthermore on the moment of occurrence of the breach or flood. If a breach breaks before the peak of the flood wave arrives, the peak may be lowered and downstream flood probabilities may be reduced, while a dike breach occurring after the passage of the peak of the flood wave will have less effect on downstream flood probabilities.

The process of hydraulic system behaviour, thus the interrelations between flood probabilities of different areas, can be used actively. An example of a measure that uses hydraulic system behaviour is a detention area that can be inundated to reduce flood probabilities of vulnerable downstream areas.

Effects of hydraulic system behaviour of the Lower Rhine
The effects of hydraulic system behaviour on flood probabilities and flood risks of the Lower Rhine River are not known yet. Van Mierlo et al. (2003) have schematised a hypothetical river system that resembles a part of the Lower Rhine system and studied the effects of system behaviour on flood risks in that hypothetical system. Their case study showed that hydraulic system behaviour can have significant effects on the flood risk of a dike ring. For the most upstream dike ring that they considered the effect was very small. However, in the most downstream dike ring the flood risk was reduced by almost 50% due to system behaviour. Flooding of the more upstream dike rings prevented floods of the more downstream dike ring. Furthermore, considering system behaviour enabled the calculation of the flood risk of the total system. The method used by Van Mierlo et al. (2003) requires much data and calculation time and has therefore not yet been applied to real case study areas. Further research is needed to make this method applicable for real systems.

Based on the results of Van Mierlo et al. (2003) it can be concluded that system behaviour in the Lower Rhine River may result in an increase of safety of the more downstream dike rings.
such as the Betuwe area. However, system behaviour may have negative effects on other areas such as the areas along the Meuse River, which may have higher flood probabilities than expected due to inundation from areas along the Rhine River. Hydraulic system behaviour is considered in this thesis by studying downstream effects of dike breaches (see section 4.3).

4.2.3 SOCIO-ECONOMIC CHARACTERISTICS OF THE SYSTEM

The socio-economic situation of the flood risk management system is embedded in the socio-economic situation of the Netherlands. This section will therefore first describe general characteristics of the socio-economic situation in the Netherlands after which specific aspects of the flood risk management system will be discussed.

The Netherlands is a densely populated country with rich, well-educated people. The economy is prosperous and depends heavily on foreign trade. The industry mainly consists in food processing, chemical industry, petroleum refining and electrical machinery (CIA, 2002). The most important chemical industry is located in the harbours at the coast and is not threatened by floods from rivers. Agriculture occupies 28% of the land surface, but only 3 to 4 % of the total labour force. It provides input for the food processing industry and export. Communication lines are highly developed and well maintained. Televisions, radios, telephone and internet are well within reach of all inhabitants. The most important airport and harbours are situated in the west of the Netherlands, outside the flood risk management system. The Netherlands is a democratic country with many political parties of which three are within the government, nowadays. Decisions are typically made through consensus.

The area that is part of the flood risk management system has mainly the same socio-economic characteristics as the Netherlands as a whole. Therefore, only the land use and transport function, which are important later on in this chapter are discussed here. The land use of the flood risk management system consists of agricultural area, built-up area, and nature reserves. The present agricultural use of the system is dominated by animal husbandry and open-air horticulture, in particular fruit trees, vegetables and tree nurseries. Animal husbandry consists predominantly of intensive dairy farming. Only in the floodplains that flood every winter, more extensive animal husbandry is found. The most densely populated part of the system is the area between the cities Arnhem and Nijmegen. Furthermore, cities are situated along the IJssel River and in the Betuwe area. Transport is an important function within the flood risk management system. Important railways and highways are situated in the Betuwe area. Over the highways A15 and A2 respectively 17 and 14 million ton goods are transported annually (WL | Delft Hydraulics, 2001). When the new Betuwe Railroad is finished (2005) even more goods may be transported through the Betuwe area. The rivers itself are mainly used for navigation. Over the Waal River alone between 139 and 157 ton goods are transported from the Rotterdam harbour to the mainland and to Germany. In 1994 ships carried 29% of all transported goods in the Netherlands. This percentage is expected to increase in the future (Baan & Klijn, 1998). Whether and how these socio-economic characteristics are related with resilience against flood waves is discussed in section 4.4.
4.3 POTENTIAL FLOOD IMPACTS

4.3.1 APPROACH

In order to estimate the potential flood impacts five steps were carried out (Figure 4.6). The data used and the five steps to estimate the potential flood impacts are described in this section; the next sections discuss the resulting impacts and the resilience of the system.

Data used

Extreme flood waves may result in dike breaches. To determine likely dike breach locations and the consequences of breaches at those locations, data on land use, elevation, and dike levels is required.

The description of the land use is based on the lgn3plus files (‘lgn’ means 'land use of the Netherlands’). These describe the current land use in a 25 m cell size grid. Plans for future developments, such as railways, motorways and planned housing areas are not incorporated. In order to describe the elevation as accurately as possible, for each area the most recent and accurate source was used. Therefore, the source of the data may differ per location. For the river elevation and hydraulic roughness not the current situation, but the most likely alternative of the research project ‘Room for the Rhine River’ (Silva et al., 2000; WL | Delft Hydraulics & RIZA, 1999) was used\(^4\). To determine whether an area is safe not the actual dike levels, but design water levels were used. Dike levels vary from place to place, and data on the actual levels is difficult to obtain. Even the difference between the left and right side can be large. The data used is summarized in table 4.1.

Table 4.1 Summary of the data used

<table>
<thead>
<tr>
<th>Subject</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schematisation River</td>
<td>Sobek RvR alternative 9 (see footnote 2)</td>
</tr>
<tr>
<td>Elevation</td>
<td>Differs per scenario</td>
</tr>
<tr>
<td>Land use</td>
<td>Lgn (Land use Netherlands, 25m cell size grid)</td>
</tr>
<tr>
<td>Dike levels</td>
<td>Design water levels + 50 cm,</td>
</tr>
</tbody>
</table>

Method

To determine what may happen when an extreme flood wave occurs on the Rhine River, firstly, representative flood waves were selected. The selected representative flood waves are based on discharge data and a discharge probability curve of discharges recorded at Lobith. Statistical analyses by WL | Delft Hydraulics (2000) and Klopstra & Duits (1999) provide methods to derive waveforms at Lobith with different probabilities and peak levels. This study used the method of Klopstra & Duits (1999), since it incorporates the entire discharge

\(^4\) RvR Alternative 9 was the most likely alternative developed in the RvR research project at the time of this study (2000). In this schematisation 16,000 m³/s (the new design discharge in the Netherlands since 2001) can be discharged safely. A description of this alternative can be found in WL | Delft Hydraulics & RIZA (1999).
Current resilience of the flood risk management system of the lower Rhine River

event including small peaks after the main peak, which are not considered in the method of WL | Delft Hydraulics (2000). This method is broadly accepted in the Netherlands.

1. Select flood waves
2. Select dike breach locations
3. Determine flow through breach & downstream effect of breach
4. Determine flood pattern in flooded area
5. Determine the damage

Downstream effects Boundary conditions FLS Flood pattern
Max. water depths Max. flow velocities

Damage corresponding with the 5 breach locations and 3 flood waves

Figure 4.6 Steps carried out to assess potential flood impacts

Flood waves with peak levels of 16,000, 18,000 and 20,000 m$^3$/s at Lobith were used. Currently, however, the use of such high flood waves is disputable since the physical maximum of the discharge at Lobith is expected to be lower than 18,000 m$^3$/s. More upstream at the upper boundary of the research area such high discharges cannot be excluded (see section 4.2.1). Figure 4.7 shows the peak discharge levels used and flood waves with different probabilities and an equal peak level of 16,000 m$^3$/s at Lobith.
The flood waves were used as upstream boundary conditions for the simulations. For the simulation of breaches upstream of Lobith the flood waves at Lobith were translated to flood waves at Ruhrtot in such a way that if no breaches would occur, the boundary conditions at Ruhrtot would result in the representative flood waves at Lobith. For the downstream boundary conditions fixed water levels were used, which were taken from the research project ‘Room for the Rhine River (RvR) (WL | Delft Hydraulics & RIZA, 1999). These water levels are sufficiently far downstream to avoid influence on the results. The inflow from tributaries and canals was schematised as a constant value equal to their maximum discharge. These boundary conditions are described in WL | Delft Hydraulics & RIZA (1999).

Secondly, likely dike breach locations were determined and the flood-prone areas behind these breaches were delineated. Dike breaches can be caused by many failure mechanisms such as erosion, piping, overflow and sliding. To determine weak locations in the dikes the structure and location of all dike sections and their sensitivity to these failure mechanisms should be studied. However, knowledge of and data on the structure and stability of dikes are not yet sufficient for such an analysis. Therefore, five likely and representative dike breach locations were selected. The study of the consequences of breaches at these locations is assumed to give a good overview of the possible consequences of an extreme discharge. The locations are presented in figure 4.8.

The locations are:
1. Rees: on the right bank of the Rhine in Germany just upstream of the boarder.
2. Kalkar: on the left bank of the Rhine in Germany.
3. Lobith: Near the border between Germany and the Netherlands on the right bank of the river.
5. Nijmegen: Downstream of Nijmegen, on the left bank of the Waal

Figure 4.7a Average flood waves with a peak of 16,000, 18,000 and 20,000 m$^3$/s at Lobith, and b: Flood waves at Lobith with different probabilities and a peak of 16,000 m$^3$/s
A peak exceeding the design discharge is most likely to cause problems in upstream areas first. Therefore, two locations in Germany just downstream of the point where the river turns into a lowland river were selected. Here, dikes form the main flood defence for the steadily widening alluvial plain. Dike breaches were simulated on either side of the river, near Rees and Kalkar respectively. The next locations were selected in the downstream dike rings.

Since the process of breach growth is very complicated and requires a lot of data on the embankments and their surroundings, an accurate simulation was not possible within the scope of this research. The breach growth process was therefore imposed to the model as a boundary condition, rather than simulating it based on the flow velocity through the breach. All simulations are based on the assumption that the breach is 200 m in width throughout the flood event and the breach growths linearly in depth from the initial level of the embankment to the level of the adjoining flood plain in three days. The models used required a constant breach width. This scenario was verified in literature and seemed reasonable (see for example Verheij (2000)).

To test the sensitivity of the inflow volume to these assumptions simulations were carried out with a breach width of 150 and 250 m and a erosion of the dike in two and four days for the breach near Lobith (De Bruijn, 2002b). The tables 4.2 and 4.3 show that the difference in total volume flowing into the area is in the order of 5 % or less. The difference in the peak discharge through the river is only 200 m$^3$/s (given a flood wave of 18,000 m$^3$/s at Lobith). The uncertainty in peak flow reduction and the volume in the area seem small compared to all the uncertainties in this study. The assumptions mentioned above are used for all cases.
Table 4.2 The volume in the flooded area near Lobith and the maximal discharge in the river downstream of the breach given different breach widths (Q = 18,000 m³/s at Lobith, breach growth duration = 3 days)

<table>
<thead>
<tr>
<th>Width breach (m)</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume through breach (* 10⁶ m³)</td>
<td>1,107</td>
<td>1,135</td>
<td>1,169</td>
</tr>
<tr>
<td>Difference in volume (%)</td>
<td>-2.6</td>
<td>0</td>
<td>2.9</td>
</tr>
<tr>
<td>Max. Q in river downstream of breach</td>
<td>16,200</td>
<td>16,300</td>
<td>16,500</td>
</tr>
</tbody>
</table>

Table 4.3 The volume in the flooded area near Lobith given different erosion speeds (Q = 16,000 m³/s at Lobith, Breach width = 200 m)

<table>
<thead>
<tr>
<th>Rate of breach growth (days)</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (* 10⁶ m³)</td>
<td>928.6</td>
<td>897.8</td>
<td>854.6</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>3.4</td>
<td>0</td>
<td>-4.8</td>
</tr>
</tbody>
</table>

Thirdly, the 1-D hydraulic model SOBEK (WL | Delft Hydraulics & RIZA 1996a, 1996b) was applied to determine the effects of the breaches on the downstream river discharge in the different branches and thus on the safety of downstream areas. The situation with and without dike breach for each flood wave was simulated and the results were compared both with each other and with the design water levels. For the simulations of breaches near Rees, Kalkar, and at the Betuwe area, it was assumed that water flow through the breach is not limited by the water level in the flooded area. At those locations large areas become flooded and there are no structures present right behind the breach. In smaller areas, such as the Land van Maas & Waal (breach near Nijmegen) and in the Rijnstrangen area (breach near Lobith), water levels in the area close to the breach may become high due to the presence of obstructions and backwater effects will occur. These effects reduce the inflow through the breach. Simulations based on the assumption of unlimited inflow overestimate the inflow in the latter areas. To overcome this problem the flows through the breaches near Lobith and near Nijmegen were simulated with a 2D model that includes both the river and the flooded area.

Fourthly, the floods were simulated with the two-dimensional model Delft-FLS (Stelling et al., 1998) to determine the flood pattern in the flooded area itself. At two locations (Nijmegen and Lobith) the river stretch around the breach was included in the 2D schematisation to simulate the relation between the inflow into the flooded area and the water levels in the flooded area. For the other locations the inflow discharge was derived from the results of the 1D model. Table 4.4 shows the boundary conditions used.

Finally, the damage resulting from the floods was determined with the Netherlands’ Standard Damage Module of the Hydraulic and Road Engineering department of the Dutch Ministry of Public Works and Water Management (Vrisou van Eck et al., 1999). This module incorporates the primary direct and indirect tangible damage in the flooded area. In this research only the primary direct damage was assessed.
Current resilience of the flood risk management system of the lower Rhine River

Table 4.4 Summary of the FLS schematisations

<table>
<thead>
<tr>
<th>Breach location</th>
<th>Schematised in FLS</th>
<th>Boundary conditions FLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rees</td>
<td>Flooded area</td>
<td>• Inflow into the area,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water level of the IJssel River to allow water to flow over the embankment into the IJssel River</td>
</tr>
<tr>
<td>Kalkar</td>
<td>Flooded area</td>
<td>• Inflow into the area,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water level in the Waal River</td>
</tr>
<tr>
<td>Lobith</td>
<td>Flooded area and a part of the river</td>
<td>• Discharge through the River,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Q-h relationship downstream in the river</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water levels in the Pannerdens Canal and IJssel River</td>
</tr>
<tr>
<td>Betuwe</td>
<td>Flooded area</td>
<td>• Inflow into the flooded area,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Water levels in the Waal River</td>
</tr>
<tr>
<td>Nijmegen (‘Land van Maas &amp; Waal’ area)</td>
<td>Flooded area and a part of the Waal River</td>
<td>• Discharge through the river,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Q-h relationship downstream in the river</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Downstream water levels in the Waal and Meuse Rivers</td>
</tr>
</tbody>
</table>

The damage D of an area was calculated as:

\[
D = \sum_{i=0}^{m} \left( \int_{h=0}^{h_{\text{max}}} \alpha_i(h) \cdot n_{id}(h) \cdot D_{i,\text{max}} \cdot dh \right)
\]  

(Eq. 4.1)

With:

- \(D\) = damage of the area [€]
- \(\alpha_i(h)\) = damage factor of the damage category \(i\), depending on the water depth \(h\) [-]
- \(h\) = water depth [m]
- \(n_{id}(h)\) = number of units in category \(i\) with flooding depth \(h\) [-]
- \(D_{i,\text{max}}\) = maximum damage per unit in category \(i\) [€]
- \(m\) = number of categories

The damage factor \((\alpha_i)\) of each damage category \(i\) is derived from the damage function of that category. This factor represents the influence of hydraulic conditions such as the depth of flooding. These functions were taken from Vrouwenvelder (1997) and Waterloopkundig Laboratorium et al. (1994b). The total damage in an area is the sum of the damage in all damage categories. Examples of damage categories and their units are agriculture (ha), houses (number of objects), infrastructure (km length), and insurance companies or banks (number of employees). For detailed information reference is made to Vrisou van Eck et al. (1999). The influence of locally applied damage reduction measures (placing of sandbags, building emergency dikes etc.) was not considered in this research. Furthermore, the influence of water quality was not incorporated.

The number of casualties resulting from floods is very uncertain. In this research the assumption was used that maximum one per thousand of the affected persons dies during the flood.
4.3.2 THE RESULTING FLOOD PATTERNS AND FLOOD IMPACTS OF EACH BREACH SCENARIO

This section gives an overview of the consequences of each dike breach by discussing the effects of the flood on the flood wave that continues flowing down the river and describing flood impacts within the flooded area behind the breach.

**Rees**

The flow through the breach at *Rees* results in a significant peak reduction of the flood wave. The maximum inflow through the breach is about 3,800 m$^3$/s given a wave with peak of 18,000 m$^3$/s. This maximum inflow through the breach is reached when the peak of the flood wave has already passed through the river. A flood wave with a peak of 18,000 m$^3$/s reaches about 16,300 m$^3$/s downstream of the breach. This means that the dike breach at *Rees* lowers flood probabilities downstream. Water levels in the river downstream remain below design water levels.

The volume of water that flows through the dike breach on the right bank of the river near *Rees*, will follow the bed of the Old IJssel River and enter the IJssel valley. A large quantity of water flows over the embankment along the IJssel River into this river (At maximum 2,800 m$^3$/s, given a discharge of 18,000 m$^3$/s at Lobith). This extra volume of water in the IJssel River may cause further floods downstream.

The resulting flood covers a large area. Water depths will vary between 0.5 and 4 m resulting in a damage of about 7 billion € (Table 4.5). As mentioned before, damage may be underestimated because flooding of other areas along the IJssel River may occur as well.

**Kalkar**

A dike breach on the left bank of the Niederrhein near *Kalkar* (kilometre 841) results in the flooding of the Ooij-Duffelt polder area (Figure 4.9). Water will flow through this area parallel to the river as far as Nijmegen, where it will flow back into the Waal River. A peak of 18,000 m$^3$/s will result in a flow of about 2,600 m$^3$/s from the polder area back into the Waal River 110 hours after the initiation of the breach. At that moment, the discharge through the Waal River is no longer extremely high. Since the inflow back into the Waal River will not result in a river discharge which exceeds the design discharge, no further downstream floods are expected. The damage is assessed at about 3.6 billion € (Table 4.5).

**Lobith**

The third scenario implies a dike breach near *Lobith*, which causes a water flow through the former riverbed of the Rijnstrangen area and from there to the IJssel River (Figure 4.9). The results of the simulations show that a dike breach near Lobith has considerable consequences in the area itself and significantly lowers the probability of floods downstream. Given a flood wave with a peak of 18,000 m$^3$/s about 700 m$^3$/s will flow from the flooded area back into the IJssel River. However, extra simulations with Sobek-1D model showed that this inflow results in river water levels that do not exceed design water levels except at a few locations along the IJssel River. Because the embankments along large parts of the IJssel River are based on a former design discharge, which is higher than the current design discharge, no further downstream effects are expected.
The fourth scenario would cause the flooding of Netherlands’ largest dike ring along the rivers: the Betuwe. The breach in this area increases safety along the Waal River and along other Rhine branches. However, during the events design water levels are exceeded with about 20 to even 35 cm at different locations along the Nederrijn, IJssel and Waal. Normally, dikes are at least 50 cm higher than the design water levels. It is therefore uncertain whether further floods will occur. Important issues to consider when discussing the effects of the flooding of the Betuwe area on other dike rings along the Rhine River are:

- The northern dike along the Nederrijn / Lek River branch is high and there are hills situated along this side of the river, therefore no floods are expected north of the river.
- The southern dike along the Nederrijn/Lek threatens the Betuwe dike ring, which is
flooded in this scenario. Although breaches in this dike will increase damage slightly, no dramatic increase in damage is expected due to more breaches along the same area. Further damage increase due to floods along the Nederrijn is therefore not likely.

- Along almost the whole IJssel River dikes are based on higher discharges than the design discharge. However, there is a small section where this is not the case. Floods might occur there.
- Along the Waal River further floods may occur, design water levels are exceeded by about 35 cm (the level of the dike should at least be equal to the design water level + 50 cm).

The flood pattern resulting from a breach in a dike along the Betuwe was found to be quite uncertain. First, the water will flow to the west until it meets the Diefdijk and fill up the Betuwe area. Then the sequence of events becomes more unpredictable. In the past the Lingewerken outlet structures (Provincie Zuid-Holland, 1990) allowed the water to flow back into the River Waal which sometimes prevented flooding of the Alblasserwaard at the west side of this Diefdijk (Figure 4.10). In this case study in which very extreme events were considered, water was assumed to flow over the Diefdijk into the Alblasserwaard dike ring, which results in a substantial increase in the damage. Due to the overflowing water this secondary dike (Diefdijk) may even breach, which would raise the expected damage even further. The flooding of the Alblasserwaard from the Betuwe area is a clear example of a negative effect of hydraulic system behaviour, as discussed in section 4.2.2.

Assuming that the Diefdijk does not breach the resulting damage is 16 billion € given a flood wave with a peak level of 18,000 m³/s. Although it takes some days, the lower end of the
Betuwe polder will eventually be flooded very deeply (> 5 m) (Figure 4.9). The vast area which is affected and the large flooding depths explain the tremendous economic damage which would result (Table 4.5).

**Nijmegen**

The fifth scenario implies a dike breach just downstream of Nijmegen. This is the least likely scenario, as it may happen only when a flood wave travels along the entire Nordrhein-Westfalen tract of the Rhine and along the Waal River up to a point downstream of Nijmegen without causing floods. A breach in the Land van Maas and Waal results in a significant lowering of the maximum water levels on the Waal River. Water levels on the IJssel River, Pannerdens Canal and Nederrijn River are lowered by this breach, but they still exceed the design water levels. This means that a combination of a breach near the Land van Maas and Waal and breaches along the IJssel or Nederrijn is possible.

A breach downstream of Nijmegen also endangers the areas along the Meuse River. Given a flood wave of 18,000 m$^3$/s, about 1,900 m$^3$/s will flow from the flooded area into the Meuse River. Since the design discharge of the Meuse River is only about 3,800 m$^3$/s, this extra discharge may cause the flooding of other areas along the Meuse River. Therefore, the given damages can be regarded as underestimations. The expected damage in the Land van Maas and Waal polder area only is 3.7 billion € (Table 4.5).

### 4.3.3 SUMMARY AND DISCUSSION OF THE RESULTING FLOOD IMPACTS

Although it is still not clear what will happen when a discharge occurs that exceeds the design discharge, an idea of what could happen has been developed. The exact location of a dike breach is difficult to forecast, but by assuming different locations an impression of consequences of possible discharges exceeding the design discharge can be given. The areas that may be flooded and the resulting damage and number of affected persons can be determined.

The tables 4.5 and 4.6 show the resulting impacts per breach. Although the figures are not very accurate, some important observations can be made. First of all, the consequences of a dike breach are enormous. The economic damage lies between 1.2 and 25 billion €, while the number of affected persons may be between about 54,000 and 480,000. Furthermore, this research shows the differences in potential impacts between different locations of the breach, with the worst situation clearly being a dike breach in the Betuwe area.

**Table 4.5 Direct primary damages of the disaster scenarios assuming that only one breach will occur and not incorporating hydraulic system behaviour for the three flood waves in billion €**

<table>
<thead>
<tr>
<th>Discharge at Lobith (m$^3$/s)</th>
<th>16,000</th>
<th>18,000</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rees</td>
<td>6.4</td>
<td>6.9</td>
<td>7.3</td>
</tr>
<tr>
<td>2. Kalkar</td>
<td>3.6</td>
<td>3.6</td>
<td>3.7</td>
</tr>
<tr>
<td>3. Lobith</td>
<td>1.2</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>4. Betuwe</td>
<td>12.0</td>
<td>16.1</td>
<td>25.0</td>
</tr>
<tr>
<td>5. Nijmegen</td>
<td>3.5</td>
<td>3.7</td>
<td>3.9</td>
</tr>
</tbody>
</table>
The results in the tables 4.5 and 4.6 must be considered as rough estimates and serve as an indication of the order of magnitude of the damage. In the simulations a simple elevation model was used, which does not adequately represent the dikes, waterways and houses. Furthermore, breach growth was not determined but imposed as a boundary condition, only the failure mechanism overflow was accounted for, and damage was estimated with the Standard Damage Module, which means that factors such as warning time, preparation and human behaviour were neglected. Water quality effects were also neglected. Therefore, the results must be interpreted very carefully. The uncertainties in these results were not quantified. For a detailed description of all estimations, boundary conditions, assumptions and simplifications reference is made to De Bruijn (2002b).

Table 4.6 The number of affected persons assuming that only one breach can occur. The number of casualties is supposed to be equal to the number of affected persons divided by 1000

<table>
<thead>
<tr>
<th>Discharge at Lobith (m³/s)</th>
<th>16,000</th>
<th>18,000</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rees</td>
<td>244,200</td>
<td>250,800</td>
<td>258,500</td>
</tr>
<tr>
<td>2. Kalkar</td>
<td>53,600</td>
<td>54,000</td>
<td>54,000</td>
</tr>
<tr>
<td>3. Lobith</td>
<td>73,882</td>
<td>97,838</td>
<td>104,410</td>
</tr>
<tr>
<td>4. Betuwe</td>
<td>401,000</td>
<td>450,000</td>
<td>478,000</td>
</tr>
<tr>
<td>5. Nijmegen</td>
<td>132,000</td>
<td>132,000</td>
<td>132,000</td>
</tr>
</tbody>
</table>

To estimate the effects of a peak discharge on the whole flood risk management system, hydraulic system behaviour has to be incorporated as was explained in section 4.2.2. We have to know which breach location is the most likely one and whether only one or more than one breach can be expected. In the discussions in the previous section the effects of the breaches on downstream water levels and discharges were included. Based on these effects, assumptions on hydraulic system behaviour can be made. Figure 4.11 presents an overview of...
the flood direction after each breach and the danger for other areas. In case of a peak discharge level of 16,000 m$^3$/s, a single breach failure seems most likely. However, for higher flood waves more than one dike ring area may become flooded. A wave of 18,000 m$^3$/s at Lobith and a breach at Rees may result in the flooding of different dike rings along the east and west side of the IJssel River. A wave of 18,000 m$^3$/s at Lobith and a breach at Kalkar will probably only cause the flooding of the Ooij-Duffelt polder area. A flood wave of 18,000 m$^3$/s at Lobith and a breach at Lobith will probably result in the flooding of the dike ring Rijn & IJssel. A breach in Betuwe dike ring due to a flood wave of 18,000 m$^3$/s at Lobith may result in both the flooding of the Betuwe area and the Alblasserwaard area. Furthermore, floods along the other Rhine branches may occur. A breach at Nijmegen will result in the flooding of the ‘Land van Maas en Waal’ dike ring and probably also in floods along the Meuse River.

4.4 THE RESILIENCE OF THE CURRENT SYSTEM

4.4.1 REACTION THRESHOLD

The reaction threshold of the system is high. The recurrence time of the lowest discharge that is expected to cause significant damage is about 1250 years. This high reaction indicates a resistant system.

4.4.2 AMPLITUDE

The amplitude can be quantified by the Expected Annual Damage (EAD) and the Expected Annual Number of Casualties (EANC). The previous section discussed the consequences of dike breaches. To assess the probability of these consequences and to calculate the EAD, the conditional probabilities of the occurrence of dike breaches and flood waves must be assessed (See equation 4.1).

$$D(Q) = \sum_{b=1}^{B} \left[ P(b \mid Q) D(b, Q) \right]$$  \hspace{1cm} (Eq. 4.1)

With:
- $D(Q)$ = Damage resulting from a discharge Q at Lobith (billion €)
- $b$ = a breach location number, $B$ = number or breach locations considered.
- $P(b \mid Q)$ = Probability of occurrence of a breach at location b given discharge Q;
- $D(b,Q)$ = Damage resulting from a breach at location b and a discharge Q at Lobith (billion €)

As explained in the previous section, the probabilities of occurrence of breaches are unknown and are also interrelated through hydraulic system behaviour. Therefore, assumptions had to be used in order to be able to continue with this analysis. To get an impression of the sensitivity of the final risk for the assumption three different sets of assumptions were compared (Tables 4.7, 4.8 and 4.9).
The probability that a breach occurs at a specific location is smaller for lower flood waves. It is thus more likely that a lower flood wave will pass the upper Rhine without causing breaches. The physical maximum of the discharge at Lobith is estimated at around 18,000 m$^3$/s to 20,000 m$^3$/s (Dijkman et al., 2003). Recently, even lower estimates of the physical maximum discharge at Lobith have been found (Lammersen, 2004) (see section 4.2.1). This means that if a flood wave with a peak of approximately 20,000 m$^3$/s would occur at the upstream boundary of the flood risk management system, floods in Germany are considered almost certain. Therefore, the conditional probabilities for breaches in Germany corresponding with that discharge level are high. In the assumptions used in the figures in table 4.7 the probabilities of a breach at Rees and Kalkar are assumed to be comparable, because they are located along the same part of the river, one at the left bank and the other at the right bank.

Since the flood probabilities of the different dike rings along the Rhine are related, flooding of one area reduces or increases the danger for other areas. The probability of a second or third breach depends on the rate of growth of the first dike breach and the effects on the discharge division over the different branches (see the section on hydraulic system behaviour 4.2.2). When a dike breaks, the other areas are often assumed to be safe. This research shows that this assumption is not always valid. However, to be able to make a rough assessment of the order of magnitude of total flood risk, this assumption is adopted here and used in the results presented in table 4.7.

Table 4.7 Damage (billion €) and breach probabilities assumed for each breach location and discharge level (see the explanation at equation 4.1)

<table>
<thead>
<tr>
<th>Discharge at Lobith (m$^3$/s)</th>
<th>16,000</th>
<th>18,000</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>P(b</td>
<td>Q)</td>
<td>D(b,Q)</td>
</tr>
<tr>
<td>Rees</td>
<td>0.2</td>
<td>6.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Kalkar</td>
<td>0.2</td>
<td>3.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Lobith</td>
<td>0.2</td>
<td>1.2</td>
<td>0.12</td>
</tr>
<tr>
<td>Betuwe</td>
<td>0.2</td>
<td>12</td>
<td>0.06</td>
</tr>
<tr>
<td>Land van Maas &amp; Waal</td>
<td>0.2</td>
<td>3.5</td>
<td>0.02</td>
</tr>
<tr>
<td>$D_Q$</td>
<td>5.3</td>
<td>5.5</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 4.8 Damage (billion €) and assumed breach probabilities for each breach location and discharge level (assuming that the Betuwe area will become flooded more frequently than indicated in table 4.7)*

<table>
<thead>
<tr>
<th>Discharge at Lobith (m$^3$/s)</th>
<th>16,000</th>
<th>18,000</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>P(b</td>
<td>Q)</td>
<td>D(b,Q)</td>
</tr>
<tr>
<td>Rees</td>
<td>0.2</td>
<td>6.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Kalkar</td>
<td>0.2</td>
<td>3.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Lobith</td>
<td>0.1</td>
<td>1.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Betuwe</td>
<td>0.3</td>
<td>12</td>
<td>0.1</td>
</tr>
<tr>
<td>Land van Maas &amp; Waal</td>
<td>0.2</td>
<td>3.5</td>
<td>0.05</td>
</tr>
<tr>
<td>$D_Q$</td>
<td>6.4</td>
<td>6.1</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*see the explanation at equation 4.1
Table 4.8 shows the results obtained when the probabilities of a breach given an extreme flood wave are changed in order to study the effect of more frequent breaches of the Betuwe area. This area has the highest potential damage.

Table 4.9 demonstrates the figures resulting when the expected cascade effects and the possibility of multiple breaches are taken into account. The damage in the flooded areas is assumed to be equal for cases with one or multiple breaches. In reality, this damage may be less when more than one area becomes flooded, since there is less water available for each breach location separately. However, the uncertainty in whether or not a polder becomes flooded is far more important than the differences in damage resulting from a flood.

The following assumptions were used in table 4.9:
- The damage resulting from a breach near Rees is twice as high as the damage assessed in the area behind the breach only, due to floods further downstream along the IJssel River;
- The damage resulting from a breach in the embankment along the Land van Maas & Waal area is two times as high as the damage in the area itself, since also floods along the Maas River will occur.

Although the assumptions behind the tree tables are disputable, the three sets together give an indication of sensitivity of the risk for different possibilities of hydraulic behaviour of the system.

Table 4.9 Damage (billion €) and assumed breach probabilities for each breach location and discharge level (assuming that multiple breaches and cascade effects may occur as indicated in the text above)

<table>
<thead>
<tr>
<th>Location</th>
<th>Discharge at Lobith (m³/s)</th>
<th>16,000</th>
<th>18,000</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P(b</td>
<td>Q)</td>
<td>D(b,Q)</td>
<td>P(b</td>
</tr>
<tr>
<td>Rees</td>
<td>0.2</td>
<td>6.4</td>
<td>0.4</td>
<td>14</td>
</tr>
<tr>
<td>Kalkar</td>
<td>0.2</td>
<td>3.6</td>
<td>0.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Lobith</td>
<td>0.2</td>
<td>1.2</td>
<td>0.12</td>
<td>1.8</td>
</tr>
<tr>
<td>Betuwe</td>
<td>0.2</td>
<td>12</td>
<td>0.06</td>
<td>16.1</td>
</tr>
<tr>
<td>Land van Maas &amp; Waal</td>
<td>0.2</td>
<td>7</td>
<td>0.02</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>D₀</td>
<td>6.0</td>
<td>8.3</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*see the explanation at equation 4.1

Table 4.10 Annual discharge probabilities and the corresponding damage (billion €) and number of affected persons and casualties derived from table 4.7

<table>
<thead>
<tr>
<th>Probability</th>
<th>Discharge at Lobith (m³/s)</th>
<th>D₀</th>
<th>Affected persons</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/600</td>
<td>15,000</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/1250</td>
<td>16,000</td>
<td>5.3</td>
<td>180,936</td>
<td>181</td>
</tr>
<tr>
<td>1/6000</td>
<td>18,000</td>
<td>5.5</td>
<td>163,300</td>
<td>163</td>
</tr>
<tr>
<td>1/10000</td>
<td>18,740*</td>
<td>5.4</td>
<td>158,774</td>
<td>159</td>
</tr>
<tr>
<td>1/100000</td>
<td>20,000</td>
<td>5.2</td>
<td>151,066</td>
<td>151</td>
</tr>
</tbody>
</table>

*The damage corresponding with this discharge is interpolated from the other results and not calculated as described in 4.3.1.
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The damage corresponding with a flood wave probability of 1/6000 a year in table 4.10 is a little higher than the damage corresponding with smaller probabilities. This may seem strange. However, it is explained in table 4.7: Because it is very unlikely that extreme discharges will pass the German areas without causing breaches, and because these breaches will reduce downstream flood probabilities enormously, it is unlikely that these most extreme discharges will reach the Betuwe area. The lower extreme discharges, however, have a higher probability of passing along the German areas and reaching the Betuwe area. Because the Betuwe area has the highest potential damage, discharges that are expected to cause floods in that area result in higher damage than those that are not expected to result in a flood in that area.

The resulting risk is determined as:

$$ R = \int_{Q_0}^{Q_{\text{max}}} D(Q)P(Q)dQ \quad \text{(Eq. 4.2)} $$

With: $Q_0 =$ Highest discharge with zero damage ($\text{m}^3/\text{s}$) and $Q_{\text{max}} =$ Discharge with an annual probability of exceedence of 1/10000.

Table 4.10 shows the probabilities of the different discharge levels. By assuming that the flood waves used and their consequences represent the whole regime of peak discharges and their consequences, the equation above can be solved. In this exercise a linear interpolation between the damages and the corresponding probabilities was used. The damage corresponding with a discharge of about 19,000 $\text{m}^3/\text{s}$ at Lobith has a probability of about 1/10000 a year. Therefore, this discharge is the highest discharge considered here. Based on the assumptions mentioned before, an EAD of about 6 M€/yr is found. If the Betuwe floods more frequently as indicated in table 4.8, the resulting EAD is 7 M€/yr. Assuming multiple breaches and downstream cascade effects as shown in table 4.9 results in an EAD of 8 M€/yr. The order of magnitude of the EAD is thus the same for all three sets of assumptions. The exact hydraulic behaviour is in this case thus not relevant for the total flood risk. However, as discussed above, hydraulic system behaviour is important when discussing the consequences of a certain breach location and to estimate flood probabilities of the dike rings. The expected number of casualties (EANC) was estimated in the same way. This resulted in about 0.2 casualties per year.

4.4.3 Graduality

Figure 4.12 shows that the graduality of the current system is low. Discharges with probabilities less than 1/600 per year do not cause any damage, while discharges of 1/1250 per year cause enormous damage. The graduality is only 0.25 (based on the assumptions indicated in table 4.9).
4.4.4 Recovery rate

The recovery rate is indicated by the recovery capacity of the system (see chapter 3). The physical, economic and social factors that determine the recovery capacity are discussed below.

The physical capacity of the system to recover is reflected by the expected duration of flooding. In the Betuwe area ancient outlets in the dikes are present, which consist in dike parts that are easy to remove. A large part of the water can be released through these outlets, however the remainder has to be drained by the drainage system used in normal conditions. The time needed to remove the water from the area is estimated as seven weeks (Provincie Zuid-Holland, 1990; WL | Delft Hydraulics, 2001). In the other areas the flood duration depends among others on the volume of water in the area, the presence of outlet structures, and the elevation pattern. The flood duration of the dike rings in the system is probably between five and eight weeks. Therefore, the physical capacity of the whole system is estimated as 6 to 7 (see chapter 3).

The economic capacity to recover is defined as the capacity to repair damage, to restore the old situation and to prevent further spreading of economic effects. As explained in section 4.2.3 the Netherlands is prosperous. Most people will be able to fund their own repairs. Besides, it is very likely that the government and the people in the Netherlands outside the flooded area will help them recover. Depending on the location and duration of the flood, spreading to other areas may occur. A flood in the eastern dike rings which have a relatively low population density and little industry will affect the Dutch economy less than floods in, for example, the Betuwe area. However, also in these areas significant spreading of flood impacts is not expected, as is explained by the following:

- As explained before, trade and the chemical industry, mainly situated in the west, are very important to the Dutch economy. These economic activities happen outside the flood risk management system.
- The effect of indirect flood losses caused by floods in the western part of the Betuwe (called TCW) was studied by WL | Delft Hydraulics (2001). If 70% of the products
from the TCW can still be delivered to other companies, or can be replaced by products from other locations, damage is estimated as 22 M€ (0.14% of the tangible direct damage in the Betuwe area).

- The most important economic activity in size of area is the agricultural sector. However, flooding of agricultural land is not expected to cause major effects on the economy of the Netherlands since, first of all, the contribution of the agriculture to the GDP is not high and secondly, floods normally occur in winter time and will therefore probably only reduce harvests or prevent cultivation of some areas. However, no complete harvests will be lost. The more vulnerable agricultural crops such as horticulture and glasshouses are normally located on higher spots and will thus face lower water depths and shorter flood durations.

- Effects on other areas may also occur due to loss of transport facilities in the flooded. Potential flood damage to the important highways and railways with a duration of 5 weeks is estimated at about 7.6 M€ (WL | Delft Hydraulics, 2001). In this estimate only extra travel time is incorporated. If floods result in transport companies avoiding Rotterdam Harbour the damage to the Netherlands will be much higher. Total costs due to losses of the use of the A15, A2 and the Waal River were estimated as 8.3 M€ (6 weeks of 6 work days no use), which is about 0.05% of the tangible direct damage.

- DWW (2003a) has assessed the secondary damage in the Netherlands in general without including site-specific characteristics as about 1% of the total damage after a flood.

Altogether, it is very likely that people will manage to find funds for reconstruction, maintain their income and that spreading of effects is prevented. Therefore, the economic capacity is estimated as 9.

The social recovery capacity scores an 8. In the Netherlands people are highly educated, communication is effective, the organizational capacities of communities are high and people are healthy. The distribution of income in the Netherlands is relatively equal. The Gini-coefficient is 33 (0 is equal and 100 means that all income is earned by one person, (see chapter 3)) (CIA, 2002). More vulnerable inhabitants, such as children, elderly, disabled persons will probably be taken care of. The people that are most vulnerable are an extremely small group of outsiders living in cities such as homeless people, illegal people, owners of small companies and their employees, house owners with extremely high mortgages and people that cannot cope with stress. However, preparation to floods is extremely low. The experience with floods and cultural knowledge of floods is about zero. The last river flood occurred in 1926 and most inhabitants consider the area to be safe. Even now, only eight years after 1995 when many people were evacuated, people feel completely safe again. Therefore, panic and shock are likely and unwise actions, such as traffic jams on the low-lying A15, are possible.

4.5 DISCUSSION AND CONCLUSIONS

This case study increased the knowledge on flood impacts, flood risks and resilience of the Lower Rhine River. Although it is not yet possible to assess what will happen when an
Current resilience of the flood risk management system of the lower Rhine River

extreme flood wave enters the flood risk management system, section 4.3 clearly shows an overview of what may happen. In the Lower Rhine River it is unsure where dike breaches will occur and how a breach at one dike ring influences the flood probabilities of other dike rings. By choosing dike breach locations in a logical way such that the full range of possible dike breach locations is represented, insight was obtained in the consequences of breaches at one location. The case study showed that flood damage differs between different dike breach locations: a dike breach along the Betuwe area results in about 8 to 10 times as much damage as a dike breach near Lobith.

To integrate the flood damages that resulted from a certain flood wave and a specific dike breach location into total flood damages for the whole system different sets of assumptions were used. These assumptions were based on simulated and expected hydraulic system behaviour. The different sets of assumptions indicate the sensitivity of the results for the assumptions used. The damages resulting from certain flood waves were combined to find the amplitude of the flood risk management system of the Lower Rhine River. The assumptions used in the process did not change the order of magnitude of the resulting flood risk. For all three sets of assumptions the current amplitude is around 6-8 M€/yr. The case study also indicated factors that influence recovery from flood damages in the Lower Rhine River.

Table 4.11 Summary of the values for the different resilience indicators

<table>
<thead>
<tr>
<th>Resilience indicator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAD</td>
<td>6-8 M€/yr</td>
</tr>
<tr>
<td>EANC</td>
<td>0.2 casualty/year</td>
</tr>
<tr>
<td>Graduality</td>
<td>0.25</td>
</tr>
<tr>
<td>Recovery capacity</td>
<td>8 (Physical 6-7, Economic: 9, Social 8)</td>
</tr>
</tbody>
</table>

The resistance of the Lower Rhine River is rather high: floods are very rare. The system has therefore a low amplitude and a low graduality (Table 4.11). The recovery rate is high. The graduality is low because there is a wide range of peak discharges that do not cause damage, while discharges that exceed the design discharge have enormous impacts. The recovery rate is high mainly because the country of the Netherlands is prosperous and support from the non-flooded areas can be expected. Furthermore, the high communication level, the social equity and the fact that people are well educated also enable an efficient recovery process. The aspect that seems to limit the resilience of the system most is the graduality of the reaction to increasing flood waves. This result will be used in the next chapter when resilience strategies are discussed.

The case study learned that the definition of resilience and the indicators of chapters two and three are applicable. With these indicators an overview of the reaction of the system to the discharge regime is obtained. In the case of the Lower Rhine River, floods are rare, but when they occur they may have large impacts. However, the rich and well-educated inhabitants will recover quickly from those impacts. In the next chapter we will see whether thinking from a resilience perspective results in alternative strategies for the Rhine River and what the impacts of these strategies are.
5 FUTURE FLOOD RISK MANAGEMENT STRATEGIES FOR THE LOWER RHINE RIVER 5

5.1 INTRODUCTION

This chapter discusses future management strategies and their effect on the resilience of the system. Chapter 4 showed that the current strategy results in a system with a very low graduality: normally no floods occur, but if floods do occur, they are catastrophic. Therefore, in order to improve the system’s resilience, especially the system’s graduality should be improved.

The chapter starts with an overview of current flood risk management and research on alternatives for the current flood risk management strategy. As a first exploration of alternative strategies for the far future, strategies based on spatial planning measures were developed in the research projects ‘Living with floods’ and River-and-Land (Vis et al., 2003). These strategies were assumed to increase the resilience of the region. However, no clear definition of resilience was given in that project and resilience was not quantified. This chapter aims at quantifying the resilience of these strategies according to the definition developed in chapters two and three. Furthermore, the usefulness of the concept of resilience for flood risk management of the Lower Rhine River is discussed.

The strategies that are discussed in this chapter are:

0. Extension of the current strategy into the future.

1. Compartmentalization combined with flood probability differentiation and physical planning.

2. ‘Green rivers’ combined with flood probability differentiation and physical planning.

3. River-and-Land: a strategy in which the river can flood large areas because all river embankments in the centre of the Netherlands except the northern dike of the Nederrijn/Lek and the southern dike of the Meuse River are removed.

The chapter first summarizes flood risk management and research on flood risk management in section 5.2. Secondly, scenarios for future changes are briefly discussed in section 5.3. The sections 5.4 to 5.7 present the different strategies and quantify their degree of resilience. In section 5.8 the strategies are evaluated and finally, in section 5.9, conclusions are drawn.

5 Parts of this chapter have been published as De Bruijn (2002a); Vis et al. (2003); and De Bruijn (2002b)
5.2 Flood risk management of the Lower Rhine River

5.2.1 Present flood risk management of the Lower Rhine River

The present flood risk management strategy is the result of developments which started centuries ago. The first inhabitants of the Lower Rhine Catchment had to adapt their lives to the river floods. They lived mainly on the higher grounds or they constructed mounds to live on. Around 1000 AD, when the population grew and technology became more advanced, people started to inhabit the lowlands and built dikes to protect themselves. Already in 1400 AD an almost completely closed dike system existed along the rivers (Commissie Rivierdijken, 1977). Dike breaches occurred regularly, leading to dike improvements after each case. Furthermore, huge changes in the course of the river and the riverbed in the form of regulation and canalisation took place (Janssen and Jorissen, 1996). The river was confined and controlled more and more. The last major flood of the Rhine River occurred in 1926, after which the dikes were improved again (Commissie Rivierdijken, 1977).

In 1953 a major flood from the North Sea took place, which incurred new regulations for safety in the Netherlands not only for the coast but also for the rivers. Previously, heights of river dikes were based on the maximal recorded water level, but since 1953 a more scientific base has been used. The Delta Commission concluded in 1960 that an approach based on flood risks would be preferable, but that flood risks could not be assessed yet. Therefore, a safety standard was developed that was based on the demand that dike levels should exceed water levels related to a discharge with an annual probability of exceedence of 1/1250 (DWW, 2003b; Commissie Rivierdijken, 1977). Since the range of measured discharges includes only 100 years, the design discharge level depends on the used method and is highly uncertain. Therefore, the procedure to estimate this design discharge is also part of the safety standard in the Netherlands. Every five years the design discharge is calculated anew based on the recorded discharges.

In 1993 and 1995 extremely high discharges occurred which provoked new interest in flood risk management policies. The extreme discharges of 1993 and 1995 increased the design discharge with an exceedence probability of 1/1250 from 15,000 to 16,000 m$^3$/s at Lobith. Following common practice, this increase in the design discharge would be expected to result in dike strengthening. However, new strategies are explored nowadays creating room for the rivers (Min. VROM and V&W, 1997).

The current flood risk management of the Lower Rhine River is thus focused on flood prevention and on designing the river in such a way that the discharge capacity equals or exceeds the design discharge. This strategy of flood prevention by building dikes has certainly contributed to the development of the Netherlands. However, the strategy also has weak points, which are discussed below (Vis et al., 2001).

Firstly, the current strategy is based on one design discharge for the entire area threatened only by floods from the Rhine River in the Netherlands. This approach leads to the same level of protection for areas with very different potential flood impacts. As chapter 4 showed, the damage resulting from breaches at the Betuwe area are about 10 times as high as damage resulting from a breach near Lobith. Dike rings with varying sizes and with large differences
in potential damage, all have dikes that are based on the same water level exceeding probability. The question arises if this is economically sensible.

Secondly, due to the fact that this strategy focuses on preventing floods, until about a decade ago little attention was paid to the potential consequences of floods, emergency measures and flood mitigation measures which also lower flood risks (Vis et al., 2001). To the inhabitants safety may seem very certain. However, they are protected only for discharges equal to or less than the design discharge.

Thirdly, restricting the natural dynamics of the river and its floodplains has created a system in which dangerous floods can occur. The water defence structures require a continuous attention, otherwise the river dynamics will damage these works and the river will try to return to its own natural behaviour. Because of the restriction of the river to narrow floodplains, large amounts of sediment were deposited resulting in a significant increase of their level (Janssen and Jorissen, 1996). The increasing level of the floodplains implies less room for the river and thus higher water levels and an increased flood risk. Besides, the land surface in the Netherlands is subsiding by the improved drainage of the land and soil composition of the area. When a dike breaches or flows over, water will enter relatively low-lying areas where many people live and work. Restricting natural dynamics has thus created a black and white situation: either the protected areas are not flooded or they are catastrophically flooded. If it were possible to avoid these sudden catastrophic floods and increase graduality without losing the important economic advantages of the low frequency of the floods, that would be favourable.

Finally, the current strategy is considered to have caused a destruction of river scenery and damage to nature and to cultural values. Recently, these values have become more important (Vis et al., 2001).

Not only these weak points, but also new technologies, new norms and values and other changes in society may require a new flood risk management strategy (Vis et al., 2001). Firstly, the potential flood damage has increased with economic development and will continue to grow. Secondly, the inhabitants do not longer accept disastrous floods as an act of God or nature, but instead they will blame the government (Commissie Waterbeheer 21<sup>e</sup> eeuw, 2000; Penning-Rowsell & Fordham, 1994). It is therefore questionable whether very rare disasters are preferable over more frequent non-catastrophic floods. Thirdly, new technology has increased the possibilities to make accurate flood forecasts and flood warnings. Also the possibility to anticipate on peak flows by opening an inlet structure and using a detention area has grown. These technologies make it easier to regulate floods and therefore reduce the need to prevent floods in all circumstances. All these developments ask for a careful evaluation of both the current and alternative strategies for flood risk management.

5.2.2 RESEARCH ON MEASURES AND STRATEGIES FOR THE LOWER RHINE RIVER

As explained in the previous section, changes in the societal preferences and the available technology ask for the consideration of alternative strategies for flood risk management. To
be able to cope with flood waves now and in the future short-term strategies (within 10 to 15 years) for flood risk management, long-term strategies (within 50 years) and strategies for the far future (within 100-300 years) were developed in the Netherlands. Table 5.1 presents an overview of the corresponding research projects.

In short-term research projects the design discharge is not disputed. These projects describe alternative measures that increase the discharge capacity to the new design discharge capacity. Examples of such measures are dike raising, lowering the unprotected parts of the floodplains, removing obstacles from the river and embankment relocations (Min V&W-DON, 1999).

In long-term research projects even the safety standard itself is subject of research. In the FLORIS project it is studied whether it is possible to change from a safety standard based on a design discharge to risk-based flood risk management (DWW, 2003b). In order to have the same flood risk in different areas, large vulnerable areas will need higher flood protection levels than, for example, small agricultural areas. Consequently, this risk-based policy may result in a differentiation of flood frequencies. Because this policy will eventually lead to differentiation of protection levels and flood probabilities and thus to a more gradual response to floods, it may increase the resilience of the total system.

By studying flood risks, not only discharge probabilities, but also the potential consequences of flood waves were considered. Furthermore, this risk approach made decision makers more conscious of the possibility that discharges may occur that exceed the design discharge. To be able to react adequately on such extreme events, strategies are being developed that include emergency detention areas: areas that will be inundated first to protect areas with a high potential damage from flooding (Commissie Noodoverloopgebieden, 2002). This identification of emergency detention areas caused a lot of discussion in the Netherlands.

Another change in long-term research projects is that not only measures in the riverbed and dike relocations, but also measures with a large impact on land use planning are studied. Examples of such measures are detention areas and green rivers or bypasses, which are, for example, used for agriculture or as natural reserves most of the time and for discharge during periods of extreme peak flow (Kors & Alberts, 2002).

For the far future completely new strategies to cope with flood waves are explored. Climate change and land use change are very important issues in these strategies. An example of a strategy for the far future that is being studied is River-and-Land project in which all dikes are being removed except the most northern dike of the northern branch of the Rhine and the southern dike of the Meuse River. This strategy allows the rivers to flood large areas and to create new channels. The river is no longer adjusted to the land use, but instead the land use in the alluvial area is adjusted to the frequent floods. The River-and-Land strategy and two other strategies, namely ‘compartmentalization’ and ‘green rivers’ are discussed and evaluated in the next sections.
Table 5.1 Recent and ongoing research on flood risk management for the Lower Rhine River

<table>
<thead>
<tr>
<th>Term</th>
<th>Title</th>
<th>Description</th>
<th>*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term</td>
<td>Room for the Rhine River (RvR)</td>
<td>River design measures to increase the discharge capacity up to the new design discharges (Rhine: 16,000 m³/s, Meuse: 3,800 m³/s).</td>
<td>1</td>
</tr>
<tr>
<td>Long term</td>
<td>Resilience Rivers</td>
<td>What if the design discharge increases to 18,000 m³/s and the sea water level increases also with 60 cm? Research to prevent regret after implementing the study ‘Room for the Rhine River’.</td>
<td>2</td>
</tr>
<tr>
<td>Long term</td>
<td>Emergency detention areas</td>
<td>Identification of regions that should be inundated first, in case of a flood wave that exceeds the design discharge. This will finally result in a governmental decision about the realisation in 2005.</td>
<td>3</td>
</tr>
</tbody>
</table>
| Long term | FLORIS                                     | 1. What are flood risks in the different dike rings?  
2. Can safety be based on flood risks? | 4 |
| Far Future| River-and-Land                             | Exploratory research on living in the Netherlands without river dikes for protection against frequent floods. | 5 |
| Far future| Living with floods                         | Exploratory study on the consequences of continuing the current strategy and of alternative long-term flood risk management strategies. | 6 |


Summarizing, for the short term the Netherlands' water managers mainly put their trust on maintaining or increasing resistance. Not much change to the current strategy is expected. The usual river-orientated measures are proposed and flood risk management remains based on the design discharge. However, resilience may increase on the longer term. Changing the discharge distribution over the different branches and more attention for bypasses and detention areas may already introduce more graduality since, as a result of these measures, flood probabilities will differ per location. For the far future resilience strategies are studied. Measures such as education, adaptation of the land use, waterproofing of houses are not discussed in short term plans, but they do appear in long term policies and visions. Whether these strategies are implemented and whether resilience will increase in the far future remains a question which can only be answered after societal debate. In the following sections the resilience and impacts of the strategies for the far future are studied.

5.3 Scenarios for future change

Although the future is unknown, some trends can be foreseen already. Nowadays, scenarios are mostly defined as consistent storylines that create different contrasting images of the future. These scenarios help to study the uncertainty surrounding the future consequences of a policy. In the English research project on sustainable flood risk management (Office of Science and Technology, 2004), for example, four scenarios were used. These scenarios are distinguished by the system of governance and social values. The system of governance varies from autonomy where power remains at the local and national level to interdependence where power moves to international institutions. Social values range from consumerist to community-orientated values. The consumerist focuses on economic growth, while in the more community-orientated scenarios ecosystems and social equity are important (Office of Science and Technology, 2004).
In this case study only one likely future scenario was used. Consequences of uncertainties in the discharge increase, economic growth rate, land use changes and other developments on the resilience and evaluation scores have thus not been studied by using different scenarios. However, in the assessment of the evaluation criterion ‘sensitivity to uncertain changes’ (flexibility) (see table 2.3) the consequences of these uncertain developments were included. For the aim of this case study, testing the indicators and studying the usefulness of applying the resilience concept for flood risk management, the use of one likely scenario and assessing roughly the flexibility of the strategies seemed sufficient.

In this section first expected trends in the socio-economic system and secondly changes in the discharge regime are discussed. These expected changes are used as a scenario for the future in the following sections.

**Socio-economic trends**

In the Netherlands the following socio-economic trends are expected or already visible.

- First of all, the economic activities are expected to increase with an average annual growth rate that is highly uncertain. In this case study the expected damages in the future are estimated by assuming an overall economic growth rate of 2%. The use of the same percentage of economic growth for all areas results in a faster absolute economic growth in areas that are already more developed. This is in line with expectation.

- Secondly, population will increase. A study on long-term population growth in the Netherlands (De Jong & Hilderink, 2004) forecasts a population of 15 to 20 million inhabitants in 2050. In this case study the assumption of Baan & Klijn (1998), based on RPD (1997) which comprehends a population of about 18 million inhabitants in the Netherlands in 2100 is copied.

- Thirdly, the land use is expected to change: the agricultural area is expected to decline to create room for residential area, infrastructure and nature reserves (Vis et al., 2001). Labour intensive industries and agriculture are expected to move to eastern Europe and Asia and mainly high-value agriculture and knowledge intensive industries remain (Vis et al., 2001).

The flood risk management system is expected to show similar developments as the Netherlands as a whole. The area used for intensive dairy farming is expected to decline with 20% in 2100. On the other hand extensive animal husbandry for meat or pet animals will grow. This extensive grassland management is expected to form 25% of all grassland in 2030 (Veeneeklaas et al., 2001). The agricultural production function will be replaced by a recreation function in a landscape that still has an agricultural appearance. The horticultural area under glass is expected to increase, while the total area of horticulture is expected to decrease slightly. The built-up area will increase in the former agricultural areas. Economic growth is expected to concentrate between and around the cities of Arnhem and Nijmegen. Furthermore, a new Betuwe railroad that is being constructed is expected to induce new economic developments in the Betuwe area. New natural reserves are being developed along the river in the floodplains that flood every winter (Vis et al., 2001). The rivers will probably be more intensively used. The percentage of goods transported by ships is expected to increase in future (Baan & Klijn, 1998). These land use changes are considered in the design of the strategies (Vis et al., 2001).
Discharge trends
The discharge regime is expected to change as well. The variability is expected to increase: summer discharges may become lower, while extreme peak discharges are expected to increase. However, the uncertainty about these changes is enormous. The current design discharge at Lobith is 16,000 m$^3$/s with a 95% reliability interval of 13,000-19,000 m$^3$/s (Van de Langemheen & Berger, 2001). According to the Commissie Waterbeheer 21e eeuw (2000) the design discharge is likely to increase to approximately 18,000 m$^3$/s in 2100. Therefore, a design discharge of 18,000 m$^3$/s at Lobith with a probability of 1/1250 per year was selected for use in this study. Figure 5.1 show the present and a possible future set of probabilities for a range of discharges.

This section discusses discharges at Lobith, because the current recurrence times of the discharges at that location are known. However, the system boundary is situated more upstream, near Bonn, where the river flows from a natural valley into wide floodplains. The physical maximum discharge at Lobith is currently estimated at around 16,000 m$^3$/s, and it is expected to increase to about 18,000 m$^3$/s in the future (Dijkman et al., 2003). This maximum at Lobith is limited by floods in Germany. In the model simulations used to calculate the system’s resilience, discharges at Lobith were translated to equivalent discharges at Bonn. At Bonn discharges might occur which are equivalent to discharge levels which exceed the physical maximum at Lobith. These very extreme discharges will not reach Lobith, because they will cause floods in Germany.

Figure 5.1 The current probability curve and a possible future probability curve

The waveform that corresponds with these extreme discharges is the average waveform derived by the method of Klopstra & Duits (1999). In chapter 4 on the current resilience of the Lower Rhine River the same waveforms were used.

In literature only forecasts of the design discharge in 2100 can be found. There is no information on discharges with other probabilities. The discharge probability curves are thus unknown. Vis et al. (2001) assumed that the discharge corresponding with an annual probability of 1/10000 is 20,000 m$^3$/s at Lobith. This assumption was copied to be able to use the results of Vis et al. (2001) in this chapter.
5.4 **THE ZERO STRATEGY: EXTRAPOLATION OF THE CURRENT STRATEGY INTO THE FUTURE**

5.4.1 **DESIGN AND HYDRAULIC FUNCTIONING**

The current strategy was studied in the previous chapter. This current strategy of adapting the river design to be able to accommodate the design discharge is extrapolated to the far future. The river’s discharge capacity in this scenario is enlarged to the new design discharge of 18,000 m$^3$/s at Lobith.

5.4.2 **RESILIENCE OF THE STRATEGY**

**Amplitude**

The resulting flood impacts for this strategy were derived from the impacts calculated in chapter 4. Since the design discharge is very uncertain and the translation of discharges to water levels along the river is also uncertain, it was assumed that discharges above 17,000 m$^3$/s may cause damage. Flood waves with a peak of 18,000 m$^3$/s at Lobith will result in the damage calculated in chapter 4, corrected for an annual economic growth of 2% (Table 5.2). It was assumed that only one breach will occur. Exceptions are (see chapter 4):

- When a dike breach near Rees occurs, further floods along the IJssel River are expected, which increase the damage with a factor 2.
- When a breach near Nijmegen occurs, not only the Land van Maas & Waal area, but also areas along the Meuse river are assumed to become flooded. This doubles the damage.

| Discharge (m$^3$/s) at Lobith | 17,000 P(b|Q) | 18,000 P(b|Q) | 20,000 P(b|Q) |
|------------------------------|--------------|--------------|--------------|
| Location                     | D(b,Q)       | D(b,Q)       | D(b,Q)       |
| 1. Rees                      | 0            | 0.2          | 0.4          | 106          |
| 2. Kalkar                    | 0            | 0.2          | 0.4          | 27           |
| 3. Lobith                    | 0            | 0.2          | 0.12         | 18           |
| 4. Betuwe                    | 0            | 0.2          | 117          | 0.06         | 181          |
| 5. Nijmegen                  | 0            | 0.2          | 54           | 0.02         | 57           |

Table 5.2 Damage (billion €) and assumed breach probabilities for each breach location and discharge level* (assumptions are the same as used in table 4.9)

*see the explanation at equation 4.1

To calculate the EAD the probability of a dike breach given these discharges has to be known. As explained in chapter 4, different assumptions for dike breaches can be made (Table 4.7 to 4.9). Just as in the current situation discussed in chapter 4, these assumptions are not expected to change the order of magnitude of the EAD. Therefore, only one set of assumptions was used (Table 5.2).
Using the assumptions mentioned above, the EAD was found to be about 64 M€/yr. The expected number of casualties (EANC) was estimated in the same way, resulting in 0.2 casualties/yr.

**Graduality**
The graduality of the system in the future was found to be 0.15, which is comparable with the current graduality.

**Recovery rate**
The recovery capacity in the future scored an 8, just like the current recovery capacity. The current recovery capacity was discussed in section 4.4.3. The physical capacity is not expected to change in the future, since the physical characteristics of the system do not change. The economic characteristics are expected to change as was discussed in section 5.3. However, these changes do not significantly change the economic recovery capacity. The country is expected to be still prosperous and the main economic activities will still occur in the western part of the country. The more intensive use of agricultural practices, the increased high-value agriculture and the increased importance of the Betuwe as a transport route between the western part of the Netherlands, the industrial areas in Germany and the rest of Europe may increase the risk of spreading of effects. Also the increased dependency on communication lines as computer networks and electricity may affect spreading of effects. On the other hand, the opposite can also be true: increased flexibility may reduce dependency on certain electricity sources and on production inputs. Based on all these remarks it cannot be concluded that spreading of effects will significantly change. Therefore, the economic capacity of the future system is estimated as a 9. The value for the social capacity to recover in 2100 is difficult to estimate. The world vision in 2100 may be different from what it is now. People may have become more individualistic and equity may have become less. However, since there is no clear information on this subject, there is no reason to expect the social capacity to be different from the current social capacity. This capacity scores, therefore, an 8, which corresponds with the score found in section 4.4.3.

**Reaction threshold**
The reaction threshold of the system is not expected to change due to this strategy. The recurrence time of the design discharge, which is an approximation of the recurrence time of the highest discharge which does not cause floods, remains about 1250 years.

### 5.5 The compartmentalization strategy

#### 5.5.1 Design and hydraulic functioning

In the compartmentalisation strategy the consequences of floods and dike breaches are reduced by constructing secondary dikes that divide the existing dike rings in smaller dike rings (Vis et al., 2003) (Figure 5.2). The secondary dikes are planned in such a way that the very vulnerable areas (cities and infrastructure) are separated from the less-valuable areas. The spatial planning for this strategy is thus based on the current location of cities and other vulnerable areas.
When an extreme discharge occurs, first the upstream compartments will be filled. These compartments will have a flood probability of about 1/360 per year in 2100 (they fill when the discharge at Lobith reaches 16,000 m$^3$/s$^6$). The higher the discharge is, the more compartments will be flooded. In this research compartments are designed to cope with flood events with an annual probability of 1/10000. Consequently, assuming adequate maintenance and operation, the remaining parts outside the compartments have a flood probability of less than 1/10000 per year. In this strategy, which is developed for the far future (around 2100 AD) it is assumed that the discharge division over the different branches and the inflow into the different compartments can be perfectly controlled. The effect of uncertainties on the resulting impacts is discussed in section 5.8.

Figure 5.2 The layout of and flood probabilities in the compartmentalisation strategy (the numbers refer to the text below)

The compartments are filled in the following sequence (Figure 5.2):

- Germany compartment 1 with an overflow to compartments 2, 3 and 4 (Achterhoek);
- Rijnstrangen area (5);
- Ooijpolder-Millingen (6);
- Betuwe area (respectively 7, 8, 9 and 10).

$^6$ In the project ‘Living with Floods’ the compartments were filled at a river’s discharge of 15000 m$^3$/s at Lobith. In this research the compartments are filled at a river’s discharge of 16000 m$^3$/s at Lobith which is assumed to have a probability of 1/360 a year in 2100. The basic idea of the strategy is, however, not changed by these modifications.
Because the current situation was taken as starting point, no measures for discharges below 16,000 m$^3$/s were considered. For higher discharge waves the volume to be stored in the compartments was assumed to be equal to the volume above this 16,000 m$^3$/s threshold. The discharge with a probability of 1/10000 a year was estimated as 20,000 m$^3$/s. This means that the maximum inflow capacity of the compartments should be about 4,000 m$^3$/s, assuming that the inlet structures can be operated efficiently.

The waveform influences the water volumes in the detention areas. In this research the average waveform calculated by assuming the method of Klopstra & Duits (1999) (see section 4.3.1) was used. In reality small waves with high peaks may inundate less compartments than mentioned here, while wide waves will inundate more compartments.

The polders were supposed to be filled up to 1 m below the level of the lowest dike surrounding them. This is a designer’s choice. Flow velocities within the polder will be small, although water depths will rise to several meters. After some hours or days, the water is almost stagnant. The emptying of the detention areas may start as soon as the flood peak has passed and may take several weeks to months though less in smaller polders.

### 5.5.2 Resilience of the strategy

**Amplitude and graduality**

To assess the flood impacts an approach similar to the approach described in chapter 4 was used. Impacts resulting from the three discharge waves with peak levels of respectively 16,000, 18,000 and 20,000 m$^3$/s at Lobith were estimated with the help of the standard damage module of DWW (Vrisou van Eck *et al.*, 1999). Damage was assessed by using the current land use pattern. Since flood frequencies of the compartments remain low, land use developments were not supposed to be influenced by this strategy. The most downstream compartments with the highest flood frequency (about once in 360 years) may develop less rapidly, but nowadays these areas also develop relatively slow.

To assess the flood impacts corresponding with this strategy the following assumptions were used:

- Through the river a volume of 16,000 m$^3$/s can be discharged safely;
- The discharge diversion through the different branches can be controlled perfectly and therefore does not cause any problems;
- The compartment inlet structures are constructed in such a way that they function optimally;
- The compartments can be filled up to a water level of one meter below the lowest dike level;
- Areas that are partially filled have full damage. Damage is equal to current damage multiplied with a factor that represents 2% annual growth over 100 years;
- Damage in Germany was assumed to be equal to the average damage per area in the compartments in the eastern part of the Netherlands (Achterhoek) (compartments 2, 3 and 4 in figure 5.2).
Chapter 5

Figure 5.3 presents the volumes to store as a function of the peak level of the discharge waves at Lobith. The resulting damages and flooded areas are presented in table 5.3.

![Graph](image_url)

Figure 5.3 Relationship between the discharge peak level and volume to store above 16,000 m³/s

Table 5.3 Overview of the volumes to store (10⁶ m³), the areas that will be inundated, the available storage volume in those areas (10⁶ m³), the resulting damage (billion €) and number of affected persons corresponding with different peak flows at Lobith (m³/s)

<table>
<thead>
<tr>
<th>Peak flow at Lobith</th>
<th>16,500</th>
<th>17,000</th>
<th>17,500</th>
<th>18,000</th>
<th>18,500</th>
<th>19,000</th>
<th>19,500</th>
<th>20,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume to store</td>
<td>27</td>
<td>93</td>
<td>189</td>
<td>306</td>
<td>461</td>
<td>654</td>
<td>864</td>
<td>1,088</td>
</tr>
<tr>
<td>Areas inundated*</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5,6</td>
<td>7,8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Available volume</td>
<td>92</td>
<td>174</td>
<td>237</td>
<td>306</td>
<td>471</td>
<td>777</td>
<td>950</td>
<td>1135</td>
</tr>
<tr>
<td>Damage</td>
<td>2,10</td>
<td>3,53</td>
<td>4,81</td>
<td>5,92</td>
<td>7,77</td>
<td>14,00</td>
<td>18,08</td>
<td>27,00</td>
</tr>
<tr>
<td>Affected persons</td>
<td>2,031</td>
<td>4,134</td>
<td>5,101</td>
<td>5,739</td>
<td>7,777</td>
<td>14,167</td>
<td>17,981</td>
<td>36,093</td>
</tr>
</tbody>
</table>

*The areas that are inundated by a flood wave with a specific peak discharge level consist of the areas mentioned in the corresponding column and all areas that were already inundated due to lower flood waves (see figure 5.2 for location)

Based on the data in table 5.3 the EAD and the graduality were calculated. The EAD of this strategy is 16 M€/yr and the EANC (expected annual number of casualties) per year is about 0.02. The graduality is estimated as 0.3. The graduality of this strategy is higher than the graduality of the current strategy. However, since no floods occur given discharges with a probability larger than 1/360 years (16,000 m³/s at Lobith) and the high damage resulting from more rare floods, graduality is still low.

Recovery rate

The recovery rate is quantified by assessing the recovery capacity (see section 3.4.4). The recovery capacity analysis of this system was based on the results of the recovery capacity of the current system (see section 4.4.3). The differences in recovery capacity resulting from the differences between the current system and the system which will be there after implementing this strategy are discussed below. The physical capacity to empty the inundated areas is expected to be higher than in the current strategy. Since it is known which areas will flood
first, the removal of the water from the area can be planned better. If the flood duration can be shortened to one month the physical recovery capacity of the system increases to about 8. The economic capacity to recover will also be higher. Since the potential damage is lowest in the areas that flood more often and the areas are designed in such a way that valuable transport routes and industries are not inundated, the capacity will be at least 9. The social capacity to recover is estimated to be higher than in the current situation, because the preparation will be better and the surprise will be less. The other factors will be comparable with the current situation. The social capacity is therefore estimated as 9. Consequently, the resulting total recovery capacity scores a 9.

**Reaction threshold**
The reaction threshold of the system decreases due to this strategy. The recurrence time of the lowest discharge that causes floods reduces from about 1250 to 360 years.

### 5.6 The Green Rivers Strategy

#### 5.6.1 Design and Hydraulic Functioning

This resilience strategy was developed in the project ‘Living with floods’ (Vis et al., 2003). The strategy involves the realisation of floodways. The green rivers, or floodways, consist of areas surrounded by dikes or high grounds that can be used for all kind of purposes all year round except during peak flows, when they are used to discharge water. In contrast with the compartmentalisation strategy as described in the previous section, this strategy does not involve only storage of flows. Rather, it involves an increase of the discharge capacity.

To main options for green rivers in the Lower Rhine River are:

1. Discharge of water to the north through the IJssel valley. In this option a large volume of water is transported to the north into the IJssel Lake. This option may require extra spilling capacity of this lake.
2. Discharge of water to the west: In this option a large volume is transported through the area along the Waal River to the Biesbosch and Hollands Diep areas where extra measures have to be taken.

The first design was developed in the project ‘Rijn op Termijn’ (Baan & Klijn, 1998). The second configuration was recently developed in the project ‘Living with floods’ (Vis et al., 2003) and is elaborated and discussed in more detail here (see figure 5.4).

To develop green rivers that discharge water to the west, the current land use and the historic-geographical landscape characteristics were taken into account in a similar way as in the design of the compartmentalisation strategy. The green rivers are dimensioned in such a way that in normal years a smaller part will be flooded, while in extreme wet years the whole area will be under water. The green rivers have a high impact on land use, since they require such a large area and have a high flood frequency. Various spatial planning variants are possible within this design.
Three design variants were developed (Vis et al., 2001). They are:
1. The spontaneous development variant.
2. The ecological optimisation variant.
3. The multi-functional development variant.

In the spontaneous development variant no agricultural, residential or industrial activities take place, only natural areas are present. Besides the structures that are required for hydraulic functioning of the green rivers such as dikes and in- and outlets, no changes in the physical environment will occur. The green rivers will have no active management unless mowing or cutting trees is necessary for an adequate hydraulic functioning. In this variant the flood frequencies differ from west to east. In the east of the Netherlands, in the Rijnstrangen area, relatively low flood frequencies and short flood durations will occur (2 to 20 days per year). Mostly, only the depressions and natural waterways will carry water. Further downstream, the green rivers surface and cross section becomes more flat. This results in smaller differences in flood frequencies over the cross section of the green rivers. Inundation will occur here about 50-150 days per year, whereas the more downstream polders (Land van Maas and Waal, Bommelerwaard) will be flooded even more than 150 days per year. In these latter areas the alluvial ridges and the old river dune tops stand out by their lower flood frequencies. In the Land van Altena a large area of permanent water will appear, separated from the Biesbosch swamps by higher grounds.

The ecological development variant does allow human influence, such as the construction of low dikes and digging of watercourses in order to enhance biodiversity in the region. Emphasis is on the maximum development of river-related forest, marsh and clear open water. Taking into account the geomorphologic situation in the green rivers, networks of habitats that offer conditions for viable populations of as many species as possible are planned. Other functions are allowed in the area within the restriction of no or minimal
influence on ecological values. Flood frequencies depend on where the managers build dikes or dig waterways.

In the *multi-functional development variant* the physical environment is structured in such a way that other functions than nature can be allowed in the green rivers. This increases the economical significance and practical value of the green rivers. In the eastern part, the Rijnstrangen area, vast forests will develop. This area has the ability for high nature values. To allow the discharge of water through this area, the central core is kept open by extensive grazing. The area between Arnhem and Nijmegen in the Betuwe, will be developed into an urban green belt that serves as a recreational area for the neighbouring cities. The dikes offer possibilities for exclusive housing. In the Land van Maas en Waal the character of the traditional, small-scale agricultural landscape, with high historical value is preserved. Grassland with cattle, orchards of fruit trees and traditional farms set the scene and offer an attractive landscape for bikers and hikers. For the Bommelerwaard and the Land van Heusden en Altena, the potential for marshes, alternated with patches of extensive dairy farming is optimized (Vis *et al.*, 2001).

### 5.6.2 RESILIENCE OF THE STRATEGY

The flood impacts that are expected to occur when a green river strategy is implemented are difficult to assess. In the spontaneous development and ecological development variants all houses and buildings as well as the ground within the green river is dispossessed. As a result no, or only little flood damage is expected. Even in the multi-functional variant damage is minimal. It only consists in the inconvenience caused by the flooding: cows have to be transported, people might have more difficulty to reach their house and in extreme situations damage may occur.

In order to be able to estimate damage of the multi-functional variant the design of Vis *et al.* (2001) was elaborated further in this case study. The multi-functional variant was designed in such a way that nature is flooded most frequently. This will not result in significant damage. Pasture areas are inundated with a frequency of about once in 5 to 10 years. Agricultural land becomes inundated with a frequency of once in 10 to once in 50 years. Residential areas face a flood damage probability of 1/50 to 1/1000 a year. They may flood more often, but are adapted in such a way that the resulting damage is negligible. When damage to houses occurs, this is lower than flood damage to houses would be currently, since in this strategy houses are adapted to more frequent floods. Table 5.4 presents the areas of the different land use types within the green rivers. The distribution of land use functions as used in this case study is only one of many possible options. In order to be able to estimate the flood impacts and resilience of the strategy a specific land use distribution had to be selected. Since the discharge capacity of the riverbed itself is not changed significantly and is thus still sufficient for a discharge of about 16,000 m$^3$/s with a probability of about 1/360 a year, the high frequency of flooding of the green rivers is a choice also. An overview of the assumed damages and the resulting EAD and graduality for all three green river variants is presented in table 5.5.
Table 5.4 Land use and maximum potential damage in the green river (multi-functional variant)

<table>
<thead>
<tr>
<th>Land use</th>
<th>% of total area</th>
<th>Flood recurrence time (Year)</th>
<th>Damage (€/m²)</th>
<th>Maximum total damage (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature</td>
<td>40%</td>
<td>1 - 5</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Adapted Grassland</td>
<td>30%</td>
<td>5 - 10</td>
<td>0.1**</td>
<td>4.8</td>
</tr>
<tr>
<td>Adapted Agriculture</td>
<td>20%</td>
<td>10 - 50</td>
<td>1**</td>
<td>32</td>
</tr>
<tr>
<td>Residential and commercial areas</td>
<td>10%</td>
<td>50 to 1000</td>
<td>33*</td>
<td>528</td>
</tr>
</tbody>
</table>

* This number is based on the assumption that the house density is 1 house/300 m² and the maximum damage to an ‘adapted’ and well-prepared house is 10000 € (copied from Vis et al. (2001)). This number is lower than a normal house’s potential damage.

** Vis et al. (2001) estimate agricultural damage as 1 guilder/m² (about 0.45 €/m²), Vrisou van Eck et al. (1999) claim that damage of high-frequent flooded areas (T < 25 year) can be calculated as the damage of low-frequent flooded areas multiplied with 0.25.

Table 5.5 The assumed damages (M€), the corresponding EAD, EANC and the graduality for the different variants of the green river strategy

<table>
<thead>
<tr>
<th>Flood recurrence time (Year)</th>
<th>Spontaneous</th>
<th>Ecological</th>
<th>Multi-functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>500</td>
<td>3</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>10000</td>
<td>5</td>
<td>10</td>
<td>528</td>
</tr>
</tbody>
</table>

EAD (M€/yr)        | 0.3 | 0.4 | 3 |
EANC (Cas/yr)      | 0   | -   | 0.96* |
Graduality (-)     | 0.75| 0.75| 0.35|

* To calculate the number of casualties per year the number affected persons per year was divided by 1000. The following data was used: Residential area: 16,000,000 m², Area of 1 house: 300 m², Number of houses in this strategy: 53,333. Number of inhabitants per house: 3, Total number of inhabitants in the green rivers: 160,000.

As expected, the amplitude is highest for the multi-functional variant and lowest for the spontaneous variant. The graduality of the damage increase with increasing discharges is lowest for the multi-functional variant. In figure 5.5 the points corresponding with the multi-functional variant are clearly located farther from the diagonal than the points of the other two variants.
The recovery capacity of this strategy is very high. In the ecological and spontaneous variants recovery is almost not necessary since no significant negative flood impacts are expected. Because the rest of the Netherlands will still be prosperous, recovery is expected to be fast. In the multi-functional variant everyone knows about the possibility of floods. Therefore, also this variant has a high recovery rate. Based on the assessment of the recovery capacity of the current strategy, the economic and social recovery capacities of this strategy are assessed as a 9, and the physical capacity as 8. The recovery capacity of all variants is thus scored as 9.

In this strategy is not possible to identify a clear reaction threshold or to quantify the system’s resistance, since all discharges considered caused floods.

5.7 THE RIVER-AND-LAND STRATEGY

5.7.1 DESIGN AND HYDRAULIC FUNCTIONING

The strategy ‘River-and-Land’ of DWW is the result of an exploratory research of possibilities and ideas for the far future. The River-and-Land strategy is more a direction to move in than a real strategy. The idea is to remove all dikes in the river-threatened area except the southern dike of the Maas River and the northern dike of the Nederrijn/Lek River. Local water defence structures such as mounds and small ring dikes are still allowed. The land use will depend on the flood depths, flood durations and water quality. River marches, lakes and woods will develop. However, there will also be space for residential areas, infrastructure and agriculture. In this futuristic scenario people live on lakes and use electricity from the tide, wind and sun. Green houses float or are build on poles, horticulture takes place in containers. The lakes also offer wide opportunity for recreation in the water and on islands. A description of this strategy is given in Vis et al. (2001). The strategy has not been developed into details yet. To be able to assess the strategies resilience, however, some information on land use and
damage is required. Therefore, a potential elaboration of this strategy was developed. The details are discussed in the next section.

### 5.7.2 Resilience of the Strategy

The damage caused by peak discharges in this strategy will be very low, because the whole land use must be adapted to frequent flooding. However, damage will not reduce to zero, because exceptional water levels will still cause annoyance and damage. An elaboration of this strategy is presented in table 5.6 and 5.7. These assumptions correspond with those made for the multi-functional variant of the green river strategy.

#### Table 5.6 Land use and potential damage in the strategy

<table>
<thead>
<tr>
<th>Land Use</th>
<th>% Area</th>
<th>Flood Recurrence Time (years)</th>
<th>Damage (€/m²)</th>
<th>Damage (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature</td>
<td>40</td>
<td>1 to 5</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Adapted pasture</td>
<td>30</td>
<td>5 to 10</td>
<td>0.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Agriculture (crops)</td>
<td>20</td>
<td>10 to 50</td>
<td>1</td>
<td>58</td>
</tr>
<tr>
<td>Adapted residential and</td>
<td>10</td>
<td>50 to 1000</td>
<td>33</td>
<td>957</td>
</tr>
<tr>
<td>commercial areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 5.7 Flooded areas as a function of the recurrence time (in years) of the peak discharge

<table>
<thead>
<tr>
<th>Recurrence Time</th>
<th>Nature (%)</th>
<th>Pasture (%)</th>
<th>Agriculture (%)</th>
<th>Residential areas (%)</th>
<th>Damage (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>50</td>
<td>3</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>500</td>
<td>100</td>
<td>75</td>
<td>50</td>
<td>20</td>
<td>381</td>
</tr>
<tr>
<td>10000</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>1462</td>
</tr>
</tbody>
</table>

The EAD resulting from these choices is 6 M€/yr. This EAD is higher than the number found for the green river strategies, because the area that may become flooded is much larger than in the green river strategy. The graduality of the River-and-Land strategy is 0.5. The expected number of casualties is about zero. The recovery rate of this strategy is comparable with the recovery rate of the multi-functional variant of the green rivers.

The reaction threshold of the system disappears due to this strategy. The recurrence time of the lowest discharge that is expected to cause floods is very low. All discharges considered cause floods.

### 5.8 Evaluation of the Strategies

The evaluation of the strategies is based on the criteria discussed in chapter two and the evaluation carried out by Vis et al. (2001). Table 5.8 presents the results.
Table 5.8 Evaluation scores of the current, compartmentalisation, green rivers and river-and-land strategies (S= Spontaneous variant, E = Ecological variant and M = multi-functional variant)*

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Sub-criteria</th>
<th>Current (in 2100)</th>
<th>Compartmentalisation</th>
<th>Green rivers</th>
<th>R&amp;L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socio-economic flood impacts</td>
<td></td>
<td></td>
<td></td>
<td>S E M S E M</td>
<td></td>
</tr>
<tr>
<td>Flood risk (M€/yr)</td>
<td></td>
<td>87</td>
<td>26</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>EANAP (pers/yr)</td>
<td></td>
<td>209</td>
<td>18</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recovery capacity (-)</td>
<td></td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Cost (billion €)</td>
<td></td>
<td>0.9</td>
<td>1 to 2</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Economic opportunities</td>
<td></td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Equity</td>
<td></td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td>Ecology &amp; land scenery</td>
<td>Effects on nature</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Landscape quality</td>
<td></td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Sensitivity to unexpected</td>
<td>Robustness</td>
<td></td>
<td></td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>events/changes</td>
<td>Flexibility for future changes</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*The score of the strategy that scores best on a certain criterion is highlighted in grey. The robustness and equity are scored relatively by comparing the different strategies with the current strategy.

Effect on socio-economy

The socio-economic effects are studied by considering four criteria: flood impacts, costs, economic opportunities and equity (see chapter 2). Equity is not significantly influenced by these strategies because it is unlikely that strategies will be accepted if the people that are put in disadvantage are not compensated. Equity is thus not a relevant criterion here and will not be discussed any further.

The flood impacts are expressed as a combination of flood risks, expected average number of casualties and recovery capacity. Unlike the resilience indicator EAD, which only includes direct damage, the flood risks in this table include both the direct and indirect damages. Since for the green river and River-and-Land strategy the indirect damages are expected to be negligible, the flood risks in this table and the values found for the EAD are equal. The alternative strategies result in much lower flood impacts than the current strategy does. The green rivers with the ecological and spontaneous variant result in the lowest flood impacts, because in those variants floods do not affect inhabited areas.

The cost figures were copied from Vis et al. (2001). They include both investment and maintenance costs and are expressed as a net present value. The costs are highest for the River-and-Land strategy and the green river strategy. These strategies are expensive because it is assumed that land is purchased from the current owners.

In order to get a rough idea about the cost-efficiency of the strategies some additional calculations were carried out. First, the flood risk was calculated by assuming that no measures would be implemented between now and 2100 and that the river design in 2100 would still be based on the current design discharge of 16,000 m³/s at Lobith. The expected economic growth and climate change discussed in section 5.3 were incorporated in this calculation. This risk (including direct and indirect damage) found in this way is 289 M€/yr. Secondly, the Net Present Value of the risk was assessed, by assuming that between 2000 and 2100 the risk will grow linearly from the value in 2000 (12 M€/yr) to the one found for 2100
(289 M€/yr). It is 1,922 M€. This number represents the NPV of the risk that would be present if the river design would not be adapted to the increased discharge frequencies. In the same way the NPV of the risk for the strategy in which the river design is adapted to a design discharge of 18,000 m³/s at Lobith was calculated. This resulted in a NPV of 734 M€. By comparing the values found the risk reduction achieved by raising the embankments from a design based on 16,000 to a design based on 18,000 m³/s at Lobith was determined. The NPV of the risk reduction found in this way is about 1.2 billion €. This number is based on rough estimations and thus only serves to indicate the order of magnitude. The costs were estimated at 0.9 billion € (Table 5.8). Continuing the current strategy and raising embankments to the level of the new design discharge thus seems to be cost-effective. If the risk in 2100 could be lowered to zero, the risk reduction achieved would be equal to the NPV of the risk resulting from doing nothing: 1,922 M€. Because all alternative strategies have costs that are about equal to or exceed this figure and all of the strategies result in at least a little remaining flood risk, none of them seems to be cost-effective. The most cost-effective resilience strategy seems to be the compartmentalisation strategy.

The scores for economic opportunities were also copied from Vis et al. (2001). They were scored on a scale from 1-10 by a group of experts. The economic opportunities are influenced only, if in a strategy the land use functions are changed or if the flood frequency changes. The strategies studied include the building, replacement or removal of dikes and land use change. The dikes will probably not significantly influence economic opportunities. However, land use change from intensively used land to nature or to extensive agriculture and an increase of flood frequencies reduce economic opportunities. In areas with more frequent floods, agriculture will be less profitable and industry and housing must be adapted to floods. Therefore, the River-and-Land strategy and the green rivers strategy which involve an increase in flood frequency and land use change from intensively used land to nature and less intensively used land provide the least economic opportunities. The experts interviewed in the project ‘Living with floods’ scored the economic opportunities of both the compartmentalization strategy and the multi-functional green river strategy higher than those of the current strategy (Vis et al., 2001). However, the motivation is not completely clear. In this thesis therefore, both strategies were assigned a 5 on the criterion ‘economic opportunities’, which is equal to the current strategy.

The overall image is that the strategies involving large natural areas score lowest on flood impacts, that the current strategy involves the lowest costs, but that the multi-functional green river strategy and the compartmentalization strategy score relatively well on flood impacts, costs, and economic opportunities.

**Effect on nature and land scenery**

The green river and River-and-Land strategy score higher on the intangible criteria nature and land scenery than the current strategy. The compartmentalization strategy scores the same as the current strategy, because land use is not significantly affected by this strategy. The scores were copied from Vis et al. (2001).

**Sensitivity of the strategy to unexpected events and changes**

The ability to cope with unexpected events in the current situation (the system’s robustness) is scored relatively, by comparing the strategies with the current strategy. The design and
implementation on local level of the compartmentalization strategy determine whether the sensitivity to unexpected events is affected. Compartmentalization prevents the flooding of large areas at once, which reduces the sensitivity to uncertainties. However, if flooding of the small valuable areas outside the compartments does occur, damage may be higher than it would have been without the compartment dikes, because water depths will rise faster. If the design is minimized in order to build structures and controls just that strong, high and flexible that in normal situation everything goes well, disasters will occur in unforeseen circumstances. However, the system can also be designed in such a way that it is able to anticipate on, for example, unexpected discharge distributions and very wide flood waves.

The ecological and spontaneous variants of the green river strategy probably work in a range of circumstances: in these strategies both the discharge capacity and available storage volume have been enlarged. The flood wave width has thus less effect than it has in the compartmentalization strategy. In these strategies floods occur more frequently than in the current and compartmentalization strategy, which means that people are more prepared. The multi-functional green river and the River-and-Land strategy affect the sensitivity to uncertainties in a positive way, because they will result in a more gradual rise of water depth, involve adapted land use, and they give water sufficient room to incorporate unexpected events such as wide flood waves and unusual discharge distributions. However, also in these strategies the sensitivity to uncertainties depends on the details of the design of the strategies.

Flexibility was scored by the Delphi Method on a scale from 1 to 10 (Vis et al., 2001). The compartmentalization scores high, because this strategy can be carried out stepwise, for example, by first identifying emergency detention areas. This is already being considered (Commissie Noodoverloopgebieden, 2002). Furthermore, compartmentalization measures do not have to be undone if in the future another strategy is chosen. The other strategies involve large investments. Phasing of the purchasing of land to create green rivers, for example, is more difficult.

5.9 DISCUSSION AND CONCLUSIONS

5.9.1 ON THE FLOOD RISK MANAGEMENT STRATEGIES

In the case study different strategies were considered. Although these strategies are just a selection of a wide range of possible strategies, together they give an overview of different possible resilience strategies and different options for the future.

Resilience of the strategies

Table 5.9 provides an overview of the resilience scores of the current strategy at this moment (which was calculated in chapter 4), the extrapolation of this strategy to the future and of the alternative strategies. If the current strategy is extrapolated into the future, the amplitude increases enormously, while the graduality and recovery rate do not change.

By implementing the alternative strategies the amplitude will reduce significantly, and also the graduality of the increase of damage with increasing discharges and the recovery rate will increase. It is thus possible to increase the resilience of the system by these strategies. The
Chapter 5

strategies that were designed to increase the resilience of the river (Vis et al., 2001) do actually result in more resilient systems.

Of all the alternative strategies the spontaneous and ecological variants of the green rivers strategy have the lowest amplitude, the highest graduality and a high recovery rate. These strategies thus result in the most resilient systems. The current strategy scores lowest on all indicators and is thus the least resilient. The green rivers’ multi-functional variant and the River-and-Land strategy have also good scores on all three resilience indicators. The compartmentalization strategy scores better than the current strategy, but worse than the other alternative strategies.

Table 5.9 Resilience of the different strategies

<table>
<thead>
<tr>
<th>N</th>
<th>Strategy</th>
<th>EAD (M€/yr)</th>
<th>EANC (cas/yr)</th>
<th>Graduality (-)</th>
<th>Recovery Capacity (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Current 2000</td>
<td>6-8</td>
<td>0.2</td>
<td>0.25</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Current 2100</td>
<td>64</td>
<td>0.3</td>
<td>0.15</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>Compartmentalization</td>
<td>16</td>
<td>0.02</td>
<td>0.3</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Green rivers spontaneous variant</td>
<td>0.3</td>
<td>-</td>
<td>0.8</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Green rivers ecological variant</td>
<td>0.3</td>
<td>-</td>
<td>0.8</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Green rivers multi-functional variant</td>
<td>3</td>
<td>0.96</td>
<td>0.4</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>River-and-Land</td>
<td>6</td>
<td>-</td>
<td>0.5 / 0.6</td>
<td>9</td>
</tr>
</tbody>
</table>

The reaction threshold of the system remains the same if the current strategy is continued in the future. In the alternative strategies this threshold is lowered or disappears at all.

Evaluation of the strategies

It is important to keep in mind that to decide which strategy is followed, resilience is not a criterion. To judge the contribution of a strategy to the sustainable development of the region involved all criteria discussed in section 2.3 were considered. The evaluation revealed that if policy makers assign most weight to the effects on the socio-economy, then the compartmentalization strategy, the multi-functional green river strategy or the current strategy are logical options, while in societies where nature and land scenery are highly valued the green river strategies must be considered. Societies that are willing and able to pay a high price to prevent disasters (extreme flood impacts) will prefer one of the green river strategies or the compartmentalisation strategy. A total score of all categories together is not presented here, since it depends on the weighing of the different categories. This relative weighing is no task for scientists.

The scores of the different strategies on the criteria mentioned depend on the elaboration of the strategies at local level. The compartmentalization strategy, for example, can have positive and adverse effects on the sensitivity for uncertainties as was explained in section 5.8.

Vis et al. (2001) point out that a green river along the IJssel branch has not been evaluated in the present study. Such a spatial variant was, however, proposed in the research project ‘the Rhine in the future’ (Baan & Klijn, 1998). It is estimated that the costs of such a variant are
substantially lower (factor 2 or more) than those of the variants that run east-west along the Nederrijn and Waal branches, because of the more favourable morphology and the lesser intensity of developments along the IJssel (Vis et al., 2001).

The strategies that increase the system’s resilience most, the ecological and spontaneous variant of the green rivers, have positive impacts on nature and land scenery. They also reduce the sensitivity of the system for unexpected circumstances. However, they are very costly and negatively affect economic opportunities. Increasing the system’s resilience is thus not always positive. The multi-functional variant of the green rivers strategy also increases the system’s resilience significantly. This strategy is less expensive than the other two green river variants are. Besides, compared to the current strategy it also improves nature and land scenery quality, it does not negatively affect socio-economy and it is more flexible. It is, therefore, concluded that it is possible to increase the resilience of the Rhine River in a way that enhances sustainable development.

In section 5.2.1 it was mentioned that it would be preferable if sudden catastrophic floods could be avoided without losing the important economic advantages of the low frequency of the floods. The evaluation of the strategies shows that it is possible to increase the graduality without deteriorating economic possibilities, namely by implementing the compartmentalisation strategy or the green river’s multi-functional variant. However, the strategies that increase graduality most reduce economic opportunities.

5.9.2 On the resilient concept and the resilience indicators

The case study aimed at quantifying the resilience of the current strategy and of a number of alternative strategies. It was found that quantifying the indicators results in an impression of the resilience of the system and of the strategies. The indicators showed which strategy is the most and which one is the least resilient. The resilience indicators were helpful in describing the system’s reaction to flood waves. The three aspects that describe such a reaction were all quantifiable. The recovery rate is not very relevant for this system, because it is very high in all strategies. The amplitude and graduality clearly differed for each strategy. The case study also showed that it is possible to increase the resilience of a system by adopting alternative flood risk management strategies.

Trying to improve the values of the indicators i.e. reducing the amplitude and increasing the graduality resulted in strategies that are different from the current strategy. Instead of strengthening embankments, strategies that involve flood probability differentiation, compartmentalization and land use adaptation were found. These strategies will certainly not be found from a perspective in which attention is focused on river design only. These resilience strategies reduce flood impacts, improve nature and land scenery, and are less sensitive to uncertainties than the current strategy. However, they are also more costly and do not affect economic opportunities positively.

Not one strategy scores best on all evaluation criteria. Neither resistance, nor resilience strategies are thus preferable in all circumstances. It is not possible to define whether resilience strategies for the Rhine are better than the current strategy is, because resilience is
not a decision criterion. How much resilience is wanted depends on the political and social preferences. If people want to avoid sudden floods and fast rising water levels, or if nature is valued higher, then some resilience strategies are serious alternatives for the current strategy. If cost-efficiency is considered important, the current strategy is favourable.

Thinking from a ‘resilience perspective’ which means, adopting a system’s approach and studying the reaction of the system to the whole regime of discharges by calculating the resilience indicators, results in an integrated view on flood risk management. It results next to valuable information on flood risks of the system as a whole in additional information, namely on the system’s graduality and recovery rate. In the Rhine case this ‘resilience approach’ resulted in other strategies than the one that is applied currently. For long-term research this widening of options is valuable.
6 RESILIENCE OF THE MEUSE IN LIMBURG

6.1 INTRODUCTION

The River Meuse is an international river that flows from France through Belgium and the Netherlands into the North Sea. In France, the river flows through a wide valley with permeable soils. From Sedan in northern France to Eijsden in the Netherlands the Meuse flows through the Ardennes. Less permeable, rocky soils and steep slopes characterize this stretch. Downstream of Eijsden the slope is less and the river starts depositing its gravel and sand. At Roermond the slope of the river becomes very small. From there the river meanders through sediments consisting of sand and clay. Downstream of Mook the river is harnessed by embankments and flows slowly to the North Sea.

![Figure 6.1 The Meuse catchment. In this case study the area between Eijsden and Mook is studied](image)

The case study in this chapter focuses on the river stretch between Eijsden and Mook and the corresponding flood-prone area (Figure 6.1). This area is interesting because there is data on
recent floods and the strategy for flood risk management is changing. The case study specifically focuses on changes in the resilience of the system over time. The resilience of the system may be influenced by changes in the discharge regime and societal and physical changes in the system itself, and by changes in the flood risk management strategy.

Although in this thesis a systems approach is advocated, this case study only involves a part of the lowland river system of the Meuse River. Because the Meuse basin downstream of Mook is comparable with the diked areas along the Rhine River which were studied in chapters 4 and 5, only the area upstream of Mook was considered in this case study. In contrast to the studied Rhine area, in the area upstream of Mook frequent floods occur because only parts of the area are protected by embankments.

The case study assesses the change of resilience of the system over time. By studying this change the applicability and usefulness of the concept of resilience and the resilience indicators on flood risk management of the Meuse River should become clear. To study the change in resilience of the flood risk management system, the system’s reaction to floods was assessed:

- In the far past around 1900;
- Around 1993, just before the construction of small embankments around villages;
- Around 2000, after the flood events of 1993 and 1995 which induced the construction of small embankments around villages;
- Around 2015, after the completion of the Maaswerken Project which involves among others the heightening of embankments around villages and cities to be able to withstand a discharge with a probability of 1/1250 a year (see section 6.2.4);
- Around 2100: in the far future.

The chapter starts with a discussion of the discharge regime, the system characteristics and the flood risk management strategy in the area. Both the current characteristics and their changes over time are discussed. Section 6.3 discusses the calculation and the values of the resilience indicators for 1993, 2000 and 2015. Section 6.4 and 6.5 explain the resilience calculations and the values for the indicators in 1900 and 2100. Finally, the results are discussed and conclusions are drawn in section 6.6 and 6.7.

6.2 **DESCRIPTION OF THE SYSTEM AND ITS CHANGES IN TIME**

6.2.1 **THE DISCHARGE REGIME**

The Meuse River is characterized by a large variation in discharge and water levels. In Borgharen (Figure 6.2), discharges can be less than 25 m$^3$/s, while during peak flows in wintertime or in spring discharges of 3,000 m$^3$/s may occur. The average discharge at Borgharen is about 230 m$^3$/s (Middelkoop, 1998). The Ardennes with their shallow soils and steep slopes evoke a fast reaction of the discharge to rainfall. Heavy rainstorms that pass from south to north over the catchment cause a fast increase of the discharge and may cause floods. In 1926 the highest discharge level was recorded at 3,175 m$^3$/s at Borgharen (Parmet *et al.*, 2001). In 1993 and 1995 extreme discharges of about 3,120 and 2,860 m$^3$/s respectively.
caused significant damage. These flood events are discussed in section 6.2.3. Table 6.1 shows the discharge probability function for the discharge at Borgharen.

Figure 6.2 Location of the flood risk management system (the flood risk management system covers the grey, flood-prone area)

Ogink & Barneveld (2002) studied the highest discharge that is physically possible, i.e. the discharge that may reach the upstream boundary of the research area. They found that upstream of Liege there is no physical limitation to the discharge. Between Ivoz-Ramet near Flemalle until Ceratte (just upstream of Liege) the discharge capacity is limited by the height of the embankments along a large low-lying area of about 100 km$^2$. This area has subsided up to 6 m by large-scale coal mining. The current maximum discharge capacity at this area is estimated at 4,600 m$^3$/s. Beyond that discharge overtopping of the embankments will occur. The maximum discharge that can reach the research area is, therefore, estimated as 4,600 m$^3$/s.

Table 6.1 Discharge probability functions of the Meuse at Borgharen (Source: Min. V&W, 2001)

<table>
<thead>
<tr>
<th>Function</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = 353.7 \ln (T) + 1332.8$</td>
<td>$2 &lt; T &lt; 250$ years</td>
</tr>
<tr>
<td>$Q = 325.2 \ln (T) + 1490.3$</td>
<td>$250 &lt; T &lt; 10000$ years</td>
</tr>
</tbody>
</table>

The discharge regime changes in time because of developments in the catchment, changes in the upstream river stretch and climate change. Min. V&W (1994) studied the effect of past
changes within the catchment on the discharge regime. They found an increase of forest of 8% and an increase of the population density and urbanization. These changes may have caused an increase in the frequency of peak discharges. However, the effects on extreme discharges are considered negligible (Min. V&W, 1994). The river geometry also changed significantly. Canalisation, shortcuts of bends and deepening and straightening of the river is thought to have increased peak discharges by up to 5%. Furthermore, differences in groundwater recharge, land subsidence, the construction of reservoirs, detention areas and changes in wetlands caused changes of the discharge regime. Ogink & Barneveld (2002) mention that a certain rainfall event will currently result in a peak discharge that is about 7% higher than about 50 years ago. In the future the upstream river stretch and the catchment are likely to change also.

Next to physical changes in the upstream area, climate change will also affect the discharge regime. The effect of climate change between 1900 and 2000 on the discharge regime is not known. Because the greenhouse effect mainly occurred after the 1960s it is assumed that the discharge regime of today is not significantly different from the discharge regime of 1900. In the far future climate change is expected to result in a 10% increase in the level of high discharges (Middelkoop, 1998).

### 6.2.2 THE PHYSICAL AND SOCIO-ECONOMIC CHARACTERISTICS

**Current physical characteristics of the area**

The flood-prone area along the studied stretch of the Meuse River is small, compared to the area along the Rhine River branches. The floodplain is limited by the surrounding hills, old river terraces, low embankments which protect the villages and cities in the floodplains and the high embankments along the Belgium ‘Mine Subsidence Area’. Flooding of the area along the river occurs when the discharge exceeds about 2,000 m$^3$/s at Borgharen. Discharges with an annual probability smaller than about 1/50 overtop the low embankments around villages.

The river stretch of the Meuse River that is the subject of this research can be divided into three reaches with different physical characteristics: the 'Border Meuse', the 'Meuse Lake Area' and the 'Controlled Meuse' (gestuwde Maas) (Figure 6.2). These three reaches are discussed in more detail below.

*The 'Border Meuse' section* is the fast flowing meandering river section between Eijsden and Maastricht where the river forms the border between Belgium and the Netherlands. This section is not navigable. Therefore, in 1935 the Juliana canal was constructed to bypass this part of the river. The riverbed has a relatively steep slope of 0.5 m/km and consists of gravel and sand. The floodplains at the Dutch side of the river become frequently inundated. As a quick reaction to the floods of 1993 and 1995 (see section 6.3) about 45 km of clay embankments were built to protect the citizens and buildings along this river stretch from flooding. These small embankments give protection against floods with a recurrence interval of 50 years. At the Belgian side of the river a low-lying area is situated called the ‘Mine Subsidence Area’. This area is protected from flooding by high embankments. The embankments are expected to be able to withstand a discharge of about 3,500 to 3,800 m$^3$/s. The level of the embankment is based on the highest recorded water level increased with 0.5
Because the potential flood impacts are high, it is very likely that after a near-flooding or after a flood disaster, embankments along this area will be raised (Ogink & Barneveld, 2002).

The Meuse Lake Area near Roermond is named after the many lakes that are situated in this stretch. These lakes are the result of gravel mining. Most lakes are connected with the Meuse River and can store part of the peak flows. Downstream of Roermond the slope of the river is very small, the river meanders and sediments consist of sand and clay.

The stretch downstream of the Meuse Lake Area, the Controlled Meuse, contains weirs and is navigable. The floodplains are rarely flooded. The first part of the river is situated in a small valley while downstream of Arcen the valley is wider and the river changes in a delta river. The riverbed is rather flat and has a hydraulic gradient of about 0.10 m/km. The sediments in this area consist of sand and a little gravel.

**Current socio-economic characteristics of the area**
The river has many functions of which the discharge of water, ice and sediments is the most important. Other functions of the river and its floodplains are navigation, water supply, residential area, mining, agriculture, forestry, tourism and recreation, and nature (Projectorganisatie De Maaswerken, 1998). There are villages and cities located within the floodplains.

**Changes in time**
The riverbed, the flood-pattern and the floodplains have changed in time. The riverbed was normalized around 1875: the main channel was fixed, deepened and narrowed to allow navigation. Some bends were cut off in the 1930’s and sand banks and islands were removed. Furthermore, some stretches were canalised and weirs were constructed to ensure enough water depth in summer (Duivenvoorden, 1997). In 1935, the Juliana canal was constructed for navigation and narrow sections of the Meuse River were widened. As mentioned before, gravel mining in the area around Roermond resulted in many lakes, which currently attenuate flood waves.

Next to the river bed itself, also the flood patterns were adjusted by changes in the physical characteristics of the system. In the past the floodplains became flooded frequently. People who lived close to the river adapted their houses to these floods by raising the entrance, adapting their furniture and by systems that allowed them to quickly lift their furniture out of reach of the floodwater. After severe floods in 1993 and 1995 (see the next section) the flood risk management strategy was changed. Until then, embankments were considered insensible, because floods in this area are not life-threatening and do not affect large areas. Besides, due to the gravel in the subsoil, seepage below the embankments is very likely. Building embankments and preventing this seepage is expensive and has disadvantages in low-flow situations. However, after the flood events of 1993 and 1995 embankments of about 75 cm to 1 m height were constructed around villages and cities. The embankments are designed to withstand discharges with a probability larger than 1/50 a year. Furthermore, the Maaswerken Project was started in 1995. After the completion of this project (in 2015) the villages and cities should be protected against discharges with a probability larger than 1/250 a year. The Maaswerken Project also addresses other river issues such as the improvement of navigability, improvement of nature values and gravel mining to reduce costs of the project.
In the most southern part of the flood risk management system gravel mining and nature development have the highest priority, while in the northern part navigation and flood protection are more important. Raising embankments, deepening of the riverbed and the creation of bypasses are important measures of the project (Maaswerken Project, 2004).

All these changes in the riverbed affected the flood patterns significantly. The Juliana Canal reduced the floodplain area of the Meuse and prevented flooding of the area east of the canal. The construction of the embankments after 1995 limited the space of the river even further.

Not only the riverbed, but also the floodplains have changed. Since 1900 the floodplains have developed from mainly agricultural to more urbanized areas. The built-up area in the floodplains has increased since 1870 by about a factor 3.5 (Van Bemmel, 2004). In the future the area is expected to develop in a similar way as the Netherlands as a whole. The expected developments in the Netherlands are summarized in section 5.3. Urbanisation and economic growth are expected to cause an increase in potential damage. Agriculture will become less important and may be partly replaced by nature. Economic growth in the most frequently flooded areas is expected to be negligible, because it is not allowed to build in those areas. However, these building regulations might also change in the future.

6.2.3 The two flood events of 1993 and 1995

In 1993 and in 1995 after periods of prolonged rainfall in the Ardennes, peak discharges occurred in the Meuse River. As a result an area of about 8% of the province of Limburg was flooded. Also some municipalities in the Province of Brabant suffered from the floods. Around 8,000 people were evacuated because their houses were flooded or the power supply and other services had stopped. The total damage in 1993 was 115 M€ and in 1995 75 M€ (De Bruijn & Den Heijer, 2001). Next to the tangible damage, also intangible damage was considered large. This section briefly summarizes the hydrologic data, the behaviour of people during the flood, the resulting damage and the response after the flood.

![Figure 6.3 Discharges during the flood events of 1993 and 1995 in the Meuse measured at Borgharen](image-url)
In December 1993 a peak discharge of 3,120 m$^3$/s with a probability of 1/160 per year passed the Belgium-Dutch border and in January-February 1995 a peak discharge of 2,861 m$^3$/s with a frequency of once in about 100 years reached the Netherlands. In 1993 the peak discharge lasted for about three days, while in 1995 the duration of the peak wave was even five days, although the peak discharge was lower than in 1993. Because of the long duration of the peak discharge in 1995 (Figure 6.3), the peak was not attenuated as much as the one of 1993. While in 1993 significant peak attenuation occurred in the lakes nearby Roermond, in 1995 these lakes were already filled before the peak had passed. This resulted in water levels that were higher downstream of Roermond in 1995 than in 1993 (De Bruijn & Den Heijer, 2001). In 1995 the maximum water levels at respectively Borgharen, Roermond and Hedel were -20, +7 and +20 cm higher than in 1993.

The floods of 1993 came as a shock. People were not prepared well. About 62% of the affected persons and 53% of the companies did not realize that they were settled in a flood-prone area. Afterwards, the inhabitants blamed the government for not giving them the information that floods might occur e.g. when houses were built and bought. They also mentioned that they expected more accurate and timely warnings and announcements of evacuations and rescue operations from the government (Waterloopkundig Laboratorium, 1994a).

Table 6.2 Summary of the 1993 and 1995 flood impacts (De Bruijn & Den Heijer, 2001)

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>1993</th>
<th>1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas (ha)</td>
<td>Total flooded area</td>
<td>17,000</td>
<td>15,500</td>
</tr>
<tr>
<td>Damage reports (Nr.)</td>
<td>Nr. of damage reports on houses</td>
<td>5,580</td>
<td>4,424</td>
</tr>
<tr>
<td></td>
<td>Nr. of agricultural damage reports</td>
<td>473</td>
<td>664</td>
</tr>
<tr>
<td>Damage to private persons (M€)</td>
<td>Furniture</td>
<td>16.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Houses</td>
<td>20.2</td>
<td>15.1</td>
</tr>
<tr>
<td>Damage to Companies (M€)</td>
<td>Glass houses</td>
<td>4.0</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Agriculture other than glass houses</td>
<td>4.8</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>Industry</td>
<td>6.7</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Trade, recreation, hotels &amp; catering business</td>
<td>21.4</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>Provision of services</td>
<td>4.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Damage to Institutes (M€)</td>
<td>Institutes and organizations</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Damage to the government (M€)</td>
<td>Governmental buildings and sites</td>
<td>7.5</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>Infrastructure and utility*1</td>
<td>20.3</td>
<td>8.9</td>
</tr>
<tr>
<td>Others</td>
<td>Cars, gardens, camp sites, recreation and unknown</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Total damage (M€)</td>
<td>Total damage</td>
<td>115</td>
<td>75</td>
</tr>
</tbody>
</table>

*1The figure of 1993 also includes maintenance of embankments and river works, costs that also would have been made if no floods had occurred.

Although the differences in peak discharge and water levels between the events of 1993 and 1995 were small, the resulting damages differed significantly (Wind et al., 1999). The low damage in 1995 compared to the figure of 1993 is caused by improved warnings, more adequate emergency measures and more efficient behaviour of the inhabitants (De Bruijn & Den Heijer, 2001). In 1995 damage that could easily be prevented (furniture) and damage to
high valued objects (industry, glass houses) was less than in 1993 (Table 6.2). These events show that the context in which the flood occurs and the preparedness of the society can make a significant difference in the resulting flood damage. During both floods no casualties occurred in the research area.

After the flood of 1993 31 M€ damage compensation was rewarded to the affected inhabitants. The Netherlands' people collected 13 M€ to help the affected inhabitants. The remaining funds came from the government. Most people were satisfied with the damage compensation they received after the 1993 flood event. However, only about 47% of the companies in the flooded area were satisfied with the damage compensation (Waterloopkundig Laboratorium, 1994a). A survey among 500 households and 200 companies showed that intangible flood impacts, such as feelings of unsafety, stress, tension, grief for loss of pictures and personal belongings were considered as important as material flood impacts (Waterloopkundig Laboratorium, 1994a).

In 1995 the inhabitants of the Netherlands raised 37 M€ to help their flooded fellow countrymen. After the flood of 1995 bitterness was found among the inhabitants (Huppertz, 1995). The inhabitants thought that experts had told them that a flood as occurred in 1993 would only happen once in 200 years and now, after only a year, it happened again. Some people doubted the capability of the government (according to them the government is responsible for the safety of the inhabitants). People complained on the bad handling of the damage compensation claims and the confusion about the compensation regulations. The confusion resulted in a lot of frustration, stress and unrest.

Waterloopkundig Laboratorium (1994a) studied the recovery process after the 1993 flood. They found that most people (70%) in the flooded area left their houses for about a week. In two third of the households a person did not go to work for a while after the flood to repair flood damage. Many people could not do their work due to stress caused by the flood. The period of stress and tension lasted in 34% of the cases about one or two weeks, in 41% two to five weeks and in 25% of the cases more than five weeks. Most people also experienced positive feelings during the floods such as solidarity, gratitude, togetherness, excitement, and involvement of the local governments. Less than 50% mentioned negative feelings such as fear, desperation, and anger. If people were able to choose where they would live, about 25% would not choose the same location again. About 20% has considered moving. Most people in this group have not moved yet because they could not sell their house or could not find a good alternative (Waterloopkundig Laboratorium, 1994a). Ninety percent of the companies in the flooded area stopped functioning for about 11 days. After 11 days work was partly resumed. In about 50% of the cases it took more than one month until the company functioned normally again, but in some cases this took even more than 9 weeks. About one third of the heads of companies feared bankruptcy due to the floods. In 54% of the companies' the heads felt ill or became stressed due to the floods. About 20% was not able to do their work due to these feelings. Summarizing, in most cases, recovery occurred within one or two months.
6.3 **RESILIENCE OF THE MEUSE SYSTEM IN 1993, 2000 AND 2015**

### 6.3.1 INTRODUCTION AND APPROACH

In order to understand the reaction of the system to flood waves, first the discharge regime will be analysed, then flood patterns will be assessed and thirdly, the damages corresponding to the different flood patterns will be calculated. These steps were applied in such a way that the different characteristics of the system in 1993, in 2000 and 2015 could be incorporated. Table 6.3 gives an overview of the differences between these years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Discharge regime</th>
<th>Land use</th>
<th>River geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>Current (2001)</td>
<td>Data of 2002. Damage was calculated by assuming an average annual economic growth of 2%</td>
<td>No embankments</td>
</tr>
<tr>
<td>2000</td>
<td>Idem</td>
<td>Idem</td>
<td>Low embankments along villages and cities (1/50)</td>
</tr>
<tr>
<td>2015</td>
<td>Idem</td>
<td>Idem</td>
<td>Higher embankments (1/250)</td>
</tr>
</tbody>
</table>

**Discharge regime**

The current discharge regime is assumed to be valid for the whole period from 1993 to 2015. The lowest discharge that does not cause damage is bankfull discharge. This discharge of about 1,900 m$^3$/s at Eijsden with a frequency of about once in five years is the lowest discharge that is considered. The highest discharge considered has a probability of 1/10000 a year and a peak level of 4,484 m$^3$/s at Eijsden (4,600 m$^3$/s at Borgharen$^7$).

Next to the peak discharge level also the waveform is important for the Meuse River. This was already shown in the discussion on the 1993 and 1995 flood events in section 6.2.3. The waveform with a probability of exceedance of 50% was used. This waveform was determined with the method of Klopstra & Duits (1999) (Figure 6.4).

**Flood patterns**

In order to assess the effects of the flood waves on the system the 1D hydrodynamic model SOBEK-River was used (Min. V&W, 2002). For each year considered a different schematization was used (Table 6.4). All three schematisations include the Meuse River between Eijsden and Keizersveer and the most important canals. For 1993 a schematization without embankments around villages was used. The low embankments that were constructed after the floods of 1995 are incorporated in the schematization of 2000. In 2015 the Maaswerken Project will be implemented. This project was therefore incorporated in the

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$^7$ The studied area has its upstream boundary at Eijsden. Because discharges have been recorded at Borgharen since 1911, statistics are calculated for the recorded data at Borgharen, the results are then translated to the discharge at Eijsden.
schematization of 2015. The schematisations were already developed, calibrated and validated in earlier projects (Min. V&W, 2002).

The boundary conditions of all schematisations consist of a discharge as a function of time at the upstream boundary near Eijsden and a stage-discharge relationship at the lower boundary near Keizersveer. For the inflow of tributaries high constant discharges were used (Min. V&W, 2002).

Table 6.4 Description of schematisations used

<table>
<thead>
<tr>
<th>Year</th>
<th>Schematisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>Situation of 1993 (without embankments around villages and cities)</td>
</tr>
<tr>
<td>2000</td>
<td>Situation of 2000 with embankments around villages and cities (‘DGR kades’), and the first implemented measures of the Maaswerken Project (baggerbestek 1). The main channel was adapted somewhat to reflect the changes that occurred between 1993 and 2000.</td>
</tr>
<tr>
<td>2015</td>
<td>Situation as planned for 2015 after the implementation of the Maaswerken Project. The embankments around villages are raised to a safety level of 1/250 a year.</td>
</tr>
</tbody>
</table>

With the help of the hydrodynamic model the river water levels corresponding with a certain inflow at Eijsden were simulated. These water levels in the river were translated to flood depths maps of the floodplains and the river with the help of Arcview and PCRaster scripts. To be able to do this, three digital elevation maps were developed with a cell size of 25m, one for each year. The one for 1993 does not contain the low embankments that were constructed after 1993. The one for 2000 does contain these embankments and for the elevation model of 2015 these low embankments are raised as is foreseen in the Maaswerken Project. The most important line elements such as the Juliana Canal, important highways and railroads are incorporated in the elevation maps. The PCRaster model script ensures that only areas that can be flooded from the river are incorporated in the flood maps. Low-lying areas behind an embankment are only flooded when these embankments are overtopped.
Damage calculations
The resulting damage in the Netherlands is calculated with the Meuse application of the Standard Damage Module (Huizinga, 2002). In this special application the original damage functions in the Standard Damage Module, which are based on assumptions of sudden disastrous floods after dike breaches, were adapted to the flood conditions in the Meuse. Floods along the studied stretch of the Meuse River occur more gradually and more frequently than along the diked rivers such as the Rhine River. This results in other depth-damage relationships. The method for the Meuse was calibrated on the flood of 1993 (Huizinga, 2002). The land use is not expected to change significantly in the period between 1993 and 2015, because of building restrictions in the frequently flooded areas. Therefore, the current standard damage module application for the Meuse is used for all three systems. The damage module is based on the price level of the year 2002 (Huizinga, 2002). The resulting damage figures are corrected for an annual economic growth rate of 2%.

In Belgium damage may occur in the ‘Mine Subsidence Area’ (Mijnverzakkingsgebied). As explained in section 6.2 this is a low-lying area with a high potential damage. The embankments surrounding this area are expected to break when they are overtopped, which is currently expected to happen at a discharge of about 3,300 m³/s. After the dike improvements of 2004 they may withstand discharges of about 3,800 m³/s (Ogink & Barneveld, 2002). Because the area has a low elevation and the available volume of water is large compared to the storage volume, it is expected that if flooding does occur, damage in this area will be equal to the maximum potential damage. The maximal direct damage in the Mine Subsidence Area is estimated as 33 M€ (WL | Delft Hydraulics, 1998).

The volume that can be stored in the Mine Subsidence Area is about 60 Mm³. The volume in the flood wave with a peak of 3,809 m³/s (T = 1250) above the 3,300 m³/s threshold is 62 Mm³ (of which 29 Mm³ occurs before the passages of the peak). The volume in the flood wave with a peak of 4,484 m³/s (T = 10000) above the critical level of 3,300 m³/s is 262 Mm³ (120 Mm³ before the peak). Therefore, for the situation of 1993 and 2000 the damage is assessed as shown in table 6.5.

Table 6.5 Assumed course of events for different flood waves in the system of 1993 and 2000

<table>
<thead>
<tr>
<th>Discharge Q (m³/s)</th>
<th>T (years)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q &lt; 3,300</td>
<td>250 &lt; T &lt; 1250</td>
<td>The Mine Subsidence Area is not flooded, damage only in the Netherlands</td>
</tr>
<tr>
<td>3,300 &lt; Q ≤ 3,809</td>
<td>T = 1250</td>
<td>The Mine Subsidence Area becomes flooded, further increase of damage in the Netherlands is prevented. Damage in the Netherlands = Damage_{Q &lt; 3300}, Damage in Belgium = maximum damage in Mine Subsidence Area</td>
</tr>
<tr>
<td>Q = 4,600</td>
<td>T &gt;1250</td>
<td>The Mine Subsidence Area is full before the peak of the wave arrives, flooding in the Mine Subsidence Area does not affect damage in the Netherlands</td>
</tr>
</tbody>
</table>

In the system of 2015 the embankments along the low-lying Mine Subsidence Area are expected to be higher than in 2000. Therefore, in 2015 flood damage is assumed to consist of

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damage in the Netherlands only, for all discharges less than 3,800 m$^3$/s ($T < 1250$) (Table 6.6). If larger discharges occur, the Mine Subsidence Area becomes flooded. It is uncertain whether in the case of a 1/10000 peak discharge the flooding of this area will affect the peak discharge level that reaches the downstream areas. We assume that the area becomes filled up too soon and that peak attenuation as a consequence of flooding of the Belgium area is negligible. Damage in the Netherlands will then be as high as it would have been without the flooding of this Mine Subsidence Area. This discussion on potential flood patterns illustrates the relevance of studies on hydraulic system behaviour as explained in section 4.2.2

### Table 6.6 Assumed course of events for different flood waves in the system of 2015

<table>
<thead>
<tr>
<th>Discharge $Q$ (m$^3$/s)</th>
<th>$T$ (years)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q \leq 3809$</td>
<td>$T &lt; 10000$</td>
<td>The Mine Subsidence Area is not flooded, damage occurs only in the Netherlands</td>
</tr>
<tr>
<td>$Q = 4,600$ m$^3$/s</td>
<td>$T = 10000$</td>
<td>The Mine Subsidence Area becomes flooded. The Mine Subsidence Area is full before the peak of the wave arrives, flooding in the Mine Subsidence Area does not affect damage in the Netherlands</td>
</tr>
</tbody>
</table>

### Verification of the method
The results of this method were verified by calculating flood damage of the 1993 flood by carrying out all steps discussed above. The resulting damage was 219 M€, while the recorded damage was 208 M€. The damage to houses and agriculture was higher than recorded, while damage to companies was lower than recorded. The order of magnitude, however, is the same.

### 6.3.2 Resulting flood patterns and flood impacts

The resulting flood impacts are shown in figure 6.5. By studying the numbers in which economic growth is not included, the effect of the embankments constructed between 1993 and 2000 and the effect of the Maaswerken Project constructed between 2000 and 2015 can be considered. The flood damages corresponding with more frequent discharges decrease due to these measures. The embankments and the Maaswerken Project protect the most vulnerable areas from flooding. In all three systems the damages corresponding with more extreme discharges are about the same. When economic growth is included, the differences between the damage figures in the different years are larger.

In the situation of 1993 floods occurred very gradual and flood depths were small. Therefore, in the situation of 1993 the number of casualties in the Netherlands is expected to be negligible. In Belgium however, 12 casualties may occur when the Mine Subsidence Area becomes flooded (WL | Delft Hydraulics, 1998). In the situation of 2000 and 2015 more sudden floods may occur in the Netherlands due to the presence of embankments in those years. The casualties for those years were calculated as 1/1000 of the number of affected persons.
6.3.3 Resilience

Based on the flood impacts discussed in the previous section the amplitude and graduality were calculated following the methods discussed in chapter 3. Table 6.7 shows the amplitude and graduality of the system in the three years. The net effect of the changes in the years (economic growth and the implementation of measures) is a reduction of both the amplitude and the graduality.

Table 6.7 Values for the amplitude and graduality indicator in the three years 1993, 2000 and 2015 (including economic growth)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Indicator</th>
<th>1993</th>
<th>2000</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>EAD (M€/yr)</td>
<td>10</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Amplitude</td>
<td>EANC (Cas/yr)</td>
<td>0.0</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality (-)</td>
<td>0.84</td>
<td>0.75</td>
<td>0.56</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>Recovery capacity (-)</td>
<td>8/9</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

The recovery capacity of the Meuse was assessed by an analysis of the physical, economic and social characteristics that determine the recovery capacity (see section 3.4.4). The physical recovery capacity of the area in the Netherlands in 1993 scores a 9, because the drying speed is fast. In Belgium, the low-lying area will remain wet for a long period and scores therefore, a 6. In 2000 and 2015 the areas behind embankments will stay wet for a longer period. Therefore, the physical capacity scores an 8 in those years. The economic recovery capacity of this area is very high (9). It is comparable with the recovery capacity of the area along the Rhine River (see chapter 4). The social recovery capacity scores an 8 as well. The three aspects context, preparation and human capital score respectively a 9, 6 and 9. In 1993 the overall recovery capacity in the Netherlands scores a 9 and the Belgium area an 8. For the other years, the recovery capacity in both areas scores an 8.
The resistance of the system is low. It does not change between 1993 and 2015, because the reaction threshold, the highest discharge that is not expected to cause floods, did not change. The resistance would only increase if the flood probability of the system as a whole would decrease. This could be arranged by building embankments along the whole length of the river.

6.4 RESILIENCE OF THE SYSTEM IN 1900

6.4.1 METHOD

The resilience of the system as it looked like in 1900, is derived from the resilience calculated for the system as it was in 1993. Between 1900 and 1993 the discharge regime changed and the flood patterns changed due to the construction of the Juliana Canal and the Lateral Canal and by the mining of gravel near Roermond and the mining in the Mine Subsidence Area in Belgium. The flood impacts increased between 1900 and 1993 due to economic growth, which caused land use changes and an increase in the value of, for example, furniture and electronic devices. These changes were considered by using the following assumptions:

- Discharge: In 1900 the discharges were about 7% lower than they are currently (see section 6.2.1).
- Flood pattern: In 1900 the flood-prone area was not yet reduced by the construction of the Juliana Canal and peak flow attenuation was not yet increased due to the artificial lakes resulting from gravel mining near Roermond. The Mine Subsidence Area was not subsided yet as far as in 1993 and the dike around that area was not yet as high as presently. Because the Mine Subsidence Area is expected to have become flooded more frequently in 1900, the potential flood impacts were probably less. Since the area is relatively small compared to the total research area, damage in the Mine Subsidence Area is considered negligible considered to the total damage. It is assumed that water levels resulting from a certain discharge are comparable with the water levels that occurred in the situation of 1993.
- Economic growth: Between 1870 and 2000 the built-up area in the flood-prone area has increased with a factor of about 3.5 (Van Bemmel, 2004). Because most damage occurs within the built-up area, the damage is expected to have been about 3.5 times lower in 1900 than it was in 1993. Next to this an average economic growth of 1% is assumed to have occurred between 1900 and 1993.

6.4.2 RESILIENCE

Based on the assumptions discussed in the previous section the resilience in 1900 was calculated. An EAD of about 0.76 M€/yr and a graduality of 0.92 were found. The low value found for the EAD for 1900 compared to the value found for 1993 is explained by the economic growth and increase of urban area that occurred after 1900. The high graduality is a result of the absence of embankments and the higher flood frequency of the Mine Subsidence Area. The recovery capacity scores on physical, economic and social factors respectively a 9, 7 and 7. The overall recovery capacity thus scores a 7, which is lower than in 1993. The physical recovery capacity is considered comparable with 1993. The economic recovery
6.5 RESILIENCE OF THE SYSTEM IN 2100

6.5.1 METHOD

If no further measures are taken, the resilience of the system in 2100 can be derived from the resilience as it was calculated for the year 2015. Between 2015 and 2100 the discharge regime will probably change due to changes in the area and climate change and the flood impacts will increase due to economic growth. These changes were considered by using the following assumptions:

- Discharge: The discharges in 2100 will be about 10% higher than they are currently (see section 6.2.1). The area that limits the physical maximum discharge to about 4,600 m$^3$/s is assumed to have higher embankments so that a discharge of about 4,900 m$^3$/s can reach the case study area.
- The flood patterns will not significantly change, because no further measures are expected.
- The built-up area outside the area protected by embankments is not increasing, because of building restrictions.
- Behind the embankments economic growth occurs with an annual rate of about 2%.

6.5.2 RESILIENCE

If the embankments are not raised after 2015, then the EAD will be about 39 M€/yr and the graduality 0.62. If the embankments are raised and maintained at a safety level of 1/250, then the amplitude is about 14 M€/yr and the graduality 0.48. The recovery capacity is comparable with the one in 2015 and scores therefore an 8 also.

6.6 DISCUSSION OF THE RESULTS: RESILIENCE IN TIME

The changes in the values of the resilience indicator are summarized in table 6.8 and figure 6.6. The amplitude increases between 1900 and 1993 and then decreases from 1993 to 2015 due to the measures taken. If after 2015 the safety level created by the Maaswerken Project is maintained, then the amplitude increases only a little between 2015 and 2100. If the embankments around the villages are not raised after 2015, the amplitude increases sharply due to both climate change and economic growth. The measures taken between 1993 and 2015 not only decrease the amplitude, they also decrease the graduality. The recovery rate increases a little after 1900 and is expected to remain high until 2100.
Chapter 6

Table 6.8. Overview of the values for the indicators at different times

<table>
<thead>
<tr>
<th>Indicator</th>
<th>1900</th>
<th>1993</th>
<th>2000</th>
<th>2015</th>
<th>2100a*</th>
<th>2100b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAD (M€/yr)</td>
<td>0.76</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>39</td>
<td>14</td>
</tr>
<tr>
<td>EANC (Casualties/yr)</td>
<td>-</td>
<td>0</td>
<td>0.9</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Graduality (-)</td>
<td>0.92</td>
<td>0.84</td>
<td>0.75</td>
<td>0.56</td>
<td>0.62</td>
<td>0.44</td>
</tr>
<tr>
<td>Recovery capacity (-)</td>
<td>7</td>
<td>8/9</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

*2100a is the scenario without dike raising after the Maaswerken Project and 2100b is the scenario in which the embankments are raised to maintain a safety level of 1/250 years.

The results clearly show that the reaction of the Meuse system to peak discharges is changing in time and that thus also the resilience is changing in time. Because in the period between 1900 and 1993 the amplitude increased significantly and the graduality decreased while the recovery rate only increased a little, it is concluded that the resilience decreased within that period. After 2015 the amplitude is expected to increase and the graduality to decrease. Thus also in that period the resilience is expected to decrease. Results show that in the period between 1993 and 2015 the reaction of the system is changing. It is, however, not possible to conclude whether the system is becoming more or less resilient within that period. The amplitude becomes lower, while the graduality also declines. The resistance of the system is not expected to change significantly within the period from 1900 to 2100, since flood probabilities of the system do not change.

![Figure 6.6 Values of resilience indicators over time (assuming that the 1/250 safety level of the embankments is maintained between 2015 and 2100)](image-url)

The accuracy of the results was verified by calculating the damage corresponding with the 1993 flood event. This verification showed that the order of magnitude is correct. Using 1D models and extrapolating the results to water depth maps is thus acceptable for this research. Damage was calculated by the special application of the Standard Dutch Damage Module developed for the Meuse. In this application the damage functions are adapted in order to incorporate the more gradual rising water levels and the more frequent floods in this area compared to the Rhine area. In the situation of 2015, however, the water levels behind the
embankments will not rise gradually and floods in the protected areas will not occur as frequently as in 1993. Therefore, damages behind the embankments may be somewhat higher than was calculated in this thesis.

The results of this case study provide indications about the efficiency of the Maaswerken Project. The costs of the Maaswerken Project are estimated at about 500 to 600 M€ (Projectorganisatie De Maaswerken, 2004). The risk reduction of the Maaswerken is about 4 M€/yr. If climate change effects are neglected and only economic growth is considered, the NPV of the risk reduction of the period between 2015 and 2100 is about 169 M€. This is a simplified comparison which neglects climate change, benefits consisting of improved economic opportunities and the other aims of the Maaswerken Project such as nature development and navigation improvement. It also neglects the benefits obtained by gravel mining. Despite the large simplifications, the figures indicate that the Maaswerken Project may not be cost-effective and the conclusion could be drawn that other reasons (equity etc.) are the driving force behind the project.

Although no strategies are defined in this research it is possible to compare the three strategies that were or are present in the Meuse System:

- Almost no embankments anywhere (as was the case in 1993);
- Low embankments around cities (as was present in 2000);
- A package of measures with amongst others bypasses, river deepening and embankments around villages with a safety level of 1/250 (as planned for 2015 by the Maaswerken Project).

Table 6.9 Resilience indicator values for the three strategies as present in 1993, 2000 and 2015 all calculated for land use and economic situation of 2002.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EAD (M€/yr)</td>
<td>12</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Graduality (-)</td>
<td>0.84</td>
<td>0.75</td>
<td>0.56</td>
</tr>
<tr>
<td>Recovery rate (-)</td>
<td>8/9</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

The resilience of the strategies is presented in table 6.9. The indicators clearly show the differences between the three strategies, but do not indicate which one is more resilient. To increase the resilience of the system as it was in 1993, the amplitude should have been reduced in such a way that graduality remained high. This may have been reached by measures that lower flood impacts instead of probabilities of flooding or by differentiating the flood probability of the villages. These measures were not studied in this thesis.

Although it was not studied in this case study, some comments can be made on what to do in the future. If no changes in policy occur, the embankments need to be raised in the future to maintain the same amplitude. However, these higher embankments will increase the risk on casualties. People will feel safer behind the embankments and because dike breaches mostly occur more suddenly than water level rise in the river, the flood water may surprise people. It is suggested that in the future next to raising the embankments alternatives are studied that consist of damage compensation and adaptation in order to lower and distribute flood risks.
The adaptation measures may consist, for example, of houses on poles or houses with easily removable objects on the ground floor and the living and sleeping rooms on the first floor or higher. Because flood forecasting and warning systems are improving significantly and because water depths are rather small and the threatened areas are not very large, these measures may be feasible in this area.

6.7 CONCLUSIONS

In relation to the research questions of this thesis the following conclusions can be drawn:

- First of all, the changes in resilience of the system in time are significant. The results indicate a reduction of the system’s resilience between 1900 and 1993 and between 2015 and 2100. For these periods the amplitude was found to increase and the graduality to decrease, while the recovery rate appeared not to change significantly. Results show that between 1993 and 2015 the reaction changes: both the amplitude and graduality become smaller. It is not possible to conclude whether the resilience has decreased during that period. The resistance has not changed since the flood probability of the system did not change.

- Secondly, the resilience indicators were successfully applied to the lowland part of the Meuse Basin. The application of the resilience indicators showed the changes in the reaction of the system to peak discharges. The indicators allowed distinguishing between the different systems present in the different years considered.
7 RESILIENCE OF THE LOWLAND PART OF THE MEKONG RIVER BASIN

7.1 INTRODUCTION

The Mekong River is one of the largest rivers in the world. The river rises at 5100 m height in Tibet and flows through China, Myanmar, Laos, Cambodia and Viet Nam before it finally reaches the South Chinese Sea. The upper river is characterised by narrow gorges, navigable reaches and major waterfalls. Downstream of Kratie in Cambodia the character of the river changes from an upstream river into a lowland river (Van Zalinge et al., 2003). The slope of the river bed becomes small, the valley widens and the river overflows its banks during the wet season and inundates vast areas. The most downstream part of the river, the Mekong Delta, has a completely different character: it is criss-crossed by a maze of canals and rivers.

This case study focuses on the lowland river stretch of the Mekong River, between Kratie in Cambodia and the Cambodian-Vietnamese border (Figure 7.1). This case study area includes the relatively densely populated area near Phnom Penh where the Tonle Sap River and Bassac River bifurcate from the Mekong River. The study area has a length of about 135 km north to south and a width of about 95 kilometres from east to west.

The lowland part of the Mekong River Basin was selected since it is one of the few lowland rivers in the world that is relatively natural and unregulated although the basin is populated and in agricultural use. The area is known for its widespread annual floods, bringing fertility and large fish resources. However, in some years extreme floods occur, which cause disasters. The challenge to reduce the impacts of severe floods, while enjoying the advantages of normal flooding makes the area an interesting case study area.

The case study aims at evaluating the applicability and usefulness of the resilience concept for flood risk management in the lowland part of the Mekong River. In order to evaluate this usefulness, the following question was addressed: ‘What is the current resilience of the lowland part of the Mekong River Basin and how do different strategies affect the system and its reactions to the discharge regime?’ To answer this question this chapter addresses the following subquestions:

- How are flood risk management and the socio-economic system related?
- How can the resilience indicators be applied to this area?
- What is the current resilience in the lowland part of the Mekong River Basin?
- Does the resilience of the system change in the future and what is the effect of alternative strategies for flood risk management?

The first subquestion was answered by a literature review and a field trip to Cambodia. It is discussed in section 7.2. The second subquestion was answered by studying available model
schematisations and data of the Mekong River Commission. As discussed in section 7.3, an existing hydrodynamic model was selected to estimate flood patterns and a new damage module was developed in order to make rough estimates of the damage. The third subquestion is discussed in section 7.4, while the fourth subquestion is answered in section 7.5. Finally, conclusions on the usefulness of the resilience concept for flood risk management of the lowland part of the Mekong Basin are drawn in section 7.6.

Figure 7.1 The location of the research area

7.2 DESCRIPTION OF THE FLOOD RISK MANAGEMENT SYSTEM

This section discusses subsequently the discharge regime at the upstream boundary of the system and the physical and socio-economic characteristics of the system itself. Because in the Mekong case the socio-economic characteristics and the seasonal and yearly variation in discharge are strongly related, they are discussed in more detail than in the Rhine and Meuse case studies.

7.2.1 SEASONAL DISCHARGE PATTERN

The discharge of the Mekong River originates from rainfall in both the upper and lower part of the catchment. Of the discharge at the mouth on average 16% is contributed by China, 2% by Myanmar, 35% by Laos, 17% by Thailand, 19% by Cambodia and 11% by Viet Nam (MRC, 2003). The rainfall shows a large variability in both space and time from 1000-1200 mm per year in north eastern Thailand until over 3000 mm year in the eastern mountain range. This variability is caused by the topography and the two prevailing winds: the wet southwest monsoon, which occurs between mid-May and early October and the dry northeast
Resilience in the lowland part of the Mekong River Basin

monsoon, which occurs between October and March. About 90% of the precipitation falls between May and October and about 80% of the discharge occurs between June and November. The Mekong River usually begins rising in May and peaks in September with the average peak flow at Phnom Penh above 45,000 m$^3$/s. The lowest discharges occur in March and April (about 1,500 m$^3$/s near Phnom Penh). The ratio between peak and base flow can thus be as high as 50. In September alone 20 to 30% of the annual flow travels down the Mekong. Next to seasonal variability also important inter-annual fluctuations occur.

Because the basin is enormous and since seasonality is that profound, the occurrence of flood waves as single events, such as discussed in the Rhine River case study, is not feasible. The flood risk management system of the lowland part of the Mekong must be able to cope with inter-annual variations in the seasonal pattern, causing extreme discharges in some years and lower peak discharges in others. This chapter studies, therefore, how the flood risk management system reacts on the discharge during the whole wet season. The ‘seasonal discharge pattern’ is defined as the discharge level as function of time within the whole wet period starting with the rise of the discharge around June until the fall of the discharge in October, including possible small periods of rising and falling discharges in between. Section 7.3.1 provides a quantitative analysis of the peak levels and volumes of these seasonal discharge patterns.

7.2.2 PHYSICAL CHARACTERISTICS OF THE SYSTEM

The research area is formed by the Central Plains of Cambodia, which are large flat areas with some isolated hills. The boundaries of the central plains are formed by the Dangrek Rang Mountains in the north at the border of Thailand, the Elephant Mountains and the Cardamom Mountains in the south near the Gulf of Thailand and the Darlac Plateau in the northeast. The south eastern boundary is not well defined.

The upper boundary of the flood risk system is situated near Kratie. From Kratie the river flows through a wide valley to Kampong Cham. Downstream of Kampong Cham the river enters a very flat area where floodplains play an important role in the flow pattern. Near Phnom Penh the Tonle Sap River joins the Mekong River. In the dry season this river flows from the Tonle Sap Lake into the Mekong River, and in the wet season, water flows in the opposite direction. The Tonle Sap Lake thus functions as a large natural storage. Just downstream of Phnom Penh the Mekong River bifurcates into the Bassac River and the Mekong River. The Bassac River is much smaller than the Mekong River (about 8 times smaller).

During low-flow periods the river flows through the main channel between natural levees. In the wet season, at a discharge of about 30,000 m$^3$/s water enters the floodplains through natural depressions and by openings in the levees along the river. The direction of the flow is indicated in figure 7.2. Along the Bassac River and at the east side of the Mekong River many small canals are present which divert water from the rivers across the levees into the flood plain. A few modern canals are gated and are designed in such a way that maximum spreading of water and silt over the floodplains is ensured.
Fujii et al. (2003) studied the flooding and drying of the floodplains. They found that in the period between 10th of July to the 17th of November 2002 about 10% of the total inflow at Kampong Cham flowed between Kampong Cham and Phnom Penh from the Mekong River into the floodplains on the left side of the river and about 7% flowed into the floodplains on the right side of the river. During the peak of the flow (about 50,000 m³/s) about 15,000 m³/s spilled over the embankments into the floodplains between Kampong Cham and Phnom Penh. One third of this 15,000 m³/s flowed to the right (north) and two third to the left (south). Downstream of Phnom Penh a part of the water flowed back from the floodplains into the river or flowed through the floodplains to Viet Nam. Furthermore, the floodplains between the Bassac and the Mekong River became inundated. The slope of the water on the floodplains is such that they do not only function as flood storage areas but also contribute significantly to the flow (MRC & JICA, 2003).

![Figure 7.2 The flow pattern in floodplains of Cambodia and the percentage of the total volume flowing in each direction (volume between 10th of July to the 17th of November 2002)](image)

Both the flood pattern in Cambodia and Viet Nam and the dry season flows are significantly influenced by the large Tonle Sap Lake. The area of the Tonle Sap Lake expands from 2500 square kilometres to 13000 square kilometres in the wet season and its maximum depth increases from about 2.2 m to more than 10 meters (Jensen, 2001). The volume of water stored in the lake is estimated as \(72 \times 10^9\) m³ (FAO, 1999). The highest water level in the lake lies around 10 m + msl. It is reached around the end of September or the beginning of October.

Flood duration varies within the area. The area between the Mekong River and Tonle Sap Lake is flooded for the longest period (about 180 days). The area at the left (south and east) of the Mekong River dries up in about 2 months. Increased development of roads and embankments around villages has adversely affected the capacity of the drainage system, making rural flooding deeper and longer in duration (FAO, 1999).
7.2.3 THE SOCIO-ECONOMIC SYSTEM

The system studied comprises about 85% of the area of Cambodia and about 80% of its population (Hoanh et al., 2003). Therefore, the socio-economic characteristics of Cambodia are considered representative for the socio-economic characteristics of the flood risk management system. For understanding the socio-economic characteristics of Cambodia, the history of the country and its neighbouring countries must roughly be known.

History and current socio-economic characteristics of the region
Cambodia is the country of the Khmer, who ruled over most of Southeast Asia from the 9th-15th century. After the fall of the Great Angkor Empire, Cambodia suffered from a succession of wars and armed conflicts. During the Khmer Rouge regime (1975-1979) about one third of the population was murdered or died in work camps or due to starvation. Vietnamese troops ended the Khmer Rouge regime, but not the Khmer Rouge guerrilla. In 1989 Viet Nam redraw its army from Cambodia and in 1991 peace was signed. Finally, in 1993 elections were held. In 1998 the Khmer Rouge leader Pol Pot died and the other leaders of Khmer Rouge gave up. Finally, the country became safe and quiet.

All these conflicts hampered development and cooperation between the different countries. The complex pattern of migration that occurred during the wars and the resettlements of hundreds of thousands of people that currently occur, still cause local tensions and problems. The stabilized political situation results in accelerated development. All countries (except Myanmar) have a policy of striving for a high rate of economic growth based on an outward-looking, export-focused macro-economic strategy. However, there are differences between the countries in development and level of exploitation of natural resources. Thailand has overexploited many of its resources, notably forests. It is an energy-hungry country, importing energy from Lao PDR and Yunan (China). It faces labour shortages and it is a source of capital for investment in neighbouring countries' economies. The other Mekong Basin countries are developing countries. There is resource competition on water, industrial development and attracting foreign investment.

The socio-economic system characteristics of Cambodia
Cambodia is a largely rural country with currently some 13 million inhabitants. A large part of the country is still covered by dense natural forest (Hoanh et al., 2003). The GDP is 270 $ per capita, of which 40% is contributed by agriculture, 20% by industry, and 40% by services. About 36% of the population lives below the poverty line (CIA, 2002). The whole life of the Cambodian people seems to be related to water. Consequently, both floods and droughts threaten the socio-economic system.

The most important economic activity in the region is agriculture. Most people (about 80 percent) earn their living from farming and about 21% of the country consists of agricultural area. Rice is the dominant crop. About 90% of the agricultural area is used for rice based farming systems. This does not only include rice paddies, but also the sugar palms at the edges of the paddies, roads, villages, small plots with other crops, grass land, fallow land and abandoned paddies. Large agricultural areas are currently not utilized because of the continued presence of land mines, which remain from the years of civil war. About 2.1 million ha was cultivated in 1993, of which 1.8 million ha was paddy rice, 122,000 ha
other annual crops and 146,000 ha orchards. Trends are: an increase in cultivated and harvested area, an increase in yield per ha and an increase in double cropping practices (Pillot et al., 2000).

Depending on soil type, elevation, flood frequency, flood depth and flood duration, different rice farming systems and rice varieties are used. The number of rice varieties is countless. All varieties can be categorized into four main groups (Nesbitt, 1997):

- Wet season rainfed rice;
- Wet season deep water rice;
- Dry season recession rice and dry season irrigated rice;
- Upland rice (not present in the research area, not discussed any further).

Because the rice varieties differ in their sensitivity to floods, they are discussed in more detail below.

The wet season rainfed rice is further classified into early, medium and late maturing varieties (Table 7.1.) The late maturing varieties, which have a long growth period and are sowed and transplanted first, are grown on the lowest fields close to the river. The higher fields, which are mostly drought prone, are used for early maturing varieties with a short growth period. Most rainfed rice varieties prefer floodwater depths between 0 to 0.25 m, but depths of 0.5 m of more can be tolerated for short periods. Some varieties of late maturing rainfed rice require rainwater during germination and early grow, while they require floodwater when they are taller. Since the flooding depth can be higher than 0.5 m, they are sometimes categorized as deep-water rice.

### Table 7.1 Different rainfed rice varieties (Nesbitt, 1997)

<table>
<thead>
<tr>
<th>Variety</th>
<th>Flowering</th>
<th>Harvest</th>
<th>Properties</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early</td>
<td>&lt; 15 Oct</td>
<td>Late Nov, early Dec</td>
<td>Non-photosensitive*, modern varieties, drought tolerant, subsistence rice</td>
<td>Upper fields, sandy soils, deepest standing water 20-30 cm</td>
</tr>
<tr>
<td>Medium</td>
<td>16 Oct -15 Nov</td>
<td>Mid-late Dec</td>
<td>Best cooking quality, best price, most are photosensitive*</td>
<td>Medium fields, sandy loam soils, deepest standing water 20-40 cm</td>
</tr>
<tr>
<td>Late</td>
<td>&gt; 15 Nov</td>
<td>Late Dec, mid Jan</td>
<td>Photosensitive*, flood tolerant, elongation ability, good cooking quality, high yield</td>
<td>Lower fields, sandy- sandy loam soils with some silt, 40 –100 cm water</td>
</tr>
</tbody>
</table>

*Photosensitive: the growth and ripening depend on the day length

Deepwater rice is grown in depressions that accumulate floodwater at a depth of 0.5 m or more for at least one month. Maximum water depth ranges to more than 3.0 m! Most varieties of deep-water rice are old traditional varieties that are photosensitive and have very good elongation capabilities. In ideal seasons, these crops receive sufficient local rainfall to allow 6 or more weeks of growth before mid-July. They are then at an advanced stage of maturity which allows them to elongate fast enough to keep pace with the rising floodwater. Some of these rice varieties can grow 0.2 - 0.3 m/d and grow up to 4 m long. Deepwater rice is
harvested in January or February. Deep-water rice cultivation is decreasing rapidly in favour of recession rice, double cropping or dry season rice. The risk of damage due to abnormal floods or droughts is high.

*Recession rice* uses the floodwater as source for moisture. As the water begins to recede, the receding water is blocked off with barriers erected by farmers. Crops are planted along the edges of the flooded areas and as the water recedes during the dry season, water is pumped back onto the crops where possible. A succession of crops follows the edge of the lakes or floodplains as the water recedes, hence the term ‘recession rice’. The soils where recession rice is grown are normally very fertile due to the yearly floods. Recession rice is normally non-photosensitive, and short in duration. The period of transplanting is, therefore, very flexible.

Rice farming in Cambodia is well adapted to the dynamic character of and the uncertainties in the rainfall pattern and the timing and level of the Mekong’s discharge. Farmers normally have plots in at least two different rice ecosystems. In that way farmers spread the required labour force more evenly over the year and prevent the loss of the whole yield at once. Farmers can also adapt their sowing and transplanting dates to the actual circumstances. If the first rains are late, then nursery bed establishment and land preparation starts late. Since mostly photosensitive varieties are used, the rice will still develop and can be harvested at about the same time as normally. If a lack of rain in July or August delays transplanting, farmers can wait until wetter days arrive and transplant older seedlings. Furthermore, if suddenly unexpected heavy rains occur on an abnormal date farmers plant early maturing non-photosensitive varieties in unused fields and enjoy extra yield (Lando & Mak, 1994). Finally, when floods are extremely severe, fields in which the crops are destroyed are replanted with recession rice. Since timing of agricultural activities depend on the rainfall and discharge pattern, and because rice is not equally sensitive to floods in all growth stages, comparable floods can result in different flood impacts.

Next to agriculture, other important water related socio-economic activities in Cambodia are fisheries, navigation, power supply and tourism. They are discussed briefly here.

One of the world’s most productive freshwater *fisheries* areas is located within the system: The Tonle Sap Lake. Fish migrations from the Tonle Sap help restock fisheries as far upstream as China and in many tributaries along the way. Flooding is one of the main attributes to the high fish production in the Basin. Areas that are flooded during part of the year can produce much more fish than permanent water bodies of the same size (Jensen, 2001). Contribution of fisheries to GDP is estimated as 16% (Van Zalinge *et al.*, 2003). Next to fishing also aquaculture production is important.

*Navigation* is only suitable for local transport and for export to Viet Nam. The Mekong is not used for transport to Laos or China. The main obstacles to navigation are the extreme difference in wet and dry season flow, as well as the rapids of the upper Mekong, and the Khone falls at the border between Cambodia and Lao PDR and the Stung Treng –Kratie reach in Cambodia.
Power supply by constructing dams is a hot issue in Cambodia. Apart from two mainstream dams in the upper river stretch in China, no dam has been built in the main channel of the Mekong River. Despite many studies that try to prove their economic attractiveness large main channel hydropower projects could not be implemented for a number of reasons relating to environmental problems, resettlement and power demands and conflicting interests of the different countries (MRC, 2003). Dams in the mainstream of the Mekong River may result in a destruction of fish resources and alteration of the flood regime. Since over 80% of the population of Cambodia depends on fisheries and agriculture, this could have severe consequences. In the 60ties Cambodia considered the construction of a large mainstream dam just upstream of Kratie near the rapids of Sambor. Although it is still mentioned sometimes, it is not considered a serious alternative anymore. Cambodia has planned and constructed small dams in tributaries such as the Prek Thnot River which joins the Mekong River near Phnom Penh.

Tourism is an activity indirectly linked to floods through biodiversity. The biodiversity of the system is estimated to be comparable with the Amazon region.

7.2.4 FLOOD IMPACT AND THE ANALYSIS OF RECENT FLOOD EVENTS

After a general introduction on flood impacts in Cambodia, this section analyses recent flood events in order to improve understanding of the way in which the flood risk management system reacts on seasonal discharge variations.

Current flood risk management and flood impacts
Flood risk management in Cambodia currently consists mainly of adaptation to floods instead of flood control. Houses are built on poles, transport is carried out by boats and the agricultural pattern is adapted to the annual flood pulse. Around Phnom Penh dikes have been constructed to protect the city. In south Cambodia low dikes provide protection to agricultural fields during the first months of the rainy season. Furthermore, canals have been constructed to control the flood path somewhat. As a result of this strategy normal floods do not cause much damage. However, sometimes extra-ordinary floods occur, which cause substantial damage to crops and infrastructure. The most important negative flood impacts are loss of human lives, destruction of infrastructure and disturbed transport, damage to property, loss of agricultural production and spread of diseases. Table 7.2 provides an overview of available data on flood impacts. The most important positive flood impacts are the deposition of fertile soil, the large fish production that they enhance, the dilution of sulphate in the soils, reduction of the number of dangerous insects and mice, and the recharge of ground water resources (Anonymus, 2003). As explained in the previous section, not only the positive flood impacts mentioned here must be considered, but also the adaptation of agriculture to the yearly flood pulse which resulted in a dependency of agriculture on floods must be taken into account. This dependency means that in dryer years yield reduction occurs. Floods are thus required for good yields.

Negative flood impacts seem to have increased recently. This increase of impacts is not only caused by the severity of recent floods, but also by the increased population density, the increased agricultural area and yield per area, the value of infrastructure, irrigation schemes
Resilience in the lowland part of the Mekong River Basin

and changes in, for example, the way houses are constructed. The traditional Khmer houses of good quality wood on poles can withstand heavy rains, winds and floods. Since good quality wood is expensive nowadays, more and more people build their houses from cheap bamboo just a little above ground level. Strong winds, rain and floods destroy these houses (CARE, 2001).

Table 7.2 Summary of available flood impact data (NCDM (2002) unless indicated otherwise)

<table>
<thead>
<tr>
<th>Damage category</th>
<th>Unit</th>
<th>1996</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice affected of which destroyed</td>
<td>$10^3$ ha</td>
<td>$290_{(2)}$</td>
<td>$253_{(2)}$</td>
<td>$347_{(1)}$</td>
<td>$149_{(5)}$</td>
</tr>
<tr>
<td>Damage rice</td>
<td>M$$</td>
<td>-</td>
<td>$58_{(2)}$; $62_{(3)}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Other crop destroyed</td>
<td>$10^3$ ha</td>
<td>$17_{(2)}$</td>
<td>$47_{(2)}$</td>
<td>10</td>
<td>3.2</td>
</tr>
<tr>
<td>Cattle (pigs / oxen)</td>
<td>*$10^4$</td>
<td>$1.9_{(2)}$</td>
<td>2.3</td>
<td>$1.6_{(3)}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Cattle</td>
<td>M$$</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total agriculture</td>
<td>M$$</td>
<td>-</td>
<td>65; 71</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Persons</td>
<td>Affected persons</td>
<td>*$10^6$</td>
<td>$1.9_{(2)}$</td>
<td>3.4</td>
<td>$2.2_{(4)}$</td>
</tr>
<tr>
<td>Evacuated families</td>
<td>nr</td>
<td>-</td>
<td>85000</td>
<td>-</td>
<td>24000</td>
</tr>
<tr>
<td>Casualties</td>
<td>nr</td>
<td>$155_{(2)}$</td>
<td>347</td>
<td>62</td>
<td>29</td>
</tr>
<tr>
<td>Houses</td>
<td>Houses damaged</td>
<td>*$10^4$</td>
<td>50</td>
<td>318</td>
<td>-</td>
</tr>
<tr>
<td>National road</td>
<td>km</td>
<td>-</td>
<td>$259_{(3)}$</td>
<td>39</td>
<td>9</td>
</tr>
<tr>
<td>Rural road</td>
<td>km</td>
<td>-</td>
<td>$730_{(3)}$</td>
<td>8000**</td>
<td>767</td>
</tr>
<tr>
<td>Bridges</td>
<td>nr</td>
<td>-</td>
<td>$115_{(1)}$</td>
<td>175</td>
<td>165</td>
</tr>
<tr>
<td>Damage infrastructure</td>
<td>M$$</td>
<td>-</td>
<td>$45_{(3)}$; $64_{(3)}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Irrigation systems (nr)</td>
<td>nr</td>
<td>-</td>
<td>123</td>
<td>201</td>
<td>945</td>
</tr>
<tr>
<td>Irrigation systems</td>
<td>M$$</td>
<td>-</td>
<td>17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rural development</td>
<td>M$$</td>
<td>-</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Others</td>
<td>Schools affected (nr)</td>
<td>-</td>
<td>988</td>
<td>911</td>
<td>129</td>
</tr>
<tr>
<td>Schools affected</td>
<td>M$$</td>
<td>-</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Health centres</td>
<td>nr</td>
<td>-</td>
<td>158</td>
<td>45</td>
<td>7</td>
</tr>
<tr>
<td>Health centres</td>
<td>M$$</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temples affected</td>
<td>nr</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>55</td>
</tr>
<tr>
<td>Total</td>
<td>Total damage</td>
<td>M$$</td>
<td>86</td>
<td>150</td>
<td>36***</td>
</tr>
</tbody>
</table>


*NCDM (2002) provides two values, 58 M$\$ is the cost and 87 M$\$ its market value.

** This number seems very high. It may be measured differently than in other years.

*** The total damage in 2001 also includes damage due to droughts and flash floods along the Prek Thnot River. Damage to drought was quantified as follows: 54000 ha rice destroyed, 192000 families had food shortage (NCDM, 2002).

Description of the flood events of 2000, 2001 and 2002

In 2000, 2001 and 2002 high peak discharges occurred. The flood impacts in these years are included in table 7.2, while the characteristics of the peak discharges are presented in table 7.3. The events in the three years are discussed below.
In 2000 an exceptional flood disaster occurred, which is considered the worst flood ever occurred in this area. A very early peak of 47,508 m$^3$/s at Kratie occurred at the 20th of July. After this peak, floodwater started to recede. However, on the 21st of August, floodwater started to rise again and reached a discharge peak of 50,500 m$^3$/s on the 10th of September (Table 7.3 and figure 7.3). This second peak was exacerbated by Typhoon Wukong, which caused severe rains in the tributaries of the Mekong River in Laos and Thailand. The recurrence time of the discharge peak level at Kratie was only 10 years. However, due to the large first peak, the highest level within at least 43 years was measured at Phnom Penh. The total flood extent was about 2.3 to 2.4 million ha (Ministry of Water Resources and Meteorology & CNMC, 2003).

Table 7.3 Description of different flood events*

<table>
<thead>
<tr>
<th>Year</th>
<th>1996</th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recurrence time of the discharge’s peak level at Kratie (years)</td>
<td>10</td>
<td>1</td>
<td>1 or 2</td>
<td>10</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>$Q_{\text{max}}$ at Kratie (m$^3$/s)</td>
<td>53,000</td>
<td>30,000</td>
<td>43,000</td>
<td>50,500</td>
<td>52,300</td>
<td>50,300</td>
</tr>
<tr>
<td>Volume &gt; 40,000 m$^3$/s at Kratie (Mm$^3$)</td>
<td>13134</td>
<td>0</td>
<td>1532</td>
<td>23739</td>
<td>18397</td>
<td>14590</td>
</tr>
<tr>
<td>Maximum WL at Phnom Penh (m+ msl)</td>
<td>9.92</td>
<td>6.88</td>
<td>8.82</td>
<td>10.13</td>
<td>9.69</td>
<td>9.82</td>
</tr>
</tbody>
</table>

*In Cambodia, the wet season of 1998 (year 98/99) is considered a dry year, 1999 a normal flood year and the years 2000, 2001 and 2002 extreme wet years (CTI & DHI, 2003)

The flood impacts resulting from the 2000 flood event were disastrous. In Cambodia alone 347 people died and millions of people were affected, either by evacuation, loss of crops and livestock or by being prevented from going to work or to school (MRC, 2002). Damage was estimated as $150 million. Most damage occurred to the agricultural sector and to
infrastructure (Table 7.2). About 20% of the rice area was destroyed by the flood. However, 4% of the destroyed area was replanted with recession rice and the harvest in the non-flooded areas and the dry season harvest were high due to the abundance of water. The total harvest in the year 2000/2001 was about 90% of the harvest in 1999/2000 and exceeded the harvests of the period from 1996 – 1999. Next to damage to crops and infrastructure also damage to flood control and irrigation systems, schools and health centres was large (World Bank, 2001). The floods caused the outbreak of epidemic diseases such as malaria, diarrhoea and dengue fever until about one month after the floodwaters had receded. Damage to agriculture was highest in Kandal (between Mekong and Bassac south of Phnom Penh) and Prey Veng province (Southeast of Mekong) in South Cambodia. The World Bank (2001) estimated that the GDP growth was about 1% lower than was expected before the flood season started. Flood damage did not only occur in the flood risk management system but also in the mountains near Stung Treng and Kratie, along tributaries, and near the coast. Although this area is not included in the research area, the damage is included in the figures presented in table 7.2, because no split-up figures were available. Figure 7.4 shows the flood extent of 2000 and of an average year.

Figure 7.4 A rough indication of the water depth difference between 2000 and 1999 (a ‘normal’ year) (both simulated with the 1D model Mike11)

The recovery after the 2000 flood was studied by CARE (2001). The families in 12 villages in Prey Veng Province coped with the loss of rice yields by fishing in the flooded areas and eating stored food reserves. They usually also cut down their daily rice consumption. To raise funds people offered labour to, for example, construction companies and garment factories in Phnom Penh. Many people tried to borrow money. However, loans are only available for
people that are expected to pay interests and do not have loans yet. Many people in Cambodia already have debts, most often incurred to meet health emergencies (CARE, 2001). Interest rates are high (10 to 20%). Therefore, succeeding years with severe floods are disastrous. Finally, people that run out of options used destructive coping strategies in order to survive: they sold their land, their house or their cattle and lost their livelihood. The successful dry season harvest after the flood helped recovery. Development and emergency aid by various donors enabled the reparation of infrastructure and irrigation structures, prevented starvation in many cases, reduced epidemics and provided new seeds for farmers. However, when the floods of 2001 occurred many structures were still not repaired.

In 2001 the discharge at Kratie increased to an even higher level than in 2000. However, flood extent was less due to the shape of the discharge wave and the fact that in 2000 two peaks occurred. In 2001, the country had not yet recovered from the 2000 disaster. The large difference in flood damage between 2000 and 2001 can be explained from the difference in flood depth and flood extent, the fact that some infrastructure was not repaired yet, the small area cultivated with crops due to drought in the beginning of the wet season of 2001, and the lack of seeds caused by the 2000 floods.

In 2002, an estimated area of only 64% of the normal cultivated area was planted because until August rainfall was insufficient for crop growth (CDRI, 2002). In September large floods occurred. Damage caused by the flood is estimated as 19 M$ (NCDM, 2002) or 40 million M$ (CDRI, 2002) and comprehends about 40000 ha of rice, 945 irrigation schemes, roads, bridges, schools, temples and health centres.

**Comparison of the historic flood events**

Different years with extreme floods resulted in very different flood impacts. The data discussed above raises questions such as: ‘Why is the difference in damage between 2000 and the years 2001 and 2002 that large, while the peak discharge levels at Kratie were comparable?’, ‘Why was damage higher in 2001 than in 2002 while flood depths and extent were larger in 2002?’. In the available data different explanations were found. These explanations are:

- Although in 2001 and 2002 the maximum discharge at Kratie was comparable with the one in 2000, the water depths in the system were much higher in 2000 due to the larger discharge volume in that year. Furthermore, timing of the floods (early start and the unexpectedly high second peak late in the wet season) may have caused extra damage in 2000.
- In 2000 also typhoons occurred which caused significant damage along the coast and in the sub-catchments. Although the coastal area and the mountainous sub-catchments are outside the system, their damage is incorporated in the figures. Therefore, actual number of casualties and actual damage to roads and agriculture within the research area was probably smaller.
- In 2001 and 2002 not only floods, but also droughts occurred. These droughts reduced the cultivated areas and thus also the potential flood damage in those years. Besides, late maturing rainfed rice which was destroyed by drought already, could not be destroyed by floods anymore. In 2002 the drought was most severe.

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8 Damage caused by the drought is estimated as 9 M$ and affected 135000 ha of rice.
Many roads, bridges and irrigation systems that were damaged in the 2000 flood were still not repaired in 2001 and 2002 and could, therefore, not be destroyed in these years.

After 2000 a lot of attention was paid to improving flood prevention. According to several news issues the safe areas that were identified after 2000 for people to evacuate to during floods, reduced the number of casualties in 2001 and 2002 (a.o. Water Conserve August 27, 2002). Furthermore, the flood early warning system was improved and organisations such as the Cambodian Red Cross and the National Committee of Disaster Management may have taken advantage from their experience from 2000 to act more efficiently in 2001 and 2002. Also the inhabitants may have behaved differently in the flood years 2001 and 2002 since they had obtained experience during the flood of 2000.

The recorded data is probably not complete and not totally consistent. The recorded damage numbers depend on the method and aim of damage recording. The figures used are a combination of damage due to different events including flash floods and typhoons. The recorded data lack damage to houses and damage of remote areas.

Based on the above it is concluded that the following factors are important for the relation between flood events and damage:

- The timing of the of the flood in relation to timing and extent of the agricultural practices such as sowing, transplanting, and harvesting which determines the stage of the crops at the moment that they become flooded and thus their sensitivity to floods;
- The state of the socio-economic system: the state of the roads, irrigation systems, number of inhabitants, number of just resettled refugees (which may be less prepared);
- Preparedness, flood early warning, emergency measures.

All discharge – flood impact relationships change over time, because the system is rapidly changing: roads are constructed differently nowadays, houses, temples and irrigation systems increase in number and in type of construction and the agricultural pattern is changing also. In such dynamic environment it is very difficult to estimate potential flood damages at this moment and even more difficult to estimate them in the future.

In section 7.3.4 the understanding of flood events and their impacts is used in the development of the damage module.

### 7.3 Methods and Models Used to Apply the Indicators

This section discusses the statistical analyses, models and data used in order to be able to calculate the values of the resilience indicators. First, the hydrological data at Kratie is analysed in order to find a quantitative description of the discharge regime to which the system may react resiliently. Secondly, the hydraulic model that is used to calculate the effects of the discharge regime is discussed and evaluated. Finally, the method used to assess flood impacts is discussed.
Section 7.3.1 Probabilities of Peak Discharge Levels and Volumes

As explained in section 7.2.1, it is not sensible to distinguish flood waves with a duration of days in the Lower Mekong. Instead, the seasonal discharge pattern within the wet season is considered. Important characteristics of this discharge pattern which determine the resulting water depths are the maximum discharge level, the discharge volume and duration.

Probability of peak discharges at Kratie

Water levels have been recorded at Kratie for about 70 years and a good rating curve was developed in 2002 (see MRC & JICA (2003)). The rating curve developed in 2002 may not be valid for the whole series of measured water levels, because the profile at Kratie and downstream of Kratie might have changed. The riverbed at Kratie seems stable, but near Kampong Cham sand bars and unstable islands are present. Changes near Kampong Cham may influence the water level and thus the rating curve at Kratie, because the slope of the river is very small (about 5 cm/km). Nevertheless, the rating curve of 2002 was used for the whole period from 1940 to 2002, because it is the only one available. Statistical analysis of the discharges calculated with this rating curve did not show a trend, which would have been expected if the riverbed would have gone up or down in time.

To calculate the resilience of the flood risk management system, discharges with frequencies between once a year and 1/10,000 a year were studied. Because the recorded water level series comprises only about 70 years, a wide extrapolation was necessary to find the 1/10,000 year discharge. The discharges with a probability of 1/10,000 a year must thus be considered carefully. The maximum physical discharge is not known. Since at Kratie the river just leaves the mountains there is no reason to assume a physical maximum.

To calculate discharge probabilities, different extreme value distributions were studied (Table 7.4). The best fit resulted from applying Gumbel with partial series (Figure 7.5). To apply Gumbel based on partial series, the recorded data were divided into three ranges at visible bends in the recorded series (Figure 7.5 and equation 7.3). Gumbel was applied to each range. Normally, this method with partial series is used to incorporate heterogeneity in the range of discharges. For example, when some discharges result from events including sudden snowmelt...
and others do not. In the case of the Mekong, typhoons or events where floods in Thailand occur may result in heterogeneity in the data series. However, based on the available data it is not possible to prove heterogeneity or to define thresholds for different processes in the catchment and to assess their effect on the discharge data at Kratie. Because of the good results for the partial series analysis, it was used anyway. The extreme value distributions differ most for the very extreme discharges. The exact value of these rare discharges is not expected to influence the EAD significantly, because of their low frequency. However, they may influence the graduality indicator. In section 7.4 the sensitivity of the results for the applied extreme value distribution is assessed by using also the two other extreme value distributions mentioned in table 7.4.

The equations used for the Gumbel partial distribution are:

1. \( Q = 13847 \cdot y_T + 48308 \) IF: \( Q < 38,000 \text{ m}^3/\text{s} \) (\( y_T < -0.74 \))
2. \( Q = 4820.1 \cdot y_T + 41632 \) IF: \( 38,000 < Q < 49,500 \) (\( -0.74 < y_T < 1.69 \)) (Eq. 7.3)
3. \( Q = 2103.1 \cdot y_T + 46211 \) IF: \( Q > 49,500 \text{ m}^3/\text{s} \) (\( y_T > 1.69 \))

**Volumes**

Not only the maximum discharge but also the volume in the wet season is relevant for the corresponding damage (see section 7.2). A larger volume causes the filling of available storage and reduces the slope of the water plain towards the lake. A similar peak discharge level at Kratie will result in higher water levels, if less storage volume is available and the
Chapter 7

The slope towards the Tonle Sap Lake is less. To study this effect, four possible discharge patterns were simulated and the resulting water levels at different locations in the system were studied.

The four discharge patterns, all with the same total volume are (Figure 7.6):

- An average shape\(^9\) and one peak level of 48,000 m\(^3\)/s (average)
- Two peaks of 48,000 m\(^3\)/s and the same volume as pattern number 1 (double)
- Brief but very high peak and the same volume as pattern number 1 (high peak)
- Wide but lower peak and the same volume as pattern number 1 (wide)

---

\(^9\) The average volume has been determined by the method of Klopstra & Duits (1999).
The results of the simulations show that the maximum discharge level at Kratie, the discharge distribution over time, and the total volume which is discharged before the peak occurs, all are important for the resulting water levels. The relative importance of these aspects differs between the river stretch upstream of Kampong Cham (for the location, see figure 7.7), the Tonle Sap Lake and the other river stretches. For the river stretch upstream of Kampong Cham the peak discharge level is the most important, while the volume of discharge does not have much influence. Because no significant flooding occurs upstream of Kampong Cham, peak attenuation is less important in that stretch than in the other stretches. For the river stretches downstream of Kampong Cham (both Mekong and Bassac), the highest water levels result from the pattern with the high peak. The wide pattern and the pattern with two peaks result in higher water levels than the average wide pattern (see, for example, the results in the Mekong near Phnom Penh, Figure 7.8). In this two-peak pattern a larger part of the available storage is already filled when the second peak occurs. Peak attenuation is thus less effective. Hence, for the river stretches downstream of Kampong Cham the volume of the discharge in the wet season, the discharge as function of time and the discharge peak level all determine the resulting water levels. For the Tonle Sap Lake and the Tonle Sap River the width of the peak is dominant (Figure 7.8). The highest water levels result from the lower wide pattern and the lowest from the sharp high peak. Because the inflow capacity to the lake is limited, a wider but lower discharge pattern results in higher water levels than a sharp high pattern.

Based on this analysis it was concluded that the shape of the discharge pattern at Kratie must be included in the analysis because it affects the corresponding water levels significantly. Therefore, probabilities of different volumes and different ‘wave forms’ were studied by using the method of Klopstra & Duits (1999; see chapter 4). The requirement of this method that volumes and durations are independent from peak level proved to be valid for the Mekong. The analysis of the relationship between flood volumes and discharges showed, however, that the variation in wave duration and volume is very large, especially for Q/Qmax of 0.75 and lower. This means that both very wide and very narrow ‘waves’ may occur. The method of Klopstra & Duits (1999) was used to calculate discharge patterns with 25 %, 50 %.
and 75 % probability of exceedance, based on all wet seasons with a peak level higher than 44,000 m$^3$/s ($T = 2$).

The method of Klopstra & Duits (1999) allows the definition of the discharge as function of time for discharges exceeding 0.75 times the peak discharge. For lower discharges, the variability is too large to determine a sensible hydrograph. In order to simulate the effect of the selected discharge patterns, however, the hydrograph has to be extended and must include also discharge values which occur before the discharge is equal to 0.75 times the maximum discharge, because of the long memory of the system. Therefore, extra discharges were added to the selected waves to create realistic initial conditions at the start of the relevant part of the flood event. As initial onset of the wet season the 2002 discharge pattern was used. The influence of this initial part of the wet season is explored by repeating the simulations with a very high initial onset. The results showed that the resulting water levels are influenced a little by the initial onset. However, the influence (about 15 to 20 cm on the resulting water levels) is small compared to the uncertainties caused by inaccuracies in the DEM, the hydraulic model, the discharges etc. The resulting seasonal discharge patterns for a peak level of 48,000 m$^3$/s at Kratie are presented in Figure 7.9.

In summary: The resilience of the present flood risk management system and of possible future strategies will be determined based on the discharge patterns with peak levels corresponding with the recurrence times as given in table 7.4 and with volumes with a probability of exceedance of 25%, 50% and 75%.

![Figure 7.9](image)

**Figure 7.9** Three discharge waves with different probabilities of exceedance for a peak of 48,000 m$^3$/s

### 7.3.2 HYDRODYNAMIC MODELLING

In this case study the MIKE11 hydrodynamic model was used, that was developed, calibrated and validated in the research project ‘Tonle Sap Lake & Vicinities’ of the MRC (CTI & DHI, 2003). The existing model validations show that the model is applicable for the simulation of
discharge waves in the research area. Therefore, the model was used without further modifications. Only the boundary conditions were changed as will be discussed below.

The schematisation covers the Mekong River from Kratie down to Tan Chau, just downstream of the Cambodian-Vietnamese border, and the Bassac River from Phnom Penh to Chau Doc as well as the Tonle Sap Lake and the Tonle Sap River. The river and its floodplains are quasi-2D described by schematising the floodplains as branches that are connected with the river at different locations (Fujii et al., 2003). The connections are schematised as link channels and the embankments as long broad-crested weirs. This quasi-2D approach enables the representation of the flow of water over the floodplains. Since the model covers a very large area, not all bridges and culverts are schematised in the model. Links are established at locations on the mainstream where measurements exist and at locations where it is known that the major portion of the flow exchange occurs.

The boundary conditions of the original model were adapted in order to make the model applicable to the case study. At the upstream boundary at Kratie a discharge as function of time is imposed. In the original model a water level boundary was used, because no discharge data was available when the model was developed (MRC & JICA, 2003). The downstream boundaries of the Mekong and Bassac Rivers are located in Viet Nam at Tan Chau and Chau Doc (Figure 7.10). These boundaries consist of stage-discharge relationships. In the original model recorded daily water levels were used as boundary conditions. This is, however, not possible here because we use hypothetical discharge patterns as input. Except daily water levels of the period 1998-2002 no other data was available at the downstream locations. Therefore, stage-discharge relationships were derived from model results. Because these relationships are probably influenced by backwaters of floods in Viet Nam, they may be not very accurate. Fortunately, the influence of the boundary is very limited (Alderlieste, 2004a). The effect of the use of new boundary conditions on the simulated discharges and water levels for the years 1998-2000 was found to be negligible. At the most northern part of the Tonle Sap Lake a very small constant discharge is used as boundary condition. The direct rainfall on the Great Lake and the floodplains and the discharge from the tributaries around the Great Lake as well as from Stung Chhlong and Prek Thnoat River are schematised as lateral inflows. The lateral inflows for the years 1998-2002 were calculated by MRC & JICA (2003). The sensitivity of the water levels and discharges for the lateral inflows has been tested and proved to be low. Although omitting the rainfall is not possible, the exact amount is not very critical (Alderlieste, 2004a). In this research the lateral inflows of 2002 were used as boundary conditions.

The resulting water levels at the river and floodplain branches were interpolated to floodmaps by using DHI GIS module, an add-on to Mike11.
Although the model was already calibrated and validated before (MRC & JICA, 2003), the years 1999 to 2002 were simulated to get more insight into the accuracy of the model results. The results showed that a good match between observed and simulated discharge was present at Kampong Cham and Chrui Changvar (Mekong River near Phnom Penh). However, the results at Phnom Penh Port (Tonle Sap River) could use some improvement. The simulated flood extent did not correspond well with the flood maps derived from satellite images. It is difficult to conclude whether the differences were caused by wrong interpretations of the RADARSAT images, errors in the model simulation or errors in the translation from 1D results to 2D flood maps. Differences between measured and simulated water levels in the floodplains were quite large (around 1m). However, no better model is available. Fujii et al. (2003) concluded that the model is fully capable to simulate not only the current situation but also the impact of future physical and infra-structural changes in the floodplain. The model was used without further modifications.

### 7.3.3 Damage Modelling

In order to calculate flood impacts a flood damage module was developed. This damage module is based on a relationship between water depths and flood impacts. Since these water depth- flood impact relationships are influenced by many complicating factors, as was described already in section 7.2.5, it is difficult to develop a comprehensive damage module. The aim of this damage module, therefore, is to generate a damage number with the correct order of magnitude. For a detailed cost-benefit analysis the module (and also the hydraulic model) should be improved.

The developed damage module is generally comparable with the Standard Damage Module of the Netherlands which was used in chapters 4, 5 and 6. Damage is calculated per grid cell of 1 ha by multiplying a damage factor with the maximum damage for that grid cell. The maximum damage depends on the land use type. The damage factor varies between 0 and 1, depending on water depth and land use type. The most important flood impacts are damage to
rice and to infrastructure. Therefore, the damage module focuses on these two damage categories. In case of extreme floods also the cities of Kampong Cham and Phnom Penh may become flooded. If this happens urban damage is included in the damage assessment as well.

**Damage to agriculture**

The damage module is based on the land use map of the MRC. Although this map indicates the agricultural area, it does neither define which area is used for rice, nor what rice variety is cultivated where. The potential flood damage to the different rice varieties, however, differs widely: floating rice and recession rice benefit from floods, while some rainfed rice varieties are harmed by large flood depths and others will be totally destroyed. Therefore, a land use map which distinguishes between different rice varieties was developed based on literature and the simulated maximum water depth map of 1999. The following assumptions were used:

- The flood depth map of 1999 is representative for a flood depth map in a normal year.
- The land use of areas that flood annually consist of crops that require flooding or are not sensitive to flood impacts.
- All agricultural areas where the maximum water depth in 1999 exceeded 3.5 m are classified as 'agriculture without negative flood impacts'.
- In all areas where the water depth ranges between 1.5 – 3.5 m floating rice or recession rice is present. Floating rice is situated mainly around the lake and recession rice mainly in southern Cambodia (Nesbitt, 1997).
- In areas where the water depth is less than 1.5 m rainfed rice varieties that are not vulnerable to floods are cultivated (Figure 7.11 ‘rainfed frequently flooded’).
- In the flooded areas relatively few roads, buildings and other crops are present.
- Damage factors were derived from the information on rice varieties as mentioned in section 7.2.3 (Figure 7.12).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>99,270</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floating</td>
<td>68,596</td>
<td>80,000</td>
<td>84,000</td>
<td>56,000</td>
<td></td>
</tr>
<tr>
<td>Recession</td>
<td>226,859</td>
<td>224,000</td>
<td>169,000</td>
<td>150,000</td>
<td>233,000</td>
</tr>
<tr>
<td>Rainfed</td>
<td>1,523,477(^*)</td>
<td>1,518,000</td>
<td>1,747,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total rice</td>
<td>1,918,202(^*)</td>
<td>1,991,000</td>
<td>2,038,000</td>
<td>2,079,000</td>
<td></td>
</tr>
<tr>
<td>Total crops</td>
<td>1,941,343</td>
<td></td>
<td></td>
<td></td>
<td>1,846,000</td>
</tr>
<tr>
<td>wet season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^*\)Agriculture which is insensitive to floods (See explanation of above (third assumption))


\(^2\)Calculated by assuming that other crops than rice occupy 250000 ha (Nesbitt, 1997; MRC, 2003)

The resulting areas of each rice variety correspond with literature (Figure 7.11 and table 7.5). Maximum damage was based on literature values (Table 7.6). The newly developed land use map based on the assumptions above was used as the basis for the newly developed damage module.
Chapter 7

Figure 7.11 Rice in the research area

Table 7.6 Maximum damage per ha used compared with literature values

<table>
<thead>
<tr>
<th>Rice type</th>
<th>Yield (Ton/ha)</th>
<th>Rice equivalents (Ton/ha)*</th>
<th>Value ($/ha)*</th>
<th>Maximum damage ($/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating</td>
<td>1.3</td>
<td>0.81</td>
<td>102</td>
<td>140</td>
</tr>
<tr>
<td>Recession</td>
<td>3.1</td>
<td>2</td>
<td>250</td>
<td>440</td>
</tr>
<tr>
<td>Rainfed</td>
<td>2</td>
<td>1.25</td>
<td>156</td>
<td>150 (frequently flooded)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>281</td>
<td>200 (rainfed and other crops)</td>
</tr>
</tbody>
</table>

*Rice equivalents are about 0.625 times total paddy production. The rice value depends on rice variety and season and varies between about 125 and 225 $/ton (Sources: MRC, 2003; FAO, 2000; CEDAC, 2003)

Figure 7.12 Used damage factor – water depth relationships for different rice varieties
Damage to infrastructure
In the model, the damage to roads and railroads is calculated by assuming that damage to roads in normal years is negligible. Therefore, all highways and provincial roads on the MRC roadmap in the area that was flooded in 1999 are supposed to be on dikes or otherwise flood proofed. They have been identified as road type zero. Furthermore, damage to rural roads is neglected. In the damage module only damage to highways, provincial roads and railroads is incorporated. Figures are based on the costs of projected infrastructure repair and reconstruction (World Bank, 2001). The figures used are presented in table 7.7 and graph 7.13. Because there are few recorded road damage figures, it was not possible to verify these assumptions.

Damage in Phnom Penh and Kampong Cham
If water levels in Phnom Penh and Kampong Cham rise above the flood levels of respectively 11 m and 16.2 m + msl, then these cities become flooded (Website MRC). None of the hypothetical discharge patterns causes such high water levels at these locations.

![Figure 7.13 Damage factors for roads and railroads and for casualties (for casualties the water depth is reduced by the water depth which occurs in normal years)](image)

Table 7.7 Maximum damage (10$^3$ $\$ per km) for different road and railroad types. Damage includes repair or reconstruction of the road itself, culverts and bridges (per 100m length)

<table>
<thead>
<tr>
<th>Types</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood-proof road</td>
<td>0</td>
</tr>
<tr>
<td>National road</td>
<td>400</td>
</tr>
<tr>
<td>Provincial road</td>
<td>80</td>
</tr>
<tr>
<td>Railway</td>
<td>1000</td>
</tr>
</tbody>
</table>

Casualties (deaths)
The calculation of the number of casualties is based on the population density map of the MRC. This population density is multiplied with a damage factor depending on the water depth (Figure 7.13). The maximum number of casualties is estimated as one per thousand inhabitants. When water depth is equal or less than the water depth in 1999 (a normal year), no casualties are expected to occur. The resulting numbers of casualties for the years 1998-
2002 are presented in table 7.9. Because this casualty assessment is simplified, the differences between calculated and recorded numbers are large. The high number of casualties in 2000 can be explained from the timing of floods, the occurrence of a typhoon and flash floods in the mountains. The damage module is supposed to result in an average number.

**Comparison with recorded values**

The damage module was validated by subsequently:
- calculating the maximum flood depths of 2000, 2001 and 2002 with the hydraulic model and GIS analyses;
- assessing the corresponding flood impacts with the damage model;
- comparing this calculated flood impacts with recorded values (Tables 7.8, 7.9 and 7.10).

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum flooded</td>
<td>328</td>
<td>484</td>
<td>436</td>
<td>462</td>
</tr>
<tr>
<td>Damage factor larger than 0</td>
<td>180</td>
<td>363</td>
<td>324</td>
<td>342</td>
</tr>
<tr>
<td>Damage factor equal to 1</td>
<td>0</td>
<td>289</td>
<td>137</td>
<td>216</td>
</tr>
<tr>
<td>Recorded as damaged*</td>
<td>-</td>
<td>617 / 450</td>
<td>245</td>
<td>152</td>
</tr>
<tr>
<td>Recorded as destroyed*</td>
<td>-</td>
<td>350</td>
<td>149</td>
<td>59</td>
</tr>
</tbody>
</table>

*Sources: (see World Bank (2001); NCDM (2002)).

<table>
<thead>
<tr>
<th>Year</th>
<th>Recorded</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>No record</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>347</td>
<td>181</td>
</tr>
<tr>
<td>2001</td>
<td>62</td>
<td>134</td>
</tr>
<tr>
<td>2002</td>
<td>29</td>
<td>156</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Rice</th>
<th>Infrastructure</th>
<th>Others*</th>
<th>Total</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>2000</td>
<td>42</td>
<td>45</td>
<td>37</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>2001</td>
<td>31</td>
<td>24</td>
<td>24</td>
<td>78</td>
<td>36</td>
</tr>
<tr>
<td>2002</td>
<td>37</td>
<td>33</td>
<td>30</td>
<td>100</td>
<td>19 and 40</td>
</tr>
</tbody>
</table>

*Other damages are supposed to be 30% of the total damages

The calculated and recorded damage for 2000 were comparable. The differences for the other years, however, are larger. The differences in calculated flood extents in 2000, 2001 and 2002 are small. Therefore, also the calculated damages differ not very much. The recorded damage values, however, differ widely. If the flood extents are calculated correctly, these differences are thus caused by factors not related to flood extent and probably not to flood depth. These
factors are not incorporated in the damage module. In reality the damage in 2000 may have been higher than in 2001 and 2002 due to drought in 2001 and 2002, due to better preparedness in the latter years, inconsistencies in damage data recording and timing of the floods. The recorded damage of 2000 may also be exceptionally high and may include data from the coastal areas and the upstream river stretch. A typhoon in 2000 may have played a role also (see section 7.2.5).

Next to negative flood impacts, floods also have positive impacts. It is, however, currently not possible to quantify all positive impacts. To get an impression of the importance of the positive flood impacts, recession rice production was quantified. The recession rice production was calculated by assuming that recession rice is grown not only in the area where recession rice is usually grown, but also in 20% of the area where rainfed rice was destroyed. This replanting of 20% of rainfed rice with recession rice happened also in 2000. Recession rice yields are much higher than rainfed rice yields. The calculated extra recession yield in 2000 compared to the normal recession yield (yield in 1999) is 16 M$ (Table 7.11). The negative flood impacts in 2000 compared to those in 1999 were 115 M$. By comparing the yield that was destroyed by floods in 2000 (42 M$) and the yield enabled by floodwater in 2000 (120 M$) the large positive effects of floods become clear. Floods also have many other positive impacts as was described in section 7.2.5.

Table 7.11 Calculated recession rice production (M$) for different years

<table>
<thead>
<tr>
<th>Year</th>
<th>Production value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>104</td>
</tr>
<tr>
<td>2000</td>
<td>120</td>
</tr>
<tr>
<td>2001</td>
<td>115</td>
</tr>
<tr>
<td>2002</td>
<td>117</td>
</tr>
</tbody>
</table>

7.4 RESILIENCE OF THE CURRENT SYSTEM

7.4.1 FLOOD DAMAGE

The different seasonal flood patterns (section 7.3.1) which resulted from the analysis in the section 7.3.1 were modelled with the hydrodynamic model discussed in section 7.3.2 and the corresponding flood impacts were assessed with the damage module developed in section 7.3.3. The resulting flood impacts are discussed in this section.

Table 7.12 shows the resulting damages for different damage categories resulting from seasonal patterns with different frequencies and average volumes. The tables 7.13 and 7.14 show the differences between the expected damage and casualties resulting from average, wide and small discharge patterns. The tables show that the damage resulting from the average volume and the expected damage calculated by incorporating all three volumes are almost the same. Furthermore, the analysis shows that the difference in damage between different volumes is very large. The volume of discharge is thus very important for the resulting damage, but by using the average volume only, the expected average damage can be approximated.
Table 7.12 Damage resulting from average discharge patterns with different recurrence times inflicted upon agriculture, infrastructure and the total damage (M$)

<table>
<thead>
<tr>
<th>T</th>
<th>Agriculture</th>
<th>Infrastructure</th>
<th>Other damage types</th>
<th>Total damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>4</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>8</td>
<td>11</td>
<td>38</td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>9</td>
<td>14</td>
<td>46</td>
</tr>
<tr>
<td>100</td>
<td>32</td>
<td>21</td>
<td>23</td>
<td>76</td>
</tr>
<tr>
<td>250</td>
<td>37</td>
<td>29</td>
<td>28</td>
<td>94</td>
</tr>
<tr>
<td>1000</td>
<td>44</td>
<td>42</td>
<td>37</td>
<td>124</td>
</tr>
<tr>
<td>2500</td>
<td>51</td>
<td>56</td>
<td>46</td>
<td>153</td>
</tr>
<tr>
<td>10000</td>
<td>57</td>
<td>79</td>
<td>58</td>
<td>194</td>
</tr>
</tbody>
</table>

Table 7.13 Total damage resulting from discharge patterns with different recurrence times and an average volume, a volume that is not exceeded in 25% and 75% of all seasonable discharge patterns and an approximation of the expected damage (M$)

<table>
<thead>
<tr>
<th>T</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>27</td>
<td>48</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>38</td>
<td>69</td>
<td>42</td>
</tr>
<tr>
<td>25</td>
<td>22</td>
<td>46</td>
<td>85</td>
<td>51</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>76</td>
<td>120</td>
<td>75</td>
</tr>
<tr>
<td>250</td>
<td>35</td>
<td>94</td>
<td>149</td>
<td>93</td>
</tr>
<tr>
<td>1000</td>
<td>44</td>
<td>124</td>
<td>203</td>
<td>124</td>
</tr>
<tr>
<td>2500</td>
<td>53</td>
<td>153</td>
<td>253</td>
<td>153</td>
</tr>
<tr>
<td>10000</td>
<td>70</td>
<td>194</td>
<td>298</td>
<td>187</td>
</tr>
</tbody>
</table>

Table 7.14 Number of casualties resulting from discharge patterns with different recurrence times and an average volume, a volume that is not exceeded in 25% and 75% of all seasonable discharge patterns

<table>
<thead>
<tr>
<th>T</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>3</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>23</td>
<td>54</td>
<td>96</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>36</td>
<td>80</td>
<td>122</td>
<td>79</td>
</tr>
<tr>
<td>25</td>
<td>53</td>
<td>109</td>
<td>147</td>
<td>103</td>
</tr>
<tr>
<td>100</td>
<td>79</td>
<td>146</td>
<td>178</td>
<td>134</td>
</tr>
<tr>
<td>250</td>
<td>93</td>
<td>165</td>
<td>199</td>
<td>152</td>
</tr>
<tr>
<td>1000</td>
<td>114</td>
<td>190</td>
<td>220</td>
<td>175</td>
</tr>
<tr>
<td>2500</td>
<td>136</td>
<td>209</td>
<td>236</td>
<td>194</td>
</tr>
<tr>
<td>10000</td>
<td>161</td>
<td>225</td>
<td>244</td>
<td>210</td>
</tr>
</tbody>
</table>

### 7.4.2 THE RESULTING VALUES FOR THE RESILIENCE INDICATORS

**Resistance**

The resistance of the system is very low. Even the lowest peak discharge considered causes floods.
Amplitude and graduality
The indicator values were calculated as described in chapter three. The sensitivity of the EAD, EANC and graduality to the probability distribution of the discharges was tested by using three different probability distribution functions (see section 7.3.2 and table 7.15). This sensitivity of the EAD and graduality proved to be very low (Table 7.16). In the remainder of the research the Gumbel partial series distribution is used.

Table 7.15 The recurrence time (years) of different discharges according to different discharge probability functions

<table>
<thead>
<tr>
<th>Q</th>
<th>T (Gumbel partial)</th>
<th>T (GEV)</th>
<th>T (Gumbel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44000</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>49000</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>51000</td>
<td>10</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>53000</td>
<td>25</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>56000</td>
<td>100</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>58000</td>
<td>250</td>
<td>1000</td>
<td>38</td>
</tr>
<tr>
<td>61000</td>
<td>1000</td>
<td>10000</td>
<td>70</td>
</tr>
<tr>
<td>63000</td>
<td>2500</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>65000</td>
<td>10000</td>
<td>-</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 7.16 The EAD and graduality calculated by using different discharge probability functions

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Gumbel partial</th>
<th>GEV</th>
<th>Gumbel*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAD (M$/yr)</td>
<td>15</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Graduality</td>
<td>0.80</td>
<td>0.83</td>
<td>0.81</td>
</tr>
</tbody>
</table>

*In order to be able to calculate these indicators it is assumed that the maximum discharge (Q = 84000, see table 7.4) with T = 10000 results in a damage of 350 M€

Recovery rate
The recovery rate was assessed by using the tables in section 3.4.4. The physical recovery capacity is quite large, although floods last long. Since the floodwater is used for irrigation, people try to retain the floodwater in the floodplains as long as possible. However, the areas that should not become flooded, such as roads and houses are usually flooded for only about a month. The water flows back to the river by gravity and the remaining low-lying areas dry by infiltration and evaporation. Therefore, the physical recovery capacity scores an eight.

The economic characteristics of Cambodia do not ensure a fast recovery. Cambodia is one of the poorest countries in the world, with about 36% of the population living below the poverty line. About 30% of the population has insufficient food (DFID, 2000) and about 46% of all children under 5 years of age are underweight (ADPC, 2002). Average life expectancy is 54 years.

Floods affect income directly, because most people depend on agriculture. However, this effect only lasts one growing season. In the dry season following a large flood, usually above average yields are obtained. If sufficient seeds and other agricultural inputs can be obtained
then a flood actually increases yields in the years after its occurrence. Problems for the people are highest during and just after floods, when it is difficult to get access to sufficient food. After the dry season harvest, the risk of starvation ends.

When a flood disaster occurs, the Cambodian Red Cross, the Buddhist monks and the authorities offer help. This help is enough to survive, but not to recover. According to Sophal (2001) an affected household receives a relief package that is estimated to cover about 10% of lost potential earnings.

Spreading of effects to non-flooded areas, for example, to Phnom Penh city or to the coast may occur. Phnom Penh will be difficult to reach from the flooded areas thus the supply of goods to the markets may be hampered and farmers may travel to the city to find work. According to the World Bank (2001) the floods of 2000 caused a reduction in GDP growth of 1%. Altogether the economic recovery factors are estimated to be 5.

Also the social context does not support a fast recovery. Except monks, people do usually not help each other (due to a suspicious attitude which was required to survive during the regime of the Khmer Rouge). The thrust in the government and the lack of social organisations is expected to hamper efficient recovery. The Gini-coefficient is relatively low (0.34), which means that equity is high (MRC, 2003). Altogether, the social context is scored as a 4. Preparation and awareness of flood risks is very high and can be estimated as 9. Human capital is low: the literacy rate is 80% for men and 57% for women (MRC, 2003). The health situation is poor. Land mines and diseases are common in the region, inadequate nutrition causes a low resistance, and access to health services is low (MRC, 2003). The score for human capital is estimated as 4. The social factors together thus score a 6.

Altogether, the recovery capacity scores a 6. This relatively low recovery capacity indicates why floods are so disastrous: floods put people who do not have reserves in very difficult positions.

**Overall resilience**

The Mekong was selected as a case study because it was supposed to be an example of a resilient system. The whole country seems to be adapted to the annual floods. Table 7.17 shows that the graduality of the increase in reaction to increasing discharges is high indeed. However, the amplitude is high and the recovery rate quite low, because its socio-economic system is not supporting a fast recovery and flood impacts are rather high. Frequent floods result in much damage.

Table 7.17 Resulting indicator values (using the expected value and the partial Gumbel discharge distributions)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Indicator</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>EAD (M$/yr)</td>
<td>15</td>
</tr>
<tr>
<td>Amplitude</td>
<td>EANC (casualties/yr)</td>
<td>27</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality (-)</td>
<td>0.79</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>Recovery capacity (-)</td>
<td>6</td>
</tr>
</tbody>
</table>
To make the system more resilient, recovery must be enhanced by reducing poverty and flood impacts must be reduced. This is easier said than done. Considering the area’s history of conflict and its fast development in the last couple of years in which extreme floods occurred, it becomes clear that poverty explains the vulnerability to floods and not the floods that explain poverty. From an optimistic point of view, the resilience of the system will thus increase in the future, because the area is developing and poverty is reducing.

**7.5 ALTERNATIVE STRATEGIES FOR FLOOD RISK MANAGEMENT**

**7.5.1 FUTURE DEVELOPMENTS AND PROPOSED MEASURES**

In order to be able to define sensible strategies for flood risk management it is important to be aware of likely developments. In the long term both the discharge regime of the Mekong and the socio-economic characteristics of the system are expected to change significantly. The IPPC predicts in her report of 1997 that, as a result of the seasonal shift in the monsoon weather patterns, a large part of Tropical Asia, including Cambodia will be exposed to increased annual floods and droughts (Hoanh et al., 2003). Next to climate change, Hoanh et al. (2003) also expects population growth. Two possible scenarios are indicated. One scenario is an annual population growth of about 1.6% in Cambodia in the period from 2000 to 2040 resulting in a population of about 22 million in 2040 in comparison to a population of 11 million in 2000. The second one suggest that successive reduction of the overall population growth rate by a factor of 25% for 2000-2020 and 2020-2040 will occur. The resulting population in 2040 according to this assumption is 20 million. Migration to Phnom Penh is already visible and is expected to increase. Roads will be improved, and there will be new roads constructed. Pillot et al. (2000) expect significant changes in agriculture. They expect the paddy prices to increase, the yield per ha to increase and the cultivated area to increase. Irrigation structures will be modernized and more agricultural inputs will be used. Furthermore, they expect a trend to diversification: fruit trees and Chinese vegetables may become important. Hydropower is expected to become important in sub-catchments only. To build hydropower dams in the main river, an agreement between all four countries of the MRC is necessary. This is considered not very likely (Hoanh et al., 2003). The industry is expected to expand. Especially labour intensive industry such as the garment industry is expected to increase further (Hoanh et al., 2003). Finally, tourism is expected to become important.

All these changes will increase flood risks: higher discharges, a larger population, more developed agriculture, more industry and infrastructure result in an increase of both the hazard and the potential damage. A reduction of the importance of agriculture and an increase of industry mean that flood advantages become less. However, agriculture will probably remain important for the majority of the population.

Next to changes in the system and in the discharge regime, also flood risk management is likely to change. General ideas on flood risk management and concrete measures proposed in literature are discussed below. Flood risk management currently consists of adaptation to floods instead of flood control (see section 7.2.5).
Chapter 7

The MRC developed the ‘Strategy for flood management and mitigation’ (MRC, 2001). This strategy contains general ideas to support flood risk management in the different countries. It does not propose concrete measures for certain locations. The strategy focuses on flood forecasting and early warning and stresses the importance of the establishment of a regional Flood Management Centre. The aim of this FMC is amongst others producing accurate regional forecasts with a suitable lead-time and a timely and effective dissemination.

The Ministry of Water Resources and Meteorology & CNMC (2003) summarize the National Water Resources Policy. On the subject of flood hazard mitigation, this Policy states:

- Phnom Penh and other localities with very high concentrations of people and or economic assets will be fully protected from flooding. Other cities will be provided with levels of protection that are economically justifiable.
- All people and institutions will be encouraged and enabled to adopt flood mitigation measures appropriate to their circumstances.
- All public facilities will be constructed above the estimated 50-years flood level in the particular locality and will provide for unimpeded drainage.

There are also more concrete proposals for flood management (Ministry of Water Resources and Meteorology & CNMC, 2003). These projects are mostly related to rehabilitation or reconstruction of irrigation systems in which flood management is not the main issue, but an important component. Examples are the rehabilitation of irrigation systems destroyed by the 2000 flood and rehabilitation of the Stung Chinit irrigation Development Project. Furthermore, a drainage canal is proposed to divert the direction of the Prek Thnot flood (flash flood) from Phnom Penh. Another important project is ‘The Flood control planning for development of the Mekong Delta covering Cambodia and Viet Nam’ (Ministry of Water Resources and Meteorology & CNMC, 2003). The main philosophy of this plan is ‘living with floods and keeping the environment natural’. It aims to dredge colmatage canals (canals through which the floodwater flows from the river into the floodplain and is spread over the floodplains), and to build dikes, bridges and sluice gates to protect the population, create safe and stable conditions for people, conserve the environment, and strengthen the capacity of flood drainage as well as irrigation. The specific recommendations for the short term are: ‘Rehabilitation of 42 colmatage canals with gates on the left side of the Mekong River from Kampong Cham to Neak Luong and rehabilitation of 14 other colmatage canals with gates along the Mekong River and Bassac River. Close off the gates until 1st August to protect human lives, infrastructures and crops from early flood’. Long-term alternatives proposed in this plan mainly incorporate the deviation of the excess of floodwater in Viet Nam to the Gulf of Thailand and to the Vaico River.

7.5.2 ALTERNATIVE FUTURES FOR THE SYSTEM

As explained in section 7.2, it is difficult to separate flood risk management strategies and socio-economic developments. Both development and flood risk management affect the same area, happen at the same time and are interactive. Therefore, three storylines are used, which describe ‘potential futures’ consisting of a combination of scenarios for changes in the discharge regime and socio-economic development and alternative flood risk management strategies. These potential futures are based on the expected developments and proposed
measures which were discussed in the previous section. They describe the situation around the year 2050. They are elaborated up to a general level only.

**Future 1: Continuation of current policies**
The socio-economic developments and climate change discussed in the previous section are assumed to have occurred in this future. However, in this future the flood risk management strategy was not adapted to these changes. This future serves as a reference, showing the effects of the current flood risk management strategy in the future. The most important expected developments in the region are an increase of flood frequencies, population growth, and improvement of infrastructure, agriculture, industry and tourism (section 7.5.1).

The effects of these changes are incorporated by translating them into the following assumptions:
- The population is expected to have doubled, which results in a doubling of the number of casualties.
- The increase of cities, infrastructure, agricultural development, industry and tourism is expected to have resulted in an average annual economic growth of 4% (currently around 5% (CIA, 2002)), which is supposed to have resulted in an increase of damage with a factor of about 7 over 50 years.
- The seasonable discharge patterns described in section 7.3 are expected to occur more frequently, as presented in figure 7.14. The increase of the maximum discharge for a given frequency is expected to be about 5 to 10%.

The assumptions used are thus rather simple. It is unlikely that population growth and economic development will occur uniformly over the area. Furthermore, the exact numbers (factor 2 for population, 7 for economic growth in 50 years, and the increase in discharge frequencies) are rather arbitrary. However, since the exact developments in 50 years are highly uncertain, assumptions had to be made. As a consequence of these changes it is
expected that the flood impacts and the number of casualties increase, compared to the current situation (Table 7.18).

**Future 2: Intermediate economic growth and a resilience strategy for flood risk management**

In the second future, it is assumed that socio-economic development and improvements in flood risk management will have resulted in 2050 in a highly developed agricultural society and a well-functioning complex water management system. Flood risk management will be totally interwoven with the most important functions of the river: allowing food production by fisheries and agriculture. Economic developments will be flood-proof.

The flood risk management measures will consist of emergency measures and flood regulation. Flood early warning systems will have been improved and be effective; in 2050 flood alerts will be provided more then a week in advance and accurate flood warnings will be distributed about 3 days before flooding occurs. Local communities will know the meaning of the flood warnings for their villages and fields and adequate emergency plans and communication strategies will exist. Flood damage and emergency needs will be reported efficiently to the National Committee of Disaster Management, which coordinates the relief and informs the Red Cross and other organisations. In flood-prone areas sufficient motorboats, radios and telephones will be present to reach the inhabitants and the Regional Flood Management Centre of the MRC. Refugees will be able to go to shelters. These shelters, which may consist of, for example, widened stretches of embanked roads or roofs of schools, will be well maintained and have sufficient emergency supplies and drinking water. Also oxen and buffaloes will be evacuated to safe areas. The maintenance of shelters will be ensured by using buildings or constructions which also have other functions, such as schools. Childcare centres will ensure that children can be brought to safe areas as soon as flood alerts are given. The drowning of children will be further prevented by teaching them how to swim.

It is assumed that in this future floods can be regulated by gates, weirs and other structures in the canals, by increasing the knowledge of the water system as a whole and by improving drainage and irrigation systems. Cities and high-value crops will be protected from floods by high embankments. Some low flood-delaying embankments will have been created in the floodplains in order to post-pone the floods and protect the wet-season harvest. These embankments are wide and have small slopes in order to allow the overflow of water without embankment failure.

Not only the flood risk management strategy, but also society will be changed and will have become more developed. More agricultural inputs such as seeds, fertilizer and pesticides will be available. Irrigation and drainage will have been improved. Due to the flood regulation, flood probabilities and depths will vary within the area. The areas that are rarely flooded will be used for high-value crops, while the areas that are frequently flooded, will be used for recession rice or other adapted crops. Aquaculture, double cropping or cropping with rice in the wet season and other crops in the dry season will be implemented to raise income. Important roads will be built on poles or embankments with sufficient openings to let water pass. Rural roads will be repaired and cleaned quickly after each flood. Improved transport will have enhanced development of the rural areas. Schools, temples, health centres and other
important buildings will have been constructed on poles or mounds. To increase awareness, to enable development and to increase knowledge of the system, education will have been strongly improved. At universities, education for agricultural engineers and civil engineers (and of course also of sociologists, economists) will be highly improved, so that the graduates can find a job and contribute to the development of Cambodia. Cambodia will have become richer, not only by agricultural development but also by industrialization. This industry may, for example, consist of labour intensive industries as garment factories and food and agricultural products processing industries (fish meal, rubber products).

This flood risk management strategy will be implemented step by step. Irrigation systems and drainage systems will be improved one by one, agricultural inputs will become available to remote farmers, with improved roads and communication systems markets will be easier reached which increases the use of agricultural inputs and the percentage of total production that is sold. Improvement will be a continuous process, which must be monitored and coordinated in order to enable efficient water and flood management.

The effects of this future were assessed qualitatively by using the following assumptions:

- Population will have doubled and flood frequencies will have increased (Figure 7.14).
- Flood preparedness will have reduced the number of casualties with a factor 100.
- Agricultural productivity will have been increased from 1.7 t/ha to about 4 t/ha of rice equivalents. When rare floods destroy rainfed rice, the losses per hectare are higher, but a smaller fraction of the total rice production will be lost.
- Although the population increases and development increases, the potential damage does not increase significantly. This is achieved by the measures discussed above.
- The government will support areas that become flooded and provide funds or materials to recover quickly.

**Future 3: Fast economic growth and a resistance strategy for flood risk management**

In future 3 the system is assumed to look completely different in 2050. The world’s large donor organisations (World Bank, JICA, ADB) will have funded the development and implementation of an impressive Flood Action Plan in the first decades of the 21st century. This plan consisted of high embankments (about 3 to 6 m) along the river and around the Tonle Sap Lake in order to prevent floods (Figure 7.15). The embankments will be designed to withstand a discharge with a probability of 1/100 a year.

Without the floods, and with help of the donors, the area will have developed fast (annual growth of average 6 % per year). Industry will be more important, especially in the areas around Phnom Penh and along the highway between Phnom Penh and Shianouk Ville. Agriculture will have changed from subsistence agriculture to export-focused agriculture. The many small agricultural plots will have converted to large-scale agricultural companies. Machines may replace part of the hand labour. Irrigation facilities and effective water management will enable yields which are comparable with those in 2000 in Korea and Thailand (5 to 6 ton/ha, instead of 1.7 ton/ha). However, due to the absence of floods the biodiversity and fisheries will have diminished enormously. Fisheries will have suffered from over-exploitation and pollution. This decline in fisheries is assumed to have negative impacts on millions of people. The reduction of labour in agriculture may result in migration of many
young people to the cities. Especially farmers that depend on floods will suffer from the construction of the dikes. The farmers along the Tonle Sap Lake will face higher flood depths and may have to leave. Poverty will increase for a part of the population, while others will become much richer. The GDP is expected to increase with 6% a year over 50 years (factor 18).

![Figure 7.15 Location of the dikes and the two studied breach locations in future 3 (the dikes are shown as black lines, the two breach locations as black dots).](image)

To get a rough idea of the effects of the embankments, the water levels in the system were calculated with the hydrodynamic model, by assuming that the flood patterns in the floodplain do not change significantly. The dikes are assumed to break when the design water levels are exceeded. The breaches are assumed to grow from crest level to about ground level in 2 hours. The width increases first rapidly from 0 to 20 m and then gradually from 20 m to 300 m in two days. Dikes are assumed to break first on the left side of the Mekong and if water levels still exceed the design water levels, also on the right side of the river a breach will occur (Figure 7.15).

The water levels and discharges in the Mekong River and in the Lake are much higher in this future with dikes than they are currently (Figure 7.16). At the downstream boundary, differences between the water level with and without dikes are highest. The maximum discharge at the downstream boundary at the Mekong River increases from 27,000 m$^3$/s to 34,000 m$^3$/s given a discharge of 55,800 m$^3$/s at Kratie (which had a probability of 1/100 in 2000). The outflow through the Bassac River doubles from 2,850 m$^3$/s to 5,160 m$^3$/s. Also the maximum inflow in the Tonle Sap River measured near Phnom Penh doubles: it changes from 7,900 m$^3$/s to 15,000 m$^3$/s. The water level in the Lake increases from 9.82 to 10.67 m + msl.
The effects of the changes in the socio-economic system and in the discharges were estimated by assuming that events with probabilities below 1/100 do not cause significant damage. The damage module developed for the current situation is not valid for the future, since land use and maximum damage of each land use category will change significantly. Besides, this module is based on the current situation in which most damage is related to agriculture and infrastructure. In this future damage to industry, houses and other buildings may have become relatively more important. Therefore, the damage levels are assessed by assuming that the damage per inhabitant increased linearly with economic growth, thus also 6% per year. So, first, flood depths are calculated with the hydrodynamic model. Secondly, damage corresponding with these flood depths is calculated with the old damage module. Then, this damage is multiplied with a factor 18.4 to include the annual economic growth of 6% over 50 years. The results are presented in table 7.18.

![Figure 7.16 Water levels resulting from the seasonal discharge pattern with a recurrence time of 100 years and an average volume along the main channel of the Mekong River for a situation with and without dikes](image)

7.5.3 FUTURE RESILIENCE

The resilience of the three potential future systems is presented in table 7.18. For future 1 and 3 the amplitude and graduality were calculated by using the assumptions discussed in the previous section. For future 2 the amplitude and graduality were assessed in a qualitative way only. The assessment of the recovery capacity is discussed below.

The physical, economic and social recovery capacity for all three futures is assessed according to the elements in the storylines. In future 1 only the economic recovery capacity is expected to change (Table 7.19). It will improve, since the country is expected to become less poor. In future 2, floods are regulated in such a way that undesired floods have a short duration. Therefore, this future scores a 9 on physical recovery capacity. Because the country will develop and financial support is provided to flood-affected persons, both the economic and social recovery capacity increase also. The economic recovery capacity scores a 7, and
the social recovery capacity an 8. The three elements of the social recovery capacity, context, human capital and preparation, score respectively a 6, 9 and 6. In future 3 dikes will hamper drainage of the floodwater. This future scores, therefore, a 6 on the physical capacity to recover. Fast economic growth will occur, but only part of the population will benefit from this economic growth. Since mainly poor people live in flood-prone areas, the economic capacity to recover is expected not to increase significantly and remains a 4. The social recovery capacity changes from about 6 to 4. Context, preparation and human capital all score a 4 in this future. Preparation is expected to be low, because dikes may suggest that the area is safe and that floods belong to the past.

Table 7.18 Overview of impacts of different futures compared to the current impacts

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Indicator</th>
<th>Current</th>
<th>Future 1</th>
<th>Future 2</th>
<th>Future 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>EAD (M$/yr)</td>
<td>15</td>
<td>107</td>
<td>As Current</td>
<td>11 *</td>
</tr>
<tr>
<td>Amplitude</td>
<td>EANC (cas/yr)</td>
<td>27</td>
<td>54</td>
<td>About none</td>
<td>?**</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality (-)</td>
<td>0.80</td>
<td>0.70</td>
<td>As Current</td>
<td>0.43</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>Recovery cap (-)</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

*If dikes are designed on T100 in 2000, future probability becomes 1/25 a year. The amplitude is then 44 M$/yr. If dikes are increased to the future T100 level, then the EAD decreases to about 11 M$/yr.

**Discharges with a probability larger than 1/100 a year will not cause floods, nor casualties. Higher discharges may cause more casualties than in future 1, because they occur more unexpectedly. Whether the average annual number of casualties increases or decreases is difficult to assess.

Table 7.19 Recovery capacities of the current system and of the three different futures

<table>
<thead>
<tr>
<th>Recovery capacity</th>
<th>Currently</th>
<th>Future 1 (Continuation)</th>
<th>Future 2 (Resilience)</th>
<th>Future 3 (Resistance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Economic</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Social</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Overall</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

The resistance of the system in future 3 has increased compared to the current resistance. The return time of the highest discharge which is not expected to cause significant floods is 100 years in this future. Consequently, the resistance of the system in this future is about 100 years. The systems in the other futures still have very little resistance.

7.5.4 EVALUATION

In this case study different flood risk management strategies were combined with different socio-economic development scenarios. The combination of the developments and the strategies was provided as a storyline. In this section the flood risk management strategies are evaluated. The impacts they have should logically correspond with the socio-economic developments that were described in the story lines. The evaluation criteria are discussed in chapter 2 (Table 2.3). The results are presented in table 7.20.
Table 7.20 Evaluation of the three strategies in the three futures (C = current system; F1, F2, F3 are future 1, 2 and 3) (‘eq’: no significant change, ‘-’: deterioration, ‘+’ = improvement compared to the current situation)

<table>
<thead>
<tr>
<th>Sub-criteria Main criteria</th>
<th>Sub-criteria Main criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>F1</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Flood impacts:</td>
<td></td>
</tr>
<tr>
<td>- Flood risk</td>
<td>15</td>
</tr>
<tr>
<td>- EANAP (*10³)</td>
<td>27</td>
</tr>
<tr>
<td>- Recovery rate</td>
<td>6</td>
</tr>
<tr>
<td>Costs reduction: Investment &amp; maintenance</td>
<td>Eq</td>
</tr>
<tr>
<td>Economic opportunities</td>
<td>Eq</td>
</tr>
<tr>
<td>Equity</td>
<td>Eq</td>
</tr>
<tr>
<td>Effects on nature</td>
<td>8</td>
</tr>
<tr>
<td>Landscape quality</td>
<td>8</td>
</tr>
<tr>
<td>Sensitivity to unexpected events and changes</td>
<td></td>
</tr>
<tr>
<td>Robustness</td>
<td>9</td>
</tr>
<tr>
<td>Flexibility</td>
<td>9</td>
</tr>
</tbody>
</table>

The scores on the criteria related to flood impacts were discussed in the previous section. It was assumed that the amplitude is comparable with the total flood risk. However, the latter should also include indirect flood impacts, which are not incorporated in the amplitude. The scores on the other subcriteria that together define the effect on socio-economic development are assessed qualitatively only. The scores on the ecology & land scenery and on unexpected events and changes were assessed on a scale of 1 to 10 in a comparable way as was done in the Rhine case study (see chapter 5 and Vis et al., 2001).

The different strategies affect socio-economic development differently. Continuation of current policies (future 1) results in an increased flood risk, while other criteria do not change significantly. The resilience strategy (future 2) results in a flood risk comparable with the current flood risk and an increase of recovery capacity. The investment and maintenance costs are higher than currently, but also the economic opportunities increase. Altogether, the resilience strategy seems to contribute positively to socio-economic development. The resistance strategy (future 3) results in a decreased flood risk, higher costs, increased economic opportunities and lowered equity. It is difficult to weigh the higher costs against the increased economic opportunities. Therefore, the criterion of enhancing socio-economic development was scored neutral.

Currently, nature and land scenery score well (see section 7.2). If the current strategy is continued into the future, these values are not expected to change significantly. In the resilience strategy (future 2) natural values may slightly decrease because water regulation makes the system less natural than it is at present. However, since the basic ideas of adaptation to floods are not changed, nature and land scenery are certainly not severely affected. In the resistance strategy dikes prevent floods. Because these floods are crucial for the biodiversity in this system, this strategy reduces natural values to a large extent. The Mekong is known for its floods and adapted houses and buildings, and the culture of the
Khmer is based on the flood pulse. Therefore, this strategy scores negative on nature and land scenery.

The sensitivity to unexpected events and changes is smallest in future 1, since this system is equally natural, robust, flexible and adaptable to unexpected circumstances as the current system (see section 7.2). The resilience strategy based on flood regulation and flood impact mitigation (future 2) can be implemented stepwise. It is also possible to change from this strategy to another strategy. This strategy can be developed in such a way that it is equally insensitive to errors and uncertainties as the current strategy. In the resistance strategy, an extreme discharge, a dike breach, or a change in the distribution of water over the different branches near Phnom Penh, may cause disasters. The dikes must be built around the whole area and cannot be built in phases. If the strategy is to be changed, made investments are lost. Therefore, the resistance strategy has the lowest ability to cope with unexpected developments and events.

In summary, carrying on according to the current strategy results in an increased flood risk and has little effect on the other criteria. The resilience strategy enhances socio-economic development, but slightly deteriorates the natural values. The resistance strategy may have both positive and negative impacts on the socio-economic development, but destroys natural values and lowers the system’s ability to cope with unexpected events.

7.6 SUMMARIZING CONCLUSIONS AND DISCUSSION

This case study aimed at evaluating the applicability and usefulness of the resilience concept for flood risk management of the lowland part of the Mekong River. The applicability and usefulness was tested by studying the question ‘What is the current resilience of the lowland part of the Mekong Basin and how do different strategies affect the system and its reactions to the discharge regime?’ This question was addressed by discussing the relationship between society and floods, the discharge regime, the method to calculate resilience, the current resilience of the system and the resilience of potential future systems. Also different flood risk management strategies were evaluated. Based on this, conclusions are formulated on the resilience of the Mekong, on flood risk management strategies for the Mekong River and on the usefulness of the resilience concept for flood risk management of the lowland part of the Mekong River.

The resilience of the lowland part of the Mekong River
The current resilience of the Mekong is not as high as would have been expected in such an adapted system. The graduality is very high indeed, but the amplitude is also high and the recovery rate is not high. Because frequent floods cause much damage, the amplitude of the reaction to the discharges is high. The low recovery rate in this system is mainly caused by poverty. The assessment of the resilience of this system showed that even in systems that seem totally adapted to annual floods, resilience is not necessarily high.

Expected developments in the future seem to change the reaction of the system to the Mekong’s discharges: population increase and socio-economic development and climate change largely increase the amplitude. The recovery rate increases slightly and graduality is
not affected. Although the different indicators cannot be weighed against each other, it may
be concluded that the resilience in the future will decrease if no changes in flood risk
management occur.

In order to increase the resilience of the system, the strategy aiming at water regulation,
agricultural development and flood early warning systems has been defined (future 2). As
references also the effects of continuing the current flood risk management strategy (future 1)
and the effects of a strategy with only embankments were studied (future 3). The resilience
strategy indeed increased the resilience of the system. The resistance strategy reduces the
EAD more than the resilience strategy does. However, it also reduces the graduality and
recovery rate.

Flood risk management of the lowland part of the Mekong River

In the Mekong flood risk management system, the socio-economic system and floods are very
strongly related. The socio-economy is adapted to floods to such a high degree that floods
have become essential for the well functioning of the economy. Below average floods result
in yield reductions. By building houses on poles, temples on mounds and by raising important
roads, damages from normal floods are prevented. However, extreme floods, such as the ones
that occurred in 1996, 2000, 2001 and 2002, still cause a lot of damage and casualties. In the
future these impacts are expected to rise, because the area is developing fast, population is
expected to double in the next 50 years and flood frequencies will increase.

It is difficult to determine the flood damage corresponding with different flood events in the
Mekong Basin, because in this system flood events cannot be characterised by their maximum
level alone. Also the discharge volume is of significant influence. Furthermore, flood impact
assessment is complicated because relationships between water depths in the system and
damage depend on many other factors. The growth of the rice at the moment of flooding, the
cultivated area, the state of infrastructure, preparedness and awareness of the inhabitants and
the emergency management organisations, population density and the adequacy of the flood
early warning system all influence these relationships.

The resilience strategy for flood risk management (future 2) looks very promising. Although
the resistance strategy may result in higher economic opportunities, the resilience strategies
also enhances socio-economic development. In addition, this strategy does not affect nature or
the sensitivity to uncertainties to a large extent, as the resistance strategy does. The resilience
strategy is worth to consider for the future, because it can be implemented step by step, it is
much cheaper than the resistance strategy and it has advantages for the millions of farmers in
the area.

The study revealed that thorough understanding of the relationships between floods,
agriculture and development is essential for this case study area. To implement adequate
small-scale flood risk management measures, therefore, analyses on both the scale of the
flood risk management system and on local scale are required. Agriculture can only be
improved with improved water and flood regulation. This requires a sound system’s
knowledge and the involvement of specialists (on irrigation, agricultural, civil engineering,
economy and social science) as well as persons who are able to integrate knowledge and
know what questions should be answered by the specialists.
Applying resilience: added value to flood risk management
The concept of resilience and the resilience indicators could successfully be applied to the lowland part of the Mekong River basin. Although the application of the indicators on the lowland part of the Mekong River required the use of many assumptions, the results are understandable, informative and useful.

The resilience concept and the systems approach proved to be useful for flood risk management of the lowland part of the Mekong River. By adopting the systems approach the relationships between society and the discharge regime and the cause of the high flood impacts are revealed. This is required for the development of sensible strategies. Furthermore, the resilience indicators establish a good overview of the reaction of the system to the whole discharge regime. The calculations of the amplitude and graduality show that flood impacts are high and that not only very rare flood, but also floods with a recurrence time of 10 years cause substantial damage. The recovery capacity analysis revealed that poverty reduces resilience in this system. The high value for graduality shows that unexpected discontinuities in damage increase with increasing discharges are absent. The calculation of the values for the resilience indicators for the current system also indicated clear directions for future strategies: the impacts of especially the most frequent floods must be reduced and recovery must be enhanced.
8 COMPARISON OF THE DIFFERENT SYSTEMS

8.1 INTRODUCTION

The resilience indicators were applied to the Rhine, Meuse and Mekong systems, which have different physical and social characteristics, and are subjected to different discharge regimes. The resilience of both current and future strategies for flood risk management was studied. Chapters 4 to 7 focused on each system separately. The aim of this chapter is to show and explain the differences in resilience between the different systems and to evaluate the applicability of the resilience indicators.

8.2 DIFFERENCES BETWEEN THE DISCHARGE REGIMES AND SYSTEMS

Table 8.1 summarizes the differences between the systems, the discharge regimes and the flood risk management strategies adopted.

Table 8.1 Overview of differences between the different systems

<table>
<thead>
<tr>
<th>Region</th>
<th>Rhine</th>
<th>Meuse</th>
<th>Mekong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge regime</td>
<td>Slow rising winter peaks, high inter-annual variability</td>
<td>Fast reacting winter peaks, high inter-annual variability</td>
<td>Monsoon, low inter-annual variability</td>
</tr>
<tr>
<td>Physical characteristics</td>
<td>Very flat area, large flood-prone area, large water depths, unexpected floods by dike breaches</td>
<td>Valley, gravel in subsoil causes seepage, small flood-prone area, small &amp; slow rising water depths</td>
<td>Flat area, large flood-prone area, small &amp; large water depths, slow rising water depths</td>
</tr>
<tr>
<td>Socio-economic characteristics</td>
<td>High welfare level, shortage of space, economy has ‘no’ relations with discharge regime, GDP(Netherlands): 516 billion $</td>
<td>High welfare level, shortage of space, economy has ‘no’ relations with discharge regime, GDP (Netherlands): 516 billion $</td>
<td>Agriculture and fisheries adapted to floods, poverty, GDP (Cambodia): 4.4 billion $</td>
</tr>
<tr>
<td>Expected changes in system &amp; discharges</td>
<td>Discharges increase, slow economic growth, change in values (nature +, disaster acceptance -)</td>
<td>Discharge increase, slow economic growth, change in values (nature +, disaster acceptance -)</td>
<td>Discharge increase, fast economic growth and population growth, fast changes in land use and values</td>
</tr>
<tr>
<td>Strategy/ measures</td>
<td>‘Full’ flood control: High embankments (P level = 1/1250)</td>
<td>Spatial planning &amp; embankments around villages</td>
<td>Adaptation</td>
</tr>
</tbody>
</table>
Chapter 8

The discharge regimes of the three systems show some significant differences. The Rhine River’s discharge regime is characterized by rather slow variations and discharge waves of a few days or weeks. The discharge of the Meuse River shows a rapid reaction to rainfall events. Peaks last only a number of days. The Mekong has a monsoon-dominated discharge regime, with a very large intra-annual variation but little inter-annual variation. Peak discharges last very long and the discharge during the whole wet season is important for the maximum water levels reached. The inter-annual discharge variation is smallest for the Mekong River (Table 8.2). The standard deviation of the annual maxima for the Mekong River is much smaller, and the minimum and maximum values are closer to the mean than those of the Rhine and Meuse Rivers.

Table 8.2 Statistics of the maximum annual discharges of the Mekong at Kratie (based on data from 1940 to 2002), the Rhine at Lobith (based on data from 1901 to 2003), and the Meuse at Borgharen (based on data from 1911-1998) (SD = standard deviation)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Rhine at Lobith</th>
<th>Meuse at Borgharen</th>
<th>Mekong at Kratie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (m³/s) % of mean</td>
<td>Q (m³/s) % of mean</td>
<td>Q (m³/s) % of mean</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>6,700 100</td>
<td>1,445 100</td>
<td>43,500 100</td>
</tr>
<tr>
<td>Median</td>
<td>6,500 97</td>
<td>1,407 97</td>
<td>44,000 101</td>
</tr>
<tr>
<td>SD</td>
<td>2,100 36</td>
<td>515 36</td>
<td>5,637 13</td>
</tr>
<tr>
<td>Lowest max.</td>
<td>2,300 34</td>
<td>524 36</td>
<td>28,500 66</td>
</tr>
<tr>
<td>Highest max.</td>
<td>12,700 191</td>
<td>3,047 211</td>
<td>55,000 126</td>
</tr>
</tbody>
</table>

The physical characteristics of each system are also different. The Rhine system consists of diked areas that may very rarely become flooded. In case of overtopping of a dike or a dike breach, large areas may become flooded and flood depths may become large (up to 6 m). The Meuse system consists of a natural valley in which a relatively small part is flood-prone. Flood depths remain small and floods are generally not life-threatening. Some, mainly urban areas are protected by embankments. In those areas more sudden and thus more dangerous floods may occur. The Mekong system is flooded every year. Flood depths vary between 0.3 m and 6 m. The flood-prone area covers a large part of the country.

The socio-economic characteristics of the Mekong system differ widely from those of the Rhine and Meuse systems (Table 8.1). Agriculture is the most important economic activity in the Mekong system. Floods are required for good yields. The area is neither densely populated and nor in full use yet. People are poor, but because the area has recently become politically stable, fast development is expected. In the Rhine and Meuse flood risk management systems, in contrast, agriculture is not very important for the economy, people are prosperous and space is scarce. In these systems, floods do not have advantages.

In future, both the discharge regimes and the systems are expected to change. In all three systems climate change is expected to cause an increase in peak discharges. In the Mekong more significant changes in land use and faster economic growth is expected than in the Rhine and Meuse systems. Changes in the flood risk management strategy are, therefore, more likely there.

The differences in the discharge regimes and in the system characteristics have resulted in the implementation of different flood risk management strategies. The current strategy for the
Comparison of the different systems

Rhine system, consisting of flood defence for a design discharge with a probability of 1/1250 a year, can be explained by the large extent of the flood-prone area, the scarcity of space in this system and the fact that floods do not have advantages. The flood risk management of the Meuse system focuses on spatial planning and adaptation, but also includes flood protection. The embankments around villages and cities are designed to withstand flood waves with a probability of 1/50 a year. Other areas are allowed to become flooded more frequently. In the near future the design flood frequency of villages will be reduced to 1/250 year. The differences between the flood risk management of the Rhine and Meuse systems are mainly explained by differences in physical characteristics. The relatively small flood-prone area and small water depths of the Meuse system compared to those of the Rhine system make floods less harmful in the Meuse system than they are in the Rhine system.

In the Mekong floods occur every year. Flood risk management here mainly consists of adaptation by building houses on poles, temples on mounds and by adapted agriculture. In the Mekong system floods have many advantages, mainly related to the importance of agriculture and fisheries for the people and the economy. There is sufficient space available. Therefore, one might conclude that the adaptation strategy matches the current socio-economic characteristics in that system.

8.3 Differences in the Resilience of the Systems

The three systems studied respond differently to peak discharges. The amplitude of the reaction, quantified by the EAD, differs widely. It is not fair to compare the absolute value of the EAD of the different systems, because the damage is not distributed over the same number of inhabitants and the different regions are not equally wealthy. Therefore, table 8.3 also provides two additional figures: the EAD as a percentage of the GDP of the socio-economic system in which the majority of the flood-prone area is situated, and the ratio between the EAD per affected person and the GDP per person (Table 8.3 and equation 8.1). This last figure, defined here as the Relative Personal Damage (RPD), is the most relevant if the affected people have to help themselves, whilst the EAD as fraction of the GDP is more relevant if it is assumed that the whole society in which the flood-prone area is situated contributes to the recovery of the affected area. The relative figures give a better indication of the relative severity of the EAD than the absolute figures do. In the comparisons of different strategies for one system as was done in the case study chapters, these relative figures were not necessary.

The Relative Personal Damage was calculated as:

$$RPD = 100 \times \frac{EAD}{EANP} \times \frac{GDP}{Inh}$$  \hspace{1cm} (Eq. 8.1)

With:
- **RPD** = relative personal damage (%)
- **EAD** = Expected annual damage (M€/yr)
- **EANP** = Expected number of affected persons (nr/yr)
- **GDP** = Gross Domestic Product (M€/yr)
- **Inh** = Number of inhabitants of the country (nr.)
Table 8.3 Values for the resilience indicators for the three different systems (see chapters 4 to 7)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Indicator</th>
<th>Rhine</th>
<th>Meuse</th>
<th>Mekong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis data</td>
<td>ENAP (persons/yr)</td>
<td>190</td>
<td>900</td>
<td>85*10^4</td>
</tr>
<tr>
<td></td>
<td>GDP (10^9 €) (World Bank, 2004)*</td>
<td>416</td>
<td>416</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Inhabitants (10^6) (World Bank, 2004)*</td>
<td>16</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>GDP per inhabitant (€/inh)</td>
<td>26,026</td>
<td>26,026</td>
<td>298</td>
</tr>
<tr>
<td>Amplitude</td>
<td>EAD (M€/yr)</td>
<td>7</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>EAD per affected person (M€/(yr* person))</td>
<td>0.037</td>
<td>0.008</td>
<td>1.4*10^4</td>
</tr>
<tr>
<td></td>
<td>EAD (% of the GDP)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>RPD (see eq. 8.1)</td>
<td>1*10^-4</td>
<td>3*10^-5</td>
<td>5*10^-6</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality (-)</td>
<td>0.25</td>
<td>0.75</td>
<td>0.79</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>Recovery capacity (-)</td>
<td>8</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

*To covert $ into € a conversion factor of 0.814 was used. The number of inhabitants and the GDP of the socio-economic unit which is expected to bear most of the damage are used (The Netherlands for the first two systems and Cambodia for the third system).

Table 8.3 shows that the RPD is lowest for the Mekong, while the absolute value of the EAD and the EAD as percentage of the GDP are highest for the Mekong system. The low value of the RPD of the Mekong system can be explained by the large number of affected persons. The high absolute value is explained by the fact that floods affect a large part of the country, a large number of inhabitants and a large part of the economic system. The graduality is highest for the Mekong and Meuse and lowest for the Rhine. The recovery rate is highest for the Meuse system and smallest for the Mekong system.

It is difficult to conclude which system is the most resilient, as this requires weighing of the different indicators. There is not one system that scores best on all criteria. Because the graduality of the Meuse and Mekong are comparable, while the amplitude of the reaction (absolute value and EAD as % of the GDP) and the recovery rate of the Meuse system are better than those of the Mekong system, one might conclude that the Meuse is presently more resilient than the Mekong system. Nevertheless, the RPD is lower for the Mekong than for the Meuse system. The Rhine system is obviously the most resistant, since all discharges with an annual probability larger than about 1/1250 are not expected to cause floods. Because of its high resistance, the Rhine system has a low absolute EAD and a low graduality.

These indicator values reflect the following systems’ reactions: In the Rhine system flood risks are low and graduality is low. This means that floods are very rare, but when they occur the impacts are large. However, the recovery rate is high, because the socio-economic context is strong. In the Meuse system, floods occur more frequently. The flood impacts are also easily recovered from. In the Mekong system, floods occur frequently and impacts are high and affect many people. Recovery is more difficult than in the other two systems.

**Differences in the expected changes of the resilience in time**

If the current flood risk management strategies in the different systems are continued, then the resilience of all three systems will decrease mainly due to climate change and economic growth. The amplitude of these systems will increase, the graduality will decrease while the recovery rate is hardly affected (Table 8.4).
Table 8.4 Expected values for the resilience indicators for the three different systems in the future assuming that the flood risk management policy does not change (Assumed annual economic growth: Rhine: 2%, Meuse 2%, Mekong: 4% and population growth factor: Rhine: 18/16, Meuse 18/16, Mekong 24/12) (see chapters 4 to 7)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Indicator</th>
<th>Rhine 2000</th>
<th>Rhine 2100</th>
<th>Meuse* 2000</th>
<th>Meuse* 2100</th>
<th>Mekong 2000</th>
<th>Mekong 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>EAD (M€/yr)</td>
<td>7</td>
<td>64</td>
<td>7</td>
<td>14</td>
<td>12</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>EAD (% of GDP)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.0005</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>RPD (see eq. 8.1)</td>
<td>$1 \times 10^{-4}$</td>
<td>$2 \times 10^{-4}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$5 \times 10^{-6}$</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Graduality</td>
<td>Graduality (-)</td>
<td>0.25</td>
<td>0.15</td>
<td>0.75</td>
<td>0.48</td>
<td>0.79</td>
<td>0.70</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>Recovery capacity (-)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

*The Meuse values include the implementation of the Maaswerken Project and the raising of the embankments in the future to maintain their safety level at 1/250 a year.

Between 2000 and 2100 the amplitude of the Meuse system increases less than the one of the Rhine system. This difference is caused by the implementation of the Maaswerken Project in the Meuse system around 2015 which includes river widening and deepening and raising of the embankments around villages from a 1/50 safety level to a 1/250 safety level. This reduces the EAD significantly.

The annual economic growth for the Meuse and Rhine regions was estimated to be 2%, and for the Mekong region 4%. The assumed economic growth determines the expected EAD. The order of magnitude of the RPD does not change in the future because economic growth, population growth and damage increase were linked in the assumptions on which the future damage calculations were based (See chapter 5 to 7). Only climate change could have changed the figure because climate change was not incorporated in the estimations of the future GDP, while it is included in the damage calculations.

In the Meuse system changes over time were studied more intensively than in the other case studies (see chapter 6). In this system the resilience decreased in the past and is expected to decrease further in the future. The amplitude is expected to increase and the graduality to decrease. These changes reflect the conversion of an adapted system to a system with more flood protection.

**Resilience strategies for the different systems**

The case studies showed that if it is intended to increase the resilience of the Rhine system, attention should be focussed on increasing graduality, since this aspect scores worse than the other two indicators that describe a system’s reaction to a discharge regime. For the Mekong and Meuse systems efforts should be directed towards damage reduction and in the Mekong system also the recovery rate should be increased. No resilience strategies were studied for the Meuse River.

The studied resilience strategies for the Rhine and Mekong differ. The studied resilience strategies for the Rhine River consisted of either compartmentalisation or the creation of green rivers or adaptation (River-and-Land strategy (see chapter 5)). All these strategies have in common that they abandon the safety standard related to one design discharge for the
whole area, increase the flood frequencies of the less vulnerable areas and decrease the flood frequency of the most vulnerable areas. For the Mekong, resilience strategies may consist of flood regulation and probability differentiation, improved water management and improved flood early warning (see chapter 7).

The differences in the measures incorporated in the resilience strategies for the Rhine and Mekong are caused by differences in the current systems. In the Rhine system increasing the system’s resilience is carried out by creating more ‘space for floods’, while in the current Mekong system floods already have almost unlimited space. There, flood damage must be reduced and recovery rate enlarged in order to increase the system’s resilience. This reduction of impacts and increase of recovery rate may be reached by managing flood patterns and frequencies (see section 7.5.2).

In the Mekong system resilience oriented strategies seem more feasible than in the Rhine system, because:

- Floods have significant positive effects for agriculture, fisheries and biodiversity;
- Space is less scarce in Cambodia than in the Netherlands;
- It is likely that society in Cambodia can develop and become prosperous without flood prevention: If floods do not cause disasters because they are regulated, flood frequencies are differentiated and land use is adapted to these floods, then development will not necessarily conflict with floods;
- The resilience strategies in the Mekong can be implemented stepwise, which is more difficult with the ones studied for the Rhine River;
- The resilience strategy of the Mekong does not require large changes in the current socio-economic characteristics of the system, but seems to correspond with ongoing developments.

If agriculture remains as important in the Mekong as it currently is, a lot of water will be needed in the paddy fields in the future also. Instead of floodwater this may, however, also be irrigation water. In the long term a gradual change may occur from very flexible agriculture adapted to uncontrolled floods to controlled flooding or irrigation of large areas in order to reach very high yields. The difference between regulated flooding and irrigation of large areas may become very small.

### 8.4 CONCLUSIONS

Based on this chapter the following conclusions can be drawn:

- The systems studied in the case studies differ significantly.
- The indicator values can distinguish between the different systems. They reveal the different reactions to the respective discharge regimes.
- The indicator values and the differences between them are explainable.
- The indicator values indicate which reaction aspect will need most attention, if it is intended to enlarge the system’s resilience. The differences in resilience oriented strategies are caused by the differences in the current situation.
- The feasibility of resilience strategies is largest in the Mekong system.
9 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

9.1 SUMMARY OF OBJECTIVES AND RESEARCH QUESTIONS

In order to find out whether applying the resilience concept to flood risk management facilitates the development of comprehensive strategies, the following main questions were addressed in this thesis:

1. Which definition of resilience is useful and applicable in the context of flood risk management of lowland river systems?
2. Which indicators can be used to make the resilience concept quantifiable in this context?

Next, case studies were carried out in which the resilience definition and indicators were applied in order to test their applicability and to evaluate the added value of resilience for the flood risk management in the case study areas.

9.2 DISCUSSION

9.2.1 RESILIENCE IN RELATION TO THE VIEW ON FLOOD RISK MANAGEMENT

The application of the resilience concept requires a specific view on flood risk management (see chapter 2). In this view the river and the physical and socio-economic aspects of the corresponding flood-prone area need to be considered as one system and the reaction of this system to the whole discharge regime must be studied. This section discusses whether this view is useful for flood risk management of lowland rivers. In order to do so, this section first discusses briefly the purpose of flood risk management.

Flood risk management as means for a better functioning society

Flood risk management, defined in chapter two as all activities that enable a region to cope with flood waves, can be carried out in many ways. In order to select the best strategy to make a region able to cope with flood waves, attention should not only be given to the river system, but also to the society in the flood-prone area. After all, not the river but the functioning of that society is at stake. Flood risk management strategies should thus contribute to the functioning of that society now and in the future, i.e. flood risk management must contribute to sustainable development of the region involved. Sustainable development is interpreted in chapter two as the development of society without deteriorating natural values, while also considering the fact that all systems and inputs are dynamic. Flood risk management strategies should thus decrease the disruption caused by flood waves in a way that serves society best and minimises impact on nature or land scenery. Furthermore, the strategy should not be too sensitive to unexpected events or changes in the system or in the discharge regime.
Society may benefit from or may be adversely affected by flood impacts and by flood risk management measures. The ‘raising of embankments’, for example, will reduce negative flood impacts and may enhance socio-economic development. However, these embankments may also have disadvantages such as keeping fish from reaching their spawning grounds in the floodplains. They may be less feasible in areas with gravel in the subsoil or in areas with extremely high monsoon discharges. Besides, they require large investment costs, and an organisation to maintain them. All other measures, including ‘doing nothing’, will also have positive and negative impacts. The net effect of measures on society depends on the physical and socio-economic system characteristics and on the discharge regime. In each region the system properties and discharge regime must, therefore, be carefully considered to select the best strategy i.e. the optimal combination of measures.

When the discharge regime and/or the system change, also the flood risk management strategy may have to change, since they will not necessarily match any longer. The changes in the system depend on autonomous developments, such as climate change and world economic developments. Changes in the system may also be influenced by flood risk management strategies themselves. After all, flood risk management and society develop at the same time and in an interacting way. This became especially clear in the Mekong case study, where it is expected that diking will result in rapid economic growth, urbanization and industrialization, while a resilience strategy is expected to result in gradual agricultural development. Since flood risk management and economic development interact, it is difficult to change from one strategy to another. Therefore, creating room for floods in a resistant system, such as the Rhine, requires large investment costs, while in a system adapted to floods such as the Mekong, constructing embankments is expensive. Interaction between embankment strengthening and economic development is called ‘the diking cycle’. After building or strengthening of embankments, flood frequencies are reduced, people feel safer, and economic development accelerates. This development increases the potential flood damage, which is usually again compensated by higher embankments. These higher embankments increase the feelings of safety again and enhance economic development, which will result in a new round of embankment strengthening, etc. This diking cycle illustrates the interaction between socio-economic development and flood risk management.

**Usefulness of a ‘resilience view’ for flood risk management**

In order to make flood risk management contribute to the sustainable development of a region tailor-made strategies are thus required. In order to develop tailor-made strategies that match the functioning of society in the flood-prone area involved, knowledge of the reaction of systems to flood waves and of the relationships between floods, society and the effect of measures is essential.

Applying the resilience concept by calculating the values for the different indicators for resilience enforces a systems approach in which the reaction of the system as a whole to flood waves is studied. This systems approach results in knowledge on the discharge regime at the upstream boundary, on flood impacts, recovery rates and the increase of damage with increasingly severe flood waves, and thus on the relationships between the river, its floods and society. This knowledge is essential for the development of comprehensive strategies. The application of resilience in flood risk management thus results in a view which facilitates
Discussion, conclusions and recommendations

the development of strategies that contribute to the sustainable development of the region involved.

This finding was experienced when assessing the resilience and developing strategies for the case study areas. In the case studies, the resilience ‘approach’ greatly increased the understanding of the systems and provided information on the basis of which strategies could be developed. In the Mekong case study the indicators revealed that not only very rare flood waves, but also flood waves with a recurrence time of about 10 years cause substantial damage. This damage may become disastrous because of the low recovery capacity of the system. Flood risk management strategies should thus focus on this recovery capacity and on reducing flood impacts caused by the more frequently occurring floods. The analysis which was required to calculate the indicators also showed the relevance of agriculture and fishery for the majority of the population and the relationships between these economic activities and floods. This information was essential for the development of comprehensive strategies which enhance sustainable development of the system. The resilience strategy for the Mekong focuses on the development of the floodplains and includes improving agriculture, water management and flood early warning systems.

In the Rhine system strategies were developed that involve flood probability differentiation, compartmentalization and land use adaptation. These strategies are clearly different from the current flood risk management strategy. Although the measures in these strategies are not new, these strategies would not have been identified if only the river had been studied or if only flood impacts had been considered. Because the application of the resilience concept resulted in knowledge on the system and the discharge regime and widened the range of strategies that was considered, applying the concept of resilience is considered useful for the flood risk management of these systems.

9.2.2 THE APPLICABILITY OF THE RESILIENCE INDICATORS

In chapter 3 it was found that a clear indication of the resilience of a system is obtained by quantifying three aspects that describe a system’s reaction to disturbances: amplitude of the reaction, the graduality of the increase in reactions with increasingly severe flood waves and the recovery rate of the system. To quantify resilience, therefore, indicators were defined for each aspect. The indicators were tested on hypothetical systems in chapter 3 and applied to the case study areas in chapters 4 to 7. This section discusses the experiences gained by applying the set of indicators.

Applicability of the indicators on the case study areas

The resilience indicators proved to be quantifiable and applicable on the systems studied in all three case studies. They reflect differences in reaction and thus in the resilience of the different systems studied (see chapter 8). They also reveal differences between different strategies for each separate system. The resilience indicators thus enable a comparison of the different flood risk management strategies for one system, as well as of different systems.

The indicators for amplitude and graduality are based on the assumption that there is a unique relationship between discharge and flood impact. This relationship, however, is not
unambiguous as was discussed in chapters 5 and 7. It is influenced by many factors, of which the probability is not always known. Damage resulting from a specific flood wave may be related to factors such as the moment of flooding (day or night), the occurrence of ice jams, the preparedness of the inhabitants of the flood-prone area, and the rainfall in the wet season (see chapter 7). Assumptions which must be made to incorporate these factors will sometimes result in an overestimation and at other times in an underestimation of the expected damage. Because the EAD, EANC and graduality indicators are average values, results are not expected to be significantly influenced by these factors. However, the damage resulting from an individual discharge event may deviate from the average if the assumptions used do not correspond with the individual event.

As described in chapter 8 the indicators were successfully applied to the three case study areas. However, many assumptions had to be made in order to be able to calculate the indicators. Assumptions were especially required when the understanding of the system was insufficient or when unknown future developments were considered. By more research, some of the gaps in understanding might be filled in. However, uncertainties about future developments and about the effects of flood risk management strategies will always require making assumptions which is best tackled by defining future scenarios. The use of assumptions does not mean that the results are of little value. By testing different assumptions, by comparing different strategies or different scenarios and by assessing their potential consequences a valuable contribution to the development of comprehensive strategies can be made as the understanding of the effect of possible developments is increased and at the same time the effects of uncertainties on the outcomes are explored.

**Reproducibility**
An important requirement for a good indicator is that it is reproducible. The resilience indicator values for the case study areas were assessed independently by different persons who worked in the case studies, and who reached the same results. The indicators for the amplitude and graduality aspect are exactly reproducible, as they are based on quantitative data. Differences in indicator values may only result from the use of different data or different assumptions. The value found for the indicator for recovery rate may however differ slightly from person to person as it relies on a qualitative analysis in which different physical, economic and social factors that influence recovery rate have to be assessed. Although the tables used to assess these factors are designed to be as clear as possible, different persons may judge differently. They will however certainly not find contradictory results. It is also possible that incomplete information results in other values. Since the method to assess the recovery capacity is clearly qualitative, it is obvious that the resulting figure only gives an indication of the recovery capacity.

**The degree to which the indicators reflect the resilience of a system**
As described in chapter three, where hypothetical systems were analysed, the indicator values are explainable and correspond with expectations. The indicators thus reflect the three aspects of a system’s reaction. Since resilience is not quantified by one indicator, but by a set of different indicators, it is not possible to express the resilience of a system by one number only. Because the indicators each contain relevant but different information, only the combination of indicators gives sufficient knowledge of a system’s resilience to peak discharges. Since the three indicators can neither be combined into one nor weighed against
each other, a ranking of systems from the most to the least resilient one is only possible when the rankings of the systems for each indicator independently all show the same order. In all other situations it is not possible to conclude which system is the most resilient. Only differences in the reaction of the systems are revealed then. By quantifying the different aspects of reaction, the indicators indicate which aspect needs to be improved most when it is intended to increase the resilience of a system. They thus indicate the direction in which solutions have to be sought.

**Overall evaluation of the applicability of the indicators**

The resilience indicators are considered useful for the quantification of the resilience of a system, because the resilience indicators are applicable on a wide range of systems, they are reproducible, and they give insight into the reaction of systems to the whole regime of peak discharges.

**9.2.3 ADVANTAGES AND DISADVANTAGES OF RESILIENCE STRATEGIES**

The system’s resilience and resistance can be changed by implementing flood risk management strategies. Strategies that increase the system’s resilience were evaluated in the different case studies in chapters 4 to 8. The case studies showed that it is possible to increase the resilience of the Rhine, Meuse and Mekong systems, although not all strategies which increase the resilience are equally feasible. In the Rhine system the strategies that result in the largest increase of resilience reduce economic opportunities. The compartmentalisation strategy and the multi-functional variant of the green river strategy, however, increase the system’s flexibility for future changes. In the Rhine case neither can all resilience strategies thus be considered positive from a sustainability point of view nor are they all negative in all circumstances. In the Mekong system, resilience strategies seem positive as was discussed in chapter 8. No resilience strategies were studied for the Meuse system. Based on the case study results the advantages and disadvantages of resilience strategies for lowland rivers in general are discussed in this section.

**Resilience strategies in systems with an initially high, respectively low resistance**

Resilience strategies may focus on one or more of the three reaction aspects amplitude, graduality and recovery rate. Which aspects need the most attention differs between developed areas with a high resistance and areas with a low resistance where floods occur frequently. In very resistant systems, which are mostly found in developed areas, the amplitude and graduality are generally low and the recovery rate high. Resilience strategies will then mainly aim at increasing the system’s graduality without increasing its amplitude. Such strategies incorporate combinations of measures such as flood probability differentiation and land use change (see chapter 5). In order to reach a large increase of the graduality, the flood probabilities of the least vulnerable areas may need to increase as was shown by the green river strategy of the Rhine case study (see chapter 5). The disadvantages of this increase of flood frequencies should be carefully weighed against the advantages of a higher graduality. The main advantage of a higher graduality is a reduction of the system’s sensitivity to uncertainties (see section 5.8). A potential disadvantage is the reduction of the economic value of some areas. Strategies such as the compartmentalisation strategy, in which
the increase of flood probabilities is little and the area that faces an increase is not as large as in the green river strategy, also increase the graduality, but to a lesser extent. Strategies which maintain the high level of resistance but slightly increase the systems resilience, such as strategies including emergency plans which indicate which areas may be inundated in order to protect more valuable areas, and compartmentalisation of the more upstream area to increase the safety of the vulnerable densely populated downstream areas may certainly be considered. If well designed and operated, these strategies decrease the sensitivity to uncertainties. During design of such plans careful attention is required to their cost-benefit ratio.

In systems with a low resistance floods occur frequently. Therefore, an easy recovery from flood impacts is essential. Recovery is easier when the system is more resilient: when flood impacts are small, the graduality is high and the recovery rate is large (see chapter 2). In systems with a low resistance all three reaction aspects (amplitude, graduality and recovery rate) may need improvement. Changing the recovery rate of a system is very difficult, because it depends mainly on the socio-economic context which is difficult to influence by flood risk management. In systems with a low resistance, strategies that aim at increasing the system’s resilience will thus mainly incorporate measures which lower the amplitude and increase graduality such as flood alleviation measures and flood probability differentiation (see chapter 7). In such systems with high flood frequencies, flood damage alleviation measures will immediately have effect. Flood probability differentiation in areas with frequent floods, does not result in increased flood probabilities as it would in the Rhine system but, instead, in reduced flood probabilities of the most vulnerable areas and of areas where vulnerable activities may be safely developed. The other areas may still have the same high flood probability.

The combination of the resilience and resistance of a system determines the system’s ability to cope with flood waves. Resistant systems, such as the Rhine system, are now able to cope with flood waves by their high resistance. In such systems increasing the system’s resilience may reduce the system’s resistance at the same time. Consequently, increasing the system’s resilience does not automatically increase the system’s ability to cope with flood waves. In areas that become flooded frequently, on the other hand, increasing resilience may result in an increased capacity to cope with flood waves. However, in these systems also resistance strategies may result in a system that is better able to cope with flood waves. Whether resilience or resistance strategies are preferable in such systems differs per case. In systems where floods have significant advantages, where pressure on land is not very high, and where adaptation to floods already has occurred or can easily be established, resistance strategies will be less feasible than resilience strategies are (see chapter 7).

Positive and negative aspects of resilience strategies
Resilience strategies were found to have both positive and negative aspects. The case studies showed that, in general, the benefits of resilience strategies depend on various factors:

- *The combination of the flow regime and socio-economic characteristics*: In systems where floods have significant advantages for economic activities such as in the Mekong system, resilience strategies are useful. In systems where economic use of floodplains is seriously hampered by floods, resistance strategies or combination of resilience and resistance strategies may be beneficial.
• **Importance of nature:** River-bounded nature needs floods. When nature is valued high, then resilience strategies are preferable (see chapter 5).

• **Importance of the ability of the system to cope with unexpected circumstances and changes:** When disasters are to be avoided, a system is needed that works in a wide range of circumstances: then resilience strategies are often preferred (see explanation below).

Resilience strategies can cope with unexpected circumstances more easily than resistance systems, because of their high graduality. Since damage increases proportionally with increasing flood waves, it is not likely that floods suddenly turn into disasters in resilient systems. Resilience strategies may result in more frequent floods than resistance strategies. However, in resistant systems the damages corresponding with discharges that do cause floods will be higher than the damages resulting from the same discharges in the more resilient alternatives. In the case studies of the Rhine and Mekong the resilience strategies were less sensitive to uncertainties than the studied resistance strategies. However, it must be noted that this sensitivity depends strongly on the design of a resistance strategy. If dikes are designed in such a way that dike failure has become impossible, e.g. by constructing enormous high and wide embankments which do not fail when they are overtopped, the sensitivity for uncertainties will be lower. In general, however, resilient systems with their gradual rising water levels and stepwise increase of damage are less sensitive to uncertainties than resistant systems with a certain design threshold. In such systems, peak discharges will either cause no flood at all or, alternatively, a catastrophe, but rarely anything in between.

Resilience strategies maintain the positive aspects of floods, they have a larger ability to cope with the effects of uncertain events, they are more beneficial for nature, and they usually reduce the likelihood that floods turn into disasters since the damages corresponding with extreme discharges are less than in resistant systems. However, in presently resistant systems a transition towards resilience strategies may require high investment costs, and it may limit economic developments (see chapter 5). On the other hand, resistance strategies are very costly in more resilient systems (see chapter 7).

In conclusion, it may be stated that the positive connotation which resilience seems to have (see chapter 1) needs nuance. Resilience strategies do have positive aspects indeed, but they also have disadvantages. This means that it must be re-emphasized that a ‘best’ strategy depends on societal preferences.

### 9.2.4 Relation with ongoing public debate

This section discusses what considerations on resilience strategies may contribute to the ongoing public debate on flood risk management of lowland rivers.

**Approach to flood risk management**

In the Netherlands, the past and current flood risk management of most large rivers is based on a design discharge and design water levels, as was discussed in section 5.2. This can be considered a ‘safety approach’ since it focuses on flood control in such a way that the area is ‘sufficiently safe’. The flood-prone area is considered ‘safe’ when the discharge with a
probability of 1/1250 a year can pass without causing floods\(^\text{10}\). This safety standard is based on calculations of acceptable flood risks (Commissie Rivierdijken, 1977). The danger of continuing with this approach is that it may result in a too narrow focus on river design and structural measures. Besides, a design discharge is just one possible discharge level of a whole peak discharge regime. In order to compare different options for flood risk management, approaches in which the whole discharge regime is studied and in which also the consequences of extreme discharges are considered are needed.

Currently, studies are carried out to establish the flood risk in the different dike rings in the Netherlands (DWW, 2003b). The question beyond this research is whether it is possible to change in the future from a safety approach to a risk approach. In a risk approach not only the river’s design and discharge probabilities, but also the consequences of floods are incorporated. The risk calculated in this approach, however, does not distinguish between systems where frequent floods cause low impacts and systems where floods are rare but catastrophic, because these systems may have the same risk. Because these different systems with equal risks will not necessarily be judged equally by the inhabitants, it is useful to study also other aspects than flood risks only. Besides, this approach may result in an overvaluing of flood risks and cost-benefit analyses as evaluation criteria. The system with the lowest risk or the optimal cost-risk reduction ratio is not necessarily the best strategy. Sometimes, disaster prevention by allowing more frequent floods, maintaining nature values, removing feelings of unsafety of inhabitants and other benefits may be more important than risk optimisation.

In the ‘resilience approach’ the flood-prone area and the river together are considered as one integrated system, the whole peak discharge regime is considered and the system’s reaction to this discharge regime is studied. This approach has additional value for flood risk management, because the EAD of the system as a whole and the graduality and recovery capacity indicators offer additional information which is neither considered in the safety nor in the risk approach discussed above. Besides, studying the whole system and its relation with flood waves increases understanding of the system and therefore facilitates strategy development. This additional information and increased understanding is expected to widen the range of options considered for flood risk management, as it did in the case studies on the Rhine and Mekong rivers.

Going from a safety approach to a risk approach and ending up at a resilience approach thus involves including more information in the analyses. This may contribute to better strategies and designs.

**Resilience strategies in relation to strategies considered**

As mentioned in chapter 1, the term resilience has a positive connotation. In policy documents on water management the wish to increase the system’s resilience is expressed. The evaluation of the resilience strategies in the case study chapters and in chapter 8, however, showed that not all resilience strategies are positive in all respects. As preluded on in section

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\(^{10}\) In 2005 in the Meuse Valley in Limburg dike rings have been defined with embankments designed according to a design discharge with a probability of 1/250 a year.
9.2.4 this positive connotation needs relativization. This conclusion may be useful for societal debate.

For the Dutch large rivers the Room for River policy has been adopted. This policy mainly changes the way in which the river design is adapted to reach the safety standard. It is, in the context of this thesis at least, considered a very small change of policy only. On the long term, however, larger changes may be expected (see section 5.2). If the flood risk management approach changes from a safety approach to a risk approach, flood probability differentiation might be implemented. This would increase the system’s resilience. The identification of emergency detention areas, or compartmentalization, which is being considered by the Dutch Government, also involves probability differentiation and, therefore, also increases the system’s resilience (see section 5.2 and 5.9). These changes may be beneficial, because they do not result in frequent flooding of large areas, while they do increase the system’s graduality and decrease the systems sensitivity to uncertainties.

In areas with a smaller resistance, such as the Mekong, resilience strategies have different effects than in resistant systems as the Rhine River. In the Mekong system resilience strategies match well with the public desire to find a flood risk management strategy that reduces the damage caused by more extreme discharges while maintaining the benefits of normal floods. The considerations on resilience strategies are likely to offer a valuable contribution to public debate on flood risk management of the Mekong River in Cambodia.

For the Meuse River no resilience strategies are planned for the near future. The design and acceptance of the Maaswerken Project (see chapter 6) show that lowering flood frequencies of villages and cities is preferred above having a high graduality. This can be explained as follows: After the floods of 1993 and 1995 politicians promised the inhabitants that such floods would not happen again and that something would be done (Projectorganisatie De Maaswerken, 2001). These floods thus induced the construction of the embankments around villages and cities. Now that these embankments are there, the inhabitants of the villages and cities feel much safer. Hence, it is very likely that people will not adapt their houses and investments to the flood threat anymore and that spatial planners will be more inclined to allow companies to settle in the floodplains. Consequently, the potential flood damage will increase. Furthermore, flood acceptance has decreased. Nowadays, the inhabitants expect the government to prevent flooding of their homes and companies. Since the embankments offer only protection to floods with a probability larger than 1/50 a year, further strengthening of the embankments in the future seems almost unavoidable. It is thus understandable from a political point of view that in the Maaswerken Project the strengthening of these embankments is incorporated. This strengthening may, however, induce a further reduction of the flood preparedness, a further increase of potential damage and an increase of the risk on casualties. The risk on casualties increases because the embankments around the villages changed the graduality: Instead of gradually rising water levels, sudden dike breaches and fast rising water levels may occur now. The advantages of the embankments consist of damage reduction, increased economic opportunities, and more satisfied inhabitants because the government protects them better from floods. These advantages ought to be weighed against the increased risk on casualties.
The considerations on resilience are valuable for the Meuse as well. The resilience indicators show the changes that have occurred and are expected to occur in time. The considerations on positive and negative aspects of resilience strategies may be used to motivate new plans in the Meuse Rivers.

9.3 CONCLUSIONS

Since the frequency and severity of flood disasters seems to increase, many governments are reconsidering their flood risk management strategies in order to improve them (see chapter 1). In this thesis the resilience concept was applied to flood risk management, because this was expected to result in new visions and improved strategies (see chapter 1). The main research question of the thesis was: ‘Does applying the resilience concept facilitate the development of comprehensive strategies for flood risk management?’.

The following conclusions are drawn:

- Resilience and resistance are both system characteristics. Applying these concepts in flood risk management thus requires a systems approach. The focal system then is a flood risk management system, which is defined as a combination of a lowland river and the adjacent flood-prone area with both its physical and socio-economic characteristics.

- The resilience and resistance of a system together determine the reaction of a system to disturbances. In general, resistance is the system’s ability to withstand certain disturbances without reacting and resilience the ability of a system to recover from a reaction on a disturbance.

- Because the relevant disturbances in flood risk management of lowland rivers are incoming flood waves, the concept of resistance is defined in this context as the ability of a system to withstand flood waves, while resilience is defined as the ability of the system to recover from floods.

- Since resilience and resistance reflect the reaction of a system to peak discharges, they can be studied by quantifying three main aspects that describe this reaction. These three aspects are the amplitude of the reaction, the graduality of the increase of reaction with increasing peak discharges and the recovery rate. The resistance of a system is indicated by the highest discharge that is expected not to cause significant disturbance of the system.

- Quantifying the three aspects of reactions results in an indication of the system’s resilience. The amplitude is quantified by the Expected Annual Damage and the Expected Annual Number of Casualties, the graduality by a relative comparison of the increase of damage and the increase of discharge, and the recovery rate is quantified by assessing the recovery capacity of the system. Resistance is indicated by the reaction threshold, which was quantified as the return time of the highest discharge.
that is not expected to cause floods. In diked systems, this return time can be approximated by the return time of the design discharge.

- The application of the indicators to the case studies of the Rhine, Meuse and Mekong Rivers showed that the indicators are applicable, reproducible and that their values are a useful indication of the resilience of the system considered. Together, the indicators express the reaction of the system to the discharge regime. The indicators allow distinguishing between different systems as well as between different flood risk management strategies for one system. Because different resilience indicators were formulated which each cover a different aspect, it is not possible to express the resilience of a system by one figure only.

- By defining and quantifying resilience, it has become a more tangible concept. It has become more clear what resilience is and what resilient strategies are. This knowledge enabled the evaluation of the resilience concept for flood risk management and of the advantages and disadvantages of resilience strategies.

- Applying resilience in flood risk management means adopting a systems approach in which the reaction of the river and flood-prone area together to the whole regime of discharges is considered by calculating the values of the resilience indicators. This ‘resilience approach’ includes a thorough analysis of society and its relation with floods.

- The indicator values reveal information on the system’s reaction to floods. Not only knowledge on risks, but also on the graduality of the reaction’s increase and the recovery rate are useful when considering flood risk management measures. The thorough analyses needed to apply the resilience concept and to find the indicator values proved to have been helpful in defining a wider range of flood risk management options. This resilience perspective facilitates the development of strategies that contribute to the sustainable development of the region involved, which is what all flood risk management strategies ultimately aim at.

- Resilience strategies have significant advantages when natural values and the ability to cope with unexpected events are valued high or when floods have important positive impacts. Resilience strategies are costly in resistant systems and they may limit economic developments in such systems. Resistance strategies, in contrast, are costly to implement in systems with presently a low resistance.

- The degree of resilience and resistance that is best depends on societal preferences.

- Some nuances have to be made upon the positive connotation that the concept resilience has:
  - In systems where floods occur frequently, such as the Mekong, resilience strategies may be very valuable, because they maintain the positive flood impacts. They must thus be seriously considered.
  - In resistant systems such as the Rhine system, however, resilience strategies may hamper economic development and are very costly. Strategies that
maintain a high resistance, but do also slightly increase the resilience may be more feasible.

- Resilience strategies can thus not always be considered positive, nor will they always be negative.

### 9.4 Recommendations

The thesis provided resilience indicators and demonstrated that applying these indicators results in more insight and facilitates the development of comprehensive strategies for flood risk management of lowland rivers. It is therefore recommended to apply the resilience indicators and to study the reaction of a system as a whole to the discharge regime when strategies for flood risk management of lowland rivers are developed.

Further research is recommended into several aspects of the approach which proved to be important and need more attention than was feasible during this PhD research. First of all this applies to the relationships between peak discharges and damage and casualties. Furthermore, the evaluation of the economic effects of the strategies may be improved by more detailed economic analyses. In systems with embankments along the river, such as the Rhine, hydraulic system behaviour should be studied in more detail. Without knowledge on hydraulic system behaviour it is neither possible to assess the current flood risk and resilience of the system nor is it possible to assess the effect of measures such as detention areas on flood risks.

This thesis applied resilience on large lowland river systems. It is advised, therefore, to also establish the usefulness of the concept of resilience to other systems such as small river systems, coastal areas and polder systems.

To be able to elaborate on the resilience concept, on dynamic processes and system approaches, it is recommended to study not only resilience to flood waves, but instead broaden the subject of resilience to climate variability at large and its related uncertainties. Furthermore, the dynamics of system in relation to resilience and flood risk management should be further elaborated by studying adaptive management.
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In her MSc study she specialized in hydrogeology and groundwater modelling. She did a second thesis on using GIS in rainfall-runoff modelling in which she developed a rainfall runoff model of the Hupselse Beek catchment in the Netherlands. She spent her practical time of 7 months in Peru where she worked on water availability and distribution in a large irrigation district for the NGO IMAR Costa Norte and La Junta de Usuarios del Distrito de Riego Chancay-Lambayeque.

During her PhD research she visited the Flood Hazard Research Centre at the Middlesex University in London to carry out a part of her PhD research. She also spent time at the Mekong River Commission in Phnom Penh (in Cambodia, now moved to Vientiane in Laos). Her work there mainly consisted in data gathering, analysing and discussing the case study approach.

At Delft University of Technology she gave guest lectures in the course ‘integrated water management’ and she supervised MSc students.

In her work at Delft Hydraulics she worked on river design, hydrodynamic modelling, inundation modelling, regional water management, hydraulic system behaviour and other related subjects.

List of publications:


