Article

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Flood-risk Management Strategies for an Uncertain Future: Living with Rhine River Floods in The Netherlands?

Social pressure on alluvial plains and deltas is large, both from an economic point of view and from a nature conservation point of view. Gradually, flood risks increase with economic development, because the expected damage increases, and with higher dikes, because the flooding depth increases. Global change, changing social desires, but also changing views, require a revision of flood-risk management strategies for the long term. These should be based on *resilience* as opposed to the resistence strategy of heightening dikes. Resilience strategies for flood-risk management imply that the river is allowed to temporarily flood large areas, whereas the flood damage is minimized by adapting land use. Such strategies are thus based on risk management and 'living with floods' instead of on hazard control. For The Netherlands, one of the most densely populated deltas in the world, alternative resilience strategies have been elaborated and assessed for their hydraulic functioning and 'sustainability criteria'.

INTRODUCTION

In 1993 and 1995, The Netherlands experienced periods of uncertainty when the Rhine and Meuse Rivers reached very high levels. In the Rhine River, only in 1926 had a higher discharge (12 600 $m^3 s^{-1}$) been recorded. Over 250 000 people were evacuated from a number of polders when the stability of the dikes seemed no longer guaranteed.

When the flood ceased, the discussions on The Netherlands' flood control strategy were intensified and extended to include climatic change as an additional relevant factor for the long term. Recent estimates of the change in the discharge regime of the Rhine River (1, 2) forecast an increase in the so-called design discharge (a peak discharge with a probability of 1/1250 years) from 15 000 $m^3 s^{-1}$ in the 1990s towards 16 800 (minimum scenario) to 18 000 $m^3 s^{-1}$ (maximum scenario) by 2100. Additionally, in a downstream deltaic area, sea level rise may hamper the discharge. For The Netherlands, sea level rise is currently estimated as between 0.2 and 1.1 m above present. Finally, in deltas and alluvial plains both shrinkage and oxidation of extensive peat layers cause the subsidence of large areas, a process which in The Netherlands is enhanced and maintained by a history of over 1000 years of drainage (Fig. 1).

Apart from these environmental changes, social changes are also relevant. The demographic and economic development of The Netherlands is such that the number of people possibly affected by a river flood has increased. By 1900 the population of The Netherlands amounted to 5 million inhabitants, whereas in 2001 the figure was over 16 million. In 1900, people lived very concentrated in relatively few cities however, whereas nowadays changing desires concerning the available room for housing, economic activity, leisure, infrastructure, etc. have resulted in a spread over vast areas, and continuously high pressure on land-surface area. Thus, the pressure on protected alluvial plains is becoming more intensive (Fig. 2) (3). The estimated financial loss through flooding of the largest dike-ring along the rivers was estimated at less than € 7 million in 1990, but has risen to over 10 million € within 10 years merely as a consequence of economic development (4). The current mean economic growth rate of 2–2.5% will imply a steady doubling of the potential flood-damage each 35–28 years. In a century, this means an increase by a factor 8.

Summarizing, the design, water levels in the rivers will probably rise because of higher peak discharges and a higher sea level, whereas the vulnerability of the protected areas will increase through population growth and economic development, aggravated by land subsidence. This calls for a change of strategy in the policy fields of both integrated river management and physical planning. So far, 2 distinct—but related—strategies can be distinguished:

– 'room for rivers', a strategy focusing on measures to lower the water levels despite a rise in the design discharge, e.g. by enlarging the discharge capacity of the channel itself and/or through lowering the floodplains (5);
– a resilience strategy for the protected areas based on minimizing flood risks by controlled flooding and by limiting the flood-damage through dedicated physical planning in tune with flood frequencies (6).

Although both strategies have to address similar issues such as the distribution of discharge from the Rhine River over the various river branches and the relationship between river manage-

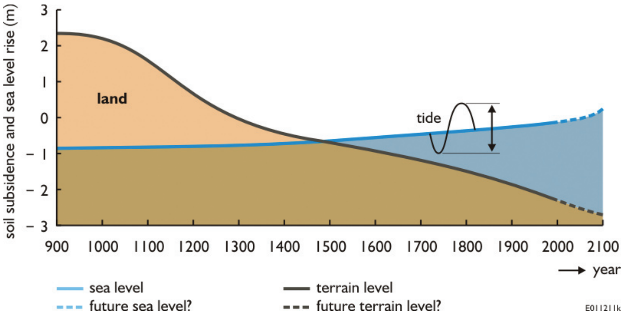


Figure 1. The land level sinks whereas the sea level rises, hampering the discharge of rivers in deltaic areas and increasing the vulnerability of the protected areas.

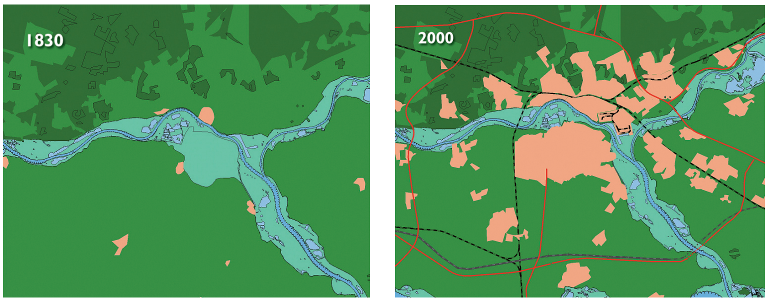


Figure 2. Floodplain area and land-use intensity around Arnhem around (a) 1830 and (b) 2000.

ment and physical planning, the first strategy is still relatively technical in character and limited to the present floodplain area. It does not question the long-term spatial planning within the protected areas. In this paper, we discuss the second strategy, which puts priority on influencing long-term spatial developments and hence sustainability. We go into the advantages but also the far-reaching implications. However, we first briefly introduce the present situation along The Netherlands' Rhine River branches.

BRIEF HISTORY AND PRESENT SITUATION

Before 1000 AD inhabitants of the delta and alluvial plains lived on natural levees, other natural heights, or they built mounds. Since then, the Dutch started to construct dikes, resulting in a closed pattern of dikes from about 1400 AD onwards. Today, this pattern of dikes is largely unchanged. It consists of 53 so-called dike-rings for the whole country, 10 of which adjoin the Rhine River branches (Fig. 3).

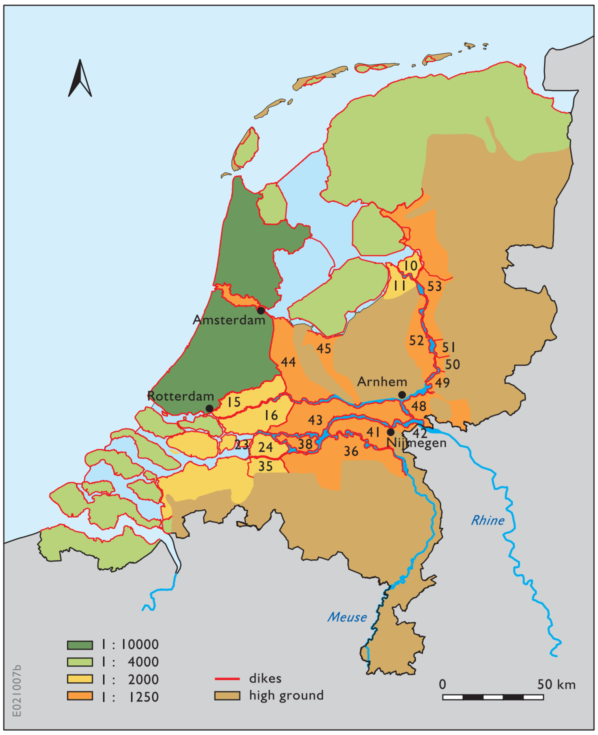


Figure 3. Dike-rings (numbered, referring to Tables 1 and 2) and safety levels along the lower Rhine River in The Netherlands.

The height of the dikes along the Rhine River has, however, steadily increased over the course of history. Initially, this meant adapting to the last-experienced flood level. From the 1950s onwards, a more scientific approach has been followed, based on hydraulic modelling for a 'design discharge' with a recurrence interval of 1/1250 years. This design discharge is determined by a statistical analysis of all floods recorded in the last 100 years. The 1993 and 1995 floods have caused the design discharge to rise from 15 000 to 16 000 $m^3 s^{-1}$, resulting in the applied linear regression becoming slightly tilted. This emphasizes the susceptibility of this statistical method to climatic fluctuations, whether normal or resulting from global change (7). It also emphasizes the uncertainty of forecasts of rare events (1/1250 years), when based on only a 100 years of records. The 1/1250 years discharge can only—with 90% certainty—be estimated to lie between 13 500 and 18 000 $m^3 s^{-1}$ (5, 7).

The fixation of the river between the dikes since about 1400 AD in combination with the steady heightening of the dikes has incurred sedimentation in the floodplains (8, 9), whereas subsidence has caused the protected areas to sink. The resulting differences between the floodplain level and the land level within the dike-rings has increased (Fig. 1), and so has the height of a flood above the level of the protected land. Consequently, the flood hazard has substantially increased.

The above-mentioned dike-rings consist of either entirely closed rings of dikes or of dikes which connect to higher grounds. Their surface area ranges from less than 35 km^2 to about 600 km^2 for the largest, the Betuwe. This already implies large differences in potential flood damage through sheer magnitude. Also the potential flooding depths differ substantially, from much less than 2 m for dike-rings adjacent to high grounds to more than 6 m in the lower parts of the enclosed Betuwe. These differences become even more accentuated when the economic status and development rate are taken into account. It is in the largest dike-ring with the largest potential depths, that the most vulnerable land-use types are now being developed, i.e. housing, industry, and (inter)national transport.

Although on the one hand flood protection has never been so sound, a further heightening of the dikes meets vast opposition. This partly follows from the notion: "the higher the dikes, the bigger the disaster", but also because of the negative effects of protective structures on natural, cultural, and scenic landscape values. Even more importantly, the improved protection sustains the negative spiral of further economic investments in the protected areas. The enhanced 'notion of safety' triggers new economic investments in the protected areas, which again raises a social call for dike reinforcements, etc. The opposition to dike reinforcement therefore calls for a change of strategy in order to escape this negative spiral.

A summary of the current situation would read: a dike-ring structure from 1400 AD, equal safety standards along most of the river, and a steadily increasing flood-damage potential because of a still largely unbridled 21st century land-use and economic development rate. The urgency of changing the direction of future developments is acknowledged and increasing, as illustrated by the many reports and the advice to the government by research institutions (3, 10), dedicated committees (3, 11), and water management authorities.

LIMITING THE RISKS OF FLOODING

A resilience strategy for flood-risk management relies on a number of principles and related measures. Firstly, we should emphasize that flood-risk management is not the same as flood control. Flooding risks result from a flood hazard in an area which is vulnerable. Without a vulnerable society or ecosystem, a flood may be regarded as a natural phenomenon which cannot be qualified in a normative way as posing 'a risk'. This also implies that the concept of flood risk embraces the concepts of flood hazard and vulnerability; often, it is expressed as a function of the 2 (the product, to be precise). In The Netherlands, however, it is common practice (12) to define flood risk as flood probability x flood damage. Obviously, the approach is the same, only the way of quantification differs. The difference lies primarily in where the flooding depth is included:

$R_f = H_f \text{ x } V = P_f \text{ x } D_f$

R_f = flood risk; H_f = flood hazard; V = vulnerability; P_f= flood probability; D_f= flood damage; with both H_f and D_f depending on flooding depth.

The vulnerability of an area depends on the number of people, the economic value (invested capital and earning power) and/or ecological values. In the downstream parts of the Rhine River basin, an adequate Flood Early Warning System (FEWS) is operational. Presently, the water levels can be predicted with sufficient accuracy 2 days ahead of a flood, and it is expected that this period can soon be lengthened to 3 or even 4 days. This means that people, cattle and other livestock can be evacuated in due time and that casualties need not be taken into further account in the risk assessment. When the ecological values of the floodplains and alluvial plains are supposed to be adapted to a natural flooding regime, the question of flooding risk can be limited to an economic analysis. That is, when we, for practical reasons only, forget about the psychological impact of evacuation and loss of goods.

Thus, the formula for flood-risk assessment can be used to identify possible directions towards a reduction of flooding risks: either by *lowering the probability*, which means the traditional flood control, and/or by *reducing the damage*, which requires *i)* spatial planning; or *ii)* adaptation of the land use to lower the flood-damage potential; or *iii)* lowering the flood level in order to curtail the flooding depth. The latter is, of course, again some kind of flood control—or rather flooding control—but much more sophisticated than by the traditional mere dike reinforcements.

Even with the main course now being known, a number of questions remain, e.g:
- What do these principles mean?
- What concrete measures must be taken?
- What are the implications of these measures?

The second and third questions are being addressed in a design study followed by an evaluation. The first question is answered as:
- We should abandon the concept of 'design discharge' because it is uncertain, because its value (1/1250 year) is arbitrary and because it is insufficiently physically based; instead, the whole discharge regime should be taken into account with all theoretically possible peaks, however, unlikely.
- We should modify the present dike-ring structure, because it allows the water to flood very large areas, because it protects cities, industries, agricultural areas, and nature conservation areas equally well, and because it denounces hydraulic principles of either a detention function or a discharge function. These distinct hydraulic functions will be elaborated below.

TWO SPATIAL CONCEPTS

In the design study, 2 spatial concepts have been elaborated with varying emphasis on the control of the flooding and the minimization of the damage by adapting the land use, respectively. Both designs rely on compartmentalization. The rationale behind compartmentalization follows from simulations of a number of disaster scenarios (13) incurred by peak discharges exceeding the design discharge. It appeared that large polders behind one single defence of a dike-ring become entirely flooded, while at the same time causing the water levels in the river to be lowered substantially to well below the design water level. Compartmentalization means splitting up a dike-ring into a number of smaller dike-rings, which may be flooded in a controlled sequence defined by the combination of expected hydraulic efficacy and minimum damage. Thus, the whole idea is to effectuate controlled flooding, but aimed at delimiting the affected area and minimizing the flood damage.

Depending on the spatial layout of the compartments, compartmentalization may have either one of the following hydraulic effects (4):
- detention, i.e. peak shaving;
- adding discharge capacity (sometimes with additional peak attenuation);
- adding storage capacity (in the furthest downstream areas and coastal zone).

With this knowledge alternative spatial designs were drawn-up. In the first alternative (detention in compartments), the first hydraulic functioning is given priority, whereas the increase of discharge capacity is the aim of a second and third alternative ('green rivers 1 and 2').

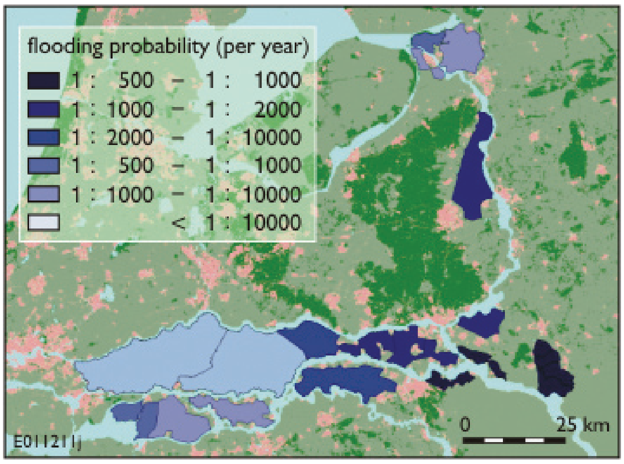


Figure 4. Compartmentalization for detention implies that large dike-rings are subdivided in parts which may flood more frequently and parts that are better protected (in dark blue the compartments that are flooded successively from upstream to downstream during a peak river discharge, in light blue the compartments that are flooded successively when the storm surge barriers must be kept closed, beginning downstream).

Detention in Compartments

The basic philosophy of detention in compartments is to design a cascade of detention areas which ensures that all possible flood peaks (of whatever probability) can be temporarily stored in such a way that overall flood-risk is minimized (Fig. 4). It includes detention areas along all 3 branches of the Rhine. The precise hydraulic functioning of these areas differs, as well as the frequency of operation. Provided the hydraulic design functions well, the remaining dike-rings and/or compartments will have a flooding probability of < 1/10 000 years, yielding them much safer than they are at present.

For a sound hydraulic functioning the order of inundation should be from upstream to downstream, as it is hydraulically practically impossible to protect upstream dike-rings by inundating areas further downstream. Therefore, protection levels usually increase downstream (1/200 in southern Germany, *via* 1/500 in Nordrhein-Westfalen, 1/1250 in the eastern Netherlands to 1/2000 and eventually 1/10 000 along the coast, because of the infinite amount of water in the sea and the extra damage caused by saline water). However, there is one exception to this rule, *viz.* in the most downstream areas where the water levels are almost level and are primarily determined by the sea level and/or the closure of storm surges. In these areas, any extra storage capacity may help to keep the water levels tolerable, which may be achieved by first connecting to the large surfaces of the detached estuaries and inlets in the southwest of The Netherlands and, secondly, by inundating 'calamity polders' (3).

In minimizing the overall flood damage, a GIS-analysis of the potential damage of flooding can be used to delimit compartments. In this context, the spatial design follows the adage; *land-use follows hydraulic functions in the sense of priority, but not in the sense of primacy: the existing land-use is largely regarded as a determinant for the design of the dike-rings and compartments.* Consequently, present land use is fully taken into account—partly because of the likely opposition towards the purposeful inundation of built-up areas—and the location of dry infrastructure of national significance (highways, railroads) is regarded a possible constraint to frequent inundation.

Table 1. Surface area and maximum flood damage in various 'detention compartments' and in the remainder of the present dike-rings (numbers of the dike-rings refer to Fig. 3).

Dike ring	Compartment	Surface area		Maximum damage		Index
		ha	%	€ * 10⁹	%	€ * 10³ ha⁻¹
Rijn and IJssel (48)	Rijnstrangen	2800	10	0.2	1	65
	Boven-IJssel	4950	17	1.8	9	365
	remainder	20 959	73	17.6	90	838
Ooij en Millingen (42)	compartment 1	2650	79	0.1	15	55
	remainder	725	21	0.9	85	1172
Betuwe (43)	compartment 1	2675	4	0.6	2	236
	compartment 2	5200	8	0.6	2	117
	compartment 3	4950	8	0.7	2	133
	compartment 4	8325	13	2.2	7	262
	compartment 5	32 725	52	14.7	45	449
	remainder	8697	14	14.0	43	1605
Land van Maas en Waal (41)	compartment 1	13 050	47	1.4	5	110
	remainder	14 852	53	26.3	95	1771
Bommelerwaard (38)	compartment 1	7875	73	1.5	25	189
	remainder	2971	27	4.4	75	1488
Land van Altena (24)	compartment 1	10 125	62	1.2	18	115
	compartment 2	3475	21	0.7	10	187
	remainder	2829	17	4.5	71	1608
Biesbosch (23)	compartment 1	2575	100	0.1	100	57
	remainder	0	0	0.0	0	
IJssel (52)	compartment 1	13 900	45	1.3	12	96
	remainder	17 025	55	9.6	88	564
IJsseldelta (11)	compartment 1	1275	8	0.1	1	60
	compartment 2	725	5	0.0	0	36
	remainder	13 125	87	5.5	98	418
Mastenbroek (10)	compartment 1	8050	86	0.8	20	95
	remainder	1325	14	3.1	80	2370

In order to cut down on costs, existing dike structures are being used wherever possible or logical combinations with roads or railroads are sought for. Thus, the flooding probability increases only for some compartments, whereas the overall flood risk decreases substantially.

Table 1 shows that most of the damage occurs in a small part of an existing dike-ring only, e.g. for Land van Maas en Waal half the area suffers 95% of the damage, the rest suffering only 5% of the damage. The Table also shows that the compartments that are required for peak saving, e.g Rijnstrangen and the compartments 1 for Ooijpolder and 1, 2, and 3 for Betuwe, are amongst the parts with the least relative damage per ha. The remainder, however, with high relative damage values, are the best protected (< 1/10 000 years flooding probability).

The detention compartments may be filled rapidly to several meters depth, though the stream velocities within the polder will probably be limited (< 1 m s^{-1}). After some hours or days, depending on capacity and filling rate, the water is almost stagnant. The emptying of the detention areas can begin after the flood peak has passed and may take several weeks, though much less in smaller polders.

Future land use should adapt to the new flooding probability. However, in this alternative strategy, economy is given priority over ecology, implying that the currently protected areas, which will be given a future hydraulic function, will remain available for primarily economic land-use types. This is in contrast to the alternative of the 'green rivers', where ecology has priority. Related to the flooding probability, spatial planning might sustain certain combinations of economic land use, for example extensive agriculture, recreation and nature in frequently flooded areas (> 1/100 years), *via* intensive agriculture and related 'green' land-use functions (1/100–1/500), horticulture, small-scale housing and (agro-)industries (1/500–1/2000) to housing and industries ('red' land-use functions) in the best protected areas (< 1/2000 years).

Green Rivers

The rationale behind this alternative strategy is slightly different from the former, although it also relies on controlled flooding and decreasing the size, and hence damage potential, of dike-rings which may accidentally be flooded. However, resilience is also achieved by lowering the water levels in the river at all times and thus the likelihood that dangerous levels will be achieved. To this end, discharge capacity is enlarged with as much surface area as seems practically feasible. This should also result in a substantial peak attenuation. The basic philosophy of the alternative can be summarized as enhancing the river's discharge capacity by enlarging the floodplain area by dike relocation and/or by 'green rivers' (bypasses in the form of additional floodplain area between dikes), which ensures that all possible flood peaks, of whatever probability, can safely be discharged.

Extra discharge capacity can be found along 3 different branches of the Rhine, presuming that the discharge distribution over the branches can be adapted to requirements. Baan and Klijn (14) already explored various routes. The most promising variant of discharge to the north through the IJssel Valley was elaborated in the study 'The Rhine River in a long-

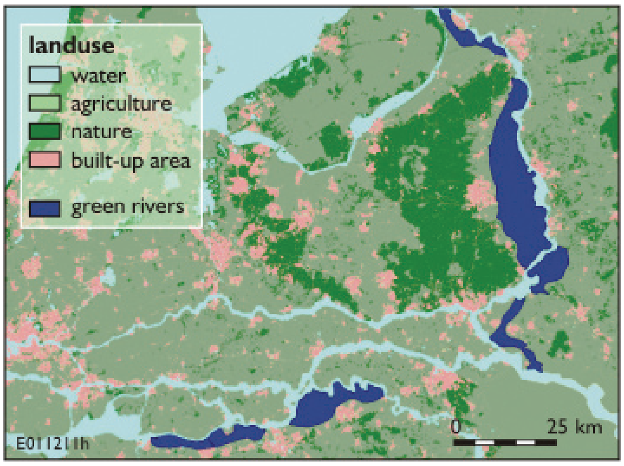


Figure 5. Compartmentalization for discharge implies that the water levels are lowered substantially by providing much more room to the river; here a spatial alternative for green rivers leading the excess discharge to the north.

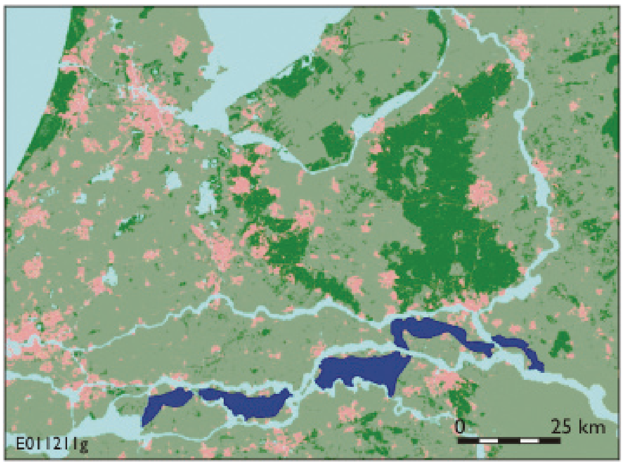


Figure 6. As Figure 5, but a spatial alternative, which discharges the floods through the backswamps in the central alluvial plain.

term perspective' (3, 15). When the design is extended to include the Meuse River (16) it implies that any excess discharge of the Rhine River, i.e. above the present design discharge, is sent north through the IJssel Valley, whereas room for the Meuse is found along its southern bank (Fig. 5).

A variant with enhanced discharge capacity in the western direction is shown in Figure 6; this implies that all excess discharge in both the rivers Rhine and Meuse is sluiced through the backswamps in the central alluvial plain. The spatial design of this variant was very difficult, as existing built-up areas and/or highways and railroads necessitate that very lengthy, and hence expensive, dikes be built. For reasons of hydraulic functioning and ecological connectivity, a routing between the rivers Waal and Meuse has been chosen. This facilitates the discharge of both rivers and can best be combined with the preservation of the current land use and landscape qualities (scenic, cultural and natural).

As in the compartmentalization alternative, the green rivers alternatives are limited to areas with relatively low maximum expected flooding damage. In Table 2, the figures are given for the second variant of the 'green rivers alternative'. The Table shows that the green rivers are located in such a way as to cause the least damage to the existing land use. In the Betuwe, 12% of the area is claimed but 97% of the economic value is protected. This is the most difficult and hence narrowest stretch, as the water must pass between the cities of Nijmegen and Arnhem, which have expanded into the alluvial plain by jumping across the rivers from their previously entirely flood-free positions. Further downstream in Land van Maas en Waal, Bommelerwaard and Land van Altena much larger areas are given a hydraulic function, 40, 23, and 67%, respectively, of the dike-rings, whereas 95%, 80% and again 95% of the economic value within these dike-rings will be protected.

Along the IJssel and Meuse, existing dikes can be moved inland away from the river and be kept relatively low because of the favorable natural relief. In the variant through the central alluvial plain, dikes must be built all along the green rivers. Because the green rivers have been designed as wide as possible, the water levels will remain relatively low, and so will the water-level rise with increasing discharge. Because of the resultant shallow water depths, flow velocities will be limited as well, causing substantial peak attenuation.

In the green-rivers alternative ecology has priority over economy. This can be regarded as a decision independent of the hydraulic principle. However, as ecology is given priority, this automatically explains the oversizing of the width of the green rivers, which should have as natural a hydrological regime as possible, whilst it also 'determines' the land use within the unprotected area. As the green rivers follow the backswamps in the alluvial plain, large areas will become permanent marshland, whereas the more elevated parts such as pointbars or natural levees will remain dry for most of the year or even for many years in succession. Within the unprotected area, nature development is promoted in accordance with the newly formed abiotic site conditions. In some parts, recreational buildings or permanent housing may be allowed, as long as they do not conflict with hydraulic and nature conservation goals. The present land use will have to be abandoned and buildings will have to be demolished or adapted, e.g. placed on poles or mounds when economically feasible.

In the protected areas the protection against flooding might be improved, but the area remains part of the alluvial plain. For maximum flexibility, it might be wiser to aim at very prudent economical development throughout the entire alluvial plain, but stakeholders might plea for intensification of the land use as compensation for the 'losses' of economic opportunities in the then enlarged floodplain area including the green rivers. However, what direction the discussion will take can be anticipated only with great difficulty and uncertainty.

EVALUATION

The 2 alternative resilience strategies have been evaluated against a zero-alternative, which is autonomous development throughout a century. The reason for this is that the estimated time frame to fully establish an alternative strategy is approximately a century, whereas questions of sustainability also require a prolonged time-frame.

The evaluation comprised an assessment of relevant criteria for sustainable development, comprising: costs (investment and maintenance); flexibility (opportunity to adapt to changes in external and/or internal circumstances, boundary conditions, normative views, etc.); resulting flood risks (a.o. expected overall damage, calculated with Delft-FLS (Flood Simulation Model) and HIS-Damage Model); economic effects/opportunities; ecological effects/opportunities; landscape qualities (scenery and cultural heritage).

We present some of the most robust findings, as the evaluation is very susceptible to the continuous changes which result from the successive approximation of either the design (optimization) and the operationalization of the criteria.

For the costs of the various strategies, is was found that the zero-alternative of successively heightening and strengthening dikes is the cheapest. Depending on the number of successive stages, a gradual heightening of the dikes will cost about 1–2 thousand million € (1 to 3 stages of heightening). Both the resilience strategies are more expensive, as they require the construction of large lengths of new dikes, the adaptation of highways and railroads at each crossing, and financial compensation for the owners and inhabitants of areas where economic development is frustrated and/or earlier investments devalue because the flooding frequency is allowed to increase. Partial compartmentalization may be realized for about € 1–2 thousand million, but the costs of both comprehensive compartmentalization and the green rivers alternative to the west are estimated to amount between € 3 and 8 thousand million. However, this large difference in costs is partly due to the fact that a change of strategy implies full implementation costs as opposed to the marginal, or incremental costs of heightening already existing dikes, without any unrecovered investment costs.

Dike strengthening can only be done in a flexible way by doing it in many subsequent stages. This means that the costs will rise enormously, that the rate of climatic change is difficult to deter-

Table 2. Surface area and maximum damage in the 'green river compartments' and the remainder of the present dike-rings (numbers of the dike-rings refer to Fig. 3).

Dike ring	Compartment	Surface area		Maximum damage		Index
		ha	%	€ * 10^9	%	€ * 10^3 ha^{-1}
Rijn & IJssel (48)	green river	2400	8	0.2	1	96
	remainder	26 309	92	19.3	99	734
Betuwe (43)	green river	7350	12	0.9	3	116
	remainder	55 222	88	31.9	97	577
Land van Maas en Waal (41)	green river	11 275	40	1.3	5	116
	remainder	16 627	60	26.4	95	1589
Bommelerwaard (38)	green river	7225	67	1.2	20	167
	remainder	3621	33	4.7	80	1298
Land van Altena (24)	green river	3800	23	0.3	5	81
	remainder	12 629	77	6.1	95	480

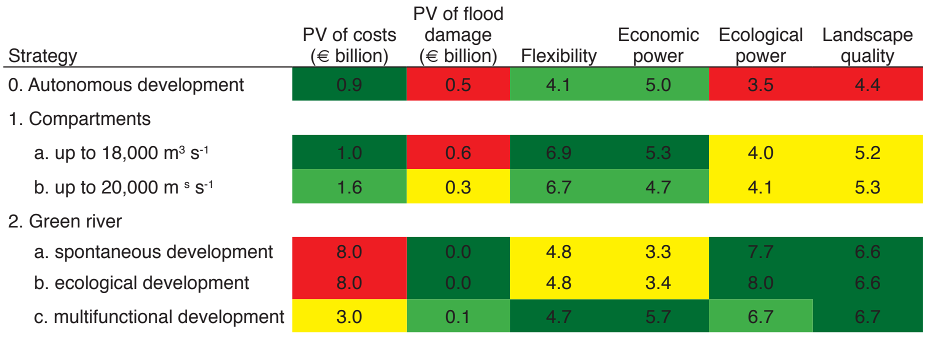
mine and that future regrets may be large. The construction of green rivers and dike-relocation can hardly be phased either, as the water will have to be discharged along the whole river. Only by changing the discharge distribution over the 3 branches of the Rhine can some phasing be realized. In contrast, the compartmentalization alternative provides little chance of regrets other than financial, as it may turn out that none of the compartments will ever be flooded. However, the financial regrets may be large if the compartmentalization alternative were to be fully implemented at once.

The overall flood risk which results from the various alternative strategies differs substantially. In the zero-alternative, the flooding probability is supposed to remain more or less constant, but the damage potential increases by a factor 8 in one century. Also the expected flooding depths will rise. In contrast, the compartmentalization alternative will imply a more frequent flooding of small parts of the present dike-rings, but the potential flooding damage in these polders will be small. This is the logical consequence of transferring economic investments to the better protected compartments, which will experience a much smaller flooding probability. The overall risk diminishes substantially, but, in economic terms, it seems that the costs far outweigh the economic benefits. The green rivers alternative lowers the water levels and thus the flooding depths. At the same time it results in the splitting up of the present large dike-rings. Most importantly, however, is the relocation of vulnerable land use towards the much better protected compartments, which is included in the cost estimate. Consequently, the overall flood risk diminishes even further than in the compartmentalization alternative.

The consequences and opportunities for economic development of the various alternatives differ mainly on the point of location. Investments can be supposed to be either scattered all over the area—in the case of the zero-alternative—or located in the best-protected compartments, in the other alternatives. This goes for industrial developments, agriculture, recreation, etc. The overall macroeconomic effect on a large spatial frame can be judged as very limited indeed.

For ecological development only green rivers create opportunities, especially when they experience similar flooding frequencies as the present floodplains. However, the decision on whether to opt for nature development or extensive agriculture in unprotected areas can be regarded as being wholly independent from the flood-risk management strategy.

From a landscape-quality point-of-view it would seem that dikes would fit best in 'the Dutch tradition'. However, recent dike-reinforcement programs have been criticized especially for neglecting the cultural heritage of old dikes and for spoiling the scenic qualities of the typical Dutch river landscape (17, 18). This is partly due to the discrepancy in dimensions between the new technical dike design and the small-scale countryside. Both resilience alternatives require the construction of huge lengths of dikes as well, but these can be located in the relatively large-scale rational landscape of the backswamps, which were parcelled out no earlier than the 1950s. Whether they contribute to or spoil the scenery depends on the precise design. It seems that the green rivers alternative may add to the identity of the river landscape by an enhanced spatial connectivity and a more acute contrast between open natural zones and more intensively used cultural zones.



Strategy	PV of costs (€ billion)	PV of flood damage (€ billion)	Flexibility	Economic power	Ecological power	Landscape quality
0. Autonomous development	0.9	0.5	4.1	5.0	3.5	4.4
1. Compartments						
a. up to 18,000 $m^3 s^{-1}$	1.0	0.6	6.9	5.3	4.0	5.2
b. up to 20,000 $m^{s} s^{-1}$	1.6	0.3	6.7	4.7	4.1	5.3
2. Green river						
a. spontaneous development	8.0	0.0	4.8	3.3	7.7	6.6
b. ecological development	8.0	0.0	4.8	3.4	8.0	6.6
c. multifunctional development	3.0	0.1	4.7	5.7	6.7	6.7

1 Qualitative scores are assigned between 0 (utmost bad) and 10 (perfect).
2 Emotional values are not included. Emotional values may be accounted for by applying a weighting factor (greater than 1) for the score on flood damage.
3 When the compartmentalisation strategy is fully implemented more compartments must be constructed resulting in still higher costs.

Figure 7. Overall evaluation of the 2 resilience alternatives in several variants in comparison to Autonomous Development. Costs and economic damage expressed as Present Value (PV).

All in all (Fig. 7), none of these strategies is best on all points. When a multiplier of 2 is used for the flood damage, to account for the emotional valuation of flooding (a rather likely minimum value), the sum of costs and flood damage for the zero-strategy and the compartmentalization strategy are of the same order of magnitude. On the other criteria the compartmentalization strategy generally performs better. The green river strategy scores significantly or slightly better than the zero-strategy on all criteria, except for the sum of costs and remaining overall flood damage. Though the overall flood damage is very low, the implementation costs are so huge, that this strategy can never be defended from a narrow economic point-of-view only. It is rather a question of whether the enhanced ecological power and landscape quality are worth the investments. Even though we started with 'sustainable development' as the overall objective, we are still stuck with a true policy dilemma.

DISCUSSION AND REFLECTION

The findings of our research are considered valid for alluvial rivers with flood protection by dikes outside the influence of the sea with its tides. The reasons for this are assumptions about the hydraulic functioning of the system: the river with its floodplains and the adjacent, protected, alluvial plains. It is presumed that loss of human or animal lives can be prevented by adequate early-warning systems and evacuation procedures. This means that considerations of the preferable flood-risk management strategy refer primarily to economic damage, although emotions as well as new opportunities are important to take into account as well.

In the last century, flood proneness seems to have played a steadily decreasing role in the spatial planning of protected areas in The Netherlands. The high safety standards create the impression that the dike-rings are safe areas to live in, with the result that there is no incentive to minimize the vulnerability to flooding by appropriate land-use planning. Consequently, it is likely that the economic damage potential of the dike-rings may continue to rise, whereas the space available for a change of strategy in the direction of compartmentalization for retention or for discharge is rapidly being consumed by building activities and land-use intensification in the protected areas. This precludes the development of a sustainable flood-risk management strategy for the whole lower Rhine River basin by virtually blocking some 'spatial alternatives'.

The evaluation demonstrated that the 2 alternative resilience strategies are both structural solutions for a comprehensive flood-risk management scheme, and, in the long run, have fewer disadvantages than the present flood protection strategy. The alternative strategies rely on the abandonment of the application of one design discharge only and the splitting up (compartmentalization) of dangerously large dike-rings, where in the case of flooding the damage would be very high. Resilience strategies require that a large surface area which is now protected by dikes is occasionally lent to the river, in order to perform essential hydraulic functions. However, this room is not permanently lost for human land use or other ecological functions, as it is only temporarily and/or incidentally needed for storage or discharge. Many types of adapted land use can be fitted in.

So, flood-risk management based on resilience is possible. However, implementation of such a strategy requires huge investments in the short-term whereas revenues of such an alternative strategy will only become clear over relatively long time periods. Thus, we are confronted with some major socioeconomic dilemmas, which might prove decisive.

For example, how to influence the opinion of the majority of society in the direction away from short-term, small-scale rationality and towards long-term, large-scale rationality? After all, when adopting the usual relatively short-term economic view, the full costs of the 'ideal' strategies are much higher than the marginal costs of recurrent slight adaptations of the once-opted-for approach. By focusing on the short-term advantages, however, opportunities are missed to achieve a more sustainable future in the long run, with natural processes working to our advantage, less maintenance costs, etc.

Small steps ahead are known and have proven reliable, whereas the ideal strategies may not be a tempting perspective in everyone's view. The recognition of more sustainable strategies for flood-risk management requires a wide-angle view and ambition, whereas pursuing such a new track requires courage and conviction. This is especially difficult when the track towards a higher peak requires crossing a valley first. Thus, the support for a change of strategy may be bound to remain too limited. The most prominent remaining question, therefore, is how to achieve the neccessary transition? Meanwhile, the only thing that may be achieved is the prevention of further regretful interventions: ensure that the track towards the tempting perspective is not obstructed any further. This implies that reservations be made in the dike-protected areas to enable providing more room for the river in a later stage.

EPILOG

The strategies presented above are the result of lengthy debate and years of study and, fortunately, not in an academic vacuum. The experiences and views described in this paper are already influencing The Netherlands' water-management policy. Green rivers, though small in size, are presently often considered as a possible measure to increase the discharge capacity of the rivers, which was inconceivable some years ago. Likewise, the controlled flooding of some compartments (so-called 'emergency polders') in order to enhance the safety of downstream dike-rings is presently being studied by a government committee.

The Netherlands is just one example of a large number of densely-populated deltaic regions, where climatic change and social developments interact and sometimes conflict. However, The Netherlands is also well-known for its sophisticated water management. The fact that the strategy on how to deal with river floods is now subject to debate might be food for thought for other regions, which may still avoid making the same mistakes (19).

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19. This paper is based on a research project of The Netherlands' Centre for River Studies (NCR), including Alterra, IHE, RIZA and WL|Delft Hydraulics. We thank all colleagues for their technical aid and for the discussions on this paper. The research was financially supported by the EC through IRMA-SPONGE, and partly conducted in the context of Delft Cluster.
20. First submitted 28 Januari 2002. Revised manuscript revised 14 Oct. 2002. Accepted for publication 17 Oct. 2002.

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