DECISION SUPPORT AND RIVER MANAGEMENT STRATEGIES FOR THE RHINE IN THE NETHERLANDS

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الخلاصة:

يَصف هذا البحث منهجية لتقييم ومقارنة بدائل استراتيجيات إدارة الفرع الهولندي من نهر الراين. وقد ناقشنا ثلاثة أهداف ، هي : السلامة في أثناء الفَيَضان لأهميتها في ديمومة ودعم الاقتصاد والتطوير في البلاد، وتحسين ظروف الملاحة على امتداد النهر ، حيث يُعتبر نهر الراين وسيلة نقل أساسية بين مرفأ روتردام وألمانيا، والهدف الأخير زيادة القيمة البيئية لبيئة النهر. وتصف هذه الدراسة أيضاً المنهجية والنماذج التي استُخدمت لتقييم الطرق البديلة لتحقيق هذه الأهداف. وقد استخدمنا النـَّمذجة الهيدروديناميكية مُدَعمة بأنظمة المعلومات الجغرافية (GIS) التي تعتبر وسيلة جديدة لها ميزات هامة مقارنة بالأسلوب التقليدي. وأظهرت التحاليل أن ما نتج عن هذه البدائل الاستراتيجية مثل (السلامة مقابل الطبيعة، والطبيعة مقابل الملاحة على اليابسة، والزراعة مقابل الطبيعة) ، والبحث عن الإمكانات للحصول على حالة الكسب في كافة الأحوال. ونتج عن هذه الدراسة تقييماً لهذه الاستراتيجيات يَظهر أثرها على أداء النهر وتداعيات ذلك المائية.

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ABSTRACT

This paper describes a methodology for assessing and comparing alternative river management strategies for the Dutch branches of the river Rhine. The three objectives considered in the analysis are: safety against flooding which is a necessary condition to maintain and enhance economic development of a major part of the Netherlands, improving inland navigation conditions along the river (the Rhine is a major transport route between the port of Rotterdam and Germany), and increasing the ecological values of the river system. This paper describes the methodology and models that are used to assess alternative ways of meeting these objectives. We used hydrodynamic modelling aided by Geographical Information Systems (GIS), which is a new approach that has some important advantages compared to traditional approaches. The analysis shows the trade-offs for various strategies (for example safety versus nature, nature versus inland navigation, agriculture versus nature, *etc.*) and looks for possibilities to create win–win situations. It also produces scorecards for various strategies, which show their impacts on the functions of the river and their financial consequences.

Key words: River Management, Flood Management, Inland Navigation, River Rehabilitation, Decision Support, GIS, River Modeling

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1. INTRODUCTION

Traditionally, rivers and their floodplains have been managed in the Netherlands in order to achieve three objectives:

1. A relatively high safety level against flooding;
2. Favourable conditions for inland navigation;
3. Year-round use of fertile agricultural lands in the floodplains.

The natural river processes have generally been guided in the desired directions by the construction of extensive river training works such as levees, (submergible) embankments, revetments, weirs, and groins. These river engineering measures have, however, produced some adverse effects. For example, freely meandering rivers and frequently flooded land have been turned into straight, deep main channels in between submergible embankments, with a resulting loss of natural habitats. The wooded river landscape has been transformed into uniform open areas with agriculture as the main function. The level of the floodplains behind the embankments is slowly increasing by sedimentation of silt during peak flows. In times of extreme discharges water levels in the river are elevated high above the land behind the levees due to the confinement, while in times of reduced discharges groundwater levels in the surrounding area fall due to lower water levels in the slowly subsiding main channel.

There are also a number of new concerns. In the floodplains clay is being excavated for levee improvement and brick production and sand is being excavated for the construction industry. With increasing population pressure, housing and urbanization is encroaching on the floodplain area. Increasing awareness of the value of the natural environment is making nature rehabilitation an important aspect of river management. As a result, plans have been developed to re-establish natural conditions in the floodplains. Uncontrolled nature development may, however, reduce the achieved level of safety against floods due to an increasing hydraulic roughness. The current landscape of the floodplains, with agriculture as the main function, can be seen as a valuable part of the Dutch scenery and should be preserved from this point of view. Also, recreation is an important function of the floodplains.

With the peak flows of the mid nineties still fresh in mind (in 1995 about 300 000 people were evacuated due to serious flood danger), and because of possible future climate changes leading to a higher potential for floods, maintaining the safety against flooding along the river Rhine is one of the key elements in Dutch modern river management. In addition, there is a need to improve one of the Rhine branches, the River Waal, in order to maintain its function as a major route for inland navigation.

There is increasing concern that it may be impossible to combine all the riverine functions with all the claims to the limited floodplain area. Clear choices may have to be made. In doing so, many questions may need to be answered. For example, where do interests clash and where may a coupling of interests offer opportunities? What possibilities and limitations are there from a river-engineering point of view? How can the riverine area be managed in an environmentally friendly way while still providing sufficient protection against flooding? Does the riverbed have sufficient capacity in order to break through the spiral of ongoing levee heightening? The need for answers to these questions was a motivating driving force behind a study that employed the decision analysis and developed a decision support system (DSS) for the Dutch branches of the river Rhine. The Ministry of Transport, Public Works and Water Management supervised the study, called Landscape Planning of the River Rhine (LPR). Its purpose was to support the analysis of river management policies on a long-term basis (20–50 years).

The study is addressing the question into what extent the riverine functions and the competing land-use claims to the limited floodplain area can be combined. This question cannot be answered by looking at single river functions in an isolated way. Applying sectoral river management to achieve certain objectives for one river function will affect other functions. In the case of the Dutch River Rhine, implemented measures that have to be taken at one location in a branch may affect processes and functions of the whole branch and even the other branches. The development of acceptable management strategies for the river system as a whole should be achieved by taking all relevant effects of alternatives on all river functions for all branches into account. This is not an innovative idea. It was already used in the 1970s in the Policy Analysis of the Oosterschelde (POLANO) study [1] and the Policy Analysis of Water management in the Netherlands (PAWN) study [2]. Moreover, the concept of integrated water management has been included in policymaking in the Netherlands for more than a decade. Implementation of integrated river management, however, has been hampered analytically by the complexity of physical river processes (hydraulics and morphology) and organizationally by the number of managing authorities involved.

Organizationally, the Ministry of Transport, Public Works, and Water Management manages the main channels of the rivers in the Netherlands, with local water boards being responsible for maintenance of the levees. Local authorities, such as provinces and municipalities, manage the floodplains. Safety against flooding and fairway maintenance are the responsibility of the Ministry, while local authorities mainly focus on land-use in the floodplains, such as agriculture, nature development, recreation, housing, *etc.* The result is an enormous scatter of plans and ideas about the use and management of the floodplains. In the LPR study, effects of various management strategies on river functions were evaluated for all Rhine branches by applying the DSS. LPR explored alternatives for sustainable landscaping of the riverine area, but did not provide a blueprint. After all, (re)landscaping is a response to social requirements and problems that change over time, and is therefore a dynamic process. However, LPR did supply information required for a substantive meaningful discussion among the parties involved in landscaping and managing the riverine area, hence contributed substantially to the conceptualisation of the "room for rivers policy" in the Netherlands. Employing the LPR-DSS tool enables responsible authorities to rapid and flexible reactions to new situations; *e.g.* shifting priorities of riverine functions or extreme events in the river system such as major floods.

2. GEOGRAPHIC COVERAGE

LPR covers the main channels and floodplains of the Rhine branches in the Netherlands (Figure 1), which are the Upper-Rhine, Waal, Pannerdensch Canal, Lower-Rhine, and IJssel.

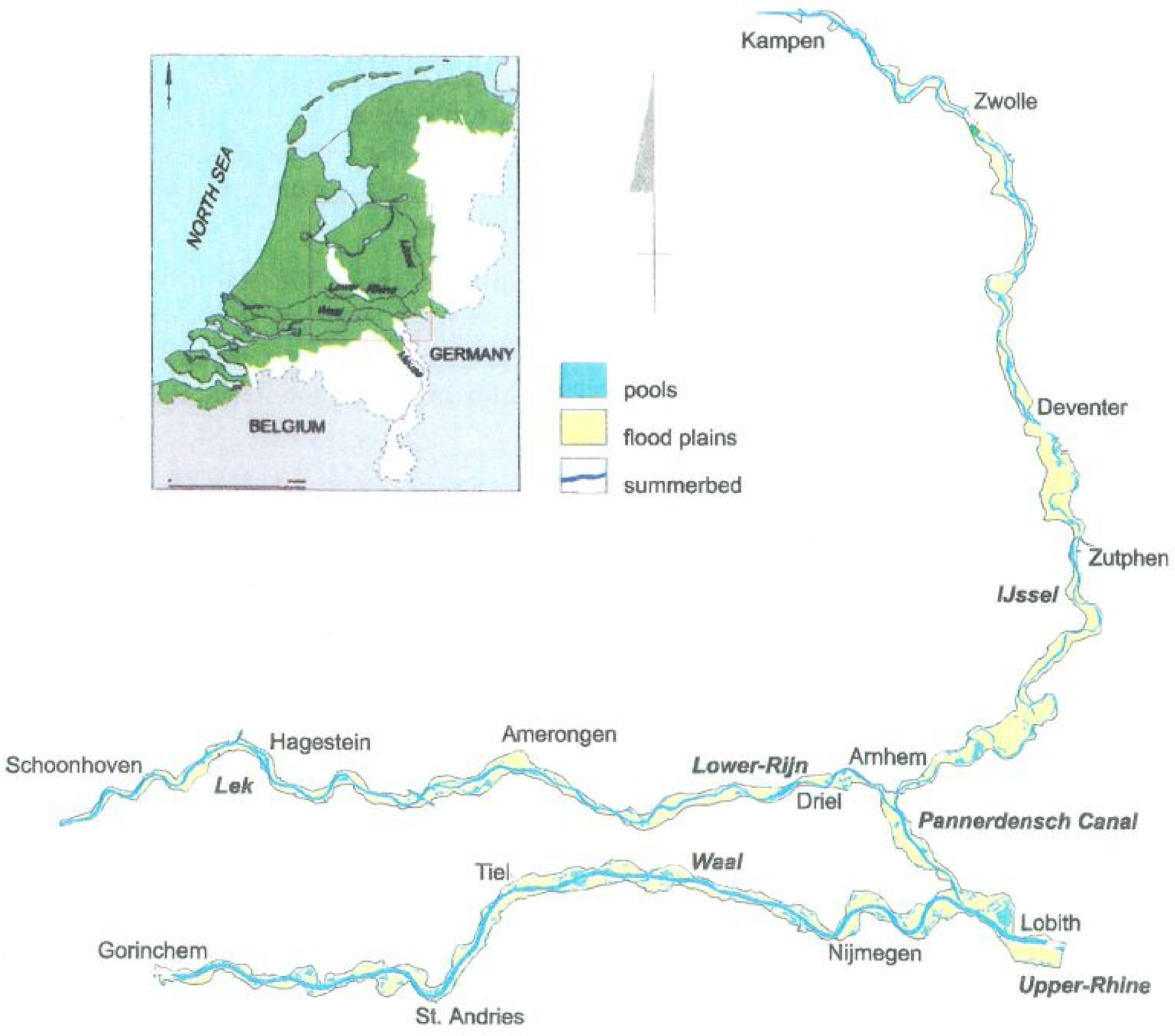

Figure 1. Study area

The upstream boundary is imposed near the town of Lobith, where the Rhine enters the Netherlands. The downstream boundaries are at the transition zone to the tidal rivers and IJssel Lake, where the typical river processes begin to lose ground. The main (winter) levees define the transverse boundaries. Figure 2 shows a typical cross section of a Rhine branch in the Netherlands, with submergible embankments, groins, floodplains, and levees.

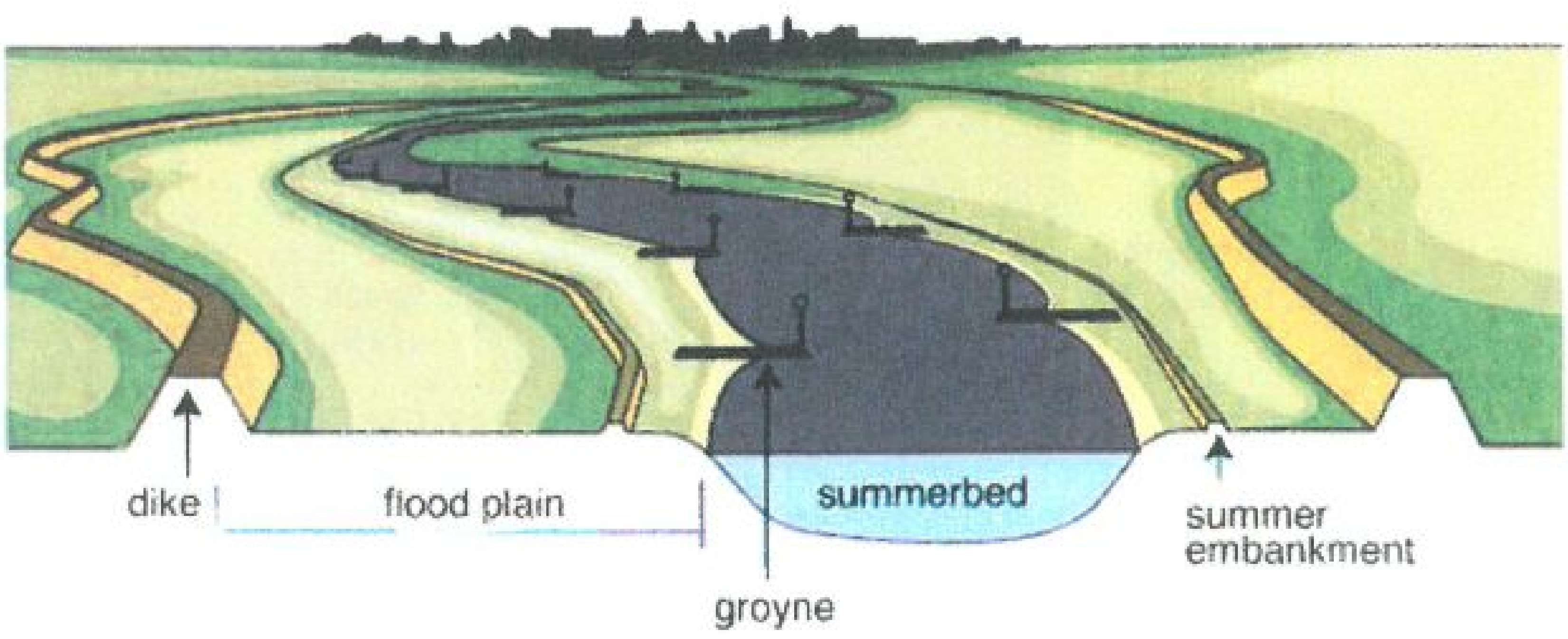

Figure 2. Typical cross section of a Dutch Rhine branch

From a hydrological, morphological, ecological, and functional point of view the Rhine branches appear to be a single coherent system, although there are large geometrical differences (Table 1). The river Waal is free flowing and wide with floodplains that have been heavily influenced by humans through the excavation of sand and clay. The inundation frequency of the floodplains along the Waal is rather high in comparison to the other branches. The main channel of the IJssel River is quite narrow, with its relatively wide floodplains still intact. In case of low discharges, water levels in the IJssel River are influenced by the operation of the weir at Driel in the Lower-Rhine.

Table 1. Characteristics of the River Rhine Branches in the Project Area

Branch	Main channel		Floodplains		
	Length (km)	Av. width (m)*	Number	Av. width (m)	Total area (ha)
Upper-Rhine	5	330/440	4	850	1100
Waal	83	260/370	43	550	8750
Pannerdensch Canal	11	140/200	9	400	1350
Lower-Rhine	62	120/190	33	450	5150
IJssel	93	90/120	49	550	9350
Total	254		138		25 700
*: in between groins/banks (groin fields)					

The Lower-Rhine has weirs along its entire length and its width is in between the width of the Waal and the IJssel. In the individual Rhine branches, the main channel is reasonably constant in width.

Branching of the Rhine in the Netherlands makes river management complex. Interferences in a branch can have consequences for other branches due to the backwater effect and bifurcations. Also, alterations in the floodplains can have (temporary) consequences for the main channel due to changing flow patterns and morphological processes during higher discharges.

From the ecotype distribution in Figure 3 it can be seen that, aggregated over the total project area, grasslands cover almost 70% of the floodplains. However, the Rhine branches cannot be considered as a uniform river system. The variations in the width of the floodplains are enormous due to the jagged pattern of the levees. Due to their diverse characteristics, Rhine branches respond differently in a hydraulic and morphological sense to alterations, *e.g.* in nature development or in floodplain excavation.

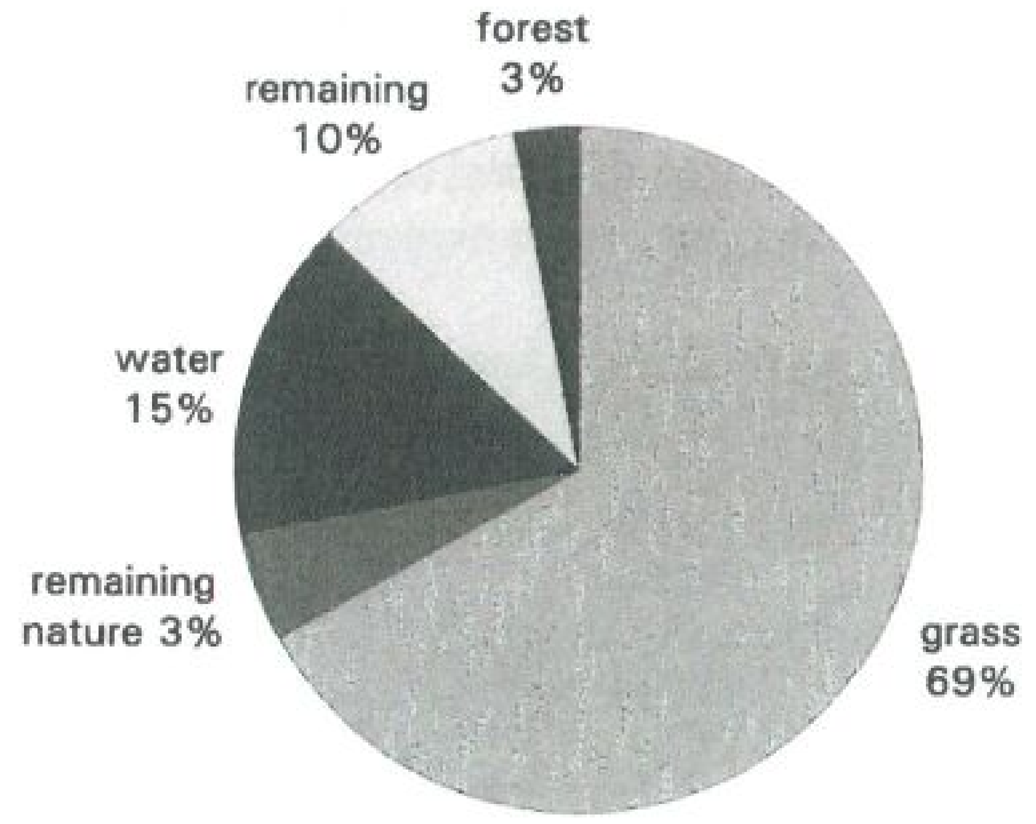

Figure 3. Present ecotype distribution in floodplains

3. POLICY MEASURES AND STRATEGIES

Safety against flooding is considered to be the most important objective of river management in the Netherlands. Design water levels for levees are determined to assure an exceedance frequency of less than 0.08 % (once every 1 250 years) [3]. The design water levels are based on the design flood discharge, which is determined every five years by the Ministry of Transport, Public Works, and Water Management by applying a standardized statistical frequency analysis of the available historic discharge records at Lobith. The current design flood discharge at Lobith is 15 000 m^3/s. However, as a result of the peak flows of December 1993 and January 1995, the design flood discharge will increase to 16 000 m^3/s. Possible future climate changes may result in an altered discharge regime, which could result in a further increase of the design flood discharge. This increase will have strong impacts on managing the floodplains of the Rhine branches in the Netherlands. In contrary to the past, the current policy of the Ministry is directed towards responding to increases in the design flood discharge by enlarging the discharge capacity, rather than increasing the height of the levees. This policy is called "room for rivers". Enlarging the conveyance capacity also has to compensate the effects of nature development on design water levels by measures other than levee heightening.

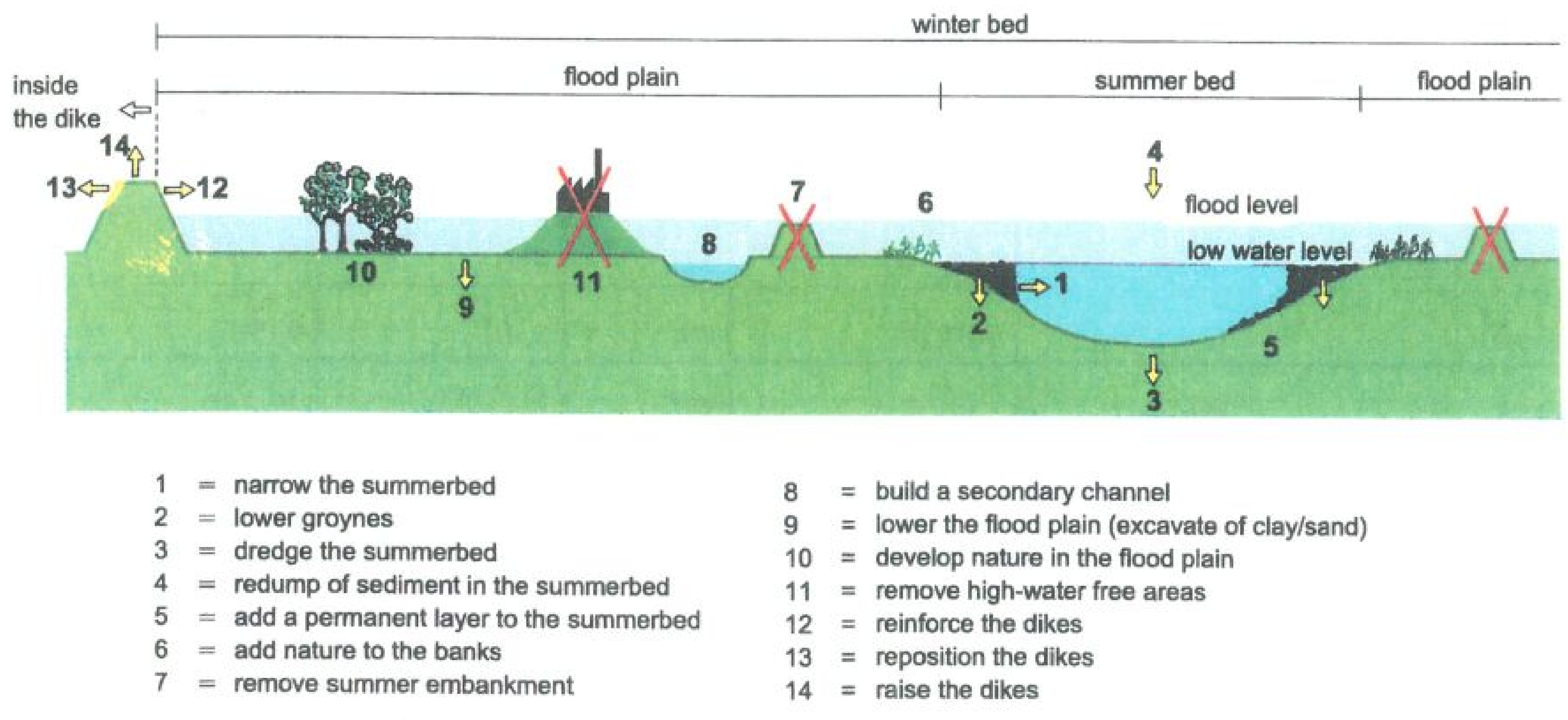

Figure 4. Set of possible river engineering measures

Figure 4 illustrates a variety of measures that can be considered for implementation in the main channel and the floodplains, to meet the different objectives of various riverine functions. In this paper a river management strategy is defined as a specific combination of measures, principally covering the entire study area.

River management strategies can be developed either with existing floodplain projects, with large-scale measures or with a combination of both. Measures 6–12 (Figure 4) are part of the currently initiated floodplain projects. However, the feasibility to maintain the design water levels with strategies based solely on floodplain projects is rather low. Therefore strategies consisting of large-scale measures should be considered as well to cope with increasing design flood discharges on the long-term.

4. OBJECTIVES AND CRITERIA

River management strategies affect the (long-term) objectives of the Ministry of Transport, Public Works and Water Management, related to safety against flooding, inland navigation, nature development and rehabilitation, preservation of cultural values, mining, agriculture, recreation, and costs optimisation.

The degree to which each of these categories of objectives is affected by a specific strategy is assessed by one or more criteria, whose values are estimated by the LPR–DSS. Below, various assessment criteria are briefly described.

4.1. Safety against Flooding

In LPR–DSS the design water levels are applied as a reference for impact assessments of river management strategies. If water levels of a certain strategy rise above the reference, which theoretically could lead to overtopping, then the safety against flooding has decreased, hence the probability of flooding has increased.

Maintaining the current discharge distribution at the bifurcations is an important constraint in the LPR study. Water level changes as a result of strategies induce backwater curves, which could influence the upstream discharge distributions at the bifurcations. To compensate for these alterations, additional measures can be implemented directly downstream of the bifurcation, such as vegetation management in the floodplains to control the hydraulic roughness and/or adjusting the presence submergible embankments to direct the river flow.

The assessment criteria for safety against flooding are:

- Increase of water level above design water level;
- Decrease of water level below design water level;
- Length of unsafe river stretch with an exceedance of design water levels of at least 0.05 m.

4.2. Inland Navigation

Inland navigation on the Rhine branches is of high importance from an economic point of view. It takes place intensively on the river Waal. In 2010 a yearly total of 215 000 passing ships is expected, with a total load of 197 million tons. The required fairway dimension of the river Waal is currently 150 * 2.50 m (width * depth) at a design discharge with a probability of exceedance of 95% (984 m^3/s at Lobith). In the year 2010 these dimensions should be enlarged to 170 * 2.80 m to cope with increasing inland navigation demands.

Measures in the main channel have a direct effect on the available fairway dimension, but also floodplain measures can have an effect. For example, floodplain excavation may result in decreasing flow velocities in the main channel during high discharges and subsequent sedimentation.

In LPR the critical depth is defined as a (spatially) minimum and/or average water depth (m) at a design discharge of 984 m^3/s at Lobith. The average depth is calculated with a hydrodynamic model, using historical discharge series at Lobith as a boundary condition.

The assessment criteria for inland navigation are:

- Increase of critical depth;
- Increase of average depth.

4.3. Nature Development and Rehabilitation

Nature development was the main objective of most of the floodplain projects surveyed in LPR. In the LPR-study, a total number of 17 ecotypes have been developed in order to define nature development projects (see Table 2).

Table 2. Ecotypes used in LPR

Ecotype	Area (ha)	Area (%)	Ecotype	Area (ha)	Area (%)
1. Natural river bank	550	2.1	10. Pasture	190	0.7
2. Constructed river bank	85	0.3	11. Agricultural grass	17180	66.8
3. River dune	55	0.2	12. Side channel	0	0
4. Natural hard-wood forest	70	0.3	13. Dynamic oxbow	1045	4.1
5. Natural soft-wood forest	380	1.5	14. Isolated oxbow	320	1.2
6. Production forest	190	0.7	15. Pool	2420	9.4
7. Herbaceous floodplain	380	1.5	16. Agricultural land	1470	5.7
8. Marsh	115	0.4	17. Built-up area	900	3.5
9. Floodplain grass	350	1.4			
Total				25 700	100

The criteria for assessing the quality of nature development are:

- Total area of nature (hectares);
- Percentage of total floodplain area covered by forest;
- Ecotype distribution.

At present, the total area of nature amounts approximately 3 500 hectares, which is about 15% of the total floodplain area. The percentage of the floodplain area covered by forest is determined by the sum of the areas of natural hard and soft wood forest (ecotypes 4, 5) and production forest (6), which currently amounts to 2.5%.

Seven different targets for nature development have been defined for each uniform river stretch. These targets are based on an estimated ecotype distributions that probably would occur under natural conditions (see Table 3). These targets have been defined with frequencies and duration of flooding, flow velocities, *etc.* Besides these 'ecological' targets, the target for nature development involves the removal of submergible embankments and floodplain excavation by one meter as well to compensate for increasing design water levels as a result of an increased hydraulic roughness. As a consequence of the nature target, the agricultural grass area will decrease from 67% to less than 3%.

Table 3. Targets for Ecotype Categories

Ecotype Target Category	Ecotypes (see Table 2)	Target (% of total area)
A. Natural river bank and river dune	1 & 3	6
B. Natural hard- and soft wood forest	4 & 5	19
C. Herbaceous floodplain	7	34
D. Floodplain grass and pasture	9 & 10	27
E. Side channel and dynamic oxbow lake	12 & 13	8
F. Marsh and isolated oxbow lake	8 & 14	3
G. Other	2, 6, 11, 15, 16 & 17	3

4.4. Preservation of Cultural Values

Important historical cultural values (C-values) of, and in floodplains, such as levees, forts, settlements, and possible undetected ancient remains under the surface, might be affected by river management strategies. However, C-values should be preserved for future generations. For each floodplain, the current C-value has been determined on a scale of 1 to 4. The assessment criterion is defined as the total floodplain area with C-values exceeding the value of 2 that would be affected by a strategy.

4.5. Mining

For decades, clay has been excavated from the floodplains to manufacture bricks and build and reinforce levees. The remaining volume of clay suitable for exploitation in the project area is estimated to be 60 million m^3. About 5 million tons of clay has been used for levee reinforcement in the period 1996 – 2000. The brick industry demands 1 million tons per year. In order not to disturb the clay-market, volumes of excavated clay should be in line with this annual demand.

Annually, approximately four tons of sand is excavated from the floodplains. However, the current provincial policy is aiming at shifting excavations from the floodplains to the land inside the levees. Compared to 1992, sand demands are expected to rise by 15 to 40 % until 2010.

Floodplain excavation also produces sludge. The pollution rate of sludge is expressed in four classes in the Netherlands. Sludge of class IV is heavily polluted, and requires storage or processing at high cost.

The following assessment criteria relate to clay and sand mining and sludge treatment:

- Volume of excavated clay (million m^3/year);
- Volume of excavated sand (million m^3/year);
- Volume of class IV sludge (million m^3).

4.6. Agriculture

As illustrated in Figure 3 and Table 2, agriculture is currently the dominant function of the floodplains. Almost 70% of the total floodplain area is in use as grassland for cattle grazing. Nature development will inevitably put pressure on the agricultural function of the floodplains and hence agricultural yields. It will require the purchase of agricultural land as well. It is estimated that approximately 150 to 200 hectares of land can be acquired per year for nature development without disrupting the market for agricultural land.

As a measure of both the loss of agricultural yield and the impact on the land acquisition market, the number of hectares of land claimed for nature development is used as an assessment criterion.

4.7. Recreation

The total area available for recreation is currently about 5 000 hectares. The recreation function of the floodplains is related to the ecotype distribution. Ecotypes 3, 4, 5, 7, and 10 (see Table 2) are suitable for land recreation, and ecotypes 1, 12, 13, and 15 are suitable for water recreation. The total area of ecotypes suitable for these two types of recreation is used as a criterion to assess objectives related to recreation.

4.8. Cost Optimization

The costs of river management strategies are expressed in expense-terms for:

- Levee heightening;
- Floodplain excavation;
- Floodplain widening;
- Processing of polluted sludge;
- River management;
- Acquisition of land;
- Nature-friendly banks;
- Nature management.

The costs are determined by unity prices, derived from expert judgments.

5. DECISION SUPPORT

LPR–DSS is developed to define river management strategies and determine and analyse impacts on river functions. The schematic structure is illustrated in Figure 5. A river management strategy can be developed by a combination of floodplain projects, large-scale measures in floodplains, nature-friendly banks, and main channel measures. After defining a strategy, looped computations are carried out iteratively until the results satisfy the target levels for one or various criteria. The assessments of safety against flooding and inland navigation criteria are related to water and bed levels of the river. The nature, landscape, agriculture, and recreation criteria are related to ecotypes. Consequently, two effect-assessment modules are developed:

(i) A module to implement measures, combined with a hydrodynamic model and;

(ii) An ecotype module.

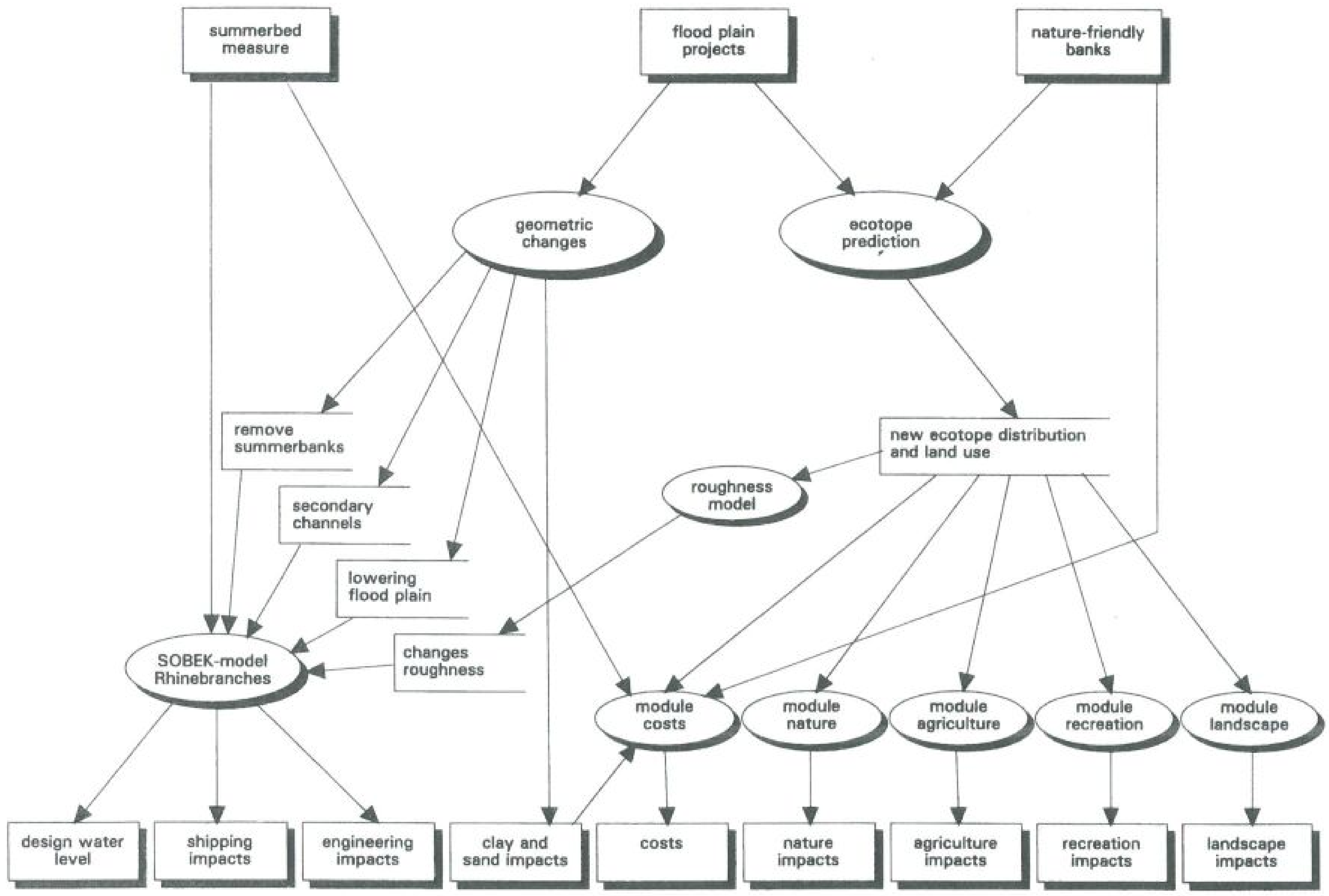

Figure 5. Structure of LPR–DSS

The impacts of a strategy are quantified per floodplain and aggregated over the total project area. They are listed in scorecards, consisting of the different assessment criteria, which show the strengths and weaknesses of the various strategies in one overview.

5.1. Floodplain Database

The layout of the floodplains in the present situation (Table 1), including parameters such as location, total area, LNC (Landscape, Nature, Culture) values, ecotype distribution, and present clay volumes, is stored in a database. The ecotypes distinguished in LPR–DSS are listed in Table 4. The ecotype distribution is determined from aerial photographs, river maps, flow velocities and the frequency and duration of floodplain inundation, as simulated by two-dimensional hydrodynamic models. All this information has been processed with a GIS (Geographical Information System).

5.2. Project Database

All floodplain projects in development have been surveyed and stored in a database. These projects vary from rough ideas to detailed designs, while the targets are equally diverse. Most of the projects account for nature development and clay or sand excavations, initiated mainly by local authorities and the corporate sector, although interest groups are also represented. In total, 256 (partly overlapping) projects have been stored in the database, covering a total area of 35 000 hectares. The types of measures by which the floodplain projects have been defined are illustrated in Figure 4 (together with main channel- and levee measures). When examining the morphological impacts of these projects, it is remarkable that the average riverbed elevation of the main channel remains relatively stable. In general, approximately 30% of the project area is covered with measures such as clay mining, secondary channels, and deep sand excavations. Grazing by cattle of a natural breed is a favorite measure when it comes to vegetation management. For nearly 20% of the project area no measures have been defined. Hence, the present use of these areas (primarily agricultural pasture) is being retained.

5.3. Hydrodynamic Model

Since the length of the project area is much bigger than its width, a one-dimensional hydrodynamic model is used in LPR–DSS. This choice was also made for practical reasons (*e.g.* computation time and feasibility of the measure module). This means that typical two-dimensional processes, such as flow and sediment transport cannot be simulated, although these processes may have an effect on upstream water levels. To validate the applicability of the one-dimensional model, the effects of a number of measures on design water levels have been compared with two-dimensional model results for a number of floodplains.

An example of this validation is shown in Figure 6. In this case the validation showed that differences between the effects of measures on design water levels as calculated by the one- and two-dimensional model differ by at most five centimetres. On the other hand, LPR–DSS is not developed for design purposes but only to compare and assess different river management strategies. However, local effects on design water levels should always be checked with a two-dimensional model before final implementation.

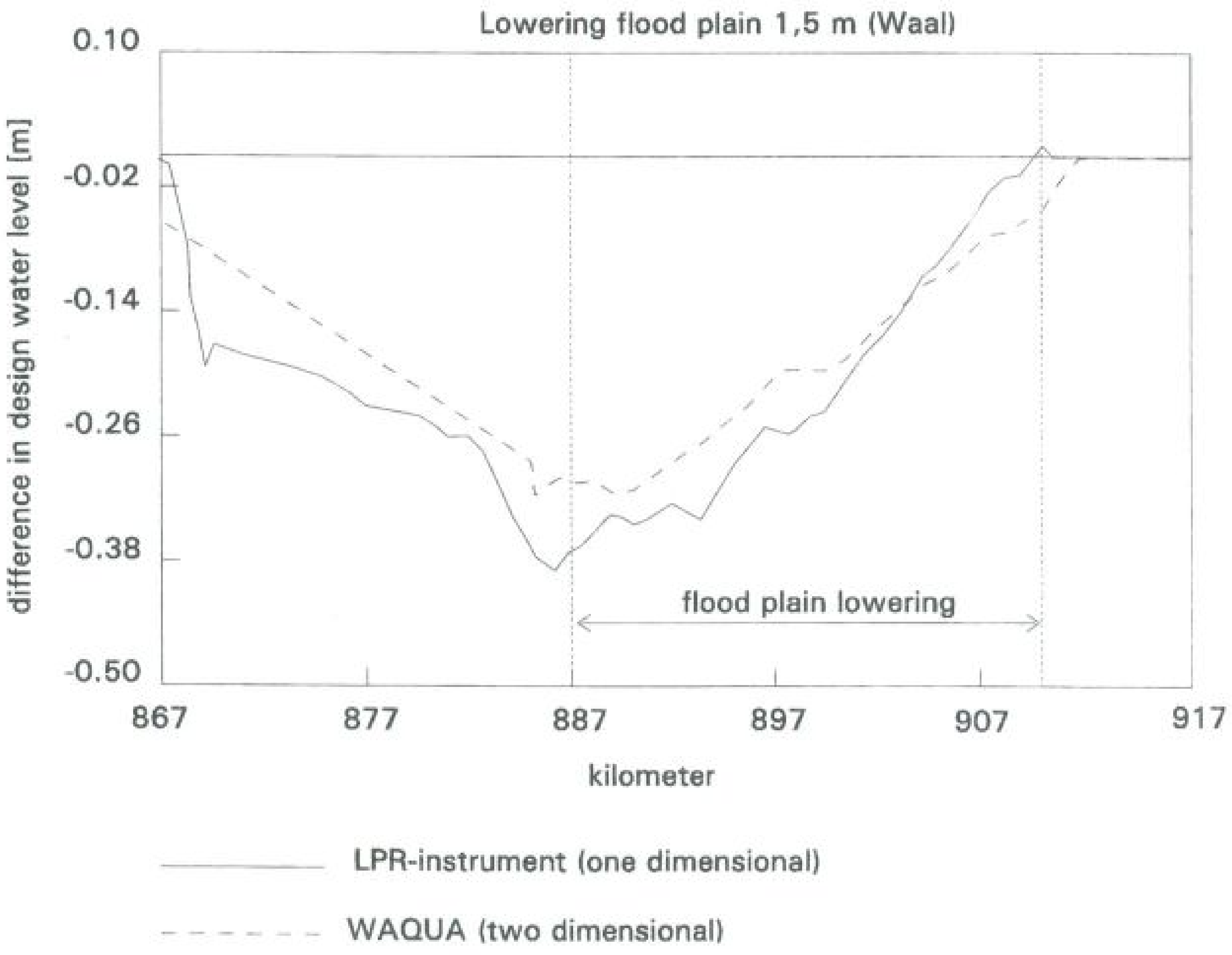

Figure 6. Effect of floodplain excavation, computed by one and two-dimensional hydrodynamic model

The one-dimensional hydrodynamic model has been developed with a GIS [4, 5]. For this, the river branches were divided into compartments of 500 metres, measured along the river axis. A GIS application was developed to generate one cross-section per compartment. For this purpose, different sources of data were collected, digitally stored in an

Arc/Info database and converted into grid files. The data include main channel bed levels, floodplain elevations, embankment and levee crest elevations, and locations of groins and submergible embankments, floodplain lakes and flow characteristics (to identify flow and storage areas in the floodplains). The use of grid files enables a simple combination of different types of spatial information to generate imaginary, but representative, cross sections for every compartment of the hydrodynamic model. Each cross section consists of three elements: a main section (or river section), a bank section (groin section), and a floodplain section (see Figure 7 for a schematic outline). These separations allow the allocation of different hydraulic roughness values to each section.

Although the cross sections are generated automatically from data stored in grid files, there are some important tasks for the modelling expert during the process:

- Selection of an appropriate space step of the model (compartment length);
- Identification of the compartment boundaries. In the transversal direction, the main levees normally determine these boundaries. In the flow direction, the boundary between adjacent compartments has to be perpendicular to the flow direction. The flow direction is derived from results of two-dimensional flow simulations.
- Identification of boundaries between flow and storage areas in the floodplains. Based on two-dimensional model results, all areas with flow velocities below 0.05 m/s were considered storage areas.
- Identification of representative crest levels of submergible embankments. In the one-dimensional model only one crest level can be used to initiate the inundation of the (floodplain) area behind the submergible embankments. In practice the level of the submergible embankments may vary inside each compartment. In LPR–DSS, a weighted average of all crest levels has been applied. The size of the area behind each submergible embankment was used as a weighting coefficient.

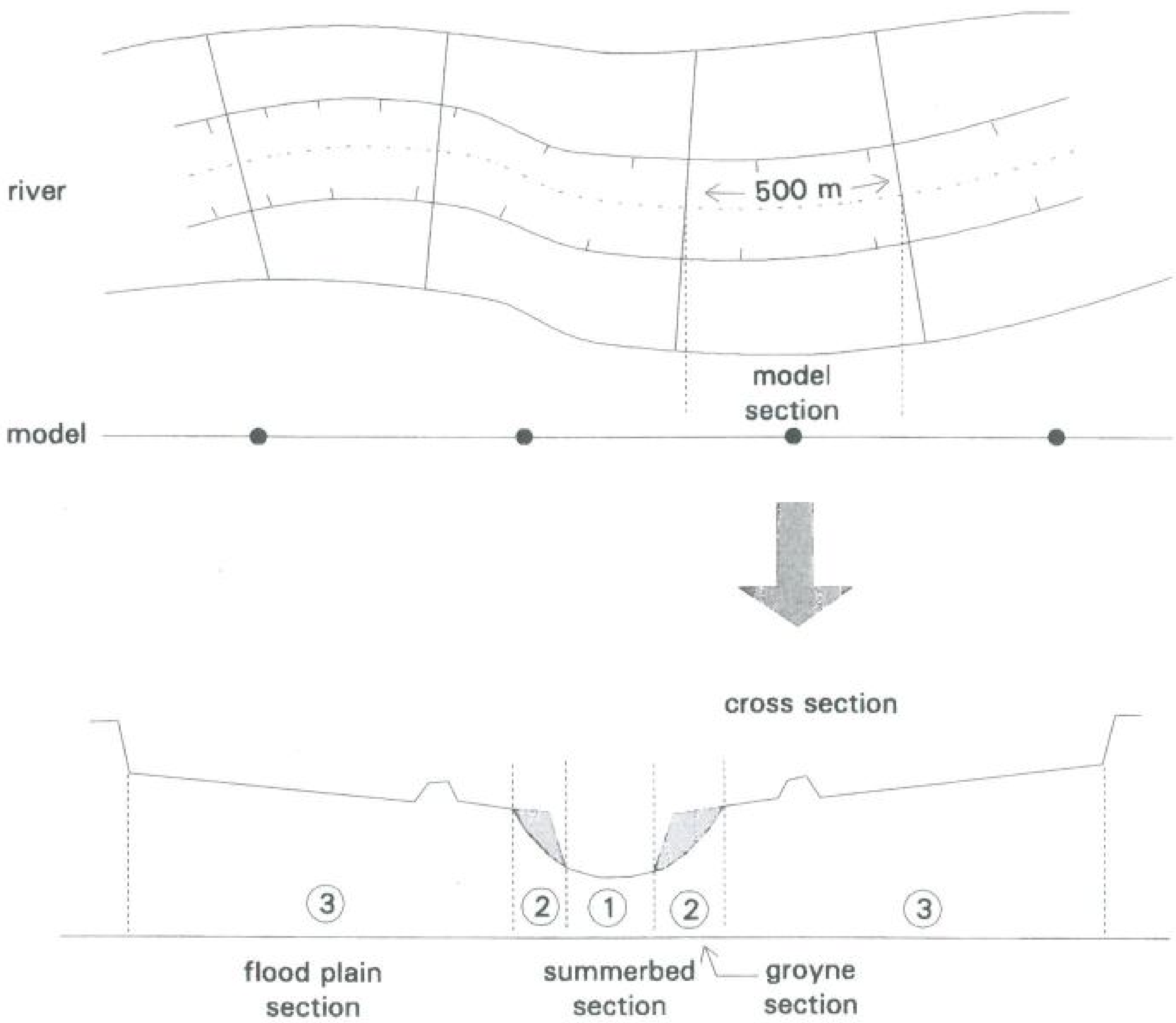

Figure 7. GIS and hydrodynamic modelling

Hydrodynamic modelling with the aid of GIS is a new approach that has some important advantages compared to traditional approaches:

- In the generated cross sections, all available information on the river compartment is averaged and taken into account instead of information of only one measured cross section;
- Cross sections are generated in a consistent and transparent way;
- Large quantities of geometrical information can be combined and processed in a relatively short time;
- Updated geometrical information can be transformed quickly into updated cross sections;
- Schematization routines can be extended or adapted easily.

5.4. Measure Module

With a set of specific measures, such as illustrated in Figure 4, the measure module adjusts the river geometry of the one-dimensional hydrodynamic model. To facilitate this procedure, all characteristic levels of the cross sections (*e.g.* bed level, groin level, submergible embankment level, floodplain level, etc.) are attached to fixed points. Secondary channels in floodplains are automatically incorporated in the model. The new hydraulic roughness of the floodplains is estimated using a new ecotype distribution generated by the ecotype module.

Table 4 shows the hydraulic roughness, expressed as Nikuradse equivalent roughness k_n (m) [6] for five ecotype roughness categories.

Table 4. Hydraulic Roughness per LPR-Ecotype

Ecotype Roughness Category	Ecotypes (see Table 2)	k_n (m)
Grass	9-11 & 16	0.3
Forest	4-6	10.0
Remaining nature	1-3 & 7,8	2.0
Water	12-15	0.1
Built-up area	17	1.0

5.5. Ecotype Module

The ecotype module automatically generates a new ecotype distribution, using the present distribution as a reference combined with the floodplain measures. The core of this module is a set of decision rules, which are based on expert judgement. However, these rules do not pretend to be able to predict dynamic natural processes in floodplains in an accurate way. The ecotype module gives a rough indication, without knowing the exact locations and required time for ecotypes to develop. The module also gives an indication of the likelihood for improvement of the situation for several ecotype bound species of birds and mammals, such as bitterns and beavers.

6. IMPACTS OF STRATEGIES

Results of strategies are computed for the years 2010 and 2050 [7]. The year 2010 is related to agreements made on acquisition of agricultural land and 2050 is based on realization of the "Living Rivers" study [8].

The impacts of the strategies on the safety against flooding criteria are determined by using reference design water levels of 1994 (so-called present situation), 2010 and 2050. These references have been computed with the one-dimensional hydrodynamic model SOBEK [9] using the 'design-hydrograph' of Lobith as an upstream boundary condition. As a result of morphological processes, the reference branching of the design flood discharge slightly changes over the years [10].

The existing floodplain projects do not offer enough opportunities to cope with a design flood discharge, which will increase to 16 000 m^3/s at Lobith. It is only with the expansion or addition of measures, such as floodplain excavation, that a sufficient reduction in design water levels will be achieved. However, the nature of the projects would then be completely lost.

In order to avoid further levee heightening and to maintain the present level of protection against flooding, it has become apparent that the implementation of a new approach to manage the riverine area is necessary.

This paper presents three long-term river management strategies that can be realised by the year 2050. These strategies are based on strategic views in which the planned floodplain projects of today do not play a role. Strategies based on long-term views should be seen in combination with the quest for solutions to cope with increasing peak flows and design flood discharges. Below each strategy is described, followed by a presentation of assessment results and a mutual comparison.

6.1. Strategy 1: Floodplain Excavation

The current, mainly agricultural use of the floodplains is maintained in this strategy. This is assumed to be possible when the floodplain elevation is at least 0.5 m above the median water level in the main channel. In order to cope with higher discharges, floodplain excavation takes place to this threshold on a differentiated basis, thus taking into account height differences within and between floodplains. The submergible embankments will be left intact and class IV sludge will be removed.

6.2. Strategy 2: Floodplain Excavation, Floodplain Widening, and Limitation of Forest and Brushwood

This strategy is based on the target situation for nature development: 5,000 hectares of forest in the floodplain areas. Agriculture is no longer present and submergible embankments are levelled out. Secondary channels offer typical river organisms a new habitat in the riverine area and the banks are designed in a nature-friendly way. In order to restore the original contact with the river and to compensate the increase of design water levels by new vegetation, clay and sand will be excavated from the floodplains, lowering the elevation by around one metre. The revenues generated by clay and sand excavation is used to acquire agricultural land and to develop and rehabilitate nature areas.

6.3. Strategy 3: Floodplain Excavation, Except in Floodplains with Relatively High Values of Landscape, Nature, and Culture

In this strategy, floodplains with relatively high values of landscape, nature and culture are left intact. These floodplains account for approximately 50% of the riverine area. Landscaping of the remaining floodplain area is based on the nature target situation with concomitant measures. Differentiated floodplain excavation is the only additional suitable measure to reduce design water levels. However, this measure will be insufficient in counterbalancing the increase in water levels that will occur at a design flood discharge of 16 000 m^3/s, which means that the levees will have to be heightened.

6.4. Assessment Results

The measures, which have to be implemented in the three different strategies, are drastic, as are the impacts. The scorecard in Table 5 gives an indication of the assessment results. It is a rough indication because the analysis, which focuses on the year 2050, is surrounded by all kinds of uncertainties.

There are great differences among the strategies in terms of total costs, ranging from 275 to 850 million Euros. Note that the costs are influenced by the assumption of profitable clay mining in the floodplains. A conspicuous role is played by the costs of processing polluted (class IV) sludge, which in one or two cases even comprise up to 50% of the total costs. These costs will be strongly influenced by the method of dealing with this sludge. In all strategies, levee heightening is the final resort. However, levee heightening as the only measure in a strategy would cost roughly 590 million Euros. The average navigation depth in the river Waal will change little or not at all in the strategies that leave the submergible embankments intact. The morphologically reasonable stable situation will be disturbed if the submergible embankments are removed, an effect that would be made even worse in combination with floodplain excavation. Removal of these embankments increases the complexity of river management. This result reveals that the main trade-off in river policy is between nature and agriculture: more nature area has higher ecological values, but is more costly.

The time required to implement the different strategies is long. Acceleration is of course possible, though this will increase the annual costs significantly. On the other hand, with an acceleration of the process the required protection level would be reached earlier, thus reducing the risk of damage through flooding if the assumption of higher peak discharges proves to be true. Another possible way to accelerate the process is to implement the present floodplain projects or an alternative plan as an intermediate stage, with possible acceleration of relevant parts of long-term river management strategies. The LPR study provides sufficient background information for the exchange of ideas. For that matter, measures will also be required downstream of the study area, in order to convey the increased design flood discharge safely. This will imply an increase in the absolute costs, though it is not expected that these effects will lead to a totally different picture.

Table 5. Scorecard for Three Strategies

Criteria	Units	Strategy*		
		1	2	3
Safety against flooding				
- Maximum increase design level	m	0.15	0.15	0.25
- Maximum decrease design level	m	0.4	0.25	0.25
- Length of unsafe river stretch	km	75	25	220
Inland navigation				
- Increase of critical depth	m	-0.2	-0.25	-0.1
- Increase of average depth	m	0	-0.1	-0.05
Nature development and rehabilitation				
- Total area of nature	ha	3,500	25,500	13,500
- Area covered by forest	%	2.3	19.5	11.7
Preservation of cultural values				
- Influenced cultural values	ha	15,000	15,000	1,500
Mining				
- Clay	$10^6 m^3/yr$	1	1	0.5
- Sand	$10^6 m^3/yr$	3	4.5	2.5
- Sludge	$10^6 m^3/yr$	6	6	3
Agriculture				
- Area of agricultural lands	ha	18,500	0	10,500
- Land claimed	ha/yr	0	350	150
Recreation				
- Water bound	ha	4,000	3,000	3,500
- Land bound	ha	1,000	21,000	10,000
Costs				
- Levee heightening	10^6 Euro	25	25	115
- Floodplain excavation	10^6 Euro	115	0**	0**
- Floodplain widening	10^6 Euro	0	275	0
- Processing of class IV sludge	10^6 Euro	135	135	70
- Acquisition of land	10^6 Euro	0	275	135
- Nature-friendly banks	10^6 Euro	0	135	70
- Nature management	10^6 Euro/yr	0	5	2.5
- River management	10^6 Euro/yr	0	2.5	1.1

*Strategy - measures to reduce water levels
1 – Floodplain excavation
2 – Floodplain excavation, floodplain widening and limitation of forest and brushwood
3 – Floodplain excavation, except in floodplains with relatively high landscape, nature & culture values
**Included in acquisition and landscaping costs of nature areas

7. UNCERTAINTY ANALYSIS

River management has to deal with many uncertainties. For the river manager it is very important to know:

- The magnitude of the various uncertainties;
- How to handle each of the uncertainties (what types of measures are available to mitigate the impacts of uncertainties).

In the LPR study, attention is paid to these two questions [11]. In this paper only uncertainties in the design water level are briefly considered. The following sources of uncertainty are relevant in the calculation of the design water levels:

1. The design flood discharge as an upstream boundary condition (Lobith);
2. The discharge distribution at the bifurcations;
3. The hydraulic roughness coefficients;
4. The future subsidence of the main channel (due to morphological developments);
5. The impacts of climate change.

The first three sources are uncertainties in the present situation and the last two represent future developments. However, there are no data available for assessing the probability distributions for future developments. Expert opinions could have been used to assess these distributions. In this study a different scenario approach is followed.

The uncertainties in the design flood discharge, the branching of water at the bifurcations, and the hydraulic roughness were modeled with uncertainty distributions [12, 13] for two values of each of the other two uncertainty sources. These uncertainty distributions were combined using UNICORN, a software package designed for uncertainty analysis [14]. The results for one of the locations (Lobith) are presented in Table 6. It can be seen that the 90% confidence interval has a width of 2.1 m, regarding the design water level. The results of climate change and the morphological changes in the main channel can principally compensate each other (the water levels will increase because of climate change, but will decrease because of morphological changes). However, the results show that the design water level is not sensitive to morphological changes. Obviously, this conclusion depends on the assumptions concerning the order of magnitude of the morphological changes. The current policy enforces a status quo of main channel subsidence; hence it is assumed that this process will be relatively small. Further research on this complex topic is of the utmost importance.

Table 6. Results of Uncertainty Analysis

Scenario	Design water level percentiles at Lobith (m +NAP)		
	5% percentile	E (50%)	95% percentile
No climate change, no subsidence main channel	16.9	18.0	19.0
Climate change, no subsidence main channel	17.5	18.6	19.6
No climate change, subsidence main channel	16.9	18.0	19.0
Climate change, subsidence main channel	17.5	18.6	19.6

8. FINAL REMARKS

Assessment tools are needed to develop policies that offer sustainable protection against flooding in the case of increasing river discharges. The LPR study developed such tools and applied them to assess a number of river management strategies. The resulting information can be used to initiate discussions about future policy options. Many stakeholders are involved in river management and the timely input and involvement of their interests is of great importance for a successful implementation of sustainable policies.

Following the peak flow of January 1995, where a flood disaster along the river Waal very nearly occurred, new plans for the river Rhine have been developed. The main issue addressed is the rehabilitation of the natural flexibility and resilience of rivers by allowing them more space. This is considered as the best strategy to be prepared for uncertain future developments. The LPR–DSS has been applied and found helpful in this planning process.

The 1995 peak flow also gave impetus to the discussion of impending flood problems by the International Commission for the Protection of the Rhine (ICPR). Integrated water management requires effective agreements among all the countries in the Rhine basin. These agreements should be based on a strategy that follows from an integrated approach towards flood protection through the systematic assessment of alternative measures. A DSS for river management such as the LPR–DSS can be very helpful to support this analysis.

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