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A Hydrodynamic-Numerical Model of the River Rhine

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Vorwort

Der Rhein unterliegt seit Jahrhunderten anthropogenen Eingriffen, die sich auf das Ablaufverhalten von Hochwasserwellen auswirken. Der Schutz und die Wiederherstellung ökologisch funktionsfähiger, naturnaher Gewässer ebenso wie eine bessere Hochwasserregulierung sind wesentliche Aufgaben der Wasserwirtschaft, wobei eine gesamtheitliche Betrachtungsweise erforderlich ist.

Um die hydraulischen Auswirkungen einer Rückgewinnung von Retentionsräumen auf Hochwasserereignisse zu quantifizieren, wurde von Frau Dr. Minh Thu in dieser Forschungsarbeit ein hydrodynamisch-numerisches Modell für die gesamte deutsche Teilstrecke des freifließenden Rheins erstellt. Es besteht aus einem 500 Kilometer langen Abschnitt des Rheins von Maxau am Oberrhein bis Lobith, dem hydrologischen Pegel an der Grenze zwischen Deutschland und den Niederlanden. Die wichtigsten Nebenflüsse des Rheins - Neckar, Main, Nahe, Lahn, Mosel, Ahr, Sieg, Ruhr und Lippe - wurden ebenfalls in dieses Modell mit einbezogen. Der Zufluss aus der Murg wird beim Pegel Maxau mit berücksichtigt.

Die Entwicklung und der Einsatz geeigneter eindimensionaler instationärer hydrodynamisch-numerischer Modelle ist der Schlüssel zur Beantwortung komplexer hydraulischer Fragestellungen. So ermöglicht dieses HN-Modell die genaue Analyse der Auswirkungen vergangener und zukünftiger wasserbaulicher Maßnahmen auf das Abflussverhalten des Rheins. Da dabei das gesamte Abflussspektrum berücksichtigt werden kann, hat sich dieses Modell als unverzichtbares wasserwirtschaftliches Werkzeug am Rhein etabliert.

Karlsruhe, 17 Juli 2002 Franz Nestmann

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Special thank to Dr. -Ing. Norbert Göbel, Head of the Department of Hydraulic Numerical Modelling, for reviewing the manuscript and having many useful helps and suggestions in preparing this Dissertation. The same thank to Dr.-Ing. Stephan Theobald, co-header of the Department. I am also grateful to the Institute of Water Resources Management, Hydraulic and Rural Engineering, who sponsor my study and give me a comfortable condition for working, to the Resources Engineering Administration who founded my study here in Karlsruhe .

I also would like to thank all of my friends and my colleagues who help me whenever I have problem during the time I am living here; to my family, my Son, my Sister and my Parents who are always beside me.

Pham Thi Minh Thu

Abstract

During the last centuries the river Rhine underwent a major regulation process which separated the river-bed from its flood plains and reduced the available areas for flooding. The river was straightened and the consequence is the discharge conditions were strongly changed and many recorded flood events were occurred.

Serious floods at the river Rhine in 1993 and 1995 resulted in the policy “Room for the Rivers” and in 1998 in the “Action Plan Flood Defence” by the International Commission for Protection of the Rhine (ICPR). The “Action Plan Flood Defence” aims at improving the protection of people and goods against flood while integrating ecological improvements of the Rhine and its flood plains. Targets include the enlargement of flood plains through dyke displacement, the protection of valuable flood plains and flood plain restoration. Further targets are the re-connection of the rivers backwaters, the restoration of hydrological and ecological interactions between river and flood plains and the restoration of the riparian zone. Changing criteria for flood retention areas will altogether contribute towards a more natural river landscape with a higher flood regulation capacity and larger biodiversity.

In order to quantitatively assess the effectiveness of flood plain restoration measures on flood regulation, the hydrodynamic-numerical model for the whole Rhine of the free flowing section is constructed. It consists of a 500 km long section of the Rhine River, starting at Maxau, the first gauging station of the free flowing section of the Upper Rhine, and ending at Lobith, the hydrology gauge at the border between Germany and the Netherlands. The important main tributaries of the Rhine (Neckar, Main, Nahe, Lahn, Mosel, Ahr, Sieg, Ruhr and Lippe) are also included in this model; the contribution from the Murg is considered at the gauge Maxau.

The hydrodynamic-numerical model (HN-Model) of the river Rhine and its flood plain areas has the ability to predict the response of the river to imposed change. These obtained scenarios are of use to make political decisions and for the common understanding of the role of the wetlands on flood regulation. Furthermore, it is also

useful for many different engineering works: The HN-Model is required for the design of flood control structures and for the assessment of impacts of alternative dyke configurations and flood retention options on the water level. And last but not least, the results obtained from the HN-Model are the boundary conditions for 2-D and 3-D numerical models and physical models and they are also one of the very important data for GIS applications on water resources management. Altogether, the HN-Model of the river Rhine gives a clear understanding on how the river adjusted to previous designs and plan implementations.

The HN-Model of the river Rhine is based on the computer software CARIMA, developed by SOGREAH (Prof. Cung, France). Since 1963, it has already been used successfully for the large-scale Mekong delta mathematical model (in Vietnam) and for many other large rivers on the World.

At the Institute for Water Resources Management and Agricultural Engineering, University of Karlsruhe, CARIMA is used for the projects of dyke replacements at the Lower Rhine with very good practical results. This model was expanded, in order to be able to assess the effects of different flood retention measures (polder) on the flood discharge at the Lower Rhine. Here is the different effect between free flowing polder and controlled polder. Moreover the model for the Upper Rhine and Middle Rhine was extended and it included an optimization of the control works. Now a mathematical model of the entire Rhine distance downstream of the barrage Iffezheim is existing, with that the effects of construction measures on the discharge of floodwater can be determined.

Kurzfassung

Während der letzten Jahrhunderte wurden am Oberlauf des Rheins gravierende Regulierungsmaßnahmen vorgenommen, die zu einer harten Trennung des Flussbetts und des Vorlandes und zu einer Reduzierung der Überflutungsgebiete führten. Dies hat zur Folge, dass sich seither die Abflussverhältnisse starte verändert haben und viele Hochwasserereignisse verzeichnet werden.

Nach den schwerwiegenden Hochwässern von 1993 und 1995 wurden die Initiative „Räume für Flüsse“ und der „Aktionsplan Hochwasser“ der „Internationalen Kommission zum Schutze des Rheins“ (IKSR) ins Leben gerufen. Letzterer zielt auf die Verbesserung des Schutzes von Anwohnern von Fließgewässern und Bauwerken vor Hochwasser, verbunden mit einer Verbesserung des Ökosystems des Rheins und seiner Vorländer, ab. Ziele sind die Vergrößerung der Vorländer durch Verlegung der Deiche, der Schutz der noch vorhandenen Rückhalteräume und die wieder Nutzbarmachung zuvor abgetrennter Überflutungsflächen. Weitere Ziele sind der Wiederanschluss von Altrheinarmen an den Hauptstrom, die Wiederherstellung des hydrologischen und ökologischen Austauschs zwischen dem Rhein und den Vorländern und die Instandsetzung der riparianen Zone. Die veränderten Rahmenbedingungen werden letztenendes zu einer natürlicheren Flusslandschaft mit einer größeren Vielfalt an Flora und Fauna und zu einer besseren Hochwasserregulierung führen.

Um die Auswirkungen einer Rückgewinnung von Rückhalteräumen auf Hochwasserereignisse quantitativ nachzuweisen, wurde ein hydrodynamisch-numerisches Modell für den gesamten freifließenden Rhein erstellt. Es besteht aus einem 500 km langen Teilabschnitt des Rheins von Maxau, dem ersten Pegel des freifließenden Oberrheins, bis Lobith, dem hydrologischen Pegel an der Grenze zwischen Deutschland und der Niederlande. Die wichtigsten Nebenflüsse des

Rheins (Neckar, Main, Nahe, Lahn, Mosel, Ahr, Sieg, Ruhr und Lippe) wurden ebenfalls in dieses Modell mit einbezogen; der Zufluss aus der Murg wird beim Pegel Maxau mit berücksichtigt.

Das hydrodynamisch-numerische Modell (HN-Modell) des Rheins und seiner Vorländer erlaubt die Vorhersage des Verhaltens des Flusses bei einer Veränderung der äußeren Gegebenheiten. Die daraus resultierenden Szenarien sind vorausetzung, um politische Entscheidungen treffen zu können und um ein allgemeines Verständnis des Einflusses von Vorländern auf die Hochwasserregulierung zu erhalten. Weiterhin ist das HN-Modell für viele Ingenieuranwendungen von Nutzen: Es wird für die Planung von Bauwerken zur Hochwasserrückhaltung und für die Bewertung der Auswirkungen von alternativen Deichverläufen und Rückhaltegebieten benötigt. Die Ergebnisse dieses Modells werden auch Rahmenbedingungen für 2- und 3-dimensionale numerische Modelle, physikalische Modelle und wichtige Daten für GIS-gestützte Anwendungen für die Wasserwirtschaft liefern. Insgesamt gesehen gibt das HN-Modell des Rheins einen genauen Aufschluss über die Auswirkungen vergangener und zukünftiger wasserbaulicher Maßnahmen.

Das HN-Modell des Rheins basiert auf der Computersoftware CARIMA, entwickelt von SOGREAH (Prof. Cunge, Frankreich). Seit 1963 wurde dieses Programm bereits erfolgreich für viele große Flussmodelle weltweit eingesetzt, wie zum Beispiel für das umfangreiche mathematische Modell des Mekongdeltas in Vietnam.

Am Institut für Wasserwirtschaft und Kulturtechnik der Universität Karlsruhe wird CARIMA bei Projekten für Deichrückverlegungen am Niederrhein mit sehr gut Ergebnissen für die Praxis eingesetzt. Dieses Modell wurde erweitert, um die Auswirkungen unterschiedlicher Hochwasserrückhaltemaßnahmen (Polder) auf den Hochwasserabfluss am Niederrhein abschätzen zu können. Hierbei wurde zwischen Flutpoldern und gesteuerten Poldern unterschieden. Des weiteren wurde das Modell auf den Oberrhein und Mittelrhein erweitert und eine Optimierung der Steuerung einbezogen. Nunmehr steht ein mathematisches Modell zu Verfügung mit dem Auswirkungen von Baumaßnahmen auf den Hochwasserabfluss in der gesamten Rheinstrecke unterhalb der Staustuffe Iffezheim berechnet werden können.

Contents

1 Introduction

1.1 The River Rhine - General Aspects

The Rhine ranks second to the Mississippi River as the World's most economically important river (Saeijs, Logemann). It is one of the major European rivers that transports most water with an average discharge of 2090 m³/s at the gauge of Cologne (Rhine km-688,8) in Germany. It originates in the Swiss Alps and flows through Germany, France and The Netherlands in to the North Sea with the length over 1320 km and the catchment area of about 200.000 km² including parts of Switzerland, Germany, France, Luxembourg, Belgium and The Netherlands. The countries this river flows through belong to the highly developed, densely populated part of Europe.

The undisturbed Rhine system could be roughly divided in to four parts (Fig. 1.1):

The High Rhine: The river originates in the Swiss Alps. Flowing out of lake Constance (Rhine km 0) to Basel the Rhine is a high mountain river with a coarse stony substrate.

The Upper Rhine: Flows from Basel (Rhine km 170) to Bingen (Rhine km-530), through the plain between the mountains of the Black Forest and the Vosges, the river freely meanders through a flood plain many kilometres wide. In this place the flood plain forest thrived with its characteristically soft-wood trees, supporting a very rich river ecosystem. The Rhine here receives five main tributaries: Aare, Ill, Murg, Neckar and Main. The floods appear of varying character, sometimes from Aare, sometimes from Neckar, Main, and are contained within the characteristic of the river and their catchment areas.

Figure 1.1 The River Rhine Catchment (IKSR, 1998)

The Middle Rhine: Flows through a small and deep river valley in the mountain area of the Taunus, Hunsrück and Eifel to Bonn. The numerous cliffs and rocks in the river bed, for example the Lorelei, are characteristic for this part of the river. The natural ecosystem there is adapted to the stony environment; large flood plains are absent. There are also five main tributaries: Nahe, Lahn, Moselle, and Ahr.

The majority of riparian dwellers on the Middle Rhine have accustomed themselves to living with the risk of floods, that means they have developed strategies to react on rising water stages. Thus, usually damages caused by floods here remain limited. However, the flood of 1993/1994 was different in this regard: because of the unusual height of the peak stages and the rapid advance of the flood wave.

The Lower Rhine: Flows from Bonn to the North Sea. Flow velocities tend to decrease, particularly where the river bed becomes wider and large flood plains are present. Sediment deposition takes place, but during floods, erosion will also take place, causing a partial or complete rearrangement of existing habitats. Going down stream the sediment gradually changes from coarse to fine sand. Silt and clay are deposited in the flood plains. Most sediment is transported to the sea. The main tributaries in Germany area are: Sieg, Ruhr and Lippe. The flood in this area occurs not from its tributaries but from the upstream of the river.

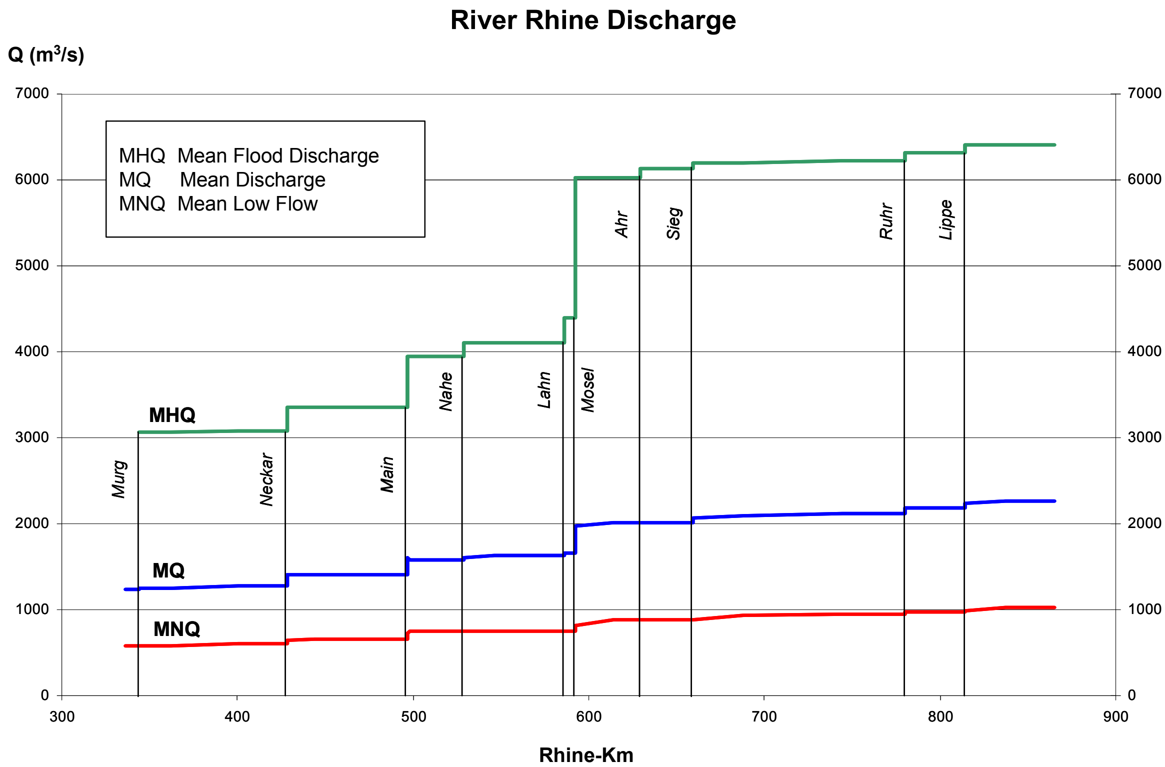


Figure 1.2 River Rhine discharges
(Deutsches Gewässerkundliches Jahrbuch 1994, time series 31/93)

Table 1.1 and Fig.1.2 indicates some characteristics of flow at the gauging stations of the Rhine in between the computational reach (Rhine km 362,3 – 862,2). After Koblenz, the river Rhine discharge has a great change up to the influence of the tributary Mosel. The middle flood discharge is changed from 4400 m³/s to approximately 6050 m³/s.

Gauge	Rhine Km	PNP (m + NN)	$A_{E\,0}$ (km^2)	MQ (m^3/s)	MHQ (m^3/s)	HQ (m^3/s)	Time Series
Maxau	362,3	97,79	50196	1250	3070	4400	31/94
Speyer	400,6	88,52	53131				
Worms	443,4	84,16	68827				
Mainz	498,3	78,43	98206	1580	3950	6950	31/93
Kaub	546,2	67,66	103488	1630	4110	7200	31/93
Koblenz	593,5	57,67	109806				
Andernach	613,8	51,47	139549	2010	6030	10000	31/93
Bonn	654,7	42,66	140901				
Cologne	688,8	34,97	144232	2090	6200	9950	31/93
Düsseldorf	744,2	24,48	147680	2120	6230	9780	31/93
Ruhrort	780,8	16,09	152895				
Wesel	814,0	11,22	154210				
Rees	837,4	8,73	159300	2260	6410	10200	84/93
Lobith	862,2						

PNP : Gauge zero point (**P**egel **N**ull **P**unkt)

Table 1.1 Specifics of flow at the main gauges along the Rhine
(Deutsches Gewässerkundliches Jahrbuch 1994)

The river Rhine shows a variety of longitudinal and cross-sectional profiles, which are strongly marked by the character of the landscape and by human influence. From Maxau to Lobith, the bed elevation of the river Rhine changes from 97,48 m to 3,5 m. The average slope of the river bed changes from 0.1 to 0.23 $°/_{oo}$. At Bingen (Rhine km-528,40), after the confluence of river Nahe, the slope of the river bed is suddenly changed, the cross section are also very narrow due to the adaptation of the profiles for navigation purpose. Figure 1.3 shows the length profiles of the Rhine (after Water and Navigation Administration South-West Germany SWD, 1988).

Until the beginning of this decade the river Rhine was from a managerial point of view considered an important water way for inland navigation and transportation, a source for drinking water, a receiver of waste water and cooling water coming from various origins and last but not least as means of transport for water, sediment and ice.

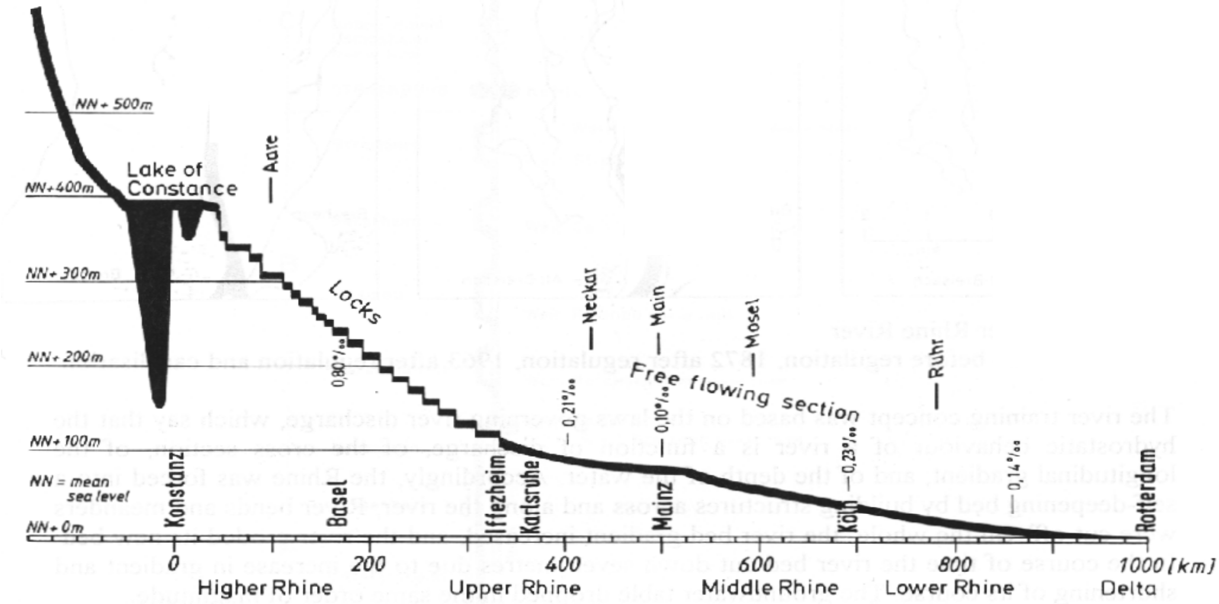


Figure 1.3 Length Profiles of the Rhine (after WSD South-West Germany, 1988)

In the early history the river Rhine was a natural frontier in this part of the world. The river formed a difficult barrier to pass. This can be illustrated by the fact that the Oldest Roman Settlements along the Rhine were all located at the left bank of the river. The strategic importance as a barrier remained.

The importance of the river as a water way, as a transport route for goods increased slowly during the middle ages. The local powers along the river dictated whose ships were allowed to use the river and collected toll from each ship that wanted to pass a stronghold. The many castles along the river Rhine in Germany are a remembrance of this period. At the end of the 18th century and during the beginning of the 19th century the necessity of freedom of navigation was recognised and an international system of shipping rights was developed.

The Rhine states agreed in 1815 to form an International Commission on the Navigation of the Rhine. An international treaty on navigation was concluded in 1831. With various modifications and revisions this treaty is still in force as is the International Commission.

Another economic asset of the river Rhine is the fishery, especially the salmon fishery. At the end of the 19th century it was recognised that co-operation between the Rhine-states was necessary to protect the stocks against over fishing and to allow a more equal distribution of catching between the nations. To end this the salmon-treaty was agreed upon in 1885. Under this treaty an International Salmon Commission was formed. Unfortunately the salmon fishery reduced rapidly despite actions of the Salmon Commission to protect the salmon stock. The last meeting of the Commission took place in 1950.

The aspect of trans-boundary pollution of the river Rhine was first given attention to in 1932 when the Dutch government protested against the issuing by France of a permit to discharge residual salt in to the river.

After the second world war pollution problems further increased. This led to diplomatic steps by the Netherlands resulting in an International Commission charge with the study of the waste water and water quality problems. This Commission commenced its work in 1950 and was granted formal international status in 1963.

The international co-operation against pollution was strengthened by two treaties, one for the protection of the Rhine against chemical pollution and one for the protection against pollution by chlorides.

Considering the river Rhine as an ecosystem has only recently been adopted by water authorities and governments. During the Minister-conference held December 1986 in Rotterdam a common ecological objective for the Rhine was formulated for the first time: the river should be improved in such a way that the return of a fish species as the salmon in the Rhine would be possible. However, as far as we are informed it made the Rhine the first major trans-boundary river in the world for which such an ecological policy goal has been formulated.

The floods along the Rhine during the winters of 1993/94 and 1994/95 and their consequences urgently highlighted a problem which has so far been neglected. On the occasion of the meeting of the EU-Ministers of Environment in Arles, February 1995, they charged the Rhine Commission to draft an action plan on flood control measures. As questions related to pollution control and ecological restoration must now be co-ordinated with measures concerning flood defence and spatial planning.

1.2 Morphological Changes

1.2.1 Dyking:

Dating back to the Roman era, the first important intervention of man was the construction of dykes in the flood plain. In the Lower Rhine in most areas the embankment was completed around 1450; the flood plain, formerly tens of kilometres wide, was restricted to narrow zones on both sides of the river (van Urk, et al. 1989). In the Upper Rhine the river found its way through a 6 km broad flood plain for many centuries, but in the 19th century it became (by river regulation) a stream of 200 to 250 m width. Fig. 1.4 shows the Upper Rhine River near Breisach in 1828, 1872 and 1963.

Attempts to tame the unruly Rhine began in the 19th century, with the ‘rectification’ works of the Upper Rhine that were undertaken by the German engineer Johann Gottfried Tulla. Until then, the upper reaches of the river had remained largely undisturbed. For most of its journey, the Rhine took a meander path across a wide flood plain of forests and water meadows. In the ‘furcation zone’, between Basel and Karlsruhe, the river splitted into innumerable branches that continually moved, disappeared and reformed. The islands between the branches were dominated by flooded forests and wet pasture. Each spring the silt Rhine water spilled over the low dykes and into the forests, meadows and fields of the flood plain.

However, the split channels and meanders prevented the passage of all but the smallest boats, and building was difficult on shifting riverbanks. The border with France moved whenever a flood passed, so Tulla forced the braided river into a single channel. ‘As a rule’, he said, ‘no stream or river needs more than one bed’. Nature never intended that this should be so, but Tulla´s maxim has since become the rule that river engineers follow. The rectification conveniently prepared the Rhine for its role as the great river highway of Germany that was created in 1871. Along its banks grew the great industrial cities of the new Germany, such as Mannheim, Koblenz, Cologne and Düsseldorf.

This was the beginning of the ecological decline and hydrological disruption of the river. More than 2000 islands in the furcation zone disappeared. The new, straight Upper Rhine was also about 100 kilometres shorter than the old river and it flowed 30 percent faster. The result was the disappearance of most of the sluggish backwaters and shallow gravel reaches in which wildlife had flourished.

1828

1872

1963

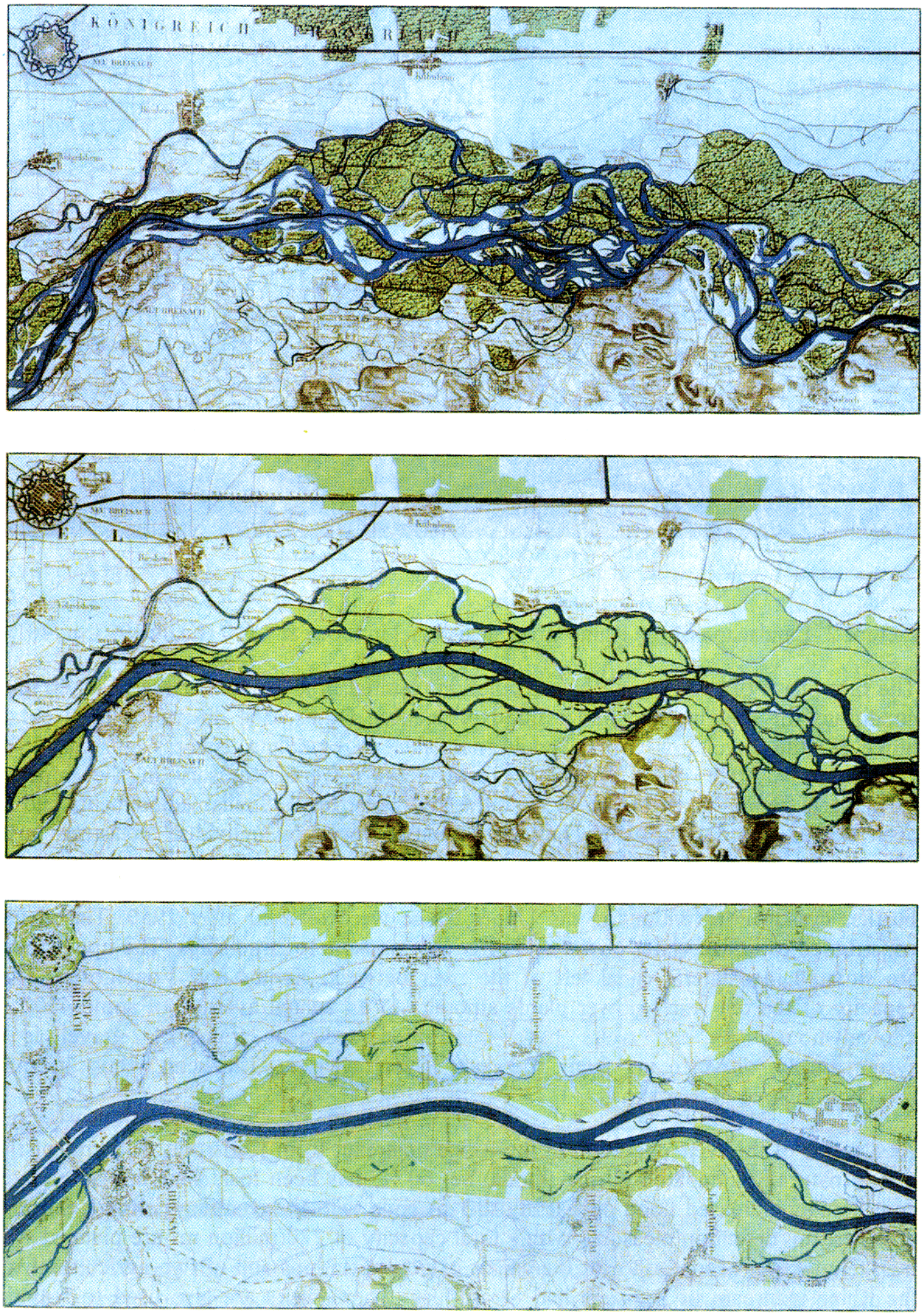


Figure 1.4 The rectification work and canalisation on the Upper Rhine (KHR, 1993)

In Figure 1.4:

1828 The furcation zone without greater human influence.
1872 The Upper Rhine after TULLA´s correction work.
1963 This figure shows the situation of the Upper Rhine today.

While Tullas plan kept high dykes well away from the river, so maintaining a broad flood plain, farmers added their own dykes nearer to the stabilised river to turn seasonally flooded pastures into the arable fields. Between Basel and Strasbourg

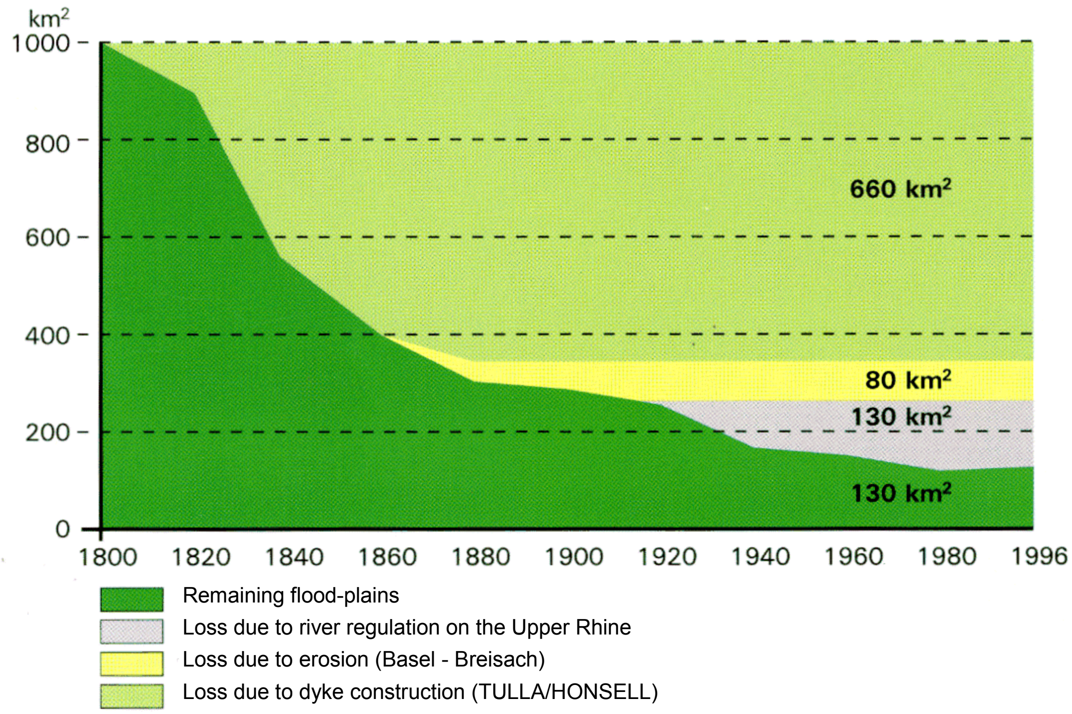


Figure 1.5 Lost of Flood Plain on the Upper Rhine between Kembs and Maxau (Integriertes Rheinprogramm, 1996)

in the past 60 years, the river has been refashioned for a second time in a scheme designed to capitalise on its navigation and hydroelectric potential. Tullas version of the Rhine (now known as the Rest Rhine) has been largely abandoned in favour of an entirely engineered channel, completed with giant locks and a series of hydroelectric plants. This has cut off the Upper Rhine from 160 square kilometres of its flood plain, leaving just 10 percent of the original area available to the river (Fig. 1.5)

1.2.2 Regulation

The effect of these developments is the faster river speed towards the sea, but it also scoured the river's bed and banks more fiercely. In the past 100 years, the river at Basel has fallen by seven metres, the height of a two storey house (Fig.1.6, Pearce, 1993).

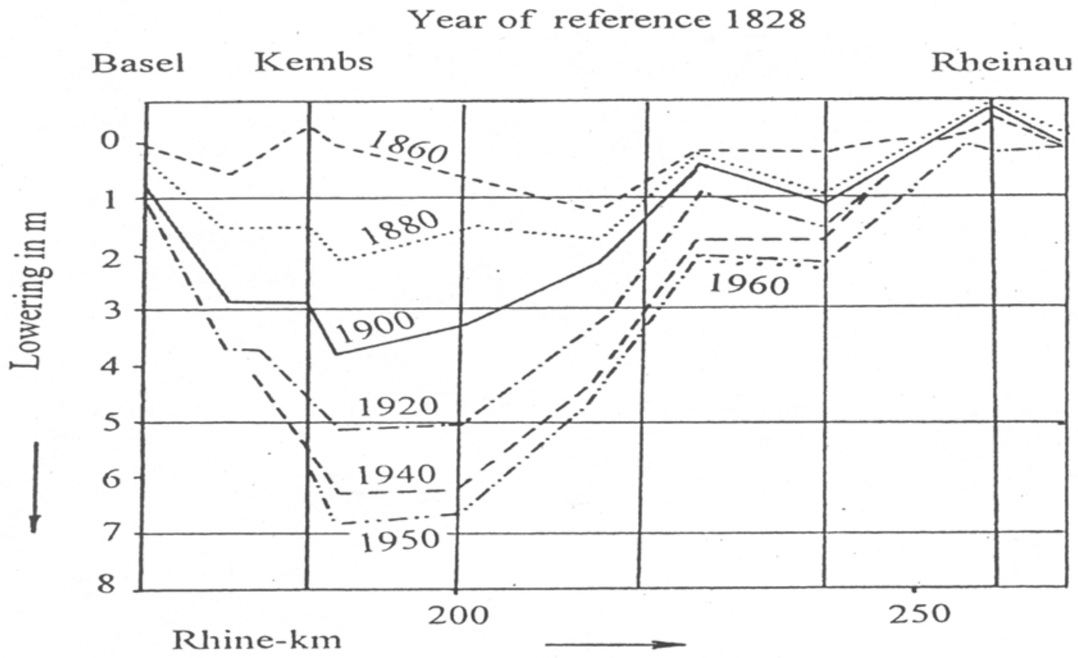


Figure 1.6 The fall of water level on the Upper Rhine after regulation (Pearce, 1993)

At the port of Duisburg, the largest inland harbour in the world, which lies 300 kilometres downstream from the end of the engineering works, the level dropped by almost four metres (Fig.1.7, Broseliske et al., 1991). As the river bed fell, so did the ground water table in the alluvial flood plain. Ancient forests of oak, elm and willow dried out, and wells ran dry.

A second effect of these developments has been to reduce the time it takes for the spring flood peak to pass out of the Alps, through Basel and as far as Karlsruhe by 30 hours. There's also evidence that disasters are becoming more common. According to historic records, the Rhine at Karlsruhe rose 7.6 meters above flood stage only four times between 1900 and 1977. Between 1978 and 1996, it reached that point 10 times (Abramovitz, 1996). After storms over the catchment, the peak flow on the Rhine itself now coincides with those in tributaries such as the Neckar as they meet the main river. This creates a flood surge that rushes down stream towards Bonn and Cologne, where there were several record river flows during the late 1980s. Peak flows are 35 percent higher than before 1955, said Peter Larsen of the Institute of Water Resources Management, Hydraulic & Rural engineering, at the University of Karlsruhe. Floods that previously were likely to occur once every 200 years can now be expected every 50 years (Bernhart, 1990).

A third effect of the artificial embankments on the remade Rhine has been to prevent the river collecting silt from its former flood plains. This reduces the supply of sediment downstream and increases the river's ability to pick up material from the river bed farther downstream. The old, slow, silt stream that laid down alluvium as it went has been turned into a fast, silt-starved river that scours its bed, in places by up to 8 metres. Almost two centuries of efforts to 'tame' the Rhine have made it wilder and more unruly.

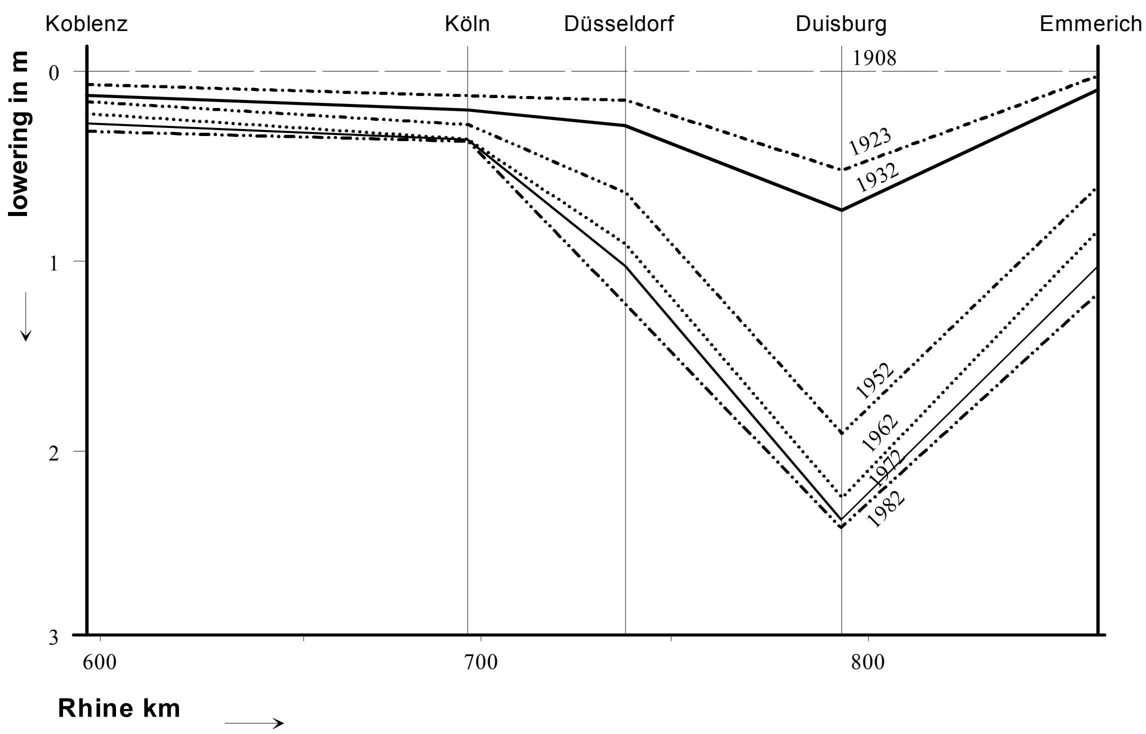


Figure 1.7 Change in water level of the Middle and Lower Rhine (Bundesministerium für Verkehr, Abt. Binnenschifffahrt und Wasserstraßen, 1987)

Engineers started to reduce the impact of scouring by dumping gravel into the river. Up to 500.000 tons would be needed each year at downstream of Iffezheim , to be obtained either by dredging it elsewhere in the river or from gravel pits in the flood plain. These pits would further combat floods by creating a dozen of 'flood retention basins’ beside the Rhine. Rather than seeing these basins become barren receptacles for flood water, ecologists hope to forge an alliance with engineers to revive the flood plains but house builders and farmers want the dykes retained.

In the Upper Rhine protection against flooding seems to be ensured, but in the Lower Rhine floods continued to occur in the 19th century. The irregular array of groins and the presence of many sand bars in the channel not only impeded flow, but in particular led to the formation of ice jams. In the second part of the 19th and the first part of the 20th century all sand bars were removed and the river channels were corrected to facilitate flow.

1.2.3 Canalisation

The river Rhine became navigable up to Basel at the turn of this century. The result was that flow water levels had to be regulated to facilitate transport in periods of low discharge. In the High Rhine ten weirs were built in the period from 1900 to 1940; canalisation of the Upper Rhine began with the construction of a lateral canal (the Grand´Alsace canal), in which four hydro-electric stations were built in the period 1927-1959. The diversion of the river Rhine water in to the lateral canal except for a small rest discharge in to the ‘Rest Rhine’ caused a fall in the water level of 2-3 m (de Jong et al., 1987). In the stretch downstream of the lateral canal to Strassbourg four weirs were built in the Upper Rhine. Down stream of each weir bed erosion increased dramatically causing new problems for navigation. Hence two new weirs had to be built down stream of Strabourg to keep the river navigable. All these measures have greatly reduced the buffering capacity for high water waves upstream, causing consequences for the high water levels in the Middle and Lower Rhine.

In the Lower Rhine some new river branches were created in the last century, as the Nieuwe Merwede and the Nieuwe Waterweg. One branch, the Nederrijn/Lek has been canalised by the construction of three weirs.

In the course of time the size of the ships navigating on the river increased, and in order to allow for sufficient water depth many stretches have been narrowed by the construction or extension of groins. This again caused an increase of bed erosion.

Together with mining activities near Duisburg a lowering of the mean water level of more than two meters since the beginning of this century has been reported.

All along the Rhine the increased navigation has caused bank erosion. For protection purposes many banks of the river have been changed in to stony shores.

The different types of human modifications on the Rhine river and their uses are summarized in Table 1.2. The modification of the Rhine has evolved a great deal during its history, from dam construction in the 11^{th} and 12^{th} centuries, to heavy canalisation in the 19^{th} and 20^{th} centuries, through current restoration attempts.

	Stage of change	Economical aim	Consequences for the environment
1	Change of the river course of the upper part of the Rhine based on Tulla´s proposal (1800-1880)	protection of flooding dry out land	lower part of the Rhine: erosion of the riverbed, disappearing of the marshes, first step to the causing ground-water level drop
2	Channeling of the Rhine between Basel and Strasbourg (from 1907 and on)	to ensure the steam shipping	Destruction of the forests which are situated near the banks of the river, second step to the causing ground-water level drop
3	The construction of power plants along the Rhine (1898, 1908, 1914)	to supply new industrial areas with energy	Destruction of the natural river environment through the building of storage reservoirs, dams and factory buildings
4	Production of waste water of the rising industries	to eliminate the waste water produced by residential and industrial areas	The polluted rivers are dangerous because they are both a source of drinking water and ecological systems for any animal life
5	The construction of the side-Rhine-channels (1918) and nuclear power plants along the Rhine (Phillipsbourg, 1972)	to facilitate the transport of goods to the water ways and to increase the production of energy	Draining and the destruction of the meadows, the water pollution and the increase of the water temperature

Table 1.2 Types of human Modification of the River Rhine (BothENDS, 2000)

Consequences of human intervention into the river:

- Lack of areas which could catch water during times of flood since the river was straightened, the riverbed was strengthened and the meadows were lost.
- Increased the amount of water flow in streams, tributaries and main rivers
- Increased velocity during times of flooding
- Increased velocity of flow
- Because the main and side rivers flow together, the chance of flooding is increased
- Catastrophically levels between the middle and the lower floodgate of main rivers

2 *The Flood Situation in the Rhine Basin*

2.1 Flood History

In consequence of human intervention into the river, there are many floods recorded during the last decade on the river Rhine. In this chapter some of the following important flood events are described.

2.1.1 Impacts of Tulla´s Correction Works

There is limited research on the direct impact of Tulla´s correction works on flood situations of the Rhine. The recorded flood water level at Isteiner Klotz, downstream of Basel from 1828 to 1882 (Kunz, 1975), gives us a very impressive picture. They show clearly, which effect the correction of the Rhine for the Upper Rhine water level had in the years 1830 to 1870, between Basel and Karlsruhe. One compares for example the flood of 1824 (before Tulla´s correction) with a discharge of about 4000 m³/s – approximately 1,2 m above datum – with the flood 1876 (after the correction) with a discharge of about 5700 m³/s and a water level of only 0,47 m above datum. Thus one finds that around 1700 m³/s the lower flood discharge was situated 1824, around 0.73 m over the highest flood water level of flood 1876 (Fig. 2.1).

One can suspect therefore, which fear these Rhine floods must have in-hunted for humans in the Upper Rhine Valley. For example, the history of Greffern, Baden-Söllingen, has always been closely associated with the Rhine River, which not only brought work and food, but also misery and distress. The regular flooding of the river produced much hardship, as much as, that the village had to be relocated further inland four times between the 15th and 17th centuries. A further planned relocation of the village in the 19th century was averted by ,,Tulla's correction" of the

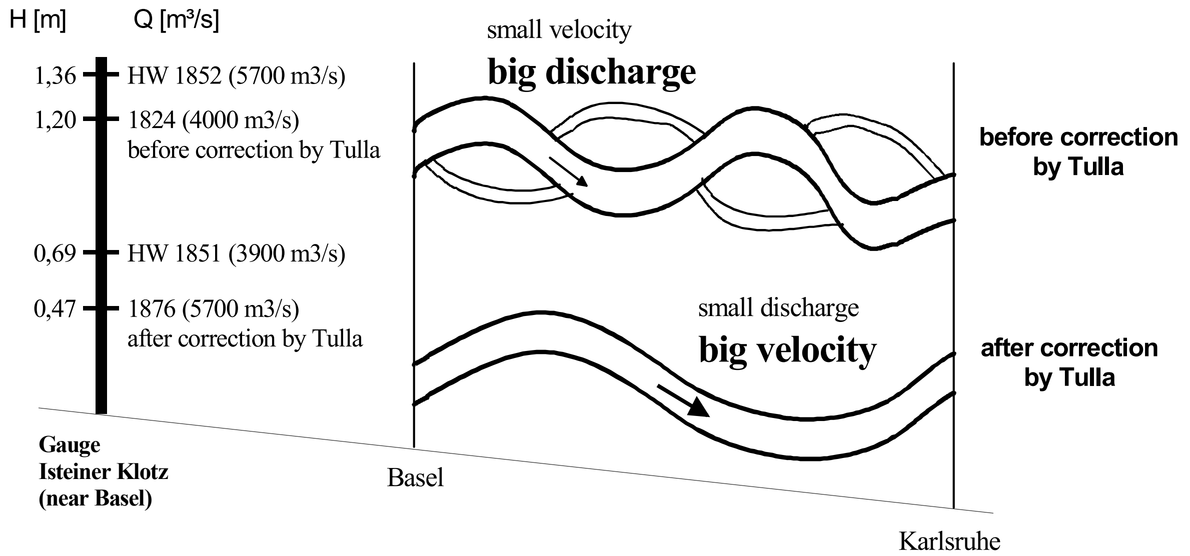


Figure 2.1 Flood water level marks at Isteiner Klotz

(Water level after Ergon Kunz, 1975)

river's course. Before the construction of levies, the floods were recorded as being the height of a man standing upright, the water flowing into the houses through the windows (Greffern, 40 years 1953-1993). Therefore it is understandable that after repeated catastrophe floods the Grand Duke Karl Friedrich of Baden aimed at the whole area´s flood protection. This measure caused the largest water-structural works of that generation both in planning and in the execution. It was documented in the well known term ,, Tulla´s correction of the Rhine " as the largest flood protection and hydraulic engineering measure of the last centuries on the Upper Rhine. However this also led to the flood acceleration down stream of the river where many floods were recorded during the last century.

2.1.2 Impacts after Barrage Weirs Development Period

Regarding to the consequences of the measures, executed between 1955 and 1977, 130 km² of the flood plain areas were lost from the total 270 km² (see Fig. 1.4). The flood wave of the Rhine was accelerated in such a way that the flow time of the wave peak between Basel and Karlsruhe was reduced from formerly 64 hours to 23 hours (see Fig. 2.2).

While before 1955 with appropriate precipitation events in the Rhine catchment area the tributaries arrived with their flood waves before the wave peak of the Rhine at the effluent, they meet today more frequently at the same time with the Rhine waves and cause a substantial height of the flood peak at downstream of the river. The Flood Studying Committee in the years from 1978 to 1992 in detailed investigations the discharge aggravation by the Upper Rhine development between 1955 and 1977 determine concretely (Fig. 2.2).

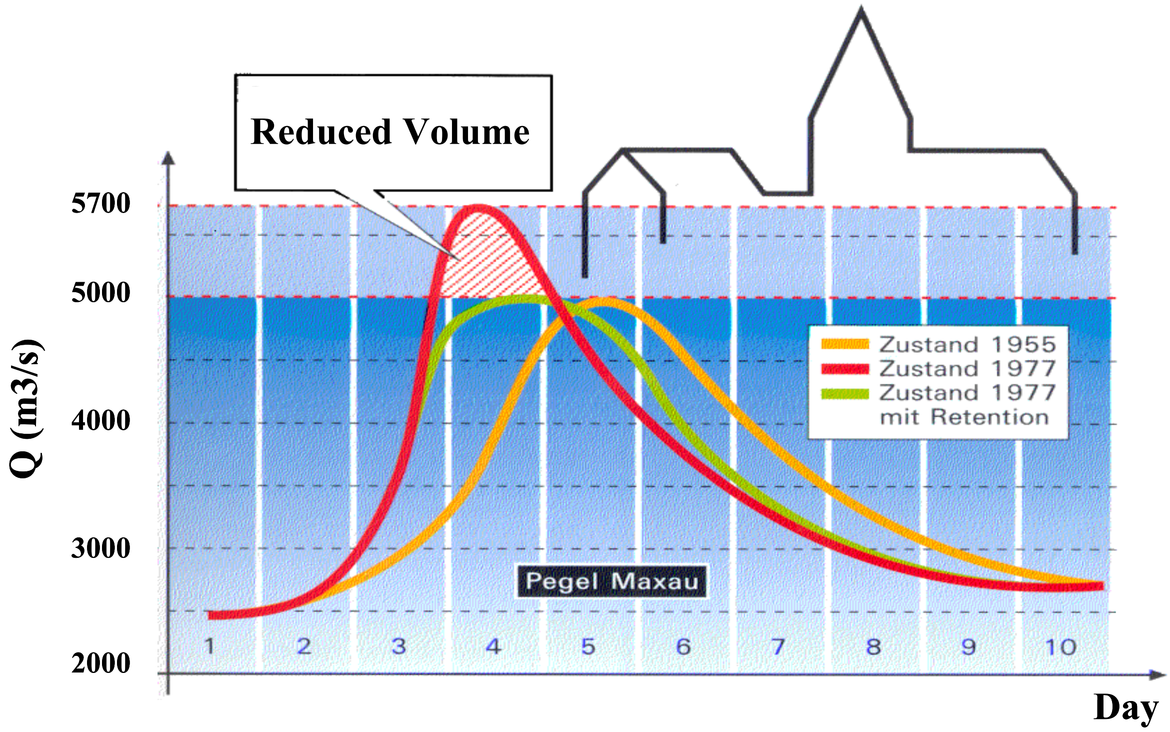


Figure 2.2 The Effects by Regulations on the Upper Rhine between 1955-1977 (Integiertes Rheinprogramm, 1996)

According to it, for both small and middle Rhine floods, especially for extreme floods, about 40 cm water level arises at Cologne (corresponding to the increase discharge of about 800 m³/s), see Table 2.1. One example, today if a flood would occur how it occurred in 1882/1883 with the water level of 10,52 m at Cologne, alone a disaster flood devastating for Cologne as a result of the Upper Rhine development would arise around 90 cm of higher water level (Ölmann, H., 1997) .

Because of the Upper Rhine development resulting in flood development themselves below Karlsruhe, on the basis of the study results of the Flood Studying Committee, a German and France agreement was decided for the balance of the flood aggravation at 6.12.1982. In this agreement, it was determined: To take the necessary measures downstream of the barrage Iffezheim in order to re-establish the available flood protection as before the development of the Upper Rhine (Fig. 2.2).

Gauge	Q (m³/s)				Q (m³/)	
	Bed status 1955		Bed status 1977		increase	
Returned period	100	200	100	200	100	200
Maxau	4700	5000	5300	5700	600	700
Worms	5700	6000	6400	6800	700	800
Mainz	7300	7900	7900	8700	600	800
Kaub	7400	8000	8000	8800	600	800
Andernach	11500	12450	12200	13250	700	800
Cologne	11800	12750	12550	13550	700	800

Table 2.1 Discharge Aggravations caused by the Upper Rhine Development 1955 and 1977
(After Flood Study Group for the Rhine distance Kaub – Rolandswerth, 1992)

2.1.3 The Flood of March/April 1988

The flood of March/April 1988 on the Rhine was caused by a number of very rainy months combined with considerable snow melt.

In the months of January and February, the average monthly precipitation exceeded the monthly averages of the period 1951-1980, and the month of March was extremely wet. At two thirds of the measuring stations, it was the wettest month of March ever recorded. Most of the precipitation fell in the south of Germany and Switzerland, where in some parts the recorded rainfall amounted to more than 400% of the long-term average for the month of March (KHR, 1990). Besides this large amount of rainfall, the contribution of snow melt was considerable as well.

A remarkable characteristic of this flood is that its discharge had two peaks. The peaks passed with an interval of about ten days (Fig. 2.3)

The flood was not equally extreme in the whole Rhine basin. In the Swiss part of the area the peak reached a value which occurs once every 5 years. At Maxau, the recorded water levels occur in average once every 10 years, at Kaub once every 50 years (Table 2.2). This due to the large contribution of the Neckar and Main to the flood. Tributaries which discharge the Rhine more downstream clearly contributed less to the flood, making its peak less extreme towards the mouth of the river.

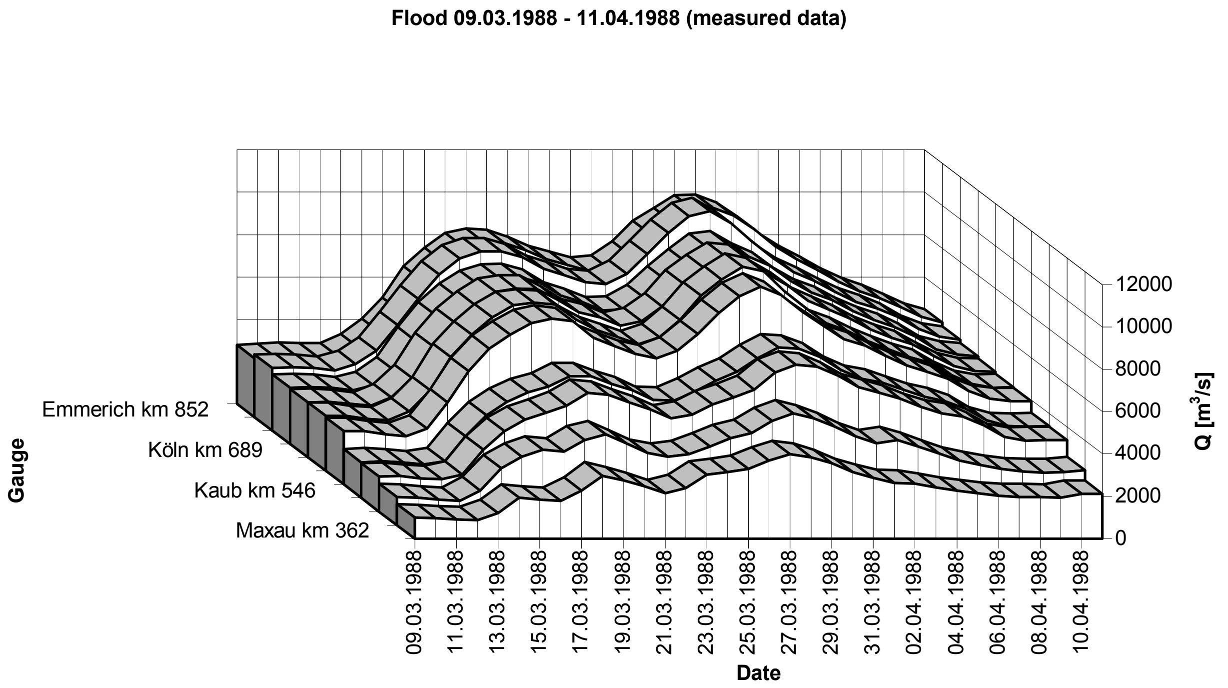


Figure 2.3 Rhine Discharge during the Flood of March/April 1988

(Bundesanstalt für Gewässerkunde, Datenbank 1988)

Table 2.2 shows the effects of men works on flood situation of the river Rhine. For example at the gauge Worms, according to the historical data, the flood of March 1988 should have the recurrence interval of about 50 years but in the case of computation with the present river bed situation it is only about 25 years, two times shorter. At the gauge Mainz it has the recurrence interval of 40 years instead of 85 years. At the gauge Kaub it has the recurrence interval of 50 years instead of 95 years.

Although the 1988 flood was exceptionally extreme in certain reaches of the river Rhine, there were no catastrophic inundations and damage remained within acceptable limits.

Gauge	Q (m^3/s)	Rank of Peak*		Recurrence in Years			
				from historic data		from homogenised data	
		Q	W	Hydrologic Year	Winter	Hydrologic Year	Winter
Maxau	4090	> 10	4	16	24	10	14
Worms	5270	3	4	50	60	25	25
Mainz	6950	2	3	95	85	45	40
Kaub	7200	1	3	95	90	50	50
Andernach	9530	7	8	29	30	-	-
Cologne	9580	8	6	21	22	-	-
Rees	10200	4	8	30	31	-	-
Lobith	10300	3	8	19	-	-	-

* Occasionally 1988 measured peak values are identical to those earlier events.

Table 2.2 Classification of the Flood1988 of the Rhine for the Time Series 1871/1988 and Recurrence Intervals (KHR, 1990).

2.1.2 The Flood 1993/1994

Between December 1993 and January 1994, a number of European countries experienced damaging flood events, which have been caused by lasting precipitation, the accumulated December precipitation was more than double the amount of the long-term averages for this month (Geb, M., 1994) . More generally, the effectiveness of flood prevention measures has been partly set off by increasing the susceptibility to flood (Rosenthal, U. et. al, 1998). As a result many rivers overflowed their banks, especially on Christmas and in particular on river Moselle and on the Middle and Lower Rhine River. When the flood hit Cologne, it over topped the protection wall (10.63 m+NN). The river inundated the old town centre for almost three days.

At the gauge Düsseldorf on the 21 of December the discharge was only 7300 m^3/s but later in December the discharge became 9690 m^3/s, and on 24.12.1993 the discharge became 10846 m^3/s (Fig.2.5), which was only about 54 m^3/s less than the highest discharge in 1926.

The water level on the Rhine was only a little lower in comparison with the water level of the flood on 1926 (see Fig. 2.4):

Pegel Köln	=	6 cm
Pegel Düsseldorf	=	78 cm
Pegel Wesel	=	139 cm
Pegel Emmerich	=	30 cm

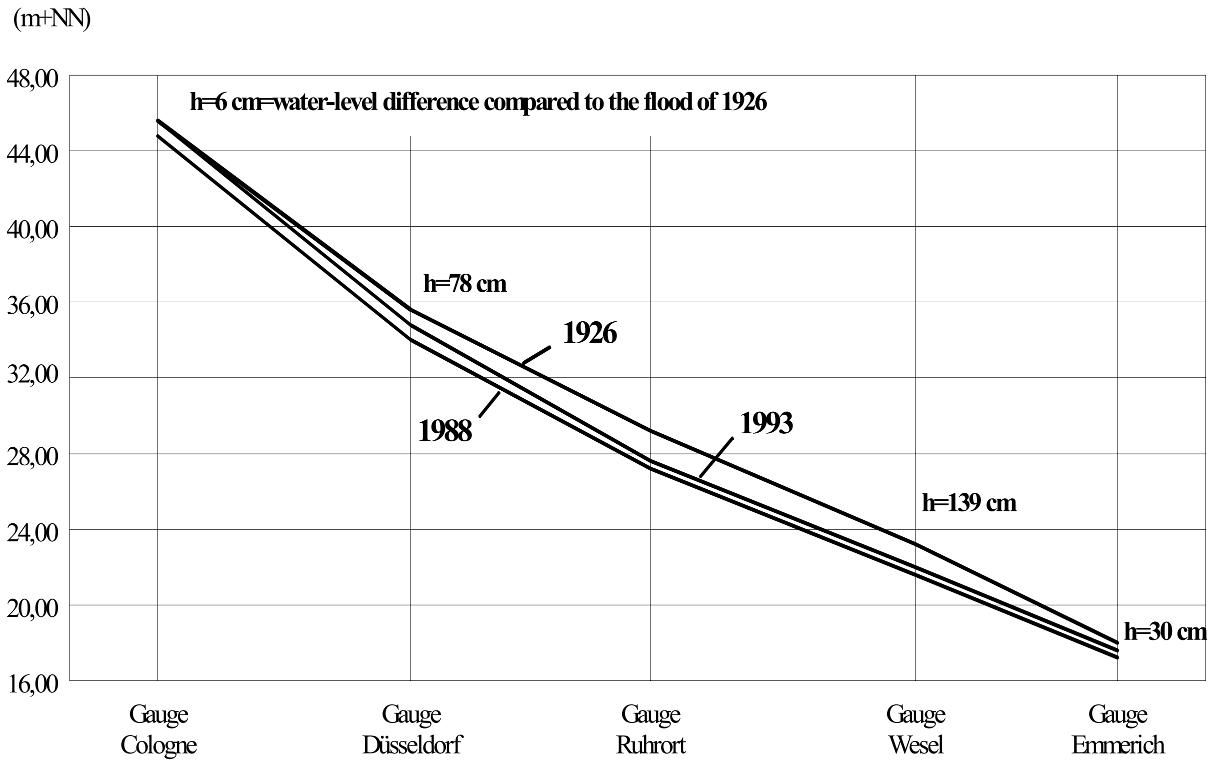


Figure 2.4 Comparison of The Water Level between the Floods 1993 and 1926 (Bornefeld, 1993, Das Weihnachtshochwasser 1993 des Rheins)

Date	21.12.93	22.12.93	23.12.93	24.12.93	25.12.93
	Q/n	Q/n	Q/n	Q/n	Q/n
Maxau	3020/2,5				
Worms		4759/10			
Mainz			5570/10		
Kaub			6500/40		
Koblenz			-		
Andernach			10600/65		
Cologne				10800/65	
Emmerich					11100/80

Q: Discharge $\left[m^3/s\right]$; n: recurrence intervals [n in years]

Table 2.3 Ranking of flood peak at some selected gauges, 1993

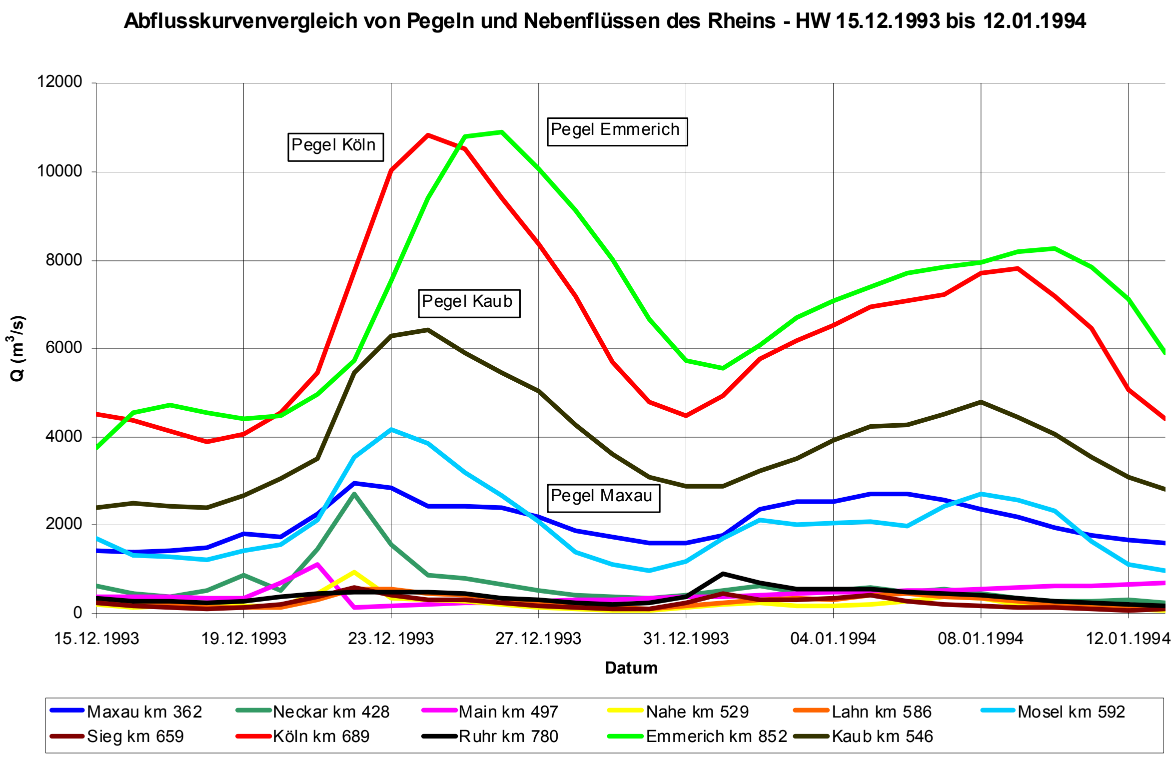


Figure 2.5 Discharge curve of the Flood 1993 at selected gauges and tributaries (Bundesanstalt für Gewässerkunde, Datenbank 1994)

Table 2.3 shows the maximum flood peaks, their arrival times and recurrence intervals for selected gauges in the Rhine basin. At Maxau, the recorded water levels occur on an average once every 2,5 years, at Kaub once every 40 years and Andernach once every 65 years. This is due to the large contribution of the Neckar, Nahe and Moselle to the flood.

It will be more illustrative with the comparison of the flood December 1993 with 7 very big other floods in the past 120 years. Table 2.4 is the ranking of flood peaks at selected gauges on river Rhine and Moselle between 1880 and 1993. It shows that floods in the Rhine river basin have very strong regional differences and the flood 1993 was extremely at the Lower Rhine.

Based on a scenario with an increase of the winter precipitation of 10% as could recently be observed within the Rhine catchment, the recurrence time of a 100 years flood, as e. g. the event of 1993, would decrease to 40 years (Bendix, J. 1997).

Flood	Rank of the peak among the floods between 1880 and 1993									
	Worms / Rhine		Kaub / Rhine		Cologne / Rhine		Emmerich / Rhine		Cochem / Mosel	
	Q	W	Q	W	Q	W	Q	W	Q	W
1882/83	2	1	2	2	> 10	8	4	3	> 10	> 10
1926	> 10	> 10	10	> 10	1	1	1	1	2	2
1955	1	2	7	8	> 10	> 10	10	> 10	9	7
4/1983	6	10	9	10	8	10	> 10	> 10	> 10	10
5/1983	5	6	8	9	6	6	8	> 10	8	8
1988	3	4	1	3	9	7	5	> 10	> 10	> 10
1993	9	> 10	6	7	2	2	2	4	1	1

Table 2.4 Ranking of Flood Peaks at Selected Gauges on River Rhine and Moselle

The first damage estimates of 1993/1994 come up to DM 650 million total loss alone in Rineland-Palatinate and DM 100 million in the Saarland. The figure quoted for the town of Cologne was about DM 110 million (Hochwasserschutzzentrale der Stadt Köln,1994) so that the overall damage in the land of North-Rhine Westphalia can be assumed to be at least DM 200 million. In Baden-Württemberg, alone the insured building damages exceeded DM 160 million. Together with the losses suffered in the Bavarian basin of river Main, the damage in the entire Rhine catchment comes to DM 1,300 million.

The flood event 1993, Koblenz (AP by Hermann Knippertz)

2.1.3 The flood of February 1999

In many places strong rains and snow melt let to have swollen rivers. The Rhine rose for the first time after short relaxation again. In Baden-Württemberg the levels of Rhine, Donau and Neckar crossed to a large extent the first peak. In Karlsruhe Maxau the river achieved 6.71 meters on Wednesday morning (with 7.50 meters on the upper Rhine navigation had to be stopped). Already on the day before, the Flood Forecast Head Office (HVS-Baden Württemberg) had again taken up its work which had been stopped before. Many highways were flooded. In North Bavaria rivers overtopped the banks.

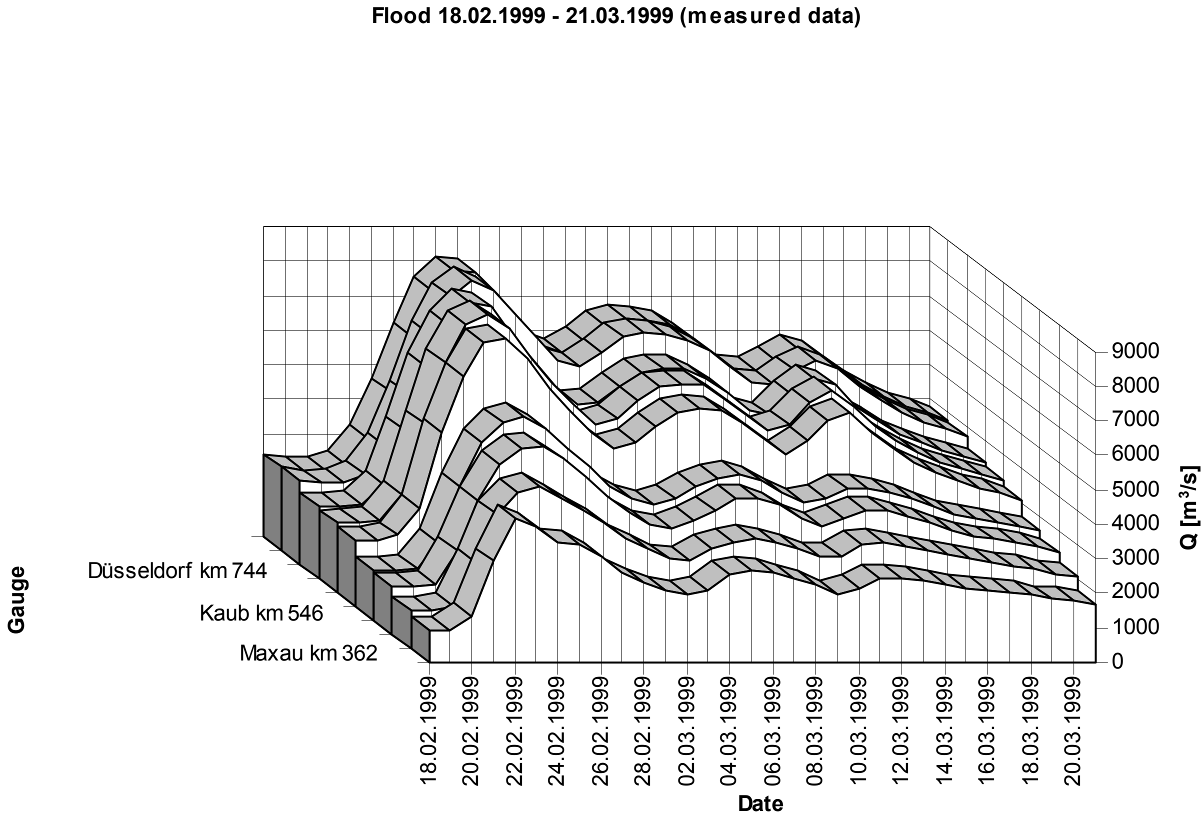


Figure 2.6: Flood discharge of the Rhine during flood event of February 1999 (Bundesanstalt für Gewässerkunde, Datenbank 1999)

In Rheineland-Pfalz the level of the Mosel in Trier crossed the six-meter level. In the south and southwest of Germany however for the coming days stagnating or falling water levels were counted. In Germany the protection of the Rhine and the flood precaution were strengthened. The State Government approved of a new convention, replacing several other declarations for the protection of the Rhine from and the 70's 60's. Ecological requirements are more strongly considered therein.

It was the first time the flood entered the retention polders along the Upper Rhine (Homagk, 2000). Figure 2.6 indicates the discharge curves of the flood event February 1999.

2.2 Existing of Flood Defences

Figure 2.7 (Modified after BfG, status 1996) shows the flood safety that is provided by embankments and dykes on river Rhine: In the Upper Rhine Graben, dyke systems protect the riparian communities all along the stretch from the Swiss-German border to the area of the town of Mainz. It must be noted, however, that the provided safety differs. Along the impounded reaches (downstream to Rhine km-354) flood peaks of recurrence intervals of about 1,000 years can safety pass.

These dykes are located directly at the banks of the river and their crests are up to 8 m high above the natural level of the land. Downstream of the last impoundment barrage in the river Rhine to the inflow of river Main, the inundation safety is sufficient against 200-year flood peaks. The increased peaks resulting from the construction of the impoundments have been compensated by providing additional retention capacity (retention in the river, impoundment weirs, polders for controlled flooding).

The actual protection dykes on this stretch of the river are often relatively distant from the banks. Smaller dykes in the foreshore areas provide protection only against summer floods, and have in winter only a peak-reducing effect for mean flood events.

Downstream of the inflow of river Main to the area of the town of Bingen, dykes protect against 100-year flood peaks. From Bingen to Cologne there are no protective dykes, except the protection wall around the town of Neuwied built in 1929 and some minor flood defence structures in the city of Cologne itself. Downstream of Cologne, from Rhine km 710, the river is again accompanied by dykes, which protect the inhabitants on the German bank of the river against peak discharges of more than 500 years recurrence. On the Dutch side, the recurrence intervals are even higher.

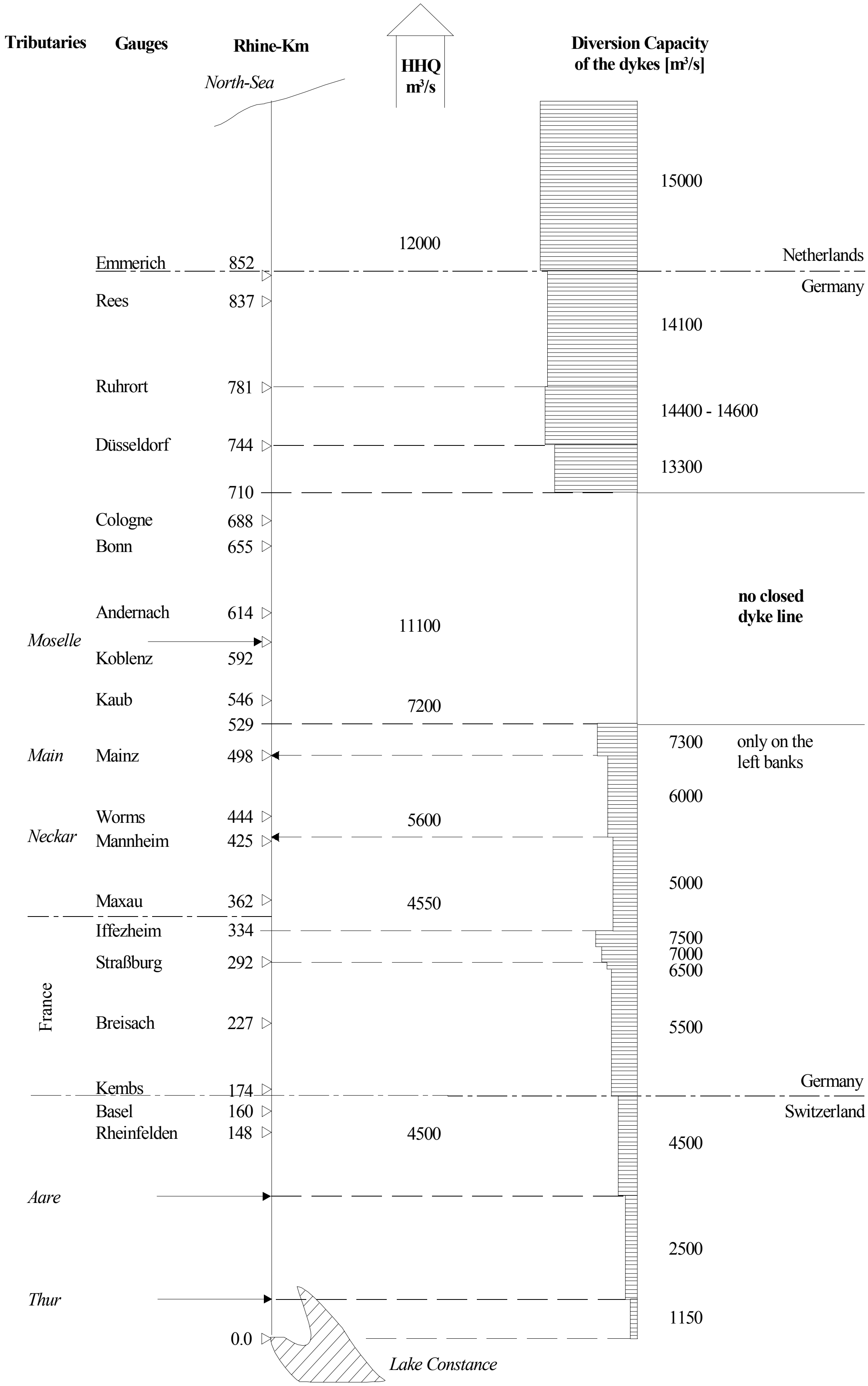


Figure 2.7 Maximum flood discharge and diversion capacity of dykes (BfG, 1996)

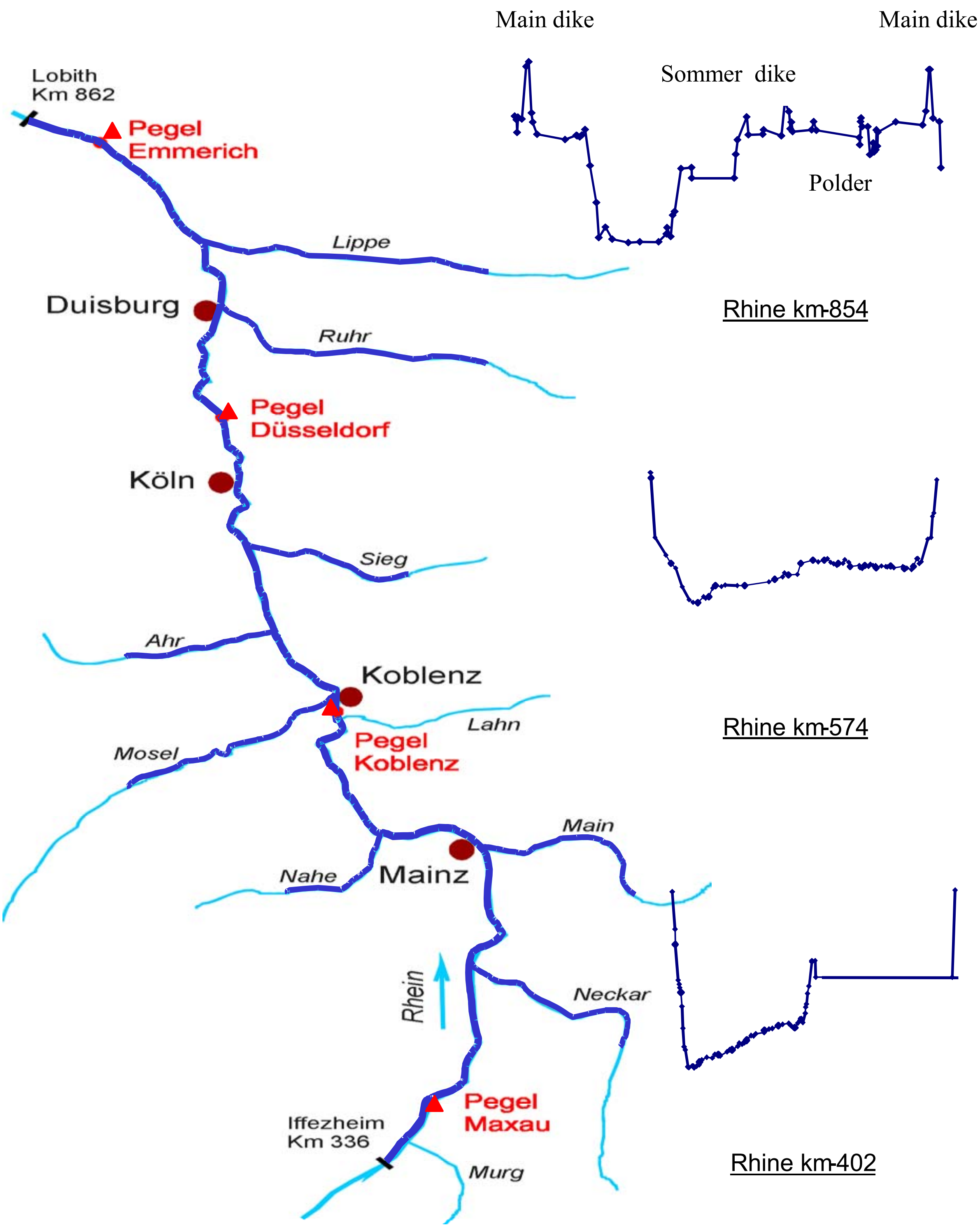


Figure 2.8 Typical cross section of the river Rhine

2.3 Water Retention on Flood Plains – The new concept for flood regulation and re-naturalisation

Protective measures against floods, land drainage, shipping, and hydroelectric engineering forced the river Rhine into channels and caused the decline of rive Rhine wetlands. Those river constructions resulted in mono-functional water systems, most of which are maintained since decades until today. The ecological functions of a river system were not known in those days and so people did not feel the need to take care of them.

Knowledge on the effects of climatic changes points out that there will probably be a general rise of risks from flooding in this century. And, partly because no-one can be certain what the future may bring, the maintenance of flood defence capable of protecting the populace from higher river flow remains the top priority, but the prospects of raising the dikes even further is no longer seen as appropriate. The central pillars of the water management policy are creating space for the river and increasing the ‘’flexibility’’ of the river system so that it can cope with floods. It means change of land use in the inundation plains to make them available for emergency flooding, even if only a part of the lost retention areas of 950 km² could be returned to this purpose, this could provide a considerable potential for retention space.

Restoration of previously engineered and regulated rivers has been undertaken in many years ago and such projects can form part of a sustainable development plan for the river basin. The objectives of river restoration are normally to create a wider diversity of eco-systems by bringing the river into a closer contact with its flood plain. The visual amenity of the watercourse may be improved and its natural function for flood storage and conveyance regained.

The natural variation of water levels is part of the feature of rivers. It is the basis for river flow dynamics and the development of a typical floodplain profile. Various human interferences have clearly altered the river regime. Thus, the starting point is to take back these human interferences with the river regime, as far as possible. This means above all to increase water storage on the surfaces and in the floodplains. A natural transition to alluvial flood plain would not only help flood prevention, it would also be beneficial to nature conservation as riverside flood plain are one of the rarest and most endangered types of biotope today.

2.3.1 Functions of Flood Plain

The functions of flood plains are generally divided into three main groups. These include: Hydrologic functions, bio-geo-chemical functions, and habitat and food web functions (National Research Council, 1995).

Many of the hydrologic roles that a flood plain plays are less well known. The reduction of downstream flood peaks due to a wetland's short-term surface water storage capability has also been accredited as one of their benefits (LAWA, 1995). Other wetlands are able to store surface water over the long term, thus allowing for the maintenance of fish habitat during periods of dry weather. Another important hydrologic function of some wetlands is their ability to maintain the water table at a high level. This allows hydro-phytic communities to be maintained, thus sustaining bio-diversity in the area.

Wetlands are also responsible for many bio-geo-chemical functions. Chemical elements are cycled through the system allowing nutrient stocks to be well maintained. Wetlands are also able to retain and remove dissolved substances and accumulate peat and inorganic sediments (National Research Council, 1995). These functions are very important as they allow for the enhancement of water quality; when water passes through a wetland, its velocity is reduced allowing for biochemical interactions to take place between the water, plants, and soil. This allows for the natural removal of nutrients, pathogens and pollutants. It is the trapping of sediments and the removal of nutrients that has the greatest impact on improving water quality.

A large diversity of plants and animals depend on wetland areas for their survival. The distinct vegetation characteristic of wetlands provides food and shelter in addition to nesting grounds for many different migratory birds, including waterfowl. Some vertebrates and invertebrates depend on wetlands for their entire life cycle while others only associate with these areas during particular stages of their life. Because wetlands provide an environment where photosynthesis can occur and where the recycling of nutrients can take place, they play a significant role in the support of food chains (Adams, 1988).

2.3.2 Flood Retention Areas on the Upper Rhine

The flood prone part covers an area of nearly 1,000 km^2 with a population of 700,000 citizens and 350,000 working places. The property value amounts to 121 bn German Marks and the annual added value to 35 bn. There are 26 protection schemes and 5 major areas without flood defence structures so that inundation levels

Nr.	Polders	Km	Phase	Area (ha)	V($10^6 m^3$)	E (m+NN)
France:						
1	Sonderbetrieb d. Rheinkraftwerke		operation		45,0	
2	Erstein		plan		7,8	
3	Moder		operation		5,6	
					58,4	
Baden-Württemberg:						
1	Südliches KW Breisach			1020	25,0	
2	Kulturwehr Breisach		plan	510	9,3	
3	Breisach/Burkheim		plan	600	6,5	
4	Wyhl/Weisweil		plan	600	7,7	
5	Elzmündung		plan	550	5,3	
6	Ichenheim/Meißenheim		plan	390	5,8	
7	Altenheim		operation	520	17,6	
8	Kulturwehr Kehl/Straßburg		operation	700	37,0	
9	Freistett		plan	460	9,0	
10	Söllingen/Greffern		construction	580	12,0	
11	Bellenkopf/Rappenwört	357,0	plan	510	14,0	106,50
12	Elisabethenwört	382,0	plan	400	11,9	98,00
13	Rheinschanzinsel	390,5	plan	210	6,2	96,00
				7050	**167,3**	
Rheinland-Pfalz:						
1	Daxlander Au	358,0	operation	200	5,1	105,50
2	Neupotz/Wörth	364,0	plan	250	10,0	104,00
3	Mechtersheim	388,0	plan	500	7,4	97,00
4	Flotzgrün	392,0	plan	300	5,0	95,00
5	Kollerinsel	409,0	plan	500	6,1	94,00
6	Waldsee/Altrip/Neuhofen	412,0	plan	500	8,1	93,50
7	Petersau/Bannen	434,0	plan	200	1,4	91,00
8	Mittelbusch (Worms II)	438,0	plan	150	2,3	90,00
9	Bodenheim/Laubenheim	492,0	plan	700	6,0	84,00
10	Ingelheim	518,0	plan	500	3,8	82,00
				3800	**55,2**	

Table 2.5 Some characteristic of polders on the Upper Rhine (ICPR, 1997)

correspond to the flood stages in the river. As the highly developed valley is very sensitive to flooding and the environmental situation along the river needs substantial improvement the decision was made to construct a large number of retention basins with a total capacity of 240 mil. m^3. In this way flood protection can be raised from a 1 : 100 to a 1 : 200 year floods event (Integriertes Rheinprogramm des Landes Baden-Württemberg). Table 2.5 indicates some figures of the flood plain areas on the Upper Rhine according to the Rhine Integrated Programme of State Baden-Württemberg and the Fig. 2.9 shows the ,,Old'' Rhine at Isteiner Klotz.

A socio-economic assessment of this programme showed not only its high efficiency but also the demand for additional flood plain management measures. The residual damage potential amounts to more than 12 bn German Marks. This figure is a convincing proof that flood plain management is a must for sustainable development. Indeed, flood events exceeding the design standard of the defence structures are rare, but when they occur they cause regional catastrophes. Without any precautionary measures this could lead so structural breaks in the economy of the affected area. At the moment such effects are not included in cost-benefit calculations. Disaster impact analysis is a very new field of research which has to be noticed to a broader extent. Several large scale disasters have shown that regional economies have not the adsorptive capacity to recover within a short time so that prosperity damage is an adverse effect of major importance.

Along the Upper Rhine in Germany, retention areas – large polders besides the river, which inundate only at the time of flood – are being created. Table 2.5 indicated some characteristics of the polders and their locations are showed in the Figure 2.10.

Figure 2.9 The Old Rhine at Isteiner Klotz

(Peter Birmann, 1820)

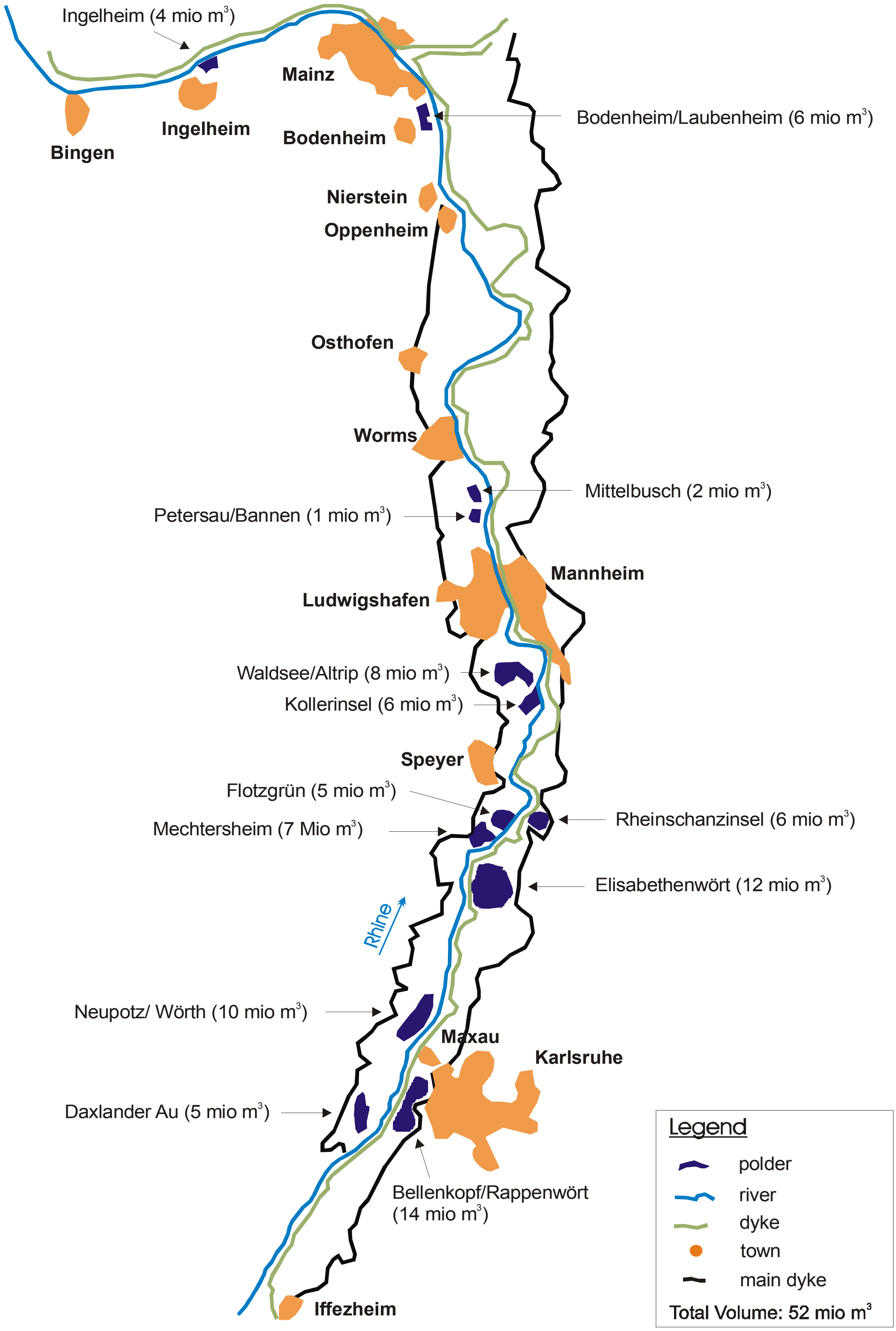


Figure 2.10 Floodplain restoration on Upper Rhine (Modified after Ministerium für Umwelt und Forsten, RheinlandPfalz, 1998)

2.3.3 Flood Retention Areas on the Lower Rhine

These retention basin will store up to 270 million cubic metres of water and are also planned in the state of Nordrhein-Westpfalen. About 100 million cubic metres of capacity is already available, and was first utilized during the high-water episode of 1988. The major objective is to re-establish natural hydrological conditions on the site, but also to integrate the land use in a sound way in parts of the area. Table 2.6 shows some characteristics of polders on the Lower Rhine (MURL, 2000) and their locations are showed on Figure 2.11.

Nr.	Polders	Km	Phase	A (ha)	V($10^6 m^3$)	E (m + NN)
Nordrhein-Westfalen:						
1	Siegmündung	657,5	plan	250		50,00
2	Niederkassel	665,0	operation	60	1,0	47,50
3	Köln-Langel (Lülsdorf)	672,0	construction	100	10,0	46,00
4	Worringer Bruch	708,0	construction	650	13,0	39,00
5	Monheim	712,0	construction	220	8,0	38,00
6	Dormagen	717,0	plan	415		36,50
7	Urdenbach	718,0	operation	600		30,70
8	Itter-Himmelgeist	727,0	construction	140	2,0	35,00
9	Illvericher Bruch (Meerbusch	753,0	construction	600	25,0	30,00
10	Lank	760,0	plan	280		30,00
11	Mündelheim	767,0	plan	250	5,0	28,00
12	Binsheim	788,0	plan	505		20,00
13	Orsoyer Land	803,0	operation	220	10,0	18,50
14	Mehrum	807,0	plan	170		20,00
15	Wallach	809,5	plan	60		21,00
16	Ginderich	815,5	plan	250		20,00
17	Flüren	817,5	plan	400		20,00
18	Bislicher Insel	823,0	operation	1000	50,0	15,00
19	Lohrwardt	834,0	plan	670	20,0	17,50
20	Löwenberg	844,0	plan	125		16,00
21	Grietherbusch	846,5	operation	1200		16,10
22	Bylerward	848,0	construction	1500	30,0	16,00
23	Salmorth	862,0	plan	1000		13,70
				10665	**174,0**	

Table 2.6 Some characteristics of polders on the Lower Rhine (MURL, 2000)

Figure 2.11 Floodplain restoration on Lower Rhine (Modified after MURL, 2000)

3 The Hydrodynamic-Numerical Model of the River Rhine (HN-Model Rhine)

Based on the computer CARIMA programme which is developed by SOGREAH (Prof. Cunge, France), the Hydrodynamic-Numerical Model of the River Rhine (HN-Model Rhine) is constructed. It includes 500 km length of the river from Iffezheim, the last weir on the Upper Rhine, to Lobith, the hydrological station at the border between Germany and The Netherlands and the main important tributaries of the section including Neckar, Main, Nahe, Lahn, Moselle, Ahr, Sieg, Ruhr and Lippe.

For simulating the actual and the future situations of the River Rhine with different flood regulation measures, the HN-Model Rhine is able to predict the response of the river to imposed changes. It can give a whole picture of the variation of the water levels effected by these changes and the advices for flood management purpose. Depending on the studies required, the entire model or simply a part of it may be used for different simulations. The HN-Model Rhine has been used for the projects of assessing the effects of dyke displacements and polder systems on the whole Rhine into flood situation and given many practical results.

3.1 Description of the Numerical Method for River Bed and Floodplain Simulation

3.1.1 Physical Foundations

A mathematical model of a river can be built using two general categories of simple schematisation elements.

One-dimensional schematisation

That part of the river having one-dimensional flow characteristics, i.e. where flow velocities perpendicular to the main flow direction are negligible, is divided into elementary sections separated by computation points. The friction coefficient defines the roughness.

At each computational point, the cross section, the elevation and the abscissa of that point are sufficient data to describe the geometry of the river.

At each of these points, the water level, discharge and velocity are calculated. The computation points are connected by one-dimensional links which are either standard links characterised by free surface flow and the complete Barré de Saint-Venant equations with all the inertia terms, or special links (weir law, lateral inflow, lateral outflow, siphon, etc.). Figure 3.1 is an example of a one-dimensional looped network.

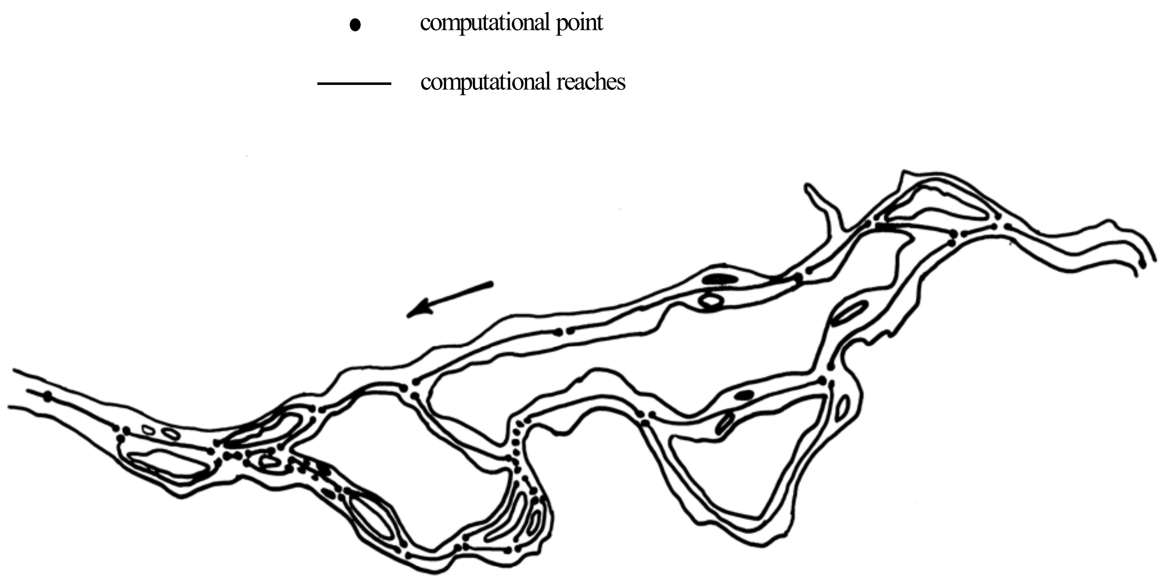


Figure 3.1 One-Dimensional Looped Network

The equations of Barré de Saint-Venant for one-dimensional unsteady river flow are written as follows:

$$\frac{\partial y}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = 0 \tag{3.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} + gA\frac{Q|Q|}{K^2} = 0 \tag{3.2}$$

Where:

x = local coordinate $[m]$

t = time coordinate $[s]$

y = water level $[m]$

B = width of water surface $[m]$

Q = discharge $[m^3/s]$

A = the wetted cross sectional area $[m^2]$

K = specific discharge $[m^3/s]$, calculation with Strickler factor

g = gravitational acceleration $[m/s^2]$

These equations are solved using the Preissmann implicit method (Ligget, et.al., 1975).

Two-dimensional schematisation

Those parts of the river having two-dimensional flow characteristics, i.e. where the velocity component perpendicular to the main flow direction is no longer negligible, are divided into elementary cells defined by the relationship between the variation in their volume as a function of the water level in the cell.

The cells are interconnected and, in some cases, linked with one-dimensional computation points by various types of two-dimensional links:

. Standard links satisfying the dynamic Barré de Saint-venant equations without inertial terms.

. weir, etc.

The programme calculates the water level at the centre of the cell and the exchange flow between this cell and another cell or one-dimensional computation points.

The association of these one-dimensional points and two-dimensional cells from the basic mathematical model of the river enable flows to be simulated.

Figure 3.2 is an example of a two-dimensional flood plain zone adjacent to a river; the arrows indicate possible flow paths between cells and the river.

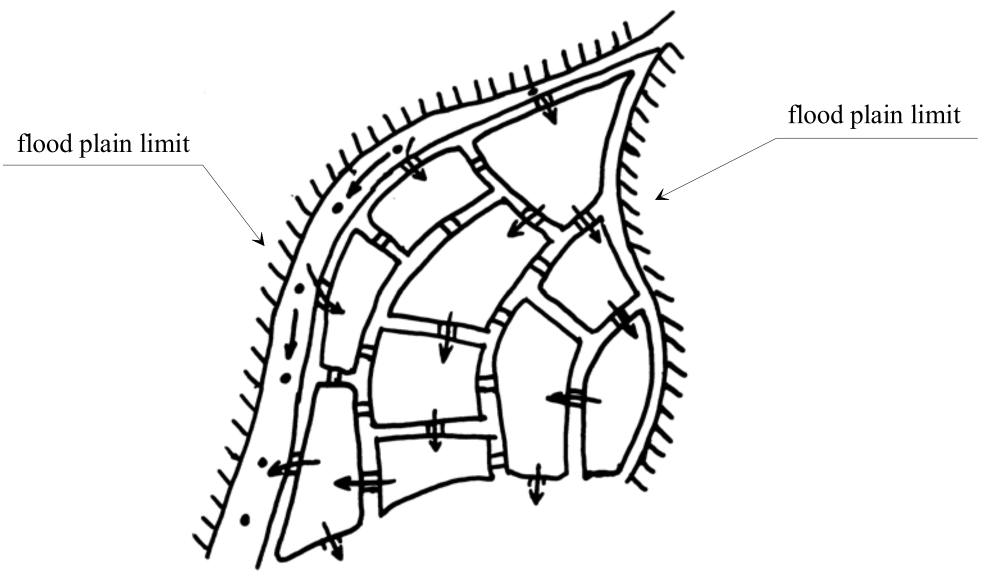


Figure 3.2 Two-Dimension Flood Plain Cell Model

Two-dimensional flow calculation is based on continuity of volume for each cell and non-inertial flow laws between cells.

Continuity of volume in a flood plain cell is expressed as:

$$\frac{\partial Vj}{\partial t} = \sum_{i=1}^{n} Qij \tag{3.3}$$

With:

V_j = volume of water in the cell j

Q_{ij} = discharge from cell i to cell j

n = number of cells which communicate with j

Weir flow between cells is computed without inertia, as follows:

Flooded: $$Q = \mu B \sqrt{2g}\ (y_{us} - y_{weir})\ (y_{us} - y_{ds})^{1/2} \tag{3.4}$$

Free-flowing: $$Q = \mu B \sqrt{2g}\ (y_{us} - y_{weir})^{3/2} \tag{3.5}$$

With:

μ = discharge coefficient

B = weir width

y_{us} = upstream water level

y_{ds} = downstream water level

y_{weir} = weir crest elevation

Channel-type flow linking two flood plain cells is computed using, for example, the Strickler resistance law, as follows:

$$Q = kAR^{2/3} \left[\frac{y_{us} - y_{ds}}{\Delta x}\right]^{1/2} \tag{3.6}$$

With:

K = Strickler roughness coefficient $[\frac{m^{1/3}}{s}]$

A = channel cross-sectional area

R = hydraulic radius

Δx = longitudinal distance between cell centres

In addition to these basic equations, CARIMA uses comparable formulations for flow through orifices, flood gates, hydroelectric plants, flow regulation, etc. The channel flow equations are integrated in time and space using the Preissmann implicit method (Preissmann, 1961). The other flow relations are solved in such a way that at the end of each time step the equation for the discharge is satisfied.

3.1.2 Numerical Solutions

The equations (3.1) and (3.2) represent a hyperbolic system of two partial differential equations. The arguments in this set of equations are the time coordinate t and the local coordinate x, which are independent variables the flow Q(x, t) and the flow through cross section area A(x, t) or the water level y(x, t). Because the set of equations is not analytically solvable, the solution takes place by means of a finite difference method, i.e. the derivatives in the equations (3.1) and (3.2) become approximated by difference quotients. With the assigned procedure it concerns around an implicit finite difference method after Preissmann (Cunge, 1980). The formation of the difference equations appear in the following form:

$$\frac{\partial f}{\partial x} \approx \theta \frac{f_{j+1}^{n+1} - f_j^{n+1}}{\Delta x} + (1-\theta)\frac{f_{j+1}^{n} - f_j^{n}}{\Delta x} \qquad (3.7)$$

$$\frac{\partial f}{\partial t} \approx \frac{f_{j+1}^{n+1} - f_{j+1}^{n} + f_j^{n+1} - f_j^{n}}{2\Delta t} \qquad (3.8)$$

where θ is a weighting coefficient, 0<θ<1, introduced in the time derivative in the numerical solutions, f is described in (3.14)

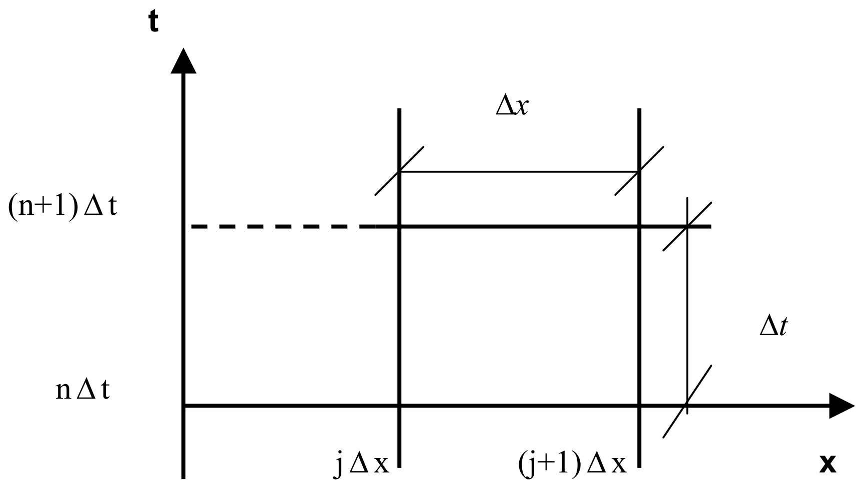


Figure 3.3 Preissmann´s Scheme

From (3.7) and (3.8) the following difference quotients result:

$$\frac{\partial y}{\partial t} \approx \frac{(y_{j+1}^{n+1} + y_j^{n+1}) - (y_{j+1}^{n} + y_j^{n})}{2\Delta t} \tag{3.9}$$

$$\frac{\partial Q}{\partial t} \approx \frac{(Q_{j+1}^{n+1} + Q_j^{n+1}) - (Q_{j+1}^{n} + Q_j^{n})}{2\Delta t} \tag{3.10}$$

$$\frac{\partial Q}{\partial x} \approx \theta \frac{(Q_{j+1}^{n+1} - Q_j^{n+1})}{\Delta x} + (1-\theta) \frac{(Q_{j+1}^{n} - Q_j^{n})}{\Delta x} \tag{3.11}$$

$$\frac{\partial}{\partial x}\left[\frac{Q^2}{A}\right] \approx \frac{\theta}{\Delta x}\left[\frac{(Q_{j+1}^{n+1})^2}{A_{j+1}^{n+1}} - \frac{(Q_j^{n+1})^2}{A_j^{n+1}}\right] + \frac{(1-\theta)}{\Delta x}\left[\frac{(Q_{j+1}^{n})^2}{A_{j+1}^{n}} - \frac{(Q_j^{n})^2}{A_j^{n}}\right] \tag{3.12}$$

$$\frac{\partial y}{\partial x} \approx \theta \frac{(y_{j+1}^{n+1} - y_j^{n+1})}{\Delta x} + (1-\theta) \frac{(y_{j+1}^{n} - y_j^{n})}{\Delta x} \tag{3.13}$$

For B (width), A (surface), and K (specific discharge) in the equation (3.1) and (3.2) a substitution with the following structure is made:

$$f(x,t) \approx \frac{\theta}{2} (f_{j+1}^{n+1} + f_j^{n+1}) + \frac{1-\theta}{2} (f_{j+1}^{n} + f_j^{n}) \tag{3.14}$$

After substitution of the derivatives by the difference quotients a further substitution takes place in the next step, proceeding from the following general relationship.

$$f^{n+1} = f^{n} + \Delta f^{n} \tag{3.15}$$

Transferred to the flow Q and the water level y the equations develop:

$$Q^{n+1} = Q^n + \Delta Q^n \tag{3.16}$$

$$y^{n+1} = y^n + \Delta y^n \tag{3.17}$$

By using the equations (3.9) to (3.14) in the equations (3.1) and (3.2) and following shaping in accordance with the equations (3.16) and (3.17) one obtains 2 equations of the following forms:

$$A_j^n \, \Delta y_{j+1}^n + B_j^n \, \Delta Q_{j+1}^n = C_j^n \, \Delta y_j^n + D_j^n \, \Delta Q_j^n + G_j^n \tag{3.18}$$

$$A'^n_j \, \Delta y^n_{j+1} + B'^n_j \, \Delta Q^n_{j+1} = C'^n_j \, \Delta y_j + D'^n_j \, \Delta Q^n_j + G'^n_j \tag{3.19}$$

The coefficients A to G and A' to G' can be determined due to geometry of a transverse profile as well as the specification of a K_{st} value and are thus well known, the quantities Δy_j^n, Δy_{j+1}^n, ΔQ_j^n and ΔQ_{j+1}^n are to be calculated. For a system with n points of calculation one receives 2n-2 equations. The solubility of the sets of equations requires an initial condition and the specification of the time simulated by boundary conditions (water level, discharge) over the duration.

3.2 Model configuration

3.2.1 Data

3.2.1.1 Hydrological data

Some of the following data sets were used on the computation:

- Water levels for seven relatively constant discharge levels (permanencies). The water levels were measured in the period 1988-1995 and cover the complete range from low to flood levels.

- Discharges of the important tributaries downstream of Karlsruhe-Maxau including Neckar, Main, Nahe, Lahn, Moselle, Ahr, Sieg, Ruhr and Lippe for the mean discharges (MQ) and flood discharges of March 1988, December 1993 (HQ93) and February 1999.
- Stage discharge relations for the gauging stations Maxau, Worms, Mainz, Kaub, Andernach, Bonn, Cologne, Duesseldorf, Ruhort, Rees, Emmerich and Lobith.
- Equidistant time series of water levels and corresponding discharges at the gauging stations in the river reach between Maxau and Lobith. The discharges were calculated using the stage discharge relations.
- Time series of discharges in the nine tributaries during the flood periods of March 1988, December 1993 and February 1999.

These hydrological data were obtained from different sources following the list below:

° Federal Institute of Hydrology

(Bundesanstalt für Gewässerkunde BfG-Koblenz).

° State Agency for Environment Protection of Baden-Württemberg

(Landesanstalt für Umweltschutz Baden-Württemberg LfU).

° State Office for Water Resources Management of Rheinland - Pfalz

(Landesamt für Wasserwirtschaft Rheinland – Pfalz)

° Water and Navigation Administration South-West

(Wasser- und Schifffahrtsdirektion Südwest)

° Water and Navigation Office Cologne (Wasser und Schiffahrtsamt Köln)

° State Ministry for Environment & Agriculture of North Rhine-Westphalia

(Ministerium für Umweltschutz und Landwirtschaft Nordrhein-Westfalen).

° Navigation Administration of North Upper Rhine

(Gewässerdirektion Nördlicher Oberrhein).

° Navigation Administration of South Upper Rhine

(Gewässerdirektion Südlicher Oberrhein).

° Navigation Administration of South West Upper Rhine

(Gewässerdirektion Südwest Oberrhein).

° State Agency of Environment Bonn (Staatliches Umweltamt Bonn)

° Ruhr Association Essen (Ruhrverband Essen)

° Lippe Association (Lippeverband)

Some of the gauging stations showing the river Rhine's characteristics are given in Table 3.1. Table 3.2 indicates some of the main tributaries' figures.

Gauge	Rhine Km	PNP (m + NN)	$A_{E\,0}$ (km^2)	MQ (m^3/s)	MHQ (m^3/s)	HQ (m^3/s)	Time Series
Maxau	362,3	97,79	50196	1250	3070	4400	31/94
Speyer	400,6	88,52	53131	~	~	~	~
Worms	443,4	84,16	68827	1410	3340	5600	31/90
Mainz	498,3	78,43	98206	1580	3950	6950	31/93
Kaub	546,2	67,66	103488	1630	4110	7200	31/93
Koblenz	593,5	57,67	109806	~	~	~	~
Andernach	613,8	51,47	139549	2010	6030	10000	31/93
Bonn	654,7	42,66	140901	~	~	~	~
Cologne	688,8	34,97	144232	2090	6200	9950	31/93
Düsseldorf	744,2	24,48	147680	2120	6230	9780	31/93
Ruhrort	780,8	16,09	152895	~	~	~	~
Wesel	814,0	11,22	154210	~	~	~	~
Rees	837,4	8,73	159300	2260	6410	10200	84/93
Lobith	862,2	~	~	~	~	~	~

Table 3.1 Some Specifications of Flood for selected gauges in the Rhine basin*

* (Deutsches Gewässerkundliches Jahrbuch 1994)

3.2.1.2 Topographic Data

An accurate model requires detailed topographic mapping to properly represent the configuration of the flood plain and the river bed. The topographical map scale 1:5000 was used for defining the flood plains and obtained from:

° State Office for Land Surveying Baden - Württemberg)

(Landesvermessungsamt Baden - Württemberg)

° State Office for Land Surveying Rheinland - Pfalz

(Landesvermessungsamt Rheinland – Pfalz)

° State Office for Land Surveying Nordrhein - Westfalen

(Landesvermessungsamt Nordrhein - Westfalen)

Tributary	Rhine Km	Gauge	PNP (m + NN)	Distance to Rhine (km)	$A_{E\,0}$ (km^2)	MQ (m^3/s)	MHQ (m^3/s)	HQ (m^3/s)	Time Series
Murg		Rotenfels	130,54	17,0	469	15,5	252	603	17/94
Neckar	428,2	Heidelberg	120,04	26,1	13783	134	1150	2690	51/94
Main	496,8	Raunheim	90,64	27,0	24849	190	907	1850	66/94
Nahe	529,1	Grolsheim	84,63	7,4	4013	31,6	431	1140	73/94
Lahn	585,8	Kalkofen	135,00	25,1	3571	31,6	284	746	36/94
Mosel	592,3	Cochem	77,00	51,6	27088	313	2050	4170	31/94
Ahr	629,3	Altenahr	0,00	0,0	746	6,88	107	214	73(94
Sieg	659,3	Menden 1	49,34	8,4	2825	52,8	562	1050	65/94
Ruhr	780,2	Hattingen	60,37	56,0	4118	69,2	559	907	68/94
Lippe	814,5	Schermbeck1	20,68	22,4	4783	45,4	247	361	65/94

Table 3.2 Characteristics of collected tributaries of the Rhine*

* (Deutsches Gewässerkundliches Jahrbuch 1994)

The cross sections of the river bed and partly flood plains were received from:

° State Ministry for Environment & Agriculture of North Rhine-Westphalia
(Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen)

° Navigation Administration of Northern Upper Rhine
(Gewässerdirektion Nördlicher Oberrhein)

° Water and Navigation Administration South-West
(Wasser- und Schifffahrtsdirektion Südwest)

° Federal Administration for Water and Navigation
(Wasser- und Schifffahrtsverwaltung des Bundes)

° Water and Navigation Office Freiburg
(Wasser und Schifffahrtsamt Freiburg)

° Water and Navigation Office Mannheim

(Wasser und Schifffahrtsamt Mannheim)

° Water and Navigation Office Mainz (Wasser und Schifffahrtsamt Mainz)

° Water and Navigation Office Bingen (Wasser und Schifffahrtsamt Bingen)

° Water and Navigation Office Cologne (Wasser und Schifffahrtsamt Köln)

3.2.2 Construction of the Model

3.2.2.1 Model network

The model includes the free flowing section of the river Rhine and its floodplains, beginning from Maxau, the first gauging station of the free flowing section on the Upper Rhine, to Lobith, the hydrological measuring station on the border between the Netherlands and Germany. The total length of the model is 500 kilometres. It contains the nine main important tributaries of this part, including Neckar, Main, Nahe, Lahn, Moselle, Ahr, Sieg, Ruhr and Lippe. The model is constructed with different elements, such as: points, reaches and cells, the tributaries are modelled as lateral inflows.

Calculation points are initially defined at each point with one or more particular characteristics:

. points with stage-discharge relationship;

. points with flood recorders;

. sites of future man-made structures (dam, spillway, power plant);

. singular head-loss sections (natural sills, narrows);

. points corresponding to storage polders;

. boundaries and upstream boundaries of tributaries;

. confluences and bifurcations;

. measured cross-sections.

And these points may be simulated in the model as:

- one-dimensional (1-D) calculation points, with assigned water leve anddischarge varying with time, hydraulically defined by its geometric cross sectional shape and roughness characteristics as a function of elevation;

- nodal-points (1-D), a fictitious points of confluence of different sections; The nodal points are only used to associate (1-D) points or simple (2-D) points (confluences).

- two-dimensional (2-D) points, calculation points with assigned water level varying with time.

Reaches: The intervals between the above mentioned points are further divided into reaches. Considering the purpose of the model (flood wave simulation) it was decided to adopt a space step of the model of about 1000 m. The resulting grid is sufficiently dense for operational flood wave simulations and does not exclude application of the model for other purpose (e.g. low flow for navigation control). Space steps shorter than 1000m are envisaged locally to guarantee that grid points are located at gauging stations, confluence points with tributaries and at the special constructed across river sections (e.g: bridge etc.).

These reaches may be described as:

- one-dimensional reach, which connects two consecutive one-dimensional fluvial points. This type may either be real (river-type reach or weir) when connecting two calculation points or fictitious when connecting a calculation point with a nodal point. A one-dimensional link is defined by the names of the points connected (upstream and downstream), length of the reach and the coefficient of weighting of the head losses in the reach;

- two-dimensional fluvial link with assigned discharge varying with time, which connects two cells (2-D), or a cell with a fluvial point in which the flow is river type. The flow in two-dimensional links is assumed to be inertia's. For definition of two-dimensional links analogous data as for one-dimensional have to be supplied;

- weir links, one and two-dimensional type, allow flow simulations which do not obey Strickler´s law. It is, thus, possible to represent natural sills in the river bed and flow over dykes, roads or dunes. Such links are mainly used to join two-dimensional cells between themselves or with one-dimensional fluvial points.

(2-D) cells: Areas in which the inertial term is not taken into account are divided into (2-D) cells limited according to the topography and the direction of flows. They act as storage volumes with assigned water levels varying with time, defined by the area of water surface in function of elevation. A (2-D) cell may serve as a node, but a cell can be attached to a nodal point only through the intermediary of a simple (2-D) point.

A ‘standard’ for spacing of computational points mainly depends on two conditions:

° Propagation time of small waves and hence the depth of water.

° The computational time step Δt.

In order to avoid numerical errors in the calculation of steep waves, it is appropriate to choose a relationship $\frac{\Delta x}{\Delta t}$ as close as possible to the length which corresponds to the wave propagation criterion $\sqrt{gh}$. Since the overall computational time step was estimated to be in the order of 15 minutes, the intervals between the definition points Δx should be around 1000 m (with the changing of water depth bigger than 4 m). Figure 3.6 indicates the construction of the model.

3.2.2.2 Hydraulic roughness

The division of each cross section in three different parallel sections (main, left and right floodplain) allows for allocation of different hydraulic roughness values for the separate section. According to experience gained with the CARIMA-Model for the Lower Rhine in Germany, the hydraulic roughness is incorporated as follows:

- River bed: Hydraulic roughness values are represented by the Strickler values. They are given for any point on the network. In between two points the Strickler values are interpolated linearly. The Strickler values are changing from 33 to 40 $[\frac{m^{1/3}}{s}]$.

- Flood plain section: Depending on the vegetation cover conditions, the chosen Strickler values are changing from 15 to 30 $[\frac{m^{1/3}}{s}]$.

In Table 3.3 the Strickler values applying for the river reach are presented. The trend of the distribution along the river bed and flood plains can be seen in Fig. 3. 5

Gauge	Rhine-km	Strickler Coefficient k_{St}		
		River-bank	River-bed	Reach
Maxau (362,3)	362 - 425	20	35	3620 - 4250
Worms (443,4)	426 - 470	25	38	4260 - 4700
Mainz (498,3)	471 - 526	18	33	4710 - 5260
Kaub (546,2)	527 - 556	15	33	5270 - 5560
Koblenz (593,5)	557 - 593	15	35	5570 - 5930
	594 - 600	15	33	5940 - 6000
Andernach (613,8)	601 - 630	25	37	6010 - 6300
Bonn (654,7)	631 - 659	15	33	6310 - 6590
Cologne (688,8)	660 - 693	30	42	6600 - 6930
	694 - 700	25	33	6940 - 7000
Düsseldorf (744,2)	701 - 750	20	35	7010 - 7500
Ruhrort (780,8)	751 - 780	25	33	7510 - 7800
Wesel (814,0)	781 - 825	15	33	7810 - 8250
Emmerich (852,0)	826 - 862	20	33	8260 - 8620

Table 3.3 The Strickler value of the flood plain and river bed [$\frac{m^{1/3}}{s}$]

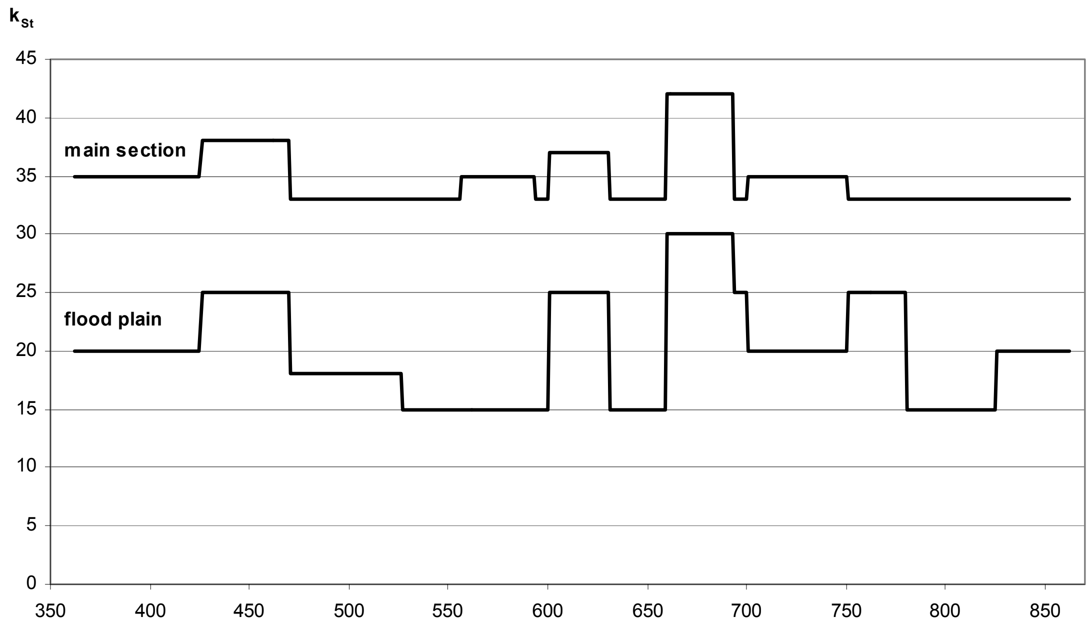


Figure 3.4 The distribution of Strickler value

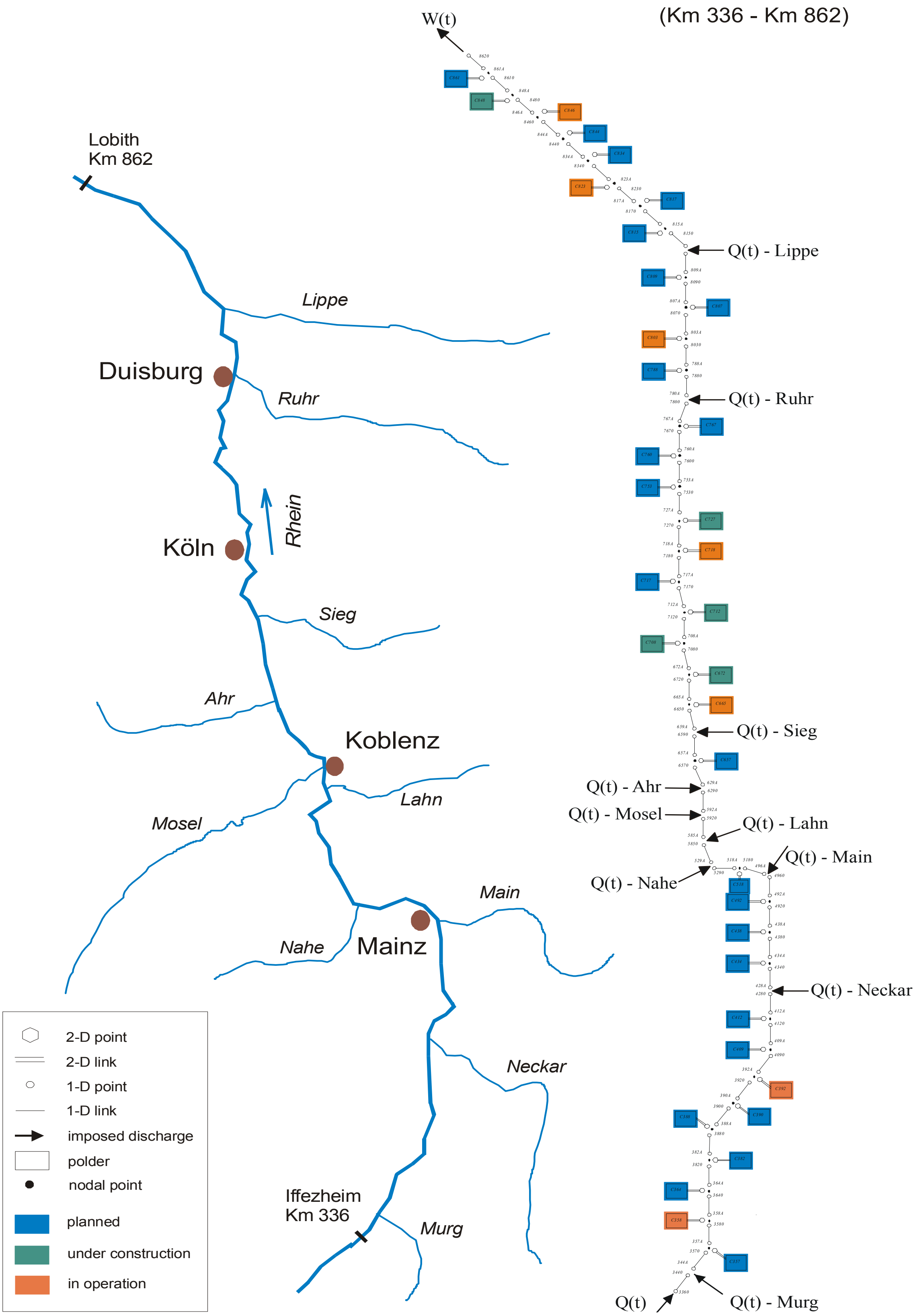


Figure 3.5 Hydrodynamic-Numerical Model of the River Rhine

3.3 Model Calibration

Calibration and verification of the constructed flow model are required to derive model coefficients and to prove that the model capable of simulating appropriately the water movement in the modelled river reach. The model is assumed well calibrated when agreement between measured and simulated water level or discharges can be achieved without unrealistically high or low hydraulic roughness values. If agreement can only be achieved by adopting unrealistic roughness values, boundary conditions and or numerical parameters, the geometry of the model should be reviewed critically and adjusted when required.

After calibration of the model the performance of the model should be additionally tested in one or more verification runs. In these runs simulation results are compared to measurements from historical events which were not used previously for calibration of the model.

For calibration and verification of the constructed flow model two different data sets are applied:

- Water levels in the river in periods of relatively constant discharge, called permanencies (in German called: Wasserspiegelfixierungen).
- Water levels and corresponding discharges at the gauging stations in the reach for three flood periods: March 1988, December 1993 and February 1999.

3.3.1 Steady Flow Calibration

3.3.1.1 Boundary conditions

The boundary conditions for the calibration runs of the steady flow conditions are shown in Table 3.4 and Table 3.5. At the upstream boundary (Maxau) and at the confluences discharges were defined. At the downstream boundary (Lobith) the stage discharge (Q~H) was applied (Table 3.5).

Q (m³/s)	773	1000	2001	3004	3999	5000
Q (m³/s)	5998	7004	7994	8999	10013	11016
Q (m³/s)	11996	13008	14003	15000		
H (m+NN)	7,01	7,60	9,40	10,90	12,06	13,01
H (m+NN)	13,84	14,55	15,08	15,54	15,97	16,35
H (m+NN)	16,68	17,003	17,31	17,62		

Table 3.4 Boundary condition at Lobith (BfG, Daten Bank)

River	Rhine-km	MQ (m³/s)	HQ93	Gauge
Rhine	362,30	1259	1480	Maxau
Neckar	428,20	135	2690	Heldelberg
Main	496,70	196	1400	Raunheim
Nahe	529,30	50	1150	Grolsheim
Lahn	585,60	51	591	Kalkofen
Ahr	629,30	26	210	Altenahr
Sieg	659,30	54	443	Menden 1
Ruhr	780,10	102	472	Hattingen
Lippe	814,50	68	255	Schermbeck 1

Table 3.5 Boundary conditions of steady simulation (BfG Daten Bank)

3.3.1.2 Steady flow calibration

For the steady flow calibration, the permanency of water level for the mean discharge (MQ) and flood discharge of December 1993 (HQ93) with the value for every 100 m of the river length were used.

The results of steady flow calibration are shown in Figure 3.6 to Figure 3.12 The difference between computed and measured water level can be seen in Table 3.6. The trend of the computed water level corresponds well with the measured one.

Reach	Rhine -km	ΔH^*_{MQ} (m)	ΔH^*_{HQ93} (m)	Trend
Maxau-Worms	362,20-443,40	0,12	0,18	good
Worms-Mainz	443,40-498,30	0,17	0,23	good
Mainz-Kaub	498,30-546,20	0,05	0,12	good
Kaub-Andernach	546,20-613,80	0,05	0,08	good
Andernach-Cologne	613,80-688,00	0,09	0,07	good
Cologne-Ruhrort	688,00-780,80	0,05	0,09	good
Ruhrort-Lobith	780,80-862,20	0,09	0,05	good

* Maximum difference between computed and measured water level

Table 3.6 The result of steady flow calibration

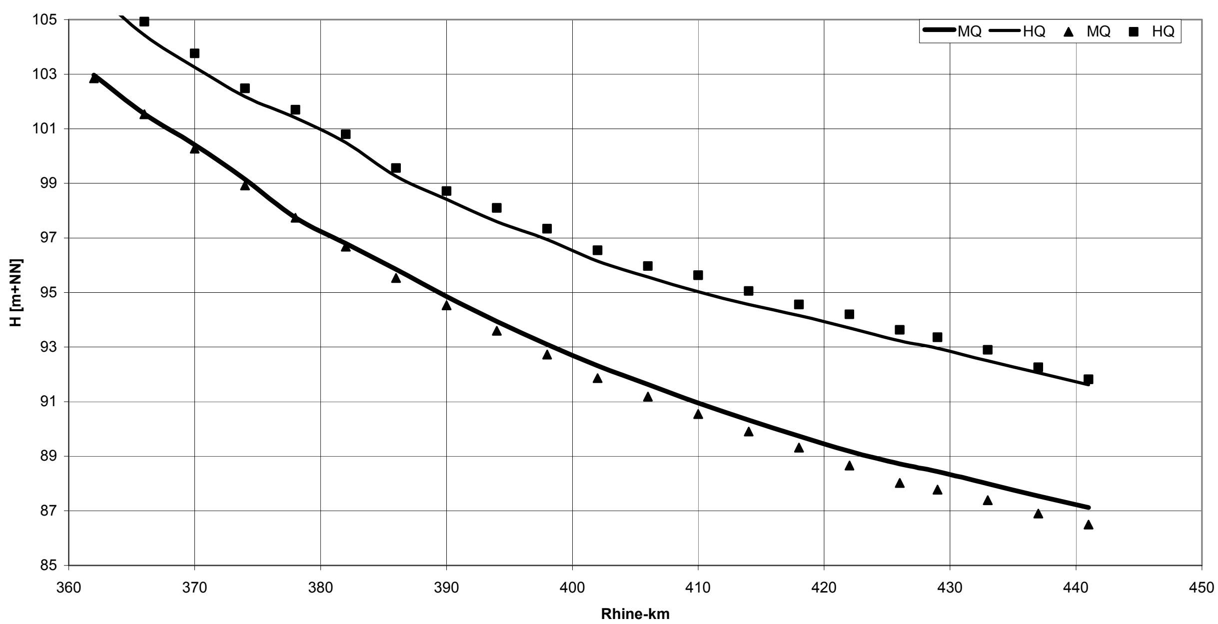


Figure 3.6 Steady flow calibration (reach Maxau – Worms)

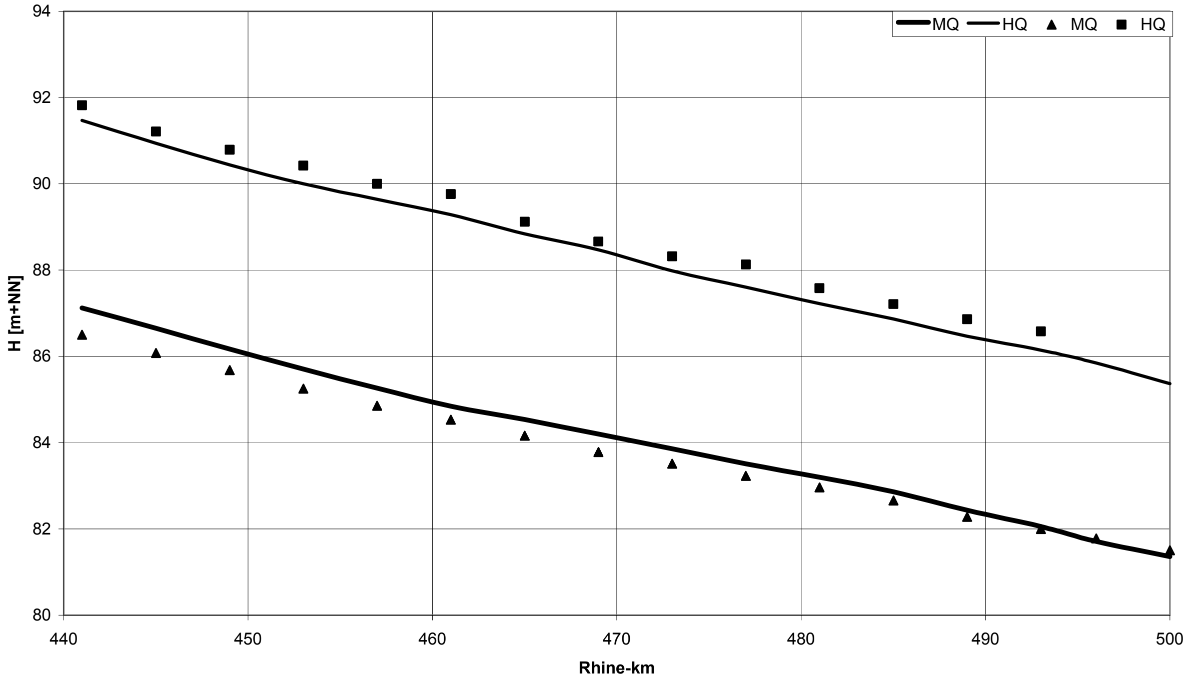


Figure 3.7 Steady flow calibration (reach Worms – Mainz)

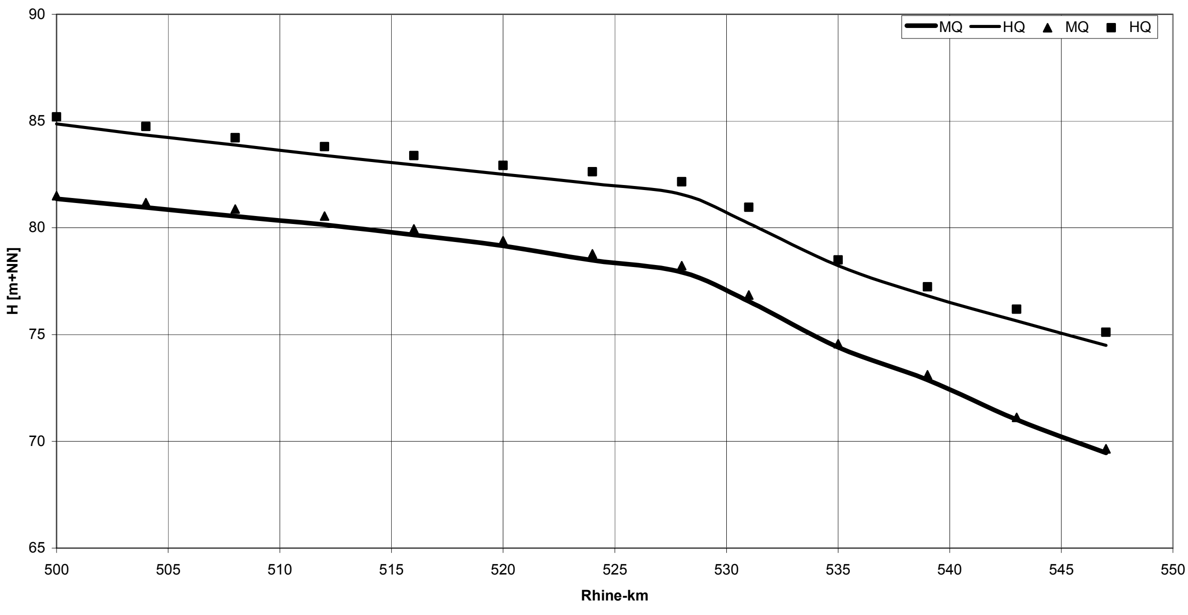


Figure 3.8 Steady flow calibration (reach Mainz - Kaub)

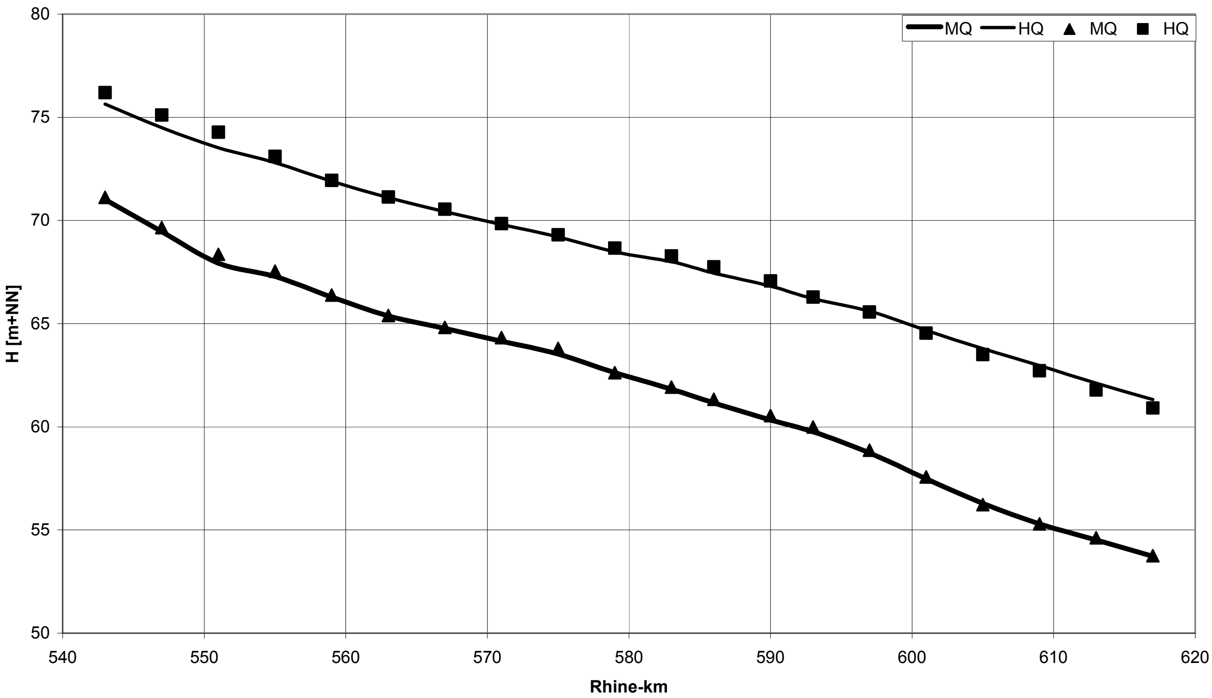


Figure 3.9 Steady flow calibration (reach Kaub - Andernach)

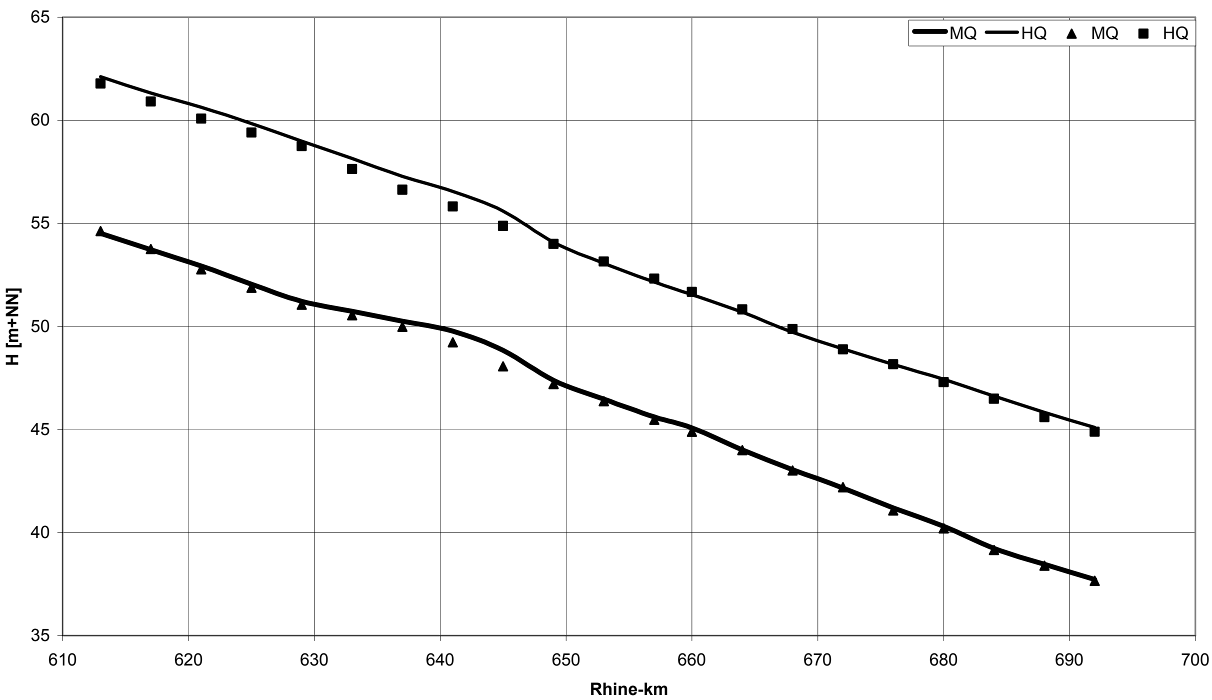


Figure 3.10 Steady flow calibration (reach Andernach - Cologne)

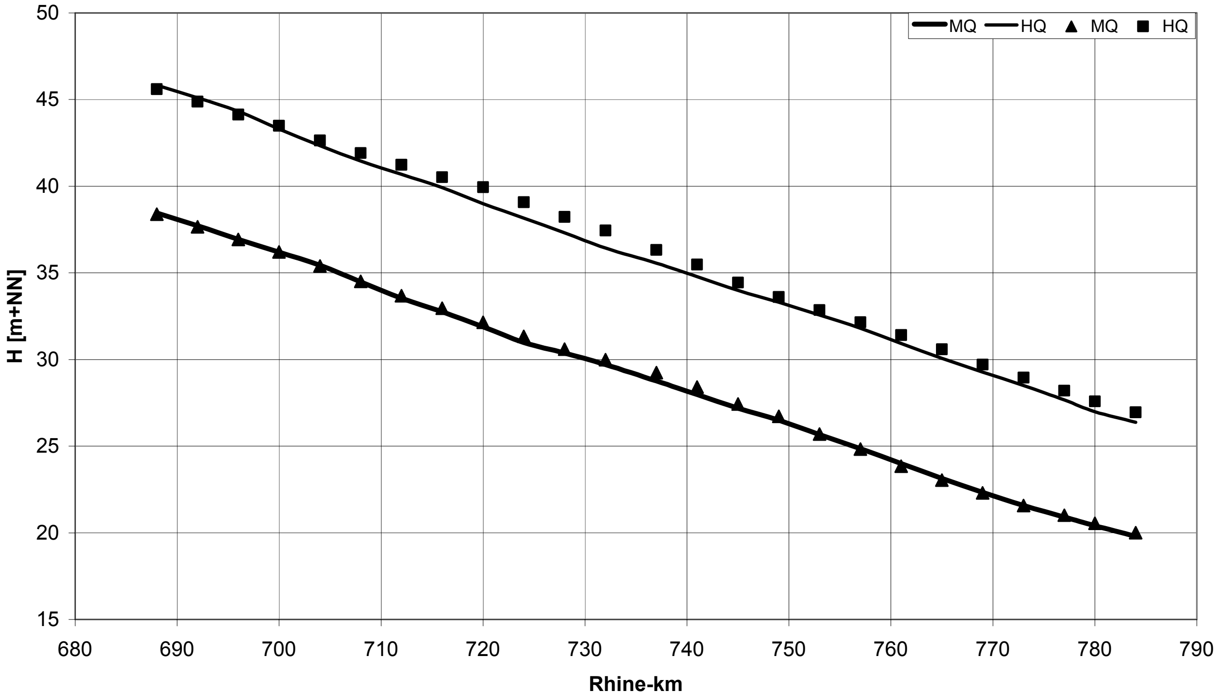


Figure 3.11 Steady flow calibration (reach Cologne - Ruhrort)

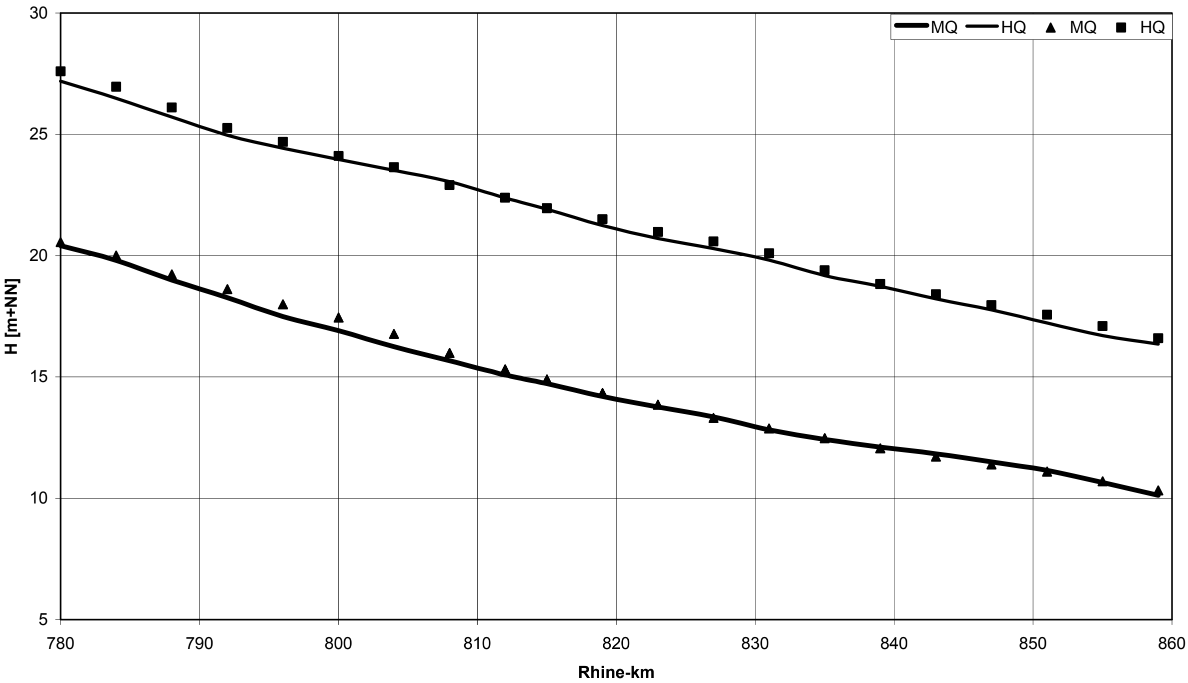


Figure 3.12 Steady flow calibration (reach Ruhrort - Lobith)

3.3.2 Unsteady flow calibration

3.3.2.1 Boundary conditions

For the unsteady flow calibration, the flood wave simulation of December 1993 was used. The flood event 1993/1994 occurred in two waves which can be considered as a hydrological entity. Generally, the first surge (Christmas flood) brought the higher discharges. So, the peak of the first wave at Andernach was associated with a recurrence interval of about 65 years, while that of the following wave peak was just around 5 years. At Koblenz, the two peaks of Rhine and Mosel met with a little time difference, that means the wave of the river Mosel came a bit in advance of the Rhine wave. It caused in the river Rhine a maximum wave that was exceeded only once in this century.

The advance of the flood wave December 1993 is depicted in Figure 3.13 for the river Rhine. The graph is based on the discharges and shows distinctly the surges in discharges in the river Rhine near Koblenz due to River Mosel confluence.

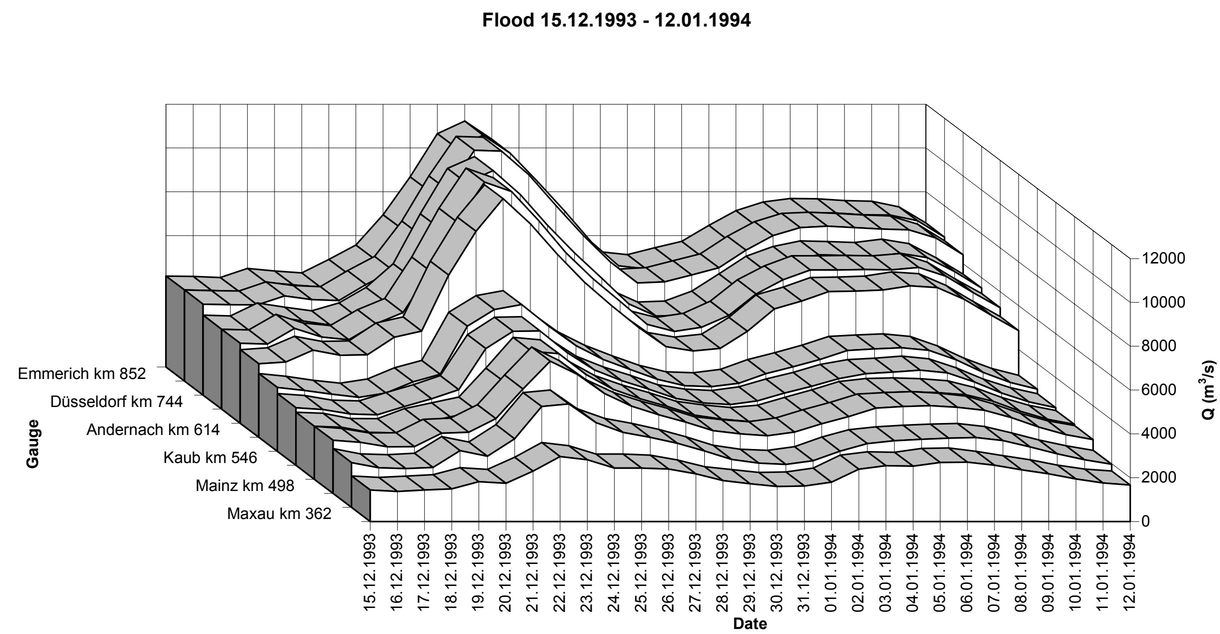


Figure 3.13 The flood discharge of December 1993

The discharge series at the gauging stations were used for unsteady calibration because of the following reasons:

- The permanencies (Wasserspiegelfixierungen) representing the flood wave of 1993 (HW93) are based on flood marks left behind after the events. Connecting the maximum water levels does not produce an actual steady state backwater curve, but an artificial one which never really occurred (BfG, 1997). Using this measured backwater curve for calibration may hamper proper calibration.

- The flood marks of the events 1993 were measured on both sides of the river. It was found that during the flood events the local transverse water surface slope can be quite significant (the differences of water level is about 0.2 m). The mean water levels were applied for the location. It should however be realised that the accuracy of the resulting mean water levels is limited.

- Although the water level measurements were carried out in periods with relatively constant discharge, changes in the river discharge are inevitable during the water level survey. This is especially true when the measurement carried out on different days and during flood periods.

Tributary	Gauging station	Distance to confluence (km)	Measuring frequency	Time lag (hours)
Neckar	Heidelberg	26,10	hourly	04,0
Main	Raunheim	27,00	houry	04,0
Nahe	Grolsheim	07,40	hourly	01,0
Lahn	Kalkofen	106,40	hourly	16,0
Mosel	Cochem	51,60	hourly	08,0
Ahr	Altenahr	30,00	hour ly	04,0
Sieg	Menden1	08,40	hourly	01,0
Ruhr	Hattingen	55,80	hourly	10,0
Lippe	Schermbeck1	22,40	hourly	04,0

Table 3.7 Time lag discharge series tributaries

For the tributaries, the time series of discharges at the confluence with the Rhine were used. As the discharges in the tributaries determined at the gauging stations some distance upstream of the confluence with the river Rhine, a certain time lag should be taken into account. Such a time lag should be based on the distance between gauging station and confluence and an adopted velocity of the flood wave.

In table 3.7 the adopted time lag for the main tributaries are given based on an estimated flood wave velocity of 1.5 m/s.

3.3.2.1 Unsteady flow calibration

The results obtained from unsteady flow calibration with the flood wave of December 1993 show that the differences between measured and computed peak discharges never exceed 300 m³/s. In addition it can be seen that the computed and the observed travel times of the flood wave are in good agreement. The difference between computed and measured travel time at the gauging stations were smaller than 8 hours. But there are still exsiting some differences between computed and measured discharge during the rising or falling limb and at the begin of computation time, especially for the gauge Rees. The sources of errors will be analysed in the next section. The detain investments of the dynamics of the model can be seen in Figures 3.14 to 3.18, Figure 3.19 shows the difference between computed and measured discharge at selected gauges. Table 3.8 indicate the results obtained from the first calibration runs.

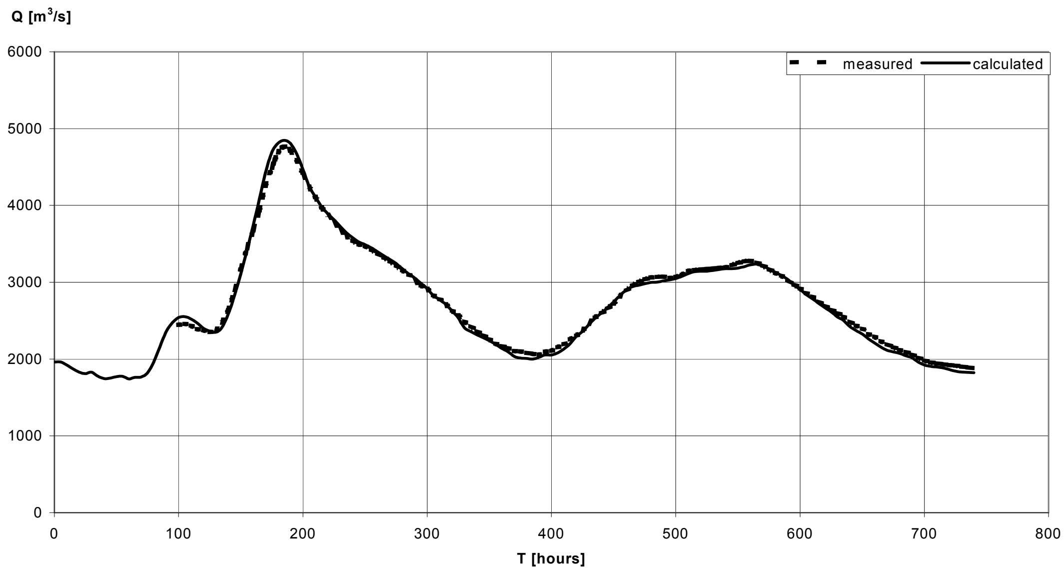


Figure 3.14 Model calibration Worms, December 1993

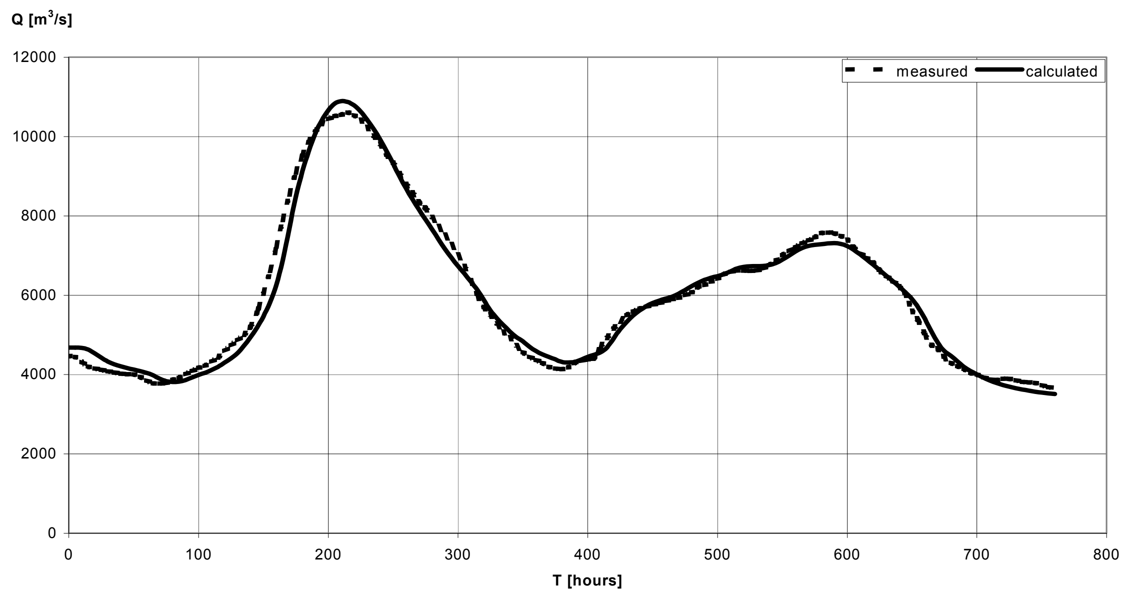


Figure 3.15 Model calibration Bonn, December 1993

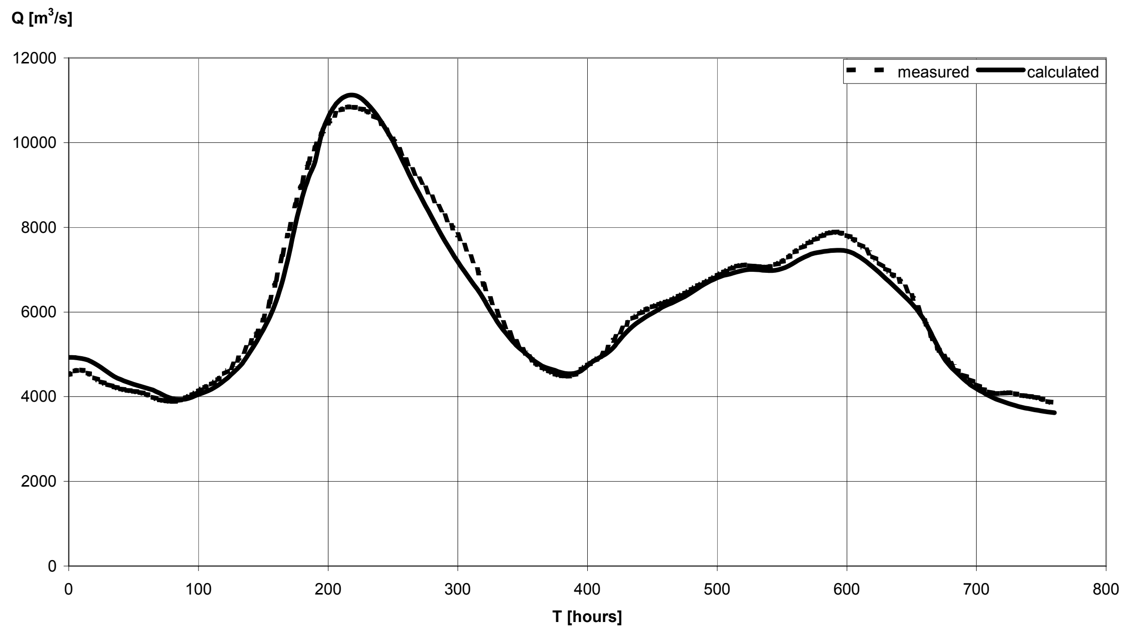


Figure 3.16 Model calibration Cologne, December 1993

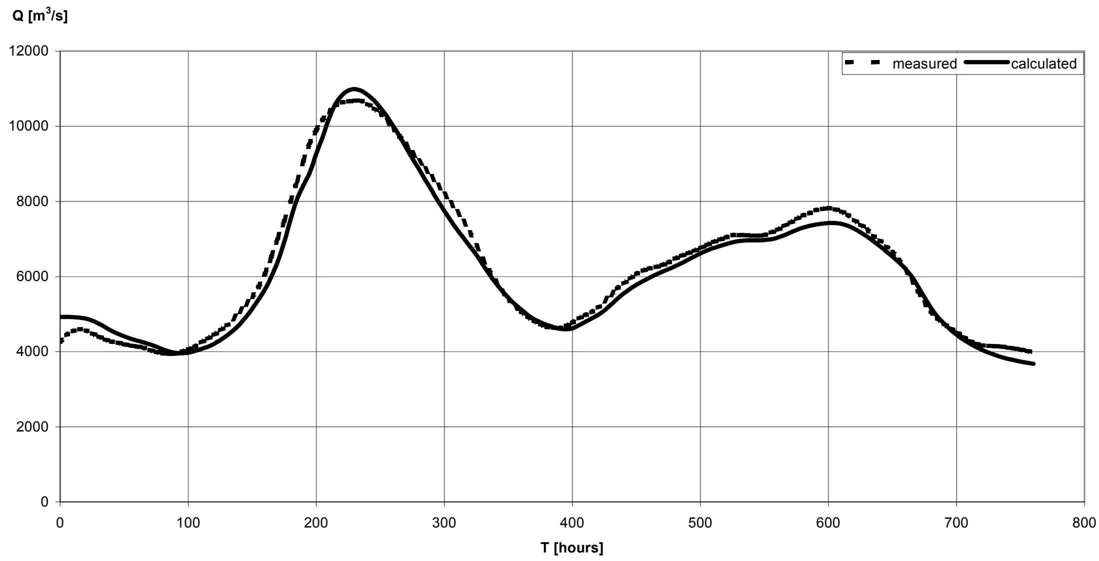


Figure 3.17 Model calibration Düsseldorf, December 1993

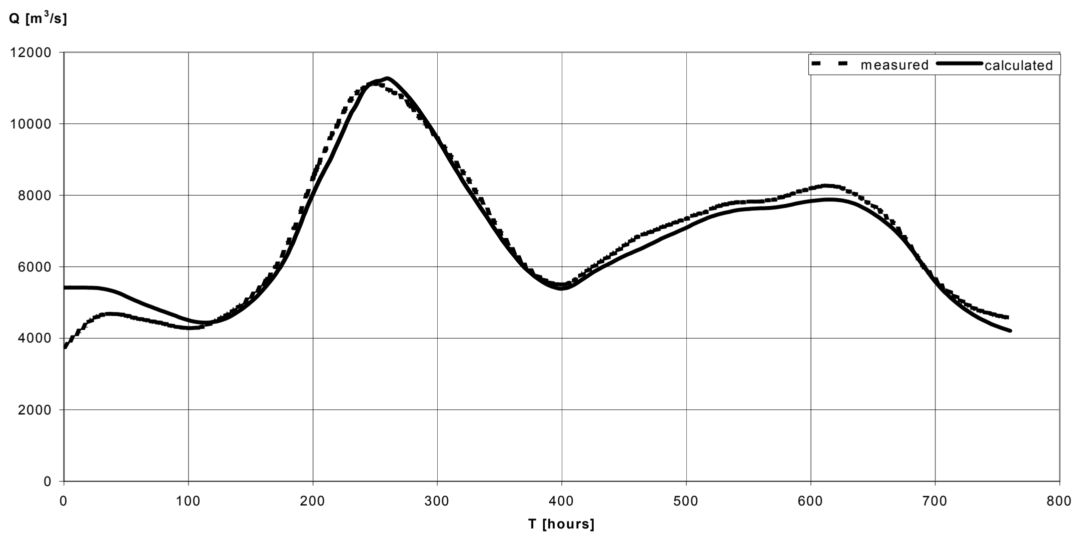


Figure 3.18 Model calibration Rees, December 1993

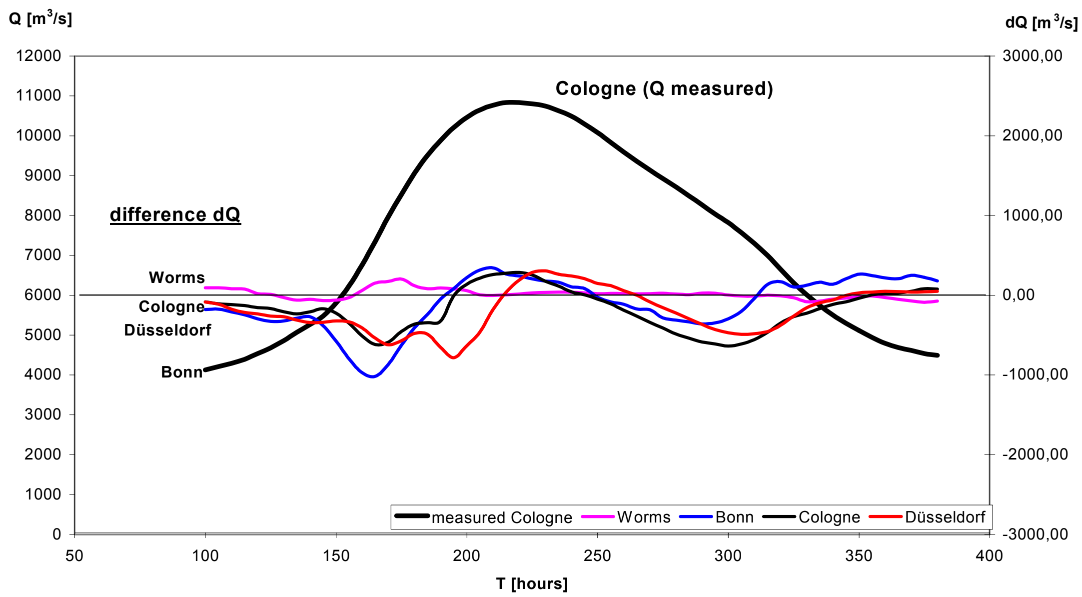


Figure 3.19 Discharge differences in calibration simulation, flood 1993

Gauge	Maxau	Worms	Andernach	Bonn	Cologne	Duesseldorf	Rees
∆Q (m^3/s)	0	73	198	237	298	256	157
∆T (hours)	0	0	6,25	0	1,25	1,75	7,75

Table 3.8 The discharge difference between computed and measured , event 1993

3.4 Analysis of Sources of Errors

The differences between calculated and measured discharges show a small overestimation of the calculated water levels and discharges in the peak of the flood waves. This observation may be explained by a combination of different factors. In this chapter the following possibilities will be discussed.

3.4.1 Structural Errors Rating Curves

The observed events are generally recordings of water stages for different steady state conditions; discharges are normally measured only in order to construct rating curves at a limited number of stations along the river. These rating curves are nearly always defined as single valued relationships between discharge and water stage, and are not always representative of real life. In order to obtain continuous discharge series, measured water level and the calibrated rating curves are used (BfG, 1997). When the condition (e.g. geometry) of the river changes, the rating curve also changes and should be revised. On the river Rhine, some reaches are subject to quicker changes , such as ongoing bed erosion (Upper Rhine), submergence (Duisburg) or rise. In consequence the rating curves are continuously changing and in consequence also the difference between the derived discharges and the real discharges.

In order to assess the reliability of the rating curves at the gauging stations, water balances were made for the flood of 1988, 1993, using the generated discharge series, here called measured discharges (BfG, 1997). For most stations the mean measured discharge agrees well with the discharge according to the water balance. Only for the stations Cologne, Wesel and Lobith larger differences are found. For Wesel this difference is most probably due to the unfortunate location of the gauging station, only 400 m upstream of the confluence with the Lippe. Due to backwater effects the discharge of the Lippe can influence the water level at Wesel and thus the calculated discharge. For this reason the discharges at Wesel are considered to be less reliable (Adler, 1996). The same could be true for Mainz as this station is situated only 1,6 km downstream of Main confluence, and Ruhrort is also located only 0,6 km downstream of the confluenceof the Ruhr. The average measured discharge at Düsseldorf appears to be about 80 m^3/s lower than the measured discharge at Cologne. The same tendency of underestimated discharges at Lobith also can be observed.

However, the uncertainties in rating curves are not the only explaination of the observed difference between calculated and measured discharges. Errors in rating curves would result in over or under-estimation of the measured discharges.

3.4.2 Hysteresis Effect

Due to non-uniformity of the flow, the rating curve (stage-discharge curve) in a flood wave differs from the curve valid for steady, uniform flow. The single curve for steady uniform flow transforms into a loop under unsteady conditions. When the Q(y) relationship is plotted at a given station during the passage of a flood wave, a multi-valued curve is observed; for a single peak flood wave the curve takes the shape of a loop as shown schematically in Figure 3-20.

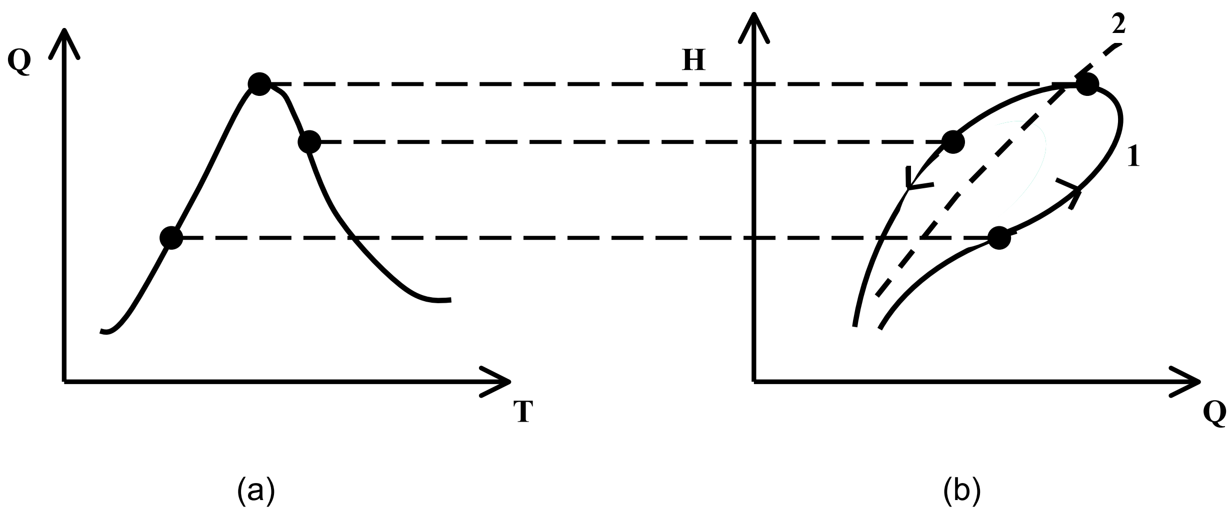


Figure 3.20 Unsteady flow Q(y) relationship

Where:

(a) Schematic representation of flood hydrograph

(b) Associated rating curve:

1 Steady flow relation

2 Unsteady flow relation

Also for the river Rhine the hysteresis effect is expected to play a role. In order to verify this supposition, continuous discharge measurements are envisaged during periods of quick rise or fall. Up to now such measurements are not carried out

(Engel, 1997). One example of the hysteresis effect at gauge Andernach of the flood event 1988 is showed in Figure 3.21.

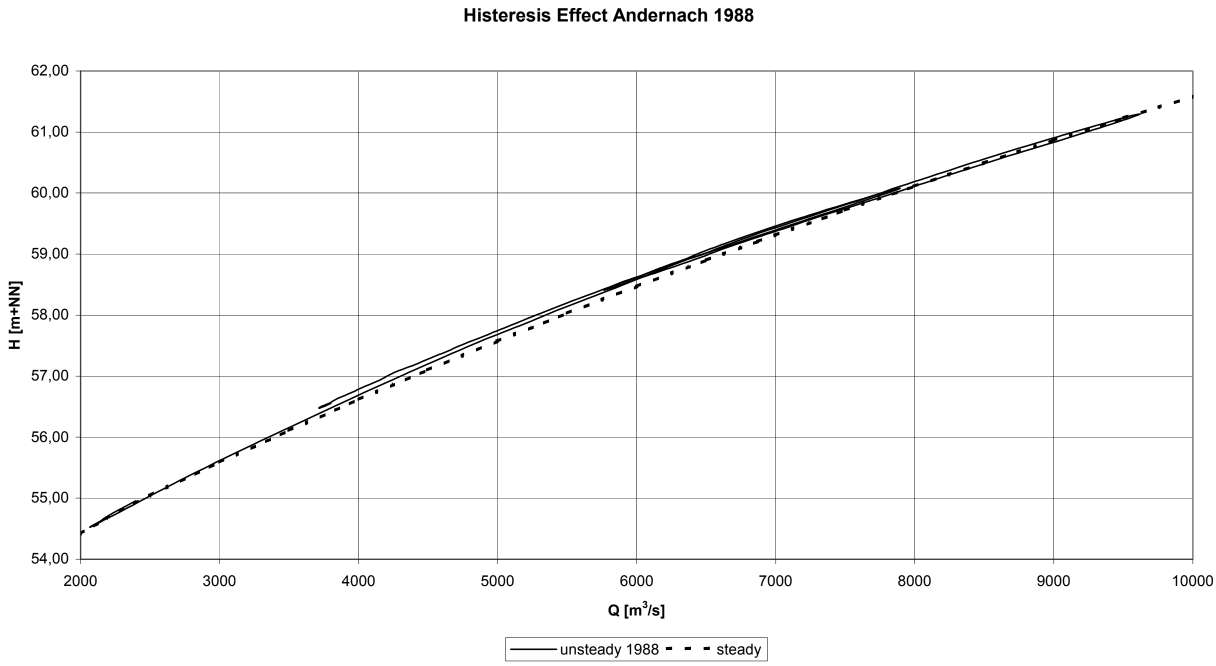


Figure 3.21 Hysteresis effect at Andernach, flood of March 1988

3.4.3 Backwater Effects of Tributaries

When the water levels in the Rhine river are high, the discharge contribution from tributaries to the Rhine river can be temporary hindered due to backwater effects. The water being hold up, should be temporary stored in the tributary or storage areas. This means that the discharge time series measured at the gauging station outside the reach influenced by back water effects, can deviate from the discharge time series at the confluence. During high water levels in the Rhine river the contribution of tributaries may be reduced. After passage of the peak water level, the temporary stored water will increase the discharge from the tributary at the confluence. In the CARIMA simulations the discharge time series from the gauging stations in the tributaries are applied with some time shift as lateral inflows (Table 3.8). If backwater effects are present, the discharge in the simulations can be overestimated during the rising limb of the flood wave in the river Rhine and underestimated in the falling limb. This effect corresponds to the observed difference between calculated and measured river discharges.

The effect of high water levels in the Rhine river on the effective discharge from the tributaries has been estimated using available data from measuring stations as well as from field experience available in Germany. Main emphasis has been put on the main tributaries:

Neckar: One of the main tributaries on the Upper Rhine, only the discharges measured at Heidelberg (26.1 km upstream of the confluence) are available. From Heidelberg to the confluence there are 3 weirs along the river and they were opened during the flood. More or less the application of the flood discharge curve at Heidelberg for the confluence may lead to the difference between computed and measured water level. The flood peak of the Neckar during December 1993 was 2400 m^3/s. This high discharge may lead to a back water effects for the river Rhine at the confluence of the river.

Main: The nearest gauging station available is Raunheim (17 km upstream of the confluence). The flood peak of the Main during December 1993 was 1400 m^3/s. The back water effect of the river Main also should be considered.

Nahe: The discharge at the gauging station Grolsheim is used (7,4 km upstream of the confluence). The flood peak of the Nahe during December 1993 was 1370 m^3/s. This high discharge may lead to the back water effects for the river Rhine at the confluence of the river.

Mosel: The measured discharges at Cochem are used (51,6 km up stream of the confluence). The peak of discharge during the flood event 1993 was 4170m^3/s. It caused a big surge flood for the Rhine downstream of Koblenz. Because of the back water effect at the confluence, the discharge can not be derived directly from the water stage at the gauging station Koblenz - 1.2 km downstream of the Mosel confluence (BfG, 1997).

Sieg: Only the discharges measured at Menden (8.4 km upstream of the confluence) are available. During flood events the area behind the road crossing the Sieg near the confluence, is also flooded. Although the flooded area and flooding depth are not exactly known, the volume of water stored is expected to be restricted (Engel, 1997). The influence on the Sieg discharge at the confluence is therefore assumed to be small.

Ruhr: Discharges are measured at Hattingen (55.8 km upstream of the confluence) and at Mülheim (13 km upstream of the confluence). The discharges at Hattingen are estimated using the rating curve. At Mülheim an acoustic measuring device is used (BfG, 1997). Due to higher turbidity of the water during flood events, the discharges at Mülheim can be measured up to about 650 m³/s so that the discharges at Hattingen should be used for computation. In Fig. 3-22 the discharges at Hattingen and Mülheim are presented for the 1993 flood event. The development of the discharge in time is similar for both stations. Clearly a time shift can be observed as well as an increase in discharge at Mülheim. This can be explained by the additional catchment area contributing to the Ruhr discharge between Hattingen and Mülheim. Both catchment area and river discharge at Mülheim are approximately 9% higher than at Hattingen (BfG, 1997).

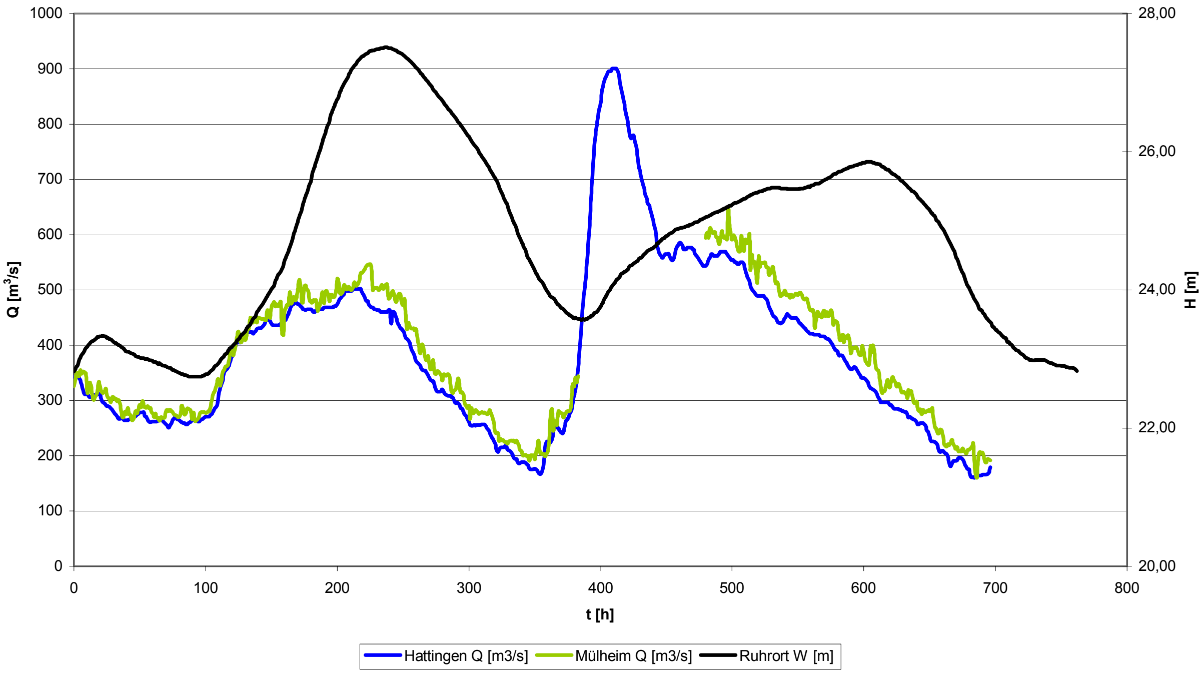


Figure 3.22 Observed Ruhr discharges at Hattingen and Mülheim (December 1993)

Lippe: The confluence of the Lippe is just 400m downstream of the gauging station Wesel. The stage discharge relation for Wesel was found to be less reliable, especially for the periods in which the Lippe discharge is high, the influence on measured water level may be significant (BfG 1997).

3.4.4 Regional Precipitation

The flood of December 1993 has been caused by lasting abundant precipitation. There is no protection embankment on the Rhine stretch from km-529 to km-710 (the Middle Rhine). In this region, the Rhine flows between rock mountains. All the raining water was concentrated in the slope area, approximately 90 km², and comes directly to the Rhine. The amount of water was not considered in the model, so that can cause some differences between computed and measured water level on the gauges Andernach, Bonn and Cologne.

3.4.5 Ground Water

Exchange of water between the river and the groundwater is an ongoing process in most rivers. During flood events the river water level changes rapidly creating a large head difference between the river and the ground water level. This results in a loss of river water to the groundwater reservoir due to which the river discharge reduces and the ground water level rises. During the falling limb of the flood wave the river water level can drop below the groundwater level, due to which the groundwater flows towards the river. The amount of water exchange between river and groundwater mainly depends on the following factors:

River geometry: wetted perimeter and its development in time

Soil: hydraulic conductivity, porosity, initial soil moisture content

Hydraulic conditions: water level and its time derivative,
duration of flood wave.

In order to assess the temporary storage of water in the groundwater, several measuring sections are operated at the Rhine River in Germany. In these measuring sections the development of the groundwater volume is continuously monitored. One of these permament measuring sections is located near Urmitz (km-602,4), approximately 11 km upstream of Andernach. In the flood reports for 1988 and 1993 the groundwater at the Urmitz is presented. Figure 3.23 shows that during these flood events, the groundwater volume increased rapidly during the rising limb of the flood wave and decreased slowly after the peak. The measurements show that the withdrawal of water to the groundwater reservoir can be as large as 3 m³/s per kilometre river length.

In addition a study was carried out by the BfG on the interaction between river flow and groundwater in the river reach Bonn-Cologne (Giebel, 1995). The study showed that for eight flood events in the period 1983 to 1991 the average loss of river water during the rising limb varied between 0,6 and 1,1 m³/s/km. The maximum withdrawal at peak flow could have been as high as 5,5 m³/s/km. This reduction in discharge through bank storage means that during floods the water stage in river Rhine is lower than it would be without this phenomenon. This effect has been computed for the gauge Andernach to reduce the water stage on average by 1,5 cm during its highest level. In the rising phase of the flood, the values of up to 2,9 cm caused even bigger differences in water level, which occurred during the events examined for this between 3 to 4 days before the arrival of the flood peak.

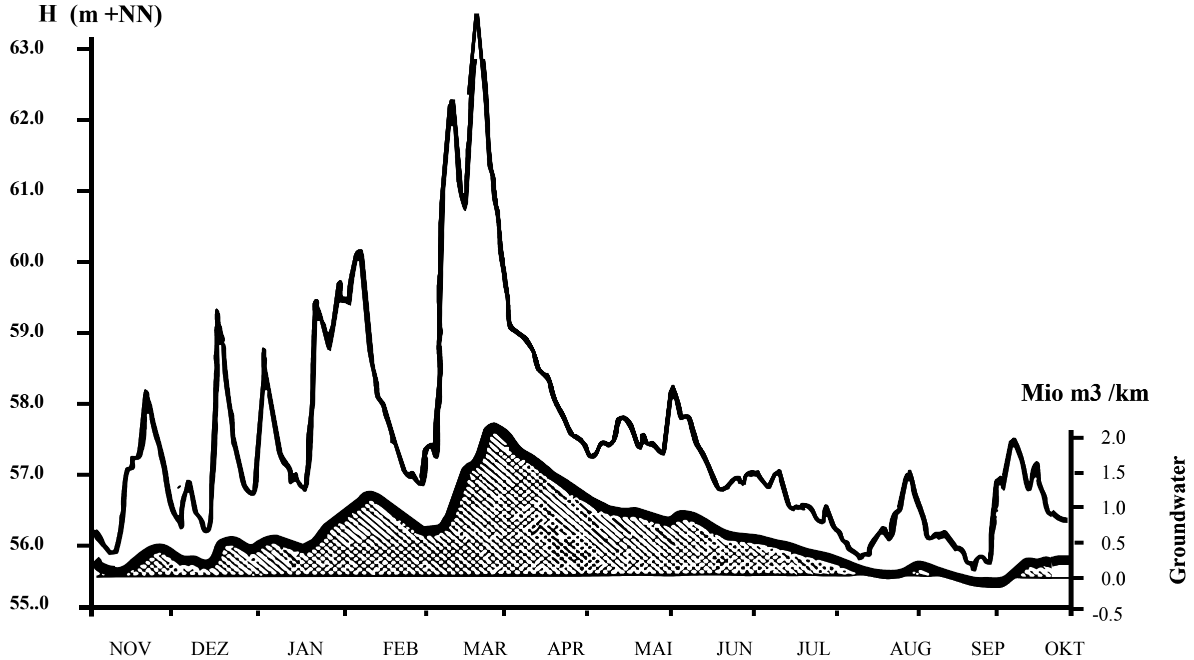


Figure 3.23 Groundwater Storage at Urmit, flood events 1988 and 1993 (BfG, 1997)

These study results clearly indicate that temporary groundwater storage can definitely play an important role in reducing the river discharges in the rising limb and increasing the discharges in the falling limb of the flood wave.

3.4.6 Flooding of the Cities

From km-529 to km-710, the dykes are absent (Fig. 2.7). In this reach the extent of flooded area is determined by the natural valley slope. During the flood events of 1993 many cities on the bank of the river Rhine were flooded. They included the cities of Königswinter (km-646), Bonn (km-655), and Cologne (km-688). Due to the relatively steep valley slopes the flooded areas were restricted to relatively narrow belts. The water volume stored in these flooded areas did therefore not considerably contribute to the difference between calculated and measured discharges.

3.4.7 Schematization

The CARIMA-Model is a one dimensional representation of the three dimensional prototype. In this section some items are discussed which may explain some of the differences between simulations and observations.

For construction of the model representative cross-sections per river reach have been generated. Besides discretization errors introduced in this process, local but important variations in geometry are smoothened due to the selected space step of 1000 m. This may lead to local differences between measurements and simulations.

Another uncertain aspect concerns the flow conveying width on the floodplains. The boundary has been defined using the cross-section profiles and sound engineering judgement through topological maps of the scale 1:5.000. One can imagine that in reaches having complex geometries – such as the reach Wesel – Lobith with its wide flood plains and numerous secondary channels – the flow area is difficult to assess. In addition the methodology adopted, provides a single vertical boundary between flow area and storage area. In reality the flow width may increase with higher water levels.

In many summer dykes gates have been constructed. These can be opened during flood conditions so as to reduce the water level difference over the summer dyke. This may prevent damage to the summer dyke, when the crest level of the summer dyke is over -topped. Operation of these gates is the responsibility of the local government. At present no overview is available how this operation has been during the simulated flood events. Most likely the operation has been even different during subsequent events. In the simulation it has been assumed that the gates remained closed. This means that the storage capacity in the simulations may have been used later than that was the case in reality. This may lead to an overestimation of the water levels in the rising limb of the flood waves.

All these possible imperfections of the model may lead to direct errors in the calculated water level, but may additionally lead to under- or overestimated travel times of the flood waves. Especially during periods with large water level gradients (quick rise or fall) even small errors in travel time may lead to considerable errors in water level.

Finally some restrictions of the one-dimensional model should be mentioned, which may cause differences between measurements and simulations:

- One-dimensional models are sensitive to abrupt changes in geometry (e.g. sudden bottle-necks). In general the local water movement is not properly represented if extreme geometrical relations are present. It is expected that this aspect is not very important for the present Rhine model.

- In a one-dimensional model the river is represented as a straight channel. During flood events the course of water over the floodplain may be shorter than the river measured along the channel axis. Such a reduction of the river length can only be simulated artificially. For example by changing the hydraulic roughness of the floodplain.

- At the boundary between main river and floodplain momentum exchange between the high velocity main river and the low velocity floodplain cannot be simulated directly in a one-dimensional model. A possibility is to include the effect in the hydraulic roughness.

- Lateral slopes (e.g. in river bends) are not simulated in a one-dimensional model.

3.4.8 Other Causes

Apart from the previously described possibilities for explaining the differences between calculated and measured water levels and discharges, other causes shall briefly be given in this section. In this respect the water level distribution through the cross section of the river, time dependent hydraulic roughness and morphological changes, lateral discharge causing by floodplain and other storage pockets could be mentioned. The water level distribution is different through the cross section of the river, especially where the river is meandering or curved. The maximum of the difference is up to 20 cm (Fig. 3.24) at the flood of December 1993 (following the measured water level). On the model, the mean water levels are used. It should however be realised that the accuracy of the resulting mean water level is limited.

During the flood events sediment transport increases and special bed forms (ripples and dunes) may develop. The dimensions of these bed forms can be different during the rising and falling limb of the flood wave. As these bed forms influence the hydraulic roughness, the hydraulic roughness may change during the event. In flood events sediment transports and morphological changes are the largest. If the riverbed changes during an event, water levels before and after the event can be different. Unfortunately no information on short term morphological changes during the event for the Rhine river are available. However, on long time scales an average river bed degradation can be observed up to 0,02 m/year (BfG, 1997).

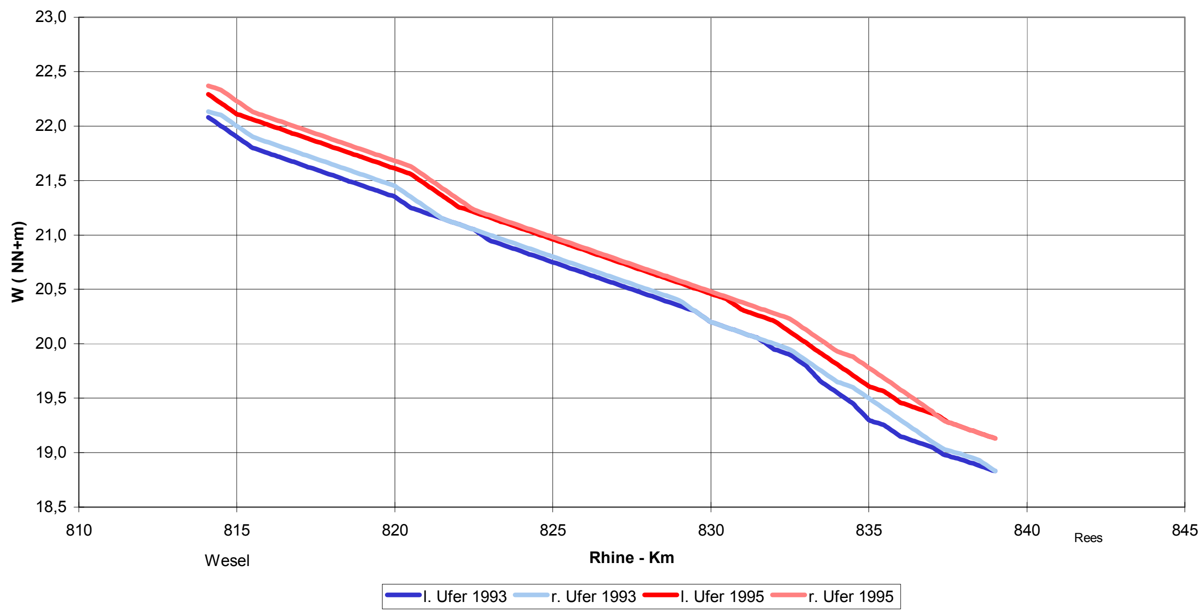


Figure 3.24 Difference of measured water level across the cross section

The floodplain and other storage pockets along the river may cause the lower water level during the rising limb and the higher water level during the falling limb of the flood. Within the model in the case of without flood retention polders, such storage volumes are not taken in to account. This may explain the difference between computed and measured water level in some locations.

3.5 Final calibration of the Model

In the previous section the CARIMA-model has been calibrated using measured steady state conditions and measured discharges during the flood event of December 1993. The errors which appeared on the previous calibration have been analysed in the section 3.4, in which the back water effects of tributaries and the groundwater play an important role during flood event.

Gauge	Rhine-km	Strickler Coefficient k_{St} $[m^{1/3}/s]$			
		Old	New	Old	New
Maxau (362,3)	362 - 425	20	15	35	32
Worms (443,4)	426 - 470	25	15	38	40
Mainz (498,3)	471 - 526	18	10	33	35
Kaub (546,2)	527 - 556	15	10	33	30
Koblenz (593,5)	557 - 593	15	15	35	35
	594 - 600	15	30	33	35
Andernach (613,8)	601 - 630	25	30	37	35
Bonn (654,7)	631 - 659	15	30	33	35
Cologne (688,8)	660 - 693	30	33	42	38
	694 - 700	25	25	33	35
Düsseldorf (744,2)	701 - 750	20	25	35	33
Ruhrort (780,8)	751 - 780	25	35	33	43
Wesel (814,0)	781 - 825	15	30	33	33
Emmerich (852,0)	826 - 862	20	25	33	35

Table 3.9 The new Strickler value application for the final calibration

For obtaining satisfactory agreement between calculated and measured water levels, the hydraulic roughness values of the river bed and floodplains can be varied. In addition corrections of the river geometry in the model can improve the simulation results.

After many simulation runs, the following Strickler values were chosen (Table 3.9). On the Upper reach, the smaller Strickler value were chosen. In the reality, in the flood plain forests are existing.

Table 3.11 shows the differences between the computation and measurement after final calibration at some collected gauges. It indicated that there is good agreement between computed and measured discharge. The difference never exceeds 300 m³/s in case of discharge and 6 hours in case of time.

Gauge	Maxau	Worms	Andernach	Bonn	Cologne	Duesseldorf	Rees
ΔQ (m³/s)	0	35	98	153	235	178	117
ΔT (hours)	0	0	1,78	0	1,25	1,75	5,25

Table 3.10 The difference between computed and measured discharges

Comparison the results obtained from the first calibration (Table 3.9) and final calibration computation (Table 3.10) shows the remarkable improvement: The difference of the computed peak discharge in comparison with the measured once now is only 235 m³/s at the hydrological gauge Cologne (Qmax = 11.000 m³/s). Approximately equal to 2% of the highest discharge, it is a very good result in 1-D hydraulic computation.

4 Model Verification

After final calibration simulation, the model has been improved with the combination of changing hydraulic roughness and geometry characteristic in some reaches on the Middle Rhine. The model obtained better agreement with the observed discharges and time series. In this section these choices are further verified using water levels measured during the events of March 1988 and February 1999.

4.1 The flood of March 1988

The flood event of March 1988 caused the highest water levels in the considered part of the Rhine since 1926 (BfG, 1997). The high rainfall causes two flood peaks of which the latest one (end of March) produced the highest water levels. Figure 2.3 shows the river discharges at the gauging stations on the river reaches in March and April 1988.

Similar to the previous calibration for the flood event of December 1993, the measured discharge at Maxau has been applied as the upstream boundary condition. The discharges time series of the tributaries with time lag were applied as the lateral discharges at the confluences. The stage discharge relation for Lobith has been used for the boundary at downstream. The Strickler values were used as in final calibration run.

Figure 4.1 – 4.8 show the results of calibration at gauging stations. Figure 4.9 is demonstrating the difference between computed and measured water level.

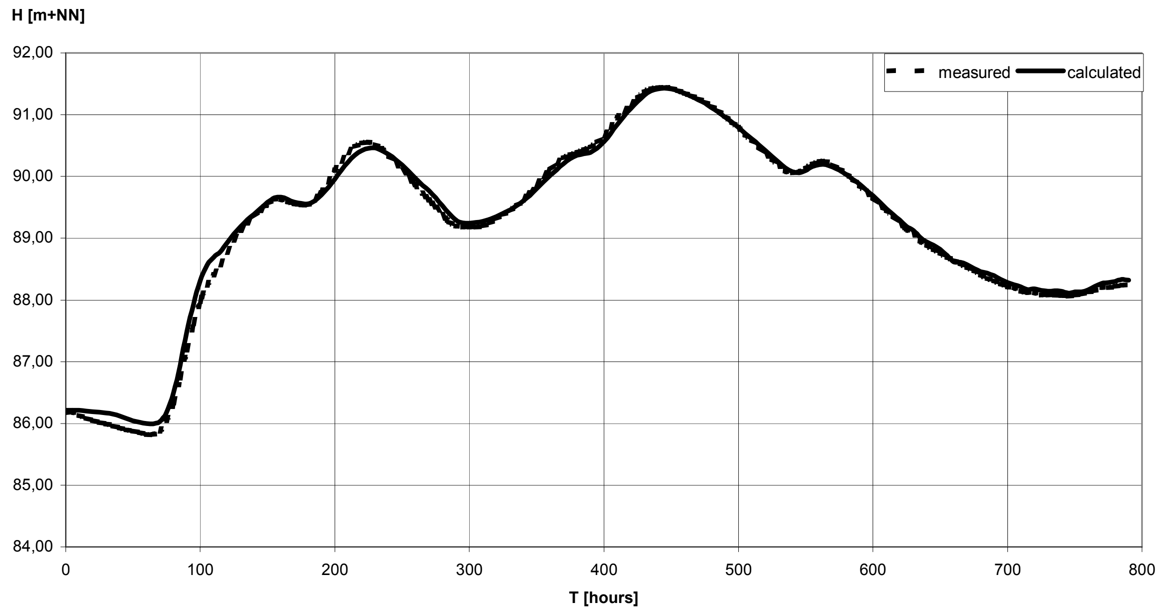


Figure 4.1 Model verification - Worms, March 1988

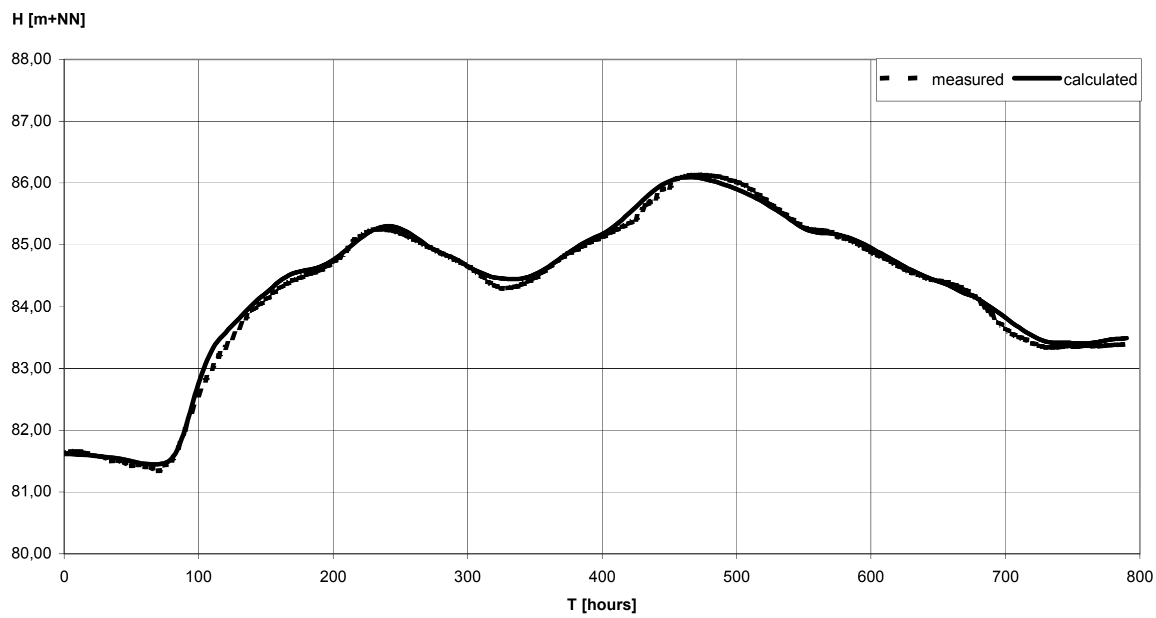


Figure 4.2 Model verification – Mainz, March 1988

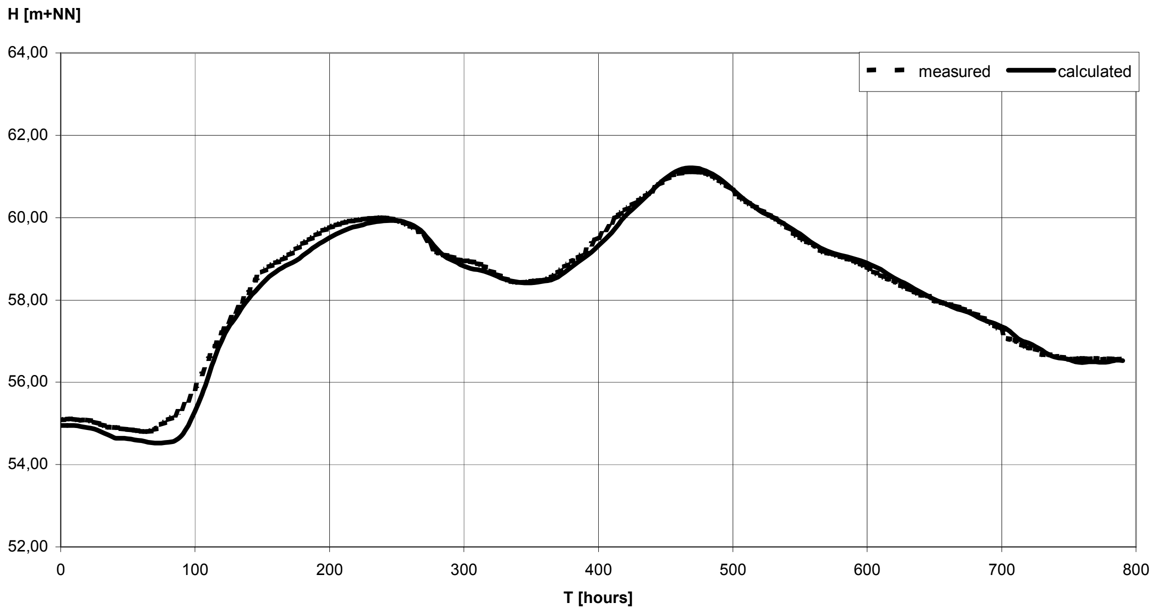


Figure 4.3 Model verification – Andernach, March 1988

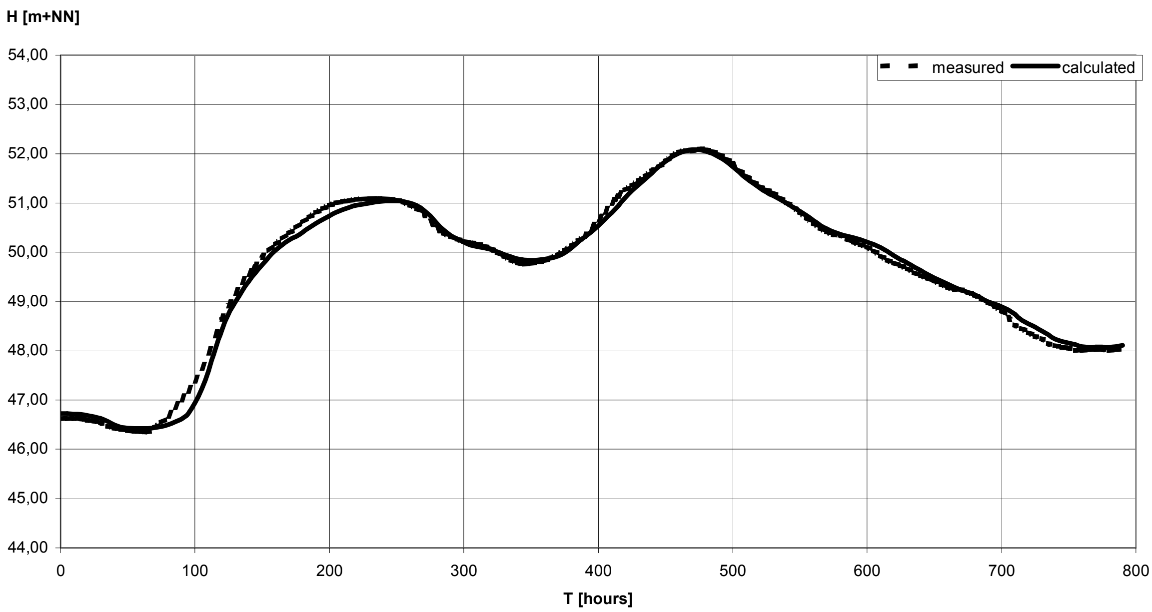


Figure 4.4 Model verification – Bonn, March 1988

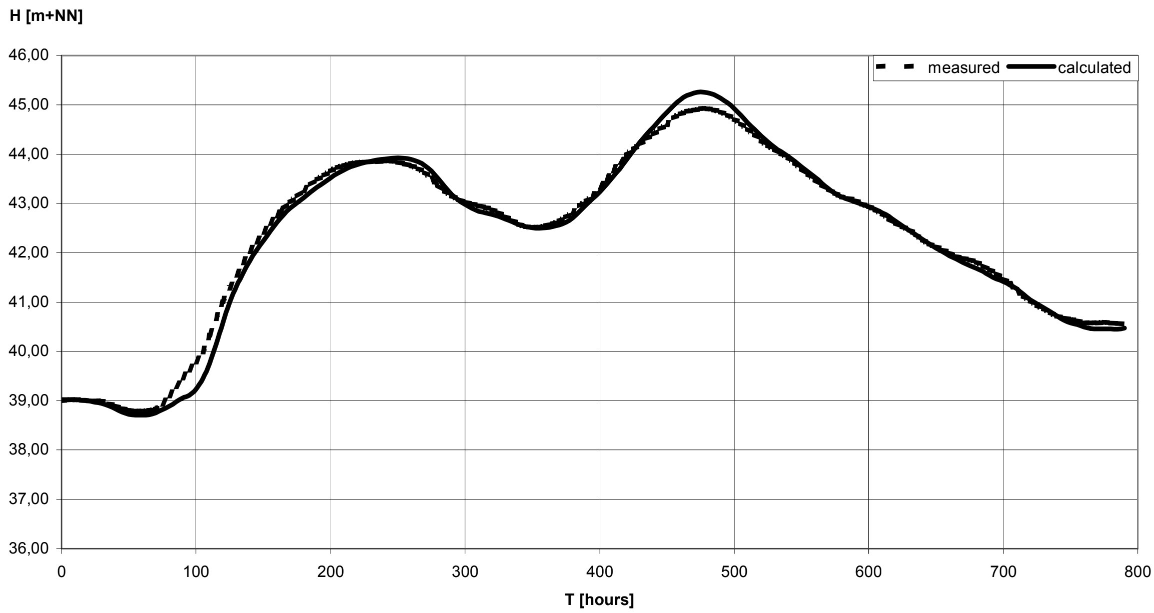


Figure 4.5 Model verification – Cologne, March 1988

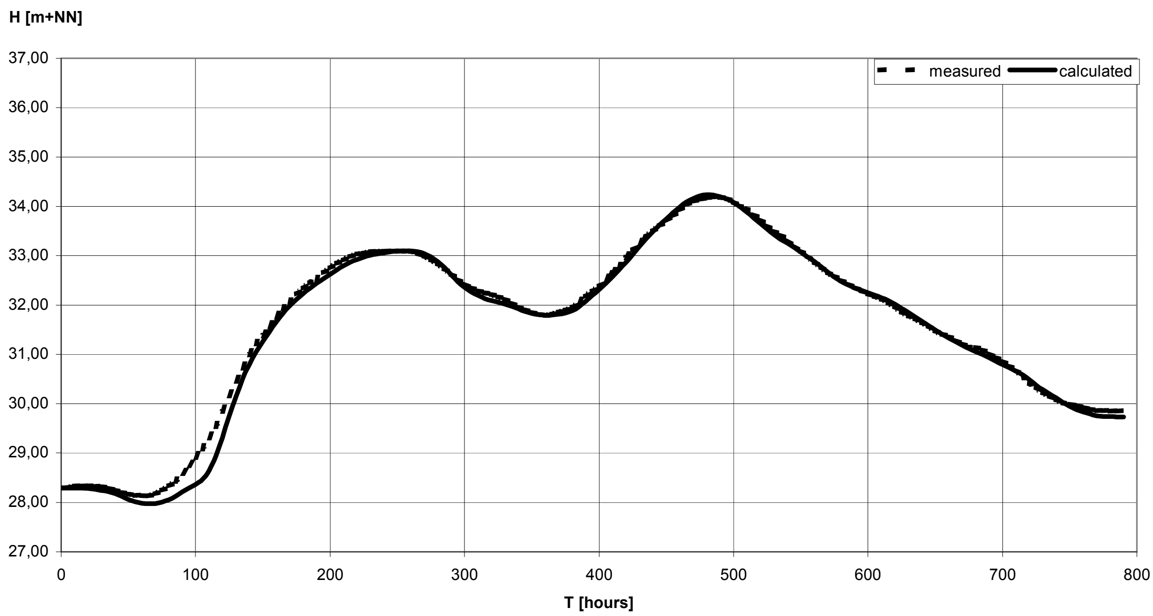


Figure 4.6 Model verification – Duesseldorf, March 1988

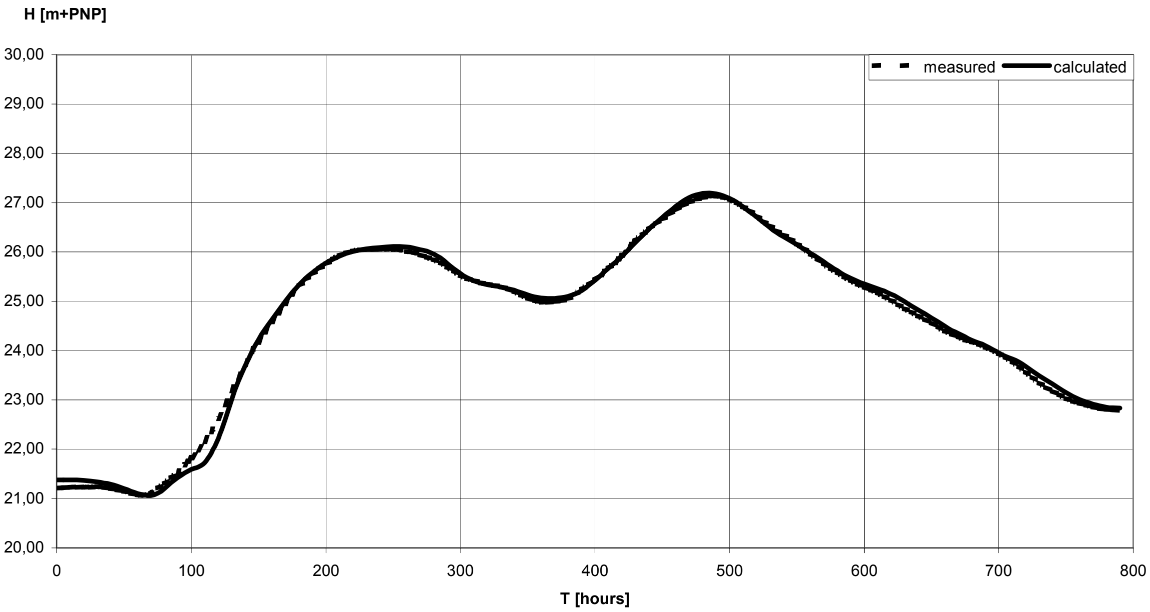


Figure 4.7 Model verification – Ruhrort, March 1988

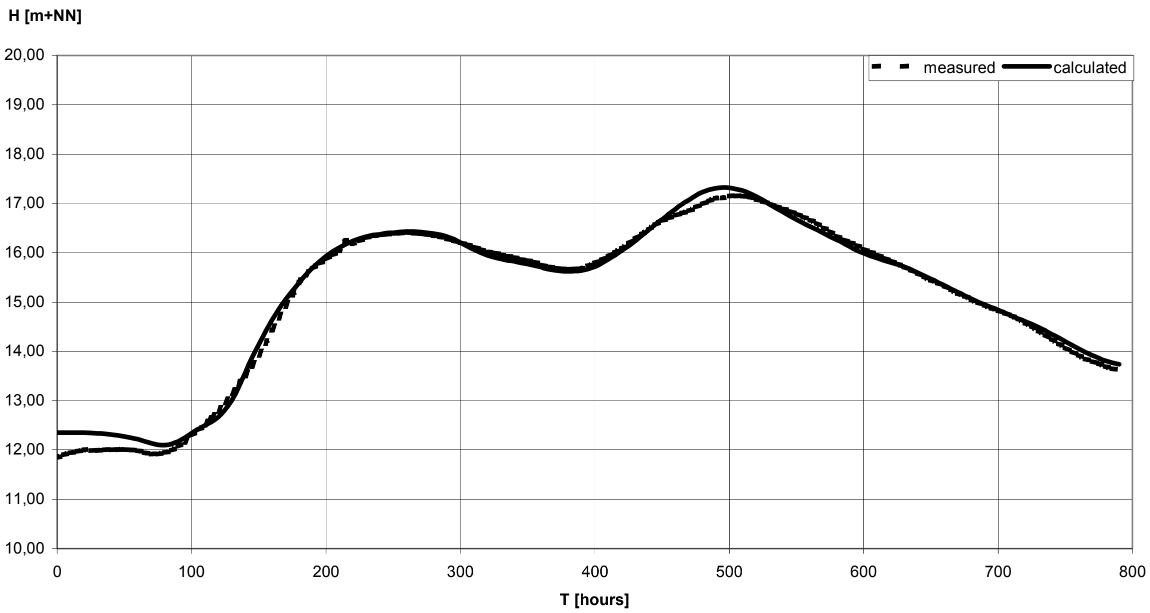
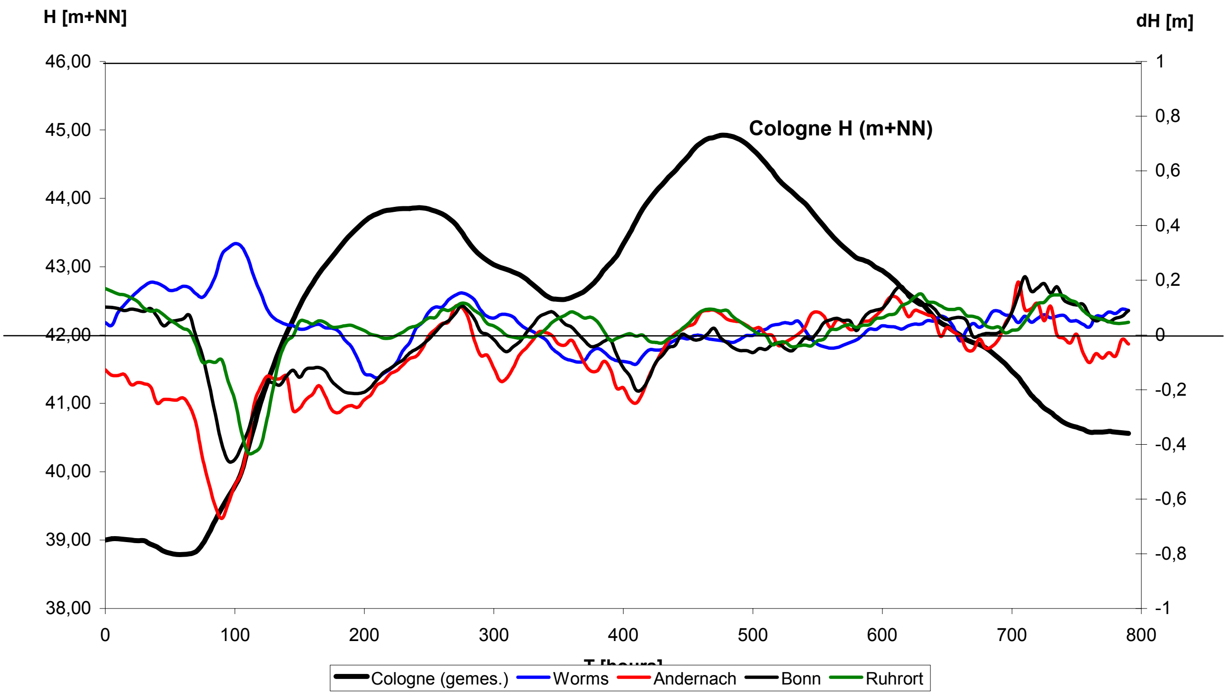


Figure 4.8 Model verification – Emmerich, March 1988



T (h)

Figure 4.9 Differences between computed and measured water level, March 1988

In Fig. 4.9 is demonstrated that the differences between computed and measured water level during flood discharge were never over 0,20 m. The differences between computed and measured water level, time can be seen in Table 4.1.

Gauge	**Worms**		**Mainz**		**Andernach**		**Bonn**	
	Peak I	Peak II	Peak I	Peak II	Peak I	Peak II	Peak I	Peak II
Δ H (m)	-0,1	0	0,02	-0,03	-0,07	0,09	-0,04	0,01
Δ T (h)	0	0	0	-1,25	3,25	0	2,75	0
Gauge	**Cologne**		**Duesseldorf**		**Ruhrort**		**Emmerich**	
	Peak I	Peak II	Peak I	Peak II	Peak I	Peak II	Peak I	Peak II
Δ H (m)	0,06	0,20	0,04	0	0,02	0,02	0,02	0,17
Δ T (h)	1,75	0	0	0	0	1	0	-5

Table 4.1 Differences between computed and measured water level, time, 1988

The difference between calculated and observed travel time of the highest flood wave of 1988 appears to be negligible. As far as the second and highest peak is concerned, the differences between computed and measured peak water levels generally fall below a maximum of 0,10 m. For the first flood wave the computed water levels fit very good with the measured water levels. For the second peak, the differences appeared to be higher at Cologne and Emmerich. A possible explanation could be the inflow from inundation areas located upstream Cologne and upstream Emmerich. These kinds of inundation areas are not simulated in the first run of the model.

4.2 The flood of February 1999

The flood of February 1999 was caused by strong rainfall and snow melting in many upper regions. In Upper Rhine some of the retention polders along the Rhine were active at the first time after construction. At Cologne, the water level was 8,88 m when in 1993, the water level was 10,60 m CW (Cologne Water level). Although the peak river discharge was much lower than in the 1988 and 1993 events, the flood wave provides good opportunity for additional verification of the model. Main reason for this is that many summer dikes are being overtopped at this event. This flood wave thus can give insight whether the geometry of the one-dimensional flow is a good representation of the prototype. Figure 2.6 shows the river Rhine discharges at the gauging stations and also the tributaries discharges at the selected gauging stations. It was the high flood, especially for the Upper Rhine leading to the attention concerning the protection of the Rhine and that the flood precaution works were to be strengthened.

The inflow discharges of the tributaries and the stage discharge relations for Lobith have been applied for the model boundary.

The results obtained from computations show a very attractive picture: The time when the peak water level appeared in computation and observation is the same. During the rising limb, the computed water levels were lower than the measured ones, during the falling limb, the computed water levels were higher the measured ones. This difference can be explained by losing water during the rising limb of the flood wave over the summer dikes and infiltration into ground water and the return of the water during the falling limb. Figure 4.10 and 4.11 show the results obtained from the simulation run. The differences between computed and measured water levels can be seen in Figure 4.12. The detail results are presented in Table 4.2.

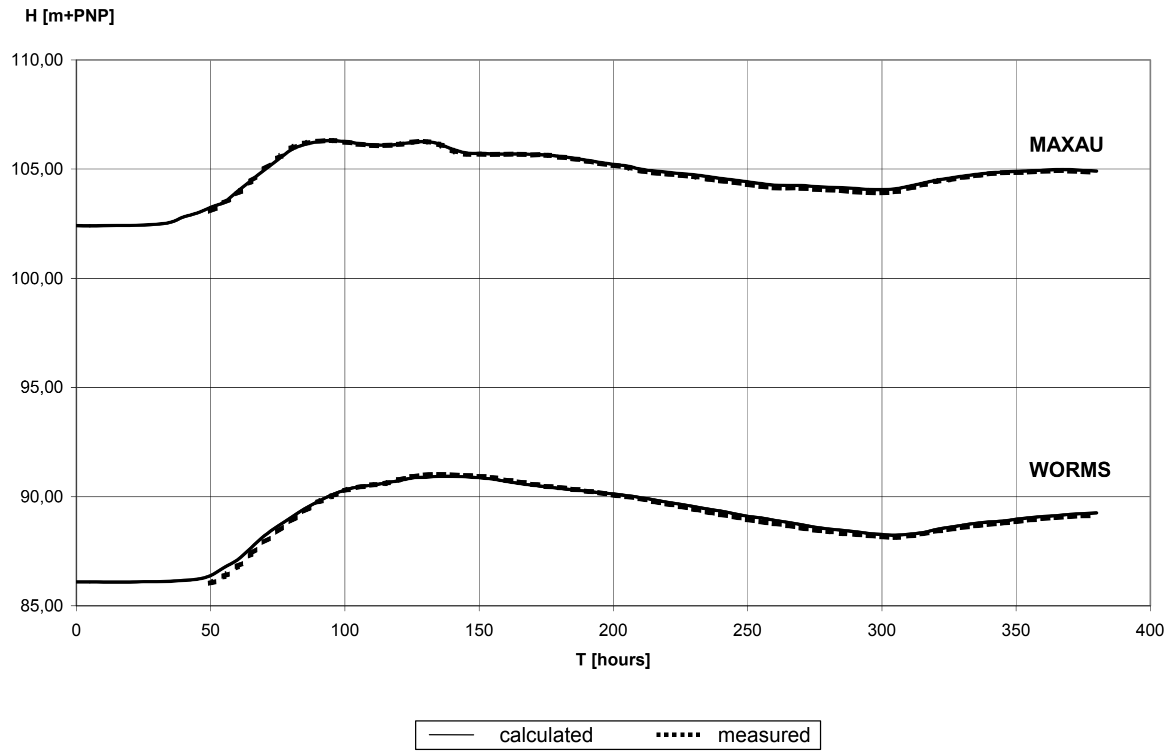


Figure 4.10 Model verification, Upper Rhine, February 1999

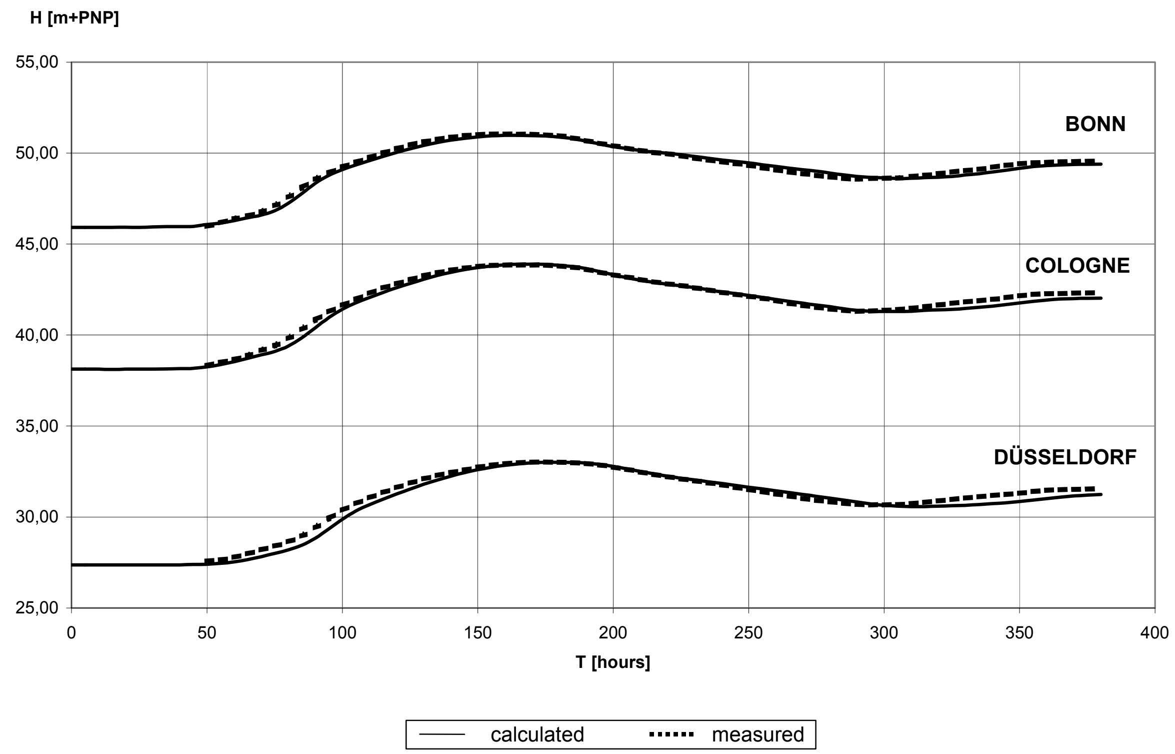


Figure 4.11 Model verification, Lower Rhine, February 1999

As it was shown in the results, the differences between computed and measured water levels never exceeds 0,10 m, the time when the peak water level appeared is smaller than 2 hours. Table 4.2 shows the results obtained from verified calibration simulation with the flood wave of 1999.

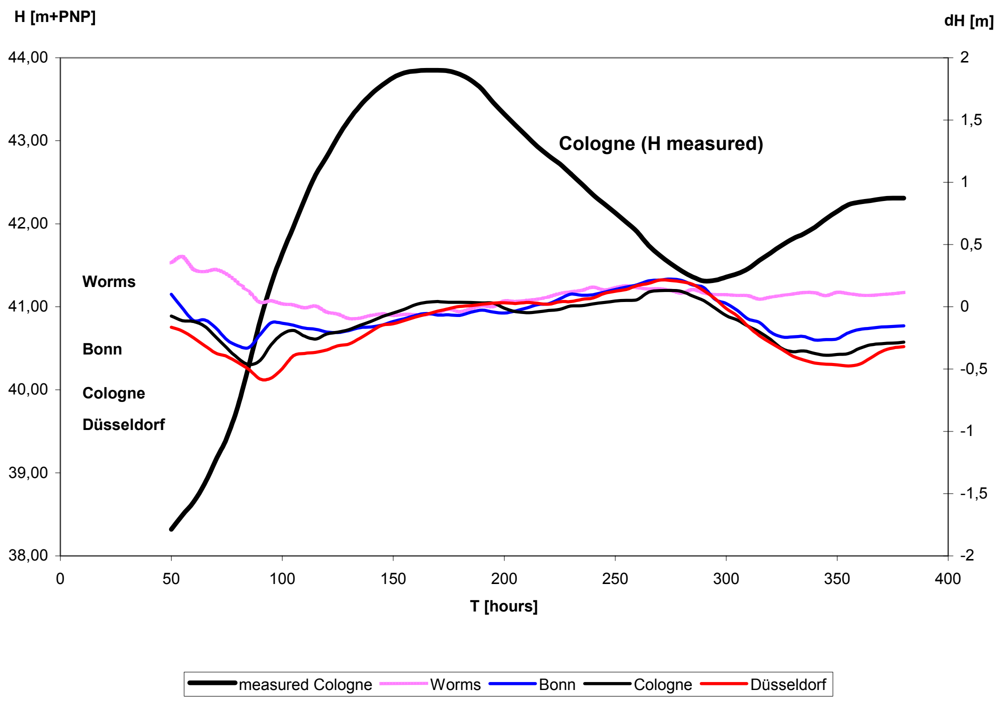


Figure 4.12 Differences between computed & measured water level, 1999

Gauge	Maxau	Worms	Bonn	Cologne	Duesseldorf
ΔH (m)	0	-0,09	-0,09	0,04	-0,02
ΔT (h)	0	0	1,75	0	0

Table 4.2 Differences between computed and measured water level & time, 1999

4.3 Conclusions and remarks

• A Hydrodynamic-Numerical Model of the river Rhine has been developed that simulates the December 1993 flood on the river Rhine from Maxau to Lobith. Calibration of the model was carried out and modelled discharges were within the target error of 235 m^3/s (Table 4.2).

Gauge	Maxau	Worms	Andernach	Bonn	Cologne	Duesseldorf	Rees
ΔQ (m^3/s)	0	73	198	237	298	256	157
ΔQ* (m^3/s)	0	35	98	153	235	178	117
ΔT (hours)	0	0	6,25	0	1,25	1,75	7,75
ΔT* (hours)	0	0	1,78	0	1,25	1,75	5,25

* After final calibration

Table 4.3 Differences between computed and measured time and discharge

• Using discharges time series obtained from rating curves may cause some difference between computation and measurement. Therefore the verified calibration of the water stage time series were used.

• The model was verified using data from the flood of March 1988 and February 1999. The results obtained very good agreement between computed and measured water levels. The differences between computed and measured water levels never exceed 0,20 m. The time when the peak water levels appeared in computation and measurement were almost the same.

• The model, however, requires accurate estimation of the time lag concerning inflows from tributaries for both calibration and verification run.

• The storage of water in the plains and other sources may cause an effect on the water level but only at the rising and falling limb.

5 Model Simulation

5.1 Impact of the retention polders along the Rhine

Along the Rhine in Germany, retention areas – large polders beside the river, which inundate only at times of flood – are being created. These will be able to store up to 270 million cubic metres of water and are planned in the state of Baden-Württemberg, Rhineland-Pfalz, Hessen and North Rhine-Westphalia. About a 100 million cubic metres of capacity is already available, and was first utilized during the high water episode of 1988. By diverting water into these retention areas, it was possible to reduce the water level downstream.

The flood event of 1988 caused one of the highest water levels in the considered part of the Rhine since 1926. The high rainfall caused two flood peaks of which the latter one (end of March) produced the higher water levels. Figure 2.3 shows the river discharges at the gauging station of the Rhine in March and April 1988.

In order to assess the effects of a polder system along the river with respect to flood regulation, the model was simulated with all the polders along the Rhine (polders already existing, polders under construction and in planning stage as have been shown in Table 5.1). The flood event of March 1988 was used for computation. The results obtained can be seen in the Figures from 5.1 to 5.7

The effects on water levels were small because during the flood event 1988 only some of the polders were active. In the Upper Rhine the effects were small. The summary results obtained from computation are showed in Table 5.2.

Nr.	Polders	Km	Construction	Area (ha)	V (10^6 m^3)	Elevation (m + NN)
1	Bellenkopf/Rappenwört	357,0	plan	510	14,0	106,50
2	Elisabethenwört	382,0	plan	400	11,9	98,00
3	Rheinschanzinsel	390,5	plan	210	6,2	96,00
4	Daxlander Au	358,0	plan	200	5,1	105,50
5	Neupotz/Wörth	364,0	plan	250	10,0	104,00
6	Mechtersheim	388,0	plan	500	7,4	97,00
7	Flotzgrün	392,0	plan	300	5,0	95,00
8	Kollerinsel	409,0	plan	500	6,1	94,00
9	Waldsee/Altrip/Neuhofen	412,0	plan	500	8,1	93,50
10	Petersau/Bannen	434,0	plan	200	1,4	91,00
11	Mittelbusch (Worms II)	438,0	plan	150	2,3	90,00
12	Bodenheim/Laubenheim	492,0	plan	700	6,0	84,00
13	Ingelheim	518,0	plan	500	3,8	82,00
14	Siegmündung	657,5	plan	250		50,00
15	Niederkassel	665,0	operation	10	0,2	47,50
16	Köln-Langel (Lülsdorf)	672,0	construction	500	6,0	46,00
17	Worringer Bruch	708,0	construction	600	29,0	39,00
18	Monheim	712,0	construction	200	8,0	38,00
19	Dormagen	717,0	plan	415		36,50
20	Urdenbach	718,0	operation	600		30,70
21	Itter-Himmelgeist	727,0	construction	60	2,0	35,00
22	Illvericher Bruch (Meerbusch)	753,0	construction	400	15,0	30,00
23	Lank	760,0	plan	280		30,00
24	Mündelheim	767,0	plan	150	5,0	28,00
25	Binsheim	788,0	plan	505		20,00
26	Orsoyer Land	803,0	operation	220	10,0	18,50
27	Mehrum	807,0	plan	170		20,00
28	Wallach	809,5	plan	60		21,00
29	Ginderich	815,5	plan	250		20,00
30	Flüren	817,5	plan	400		20,00
31	Bislicher Insel	823,0	operation	1100	50,0	15,00
32	Lohrwardt	834,0	plan	275	15,0	17,50
33	Löwenberg	844,0	plan	125		16,00
34	Grietherbusch	846,5	operation	1100	25,0	16,10
35	Bylerward	848,0	construction	720	30,0	16,00
36	Salmorth	862,0	plan	1000		13,70

Table 5.1 Polder system along the Rhine used for model simulation

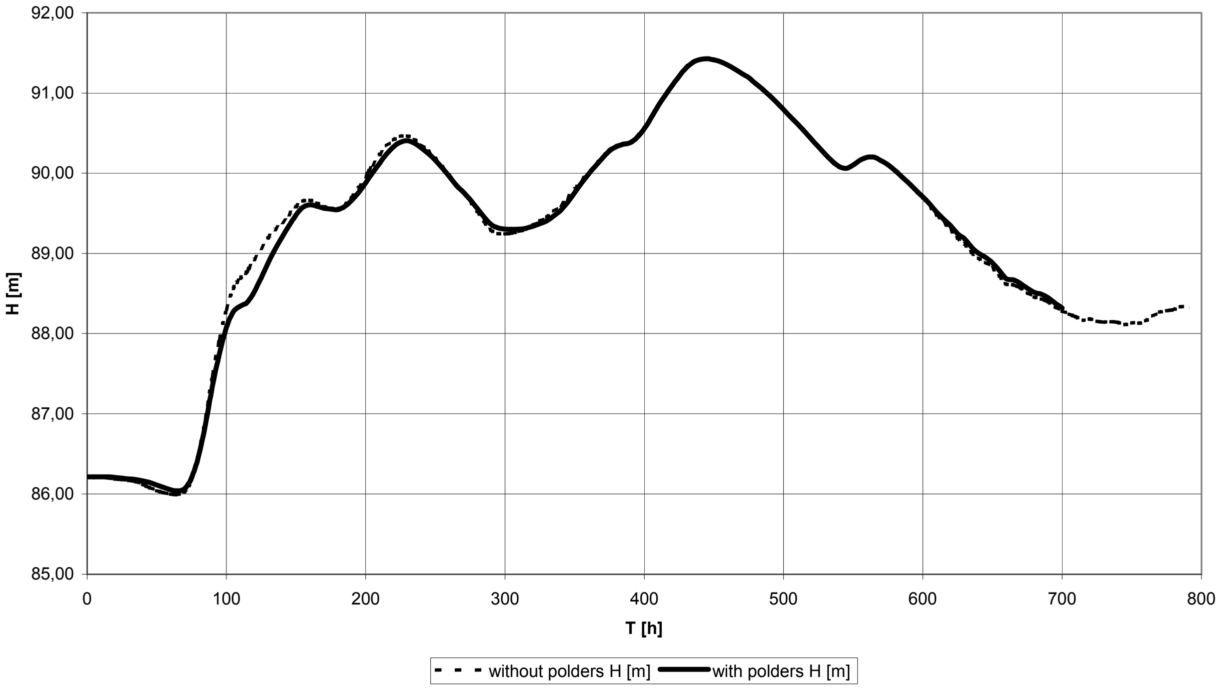


Figure 5.1 Water level comparison, Worms

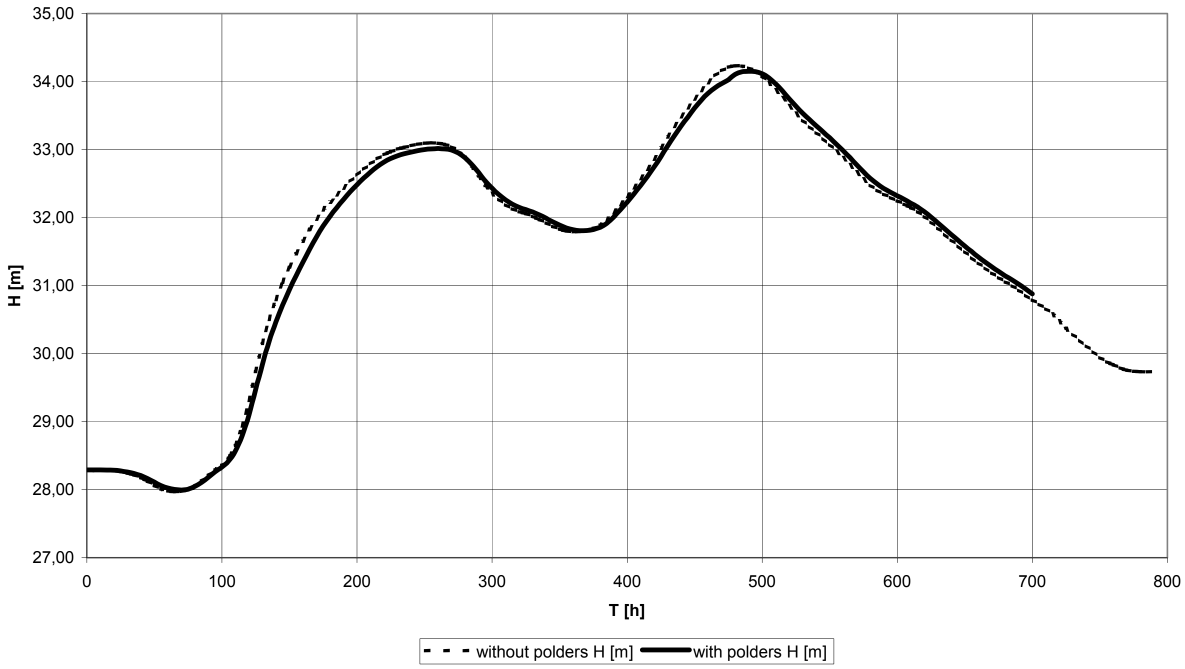


Figure 5.2 Water level comparison, Düsseldorf

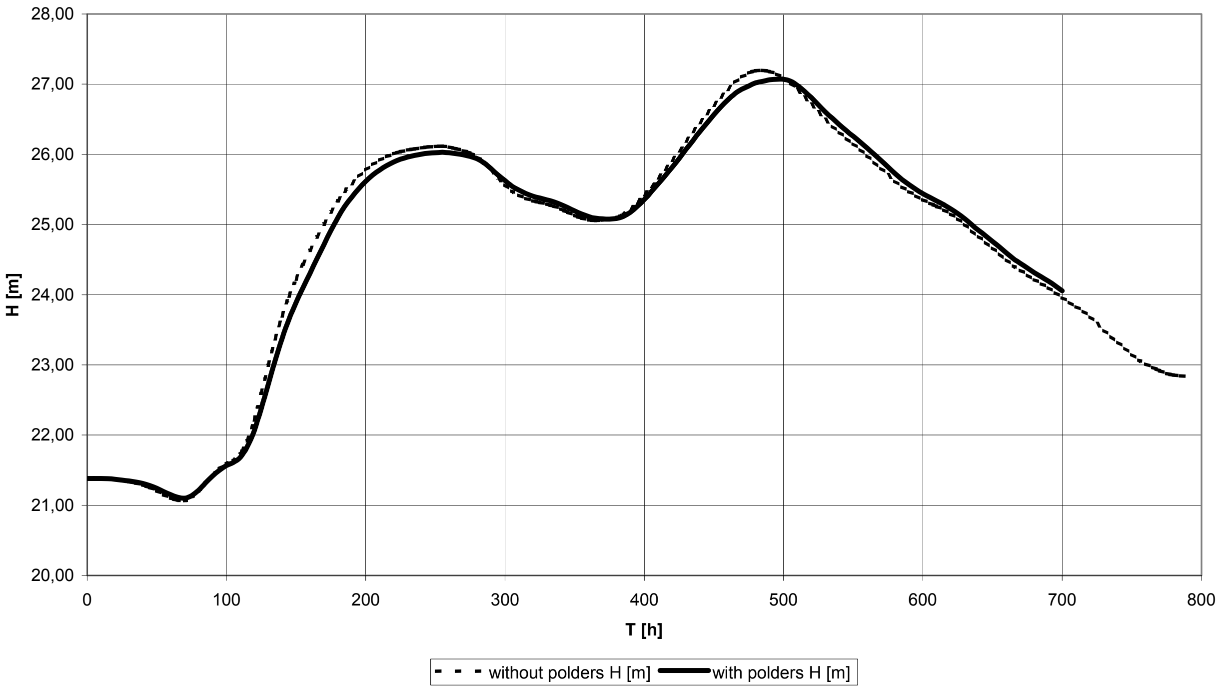


Figure 5.3 Water level comparison, Ruhrort

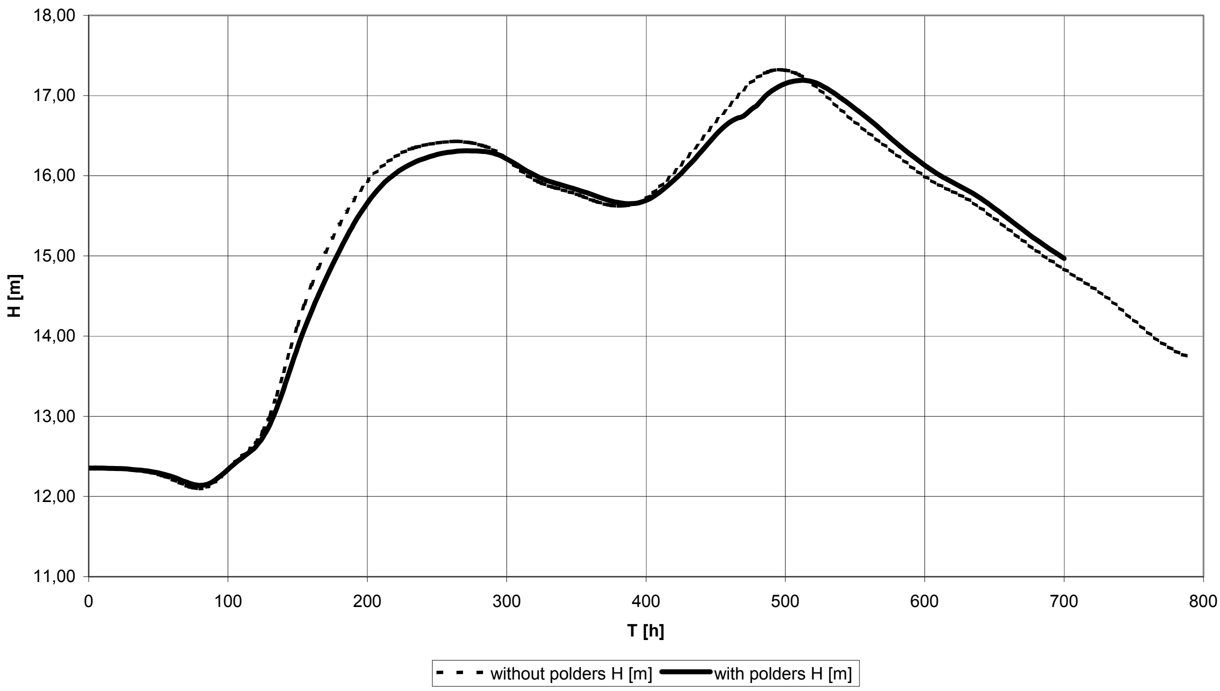


Figure 5.4 Water level comparison, Emmerich

Gauge	Andernach	Bonn	Cologne	Düsseldorf	Ruhrort	Emmerich
ΔH (m)	0,05	0,05	0,06	0,09	0,09	0,012
ΔT (hour)	0	0	5,25	5,75	10,25	11,50

Table 5.2 The effect of polder system along the Rhine

5.2 Impact of the retention polders on the Lower Rhine

The flood of December 1993 due to the large contribution of the Neckar, Nahe and Moselle was one of the biggest floods in the past 120 years causing the most serious consequences for the Lower Rhine.

The simulation of the model with all 23 polders situated on the Lower Rhine (already existing, in construction and in plan – see Table 2.5) for the flood event December 1993 will give us the whole picture of how the polders on Lower Rhine should act during flood events.

Figure 5.5 to 5.7 are demonstrating the results obtained from the simulation. The summary of results can be seen in Table 5.3.

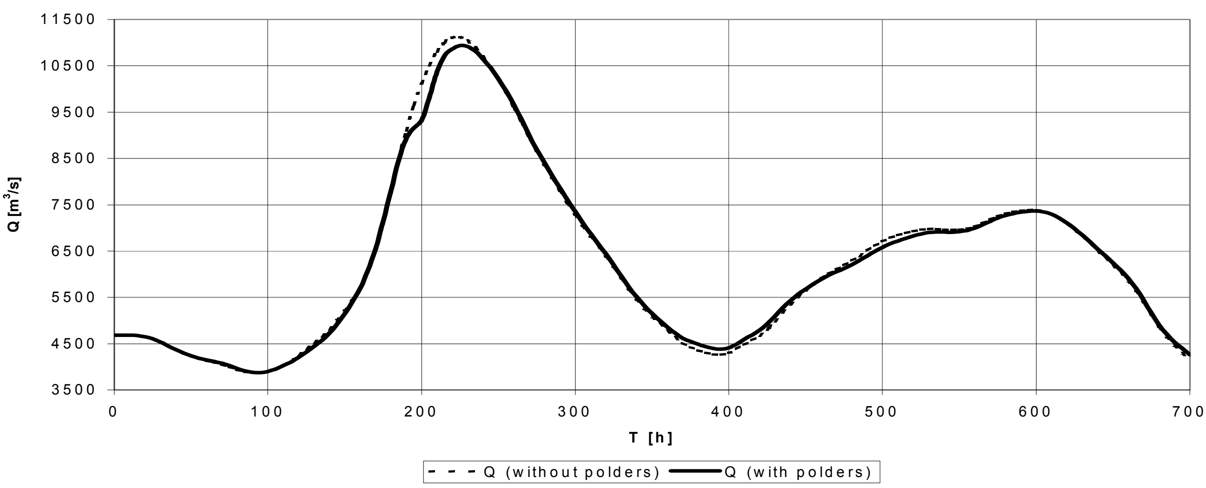


Figure 5.5 Discharge comparison, Duesseldorf

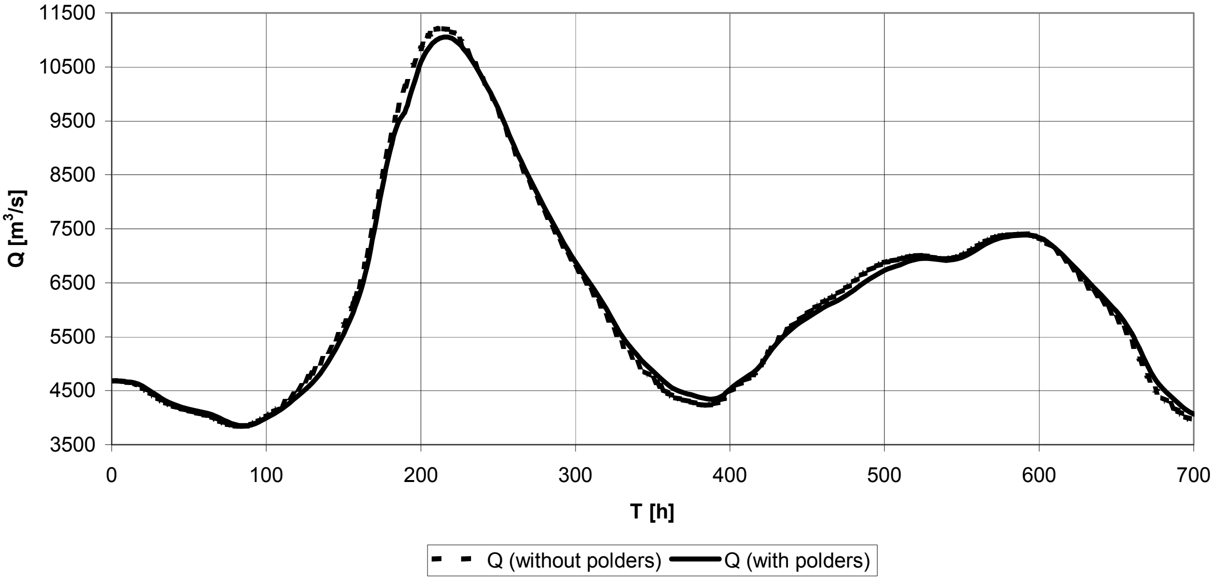


Figure 5.6 Discharge comparison, Cologne

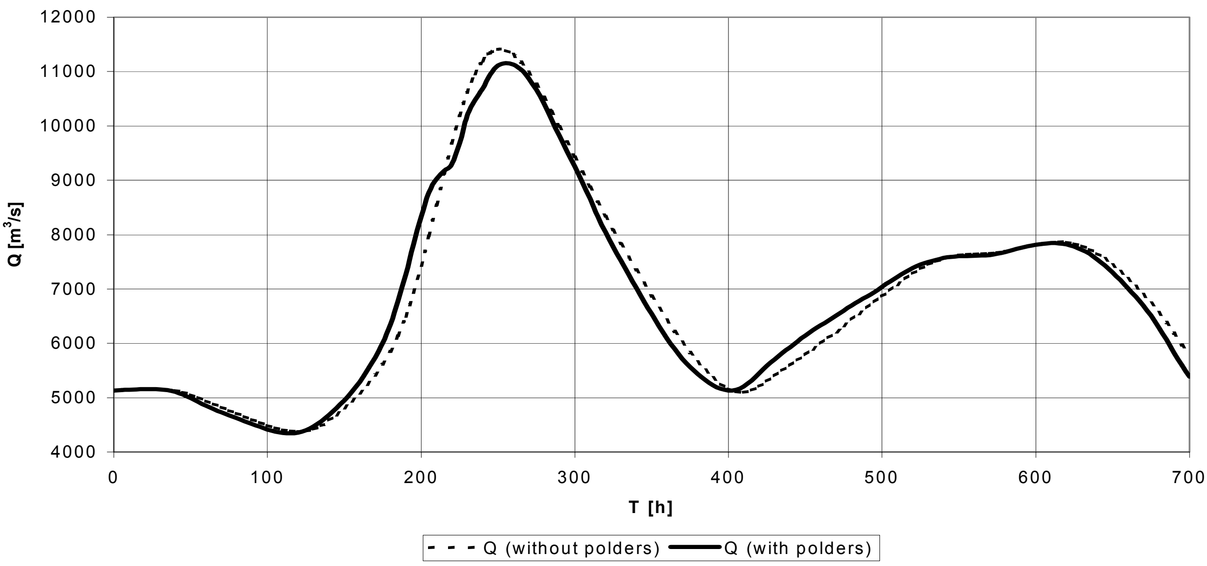


Figure 5.7 Discharge comparison, Emmerich

Gauge	Bonn	Cologne	Duesseldorf	Emmerich
ΔH (m)	0,08	0,06	0,07	0,06
ΔT (hour)	4,25	5,75	5,55	7,75
ΔQ (m^3/s)	136	178	192	275
ΔT (hour)	3,75	4,25	4,25	10,25

Table 5.3 The effect of a polder system (according to Table 2.6) on Lower Rhine

5.3 Impact of the retention polders on the Upper Rhine to the water lever on the Lower Rhine

5.3.1 Model simulation

As mentioned in chapter 4, the flood of February 1999 was caused by strong rain fall and snow melting in many upper regions. In the Upper Rhine some of the retention polders along the Rhine were active at the first time after construction.

In order to assess the effect of polder system on the Upper Rhine into flood regulation, the model is simulated with the case of all polders situated on the Upper Rhine from Maxau (Rhine km-362,20) to Bingen (Rhine km-528,40) and for the flood situation of February 1999.

In Figure 5.8 to Figure 5.13 the results obtained from simulation run can be seen. It is very clear that with the effects of the polders from Upper Rhine, the water levels at the gauging stations were reduced up to 20 cm at the peak water level. The time where the peak water level appeared were also up to 12 hours later in comparison with the case simulation without polders. They also show that the impact of the polder system on the Upper Rhine is not only acting for the local area but also for the region downstream of the area.

The water level during the rising limb curves was always lower than the water level in case without polders because when the water level on the Rhine was going up to a certain level (e.g. above summer dike crest), the filling of the polders is beginning. The opposite can be seen during the falling limb because when the water level on the Rhine is going down to a certain level (e.g. smaller than the water level in the polder), the water from polder is beginning to come back to the Rhine. These results show the effect of polder systems more clear.

In Table 5.4 the summary of the effectiveness of polders from Upper Rhine on flood regulation is given.

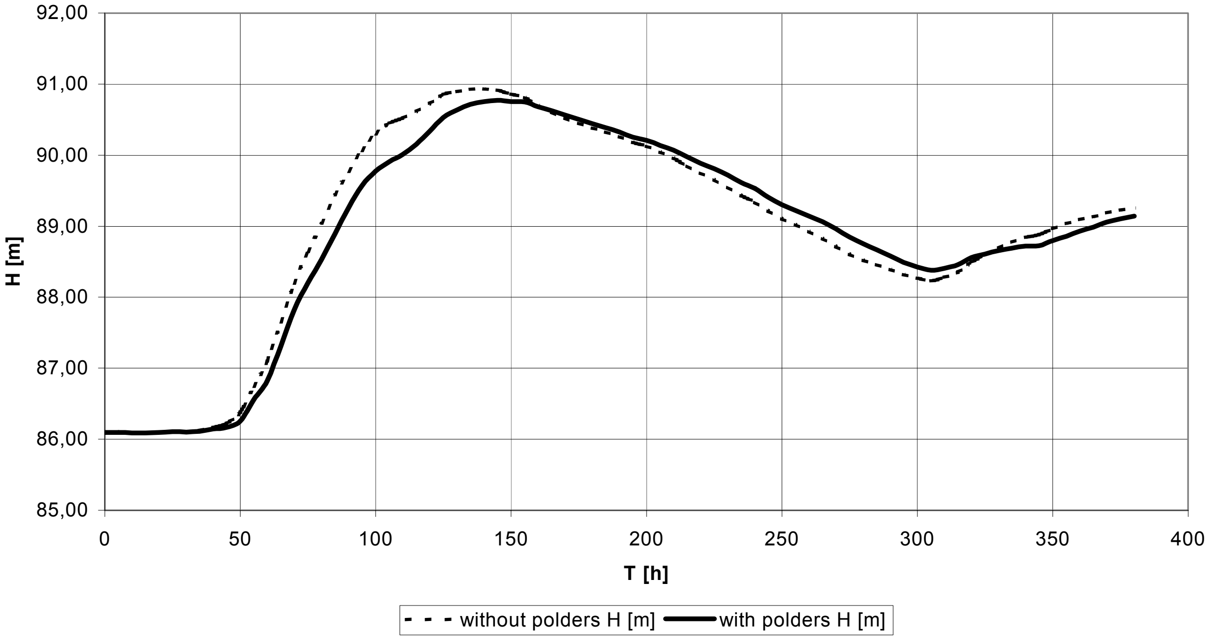


Figure 5.8 Water level comparison with and without polder, Worms

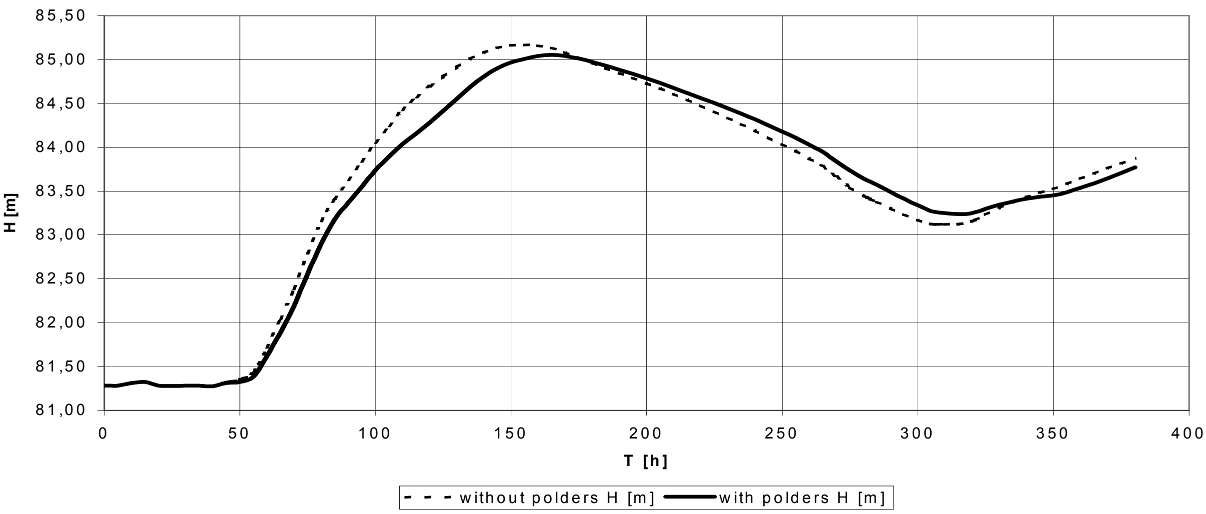


Figure 5.9 Water level comparison with and without polder, Mainz

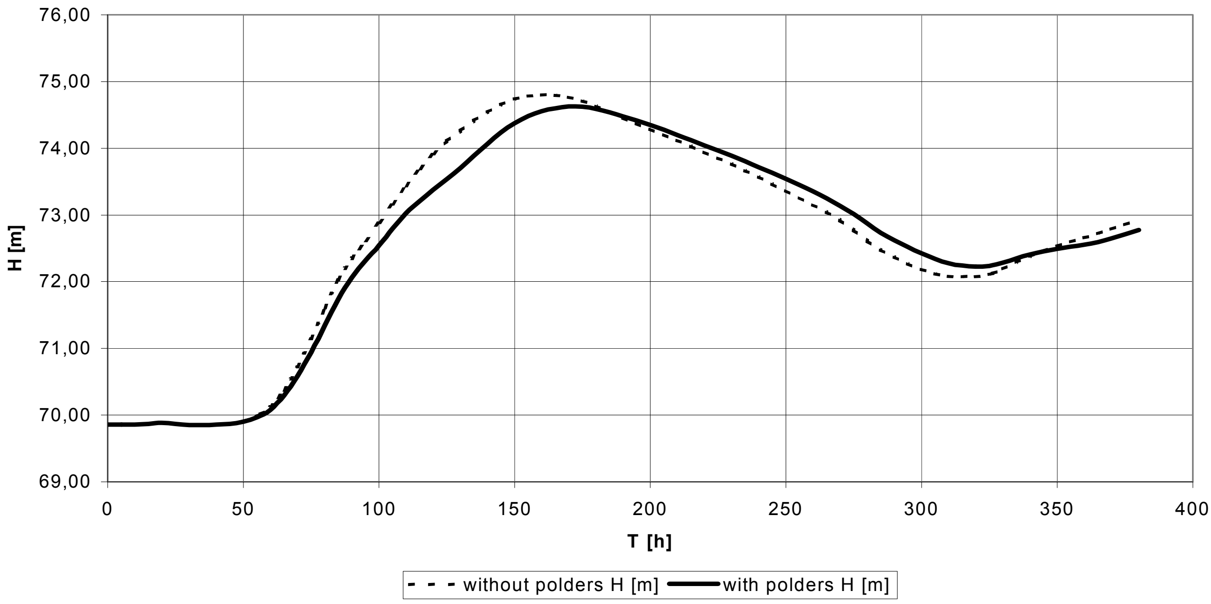


Figure 5.10 Water level comparison with and without polder, Kaub

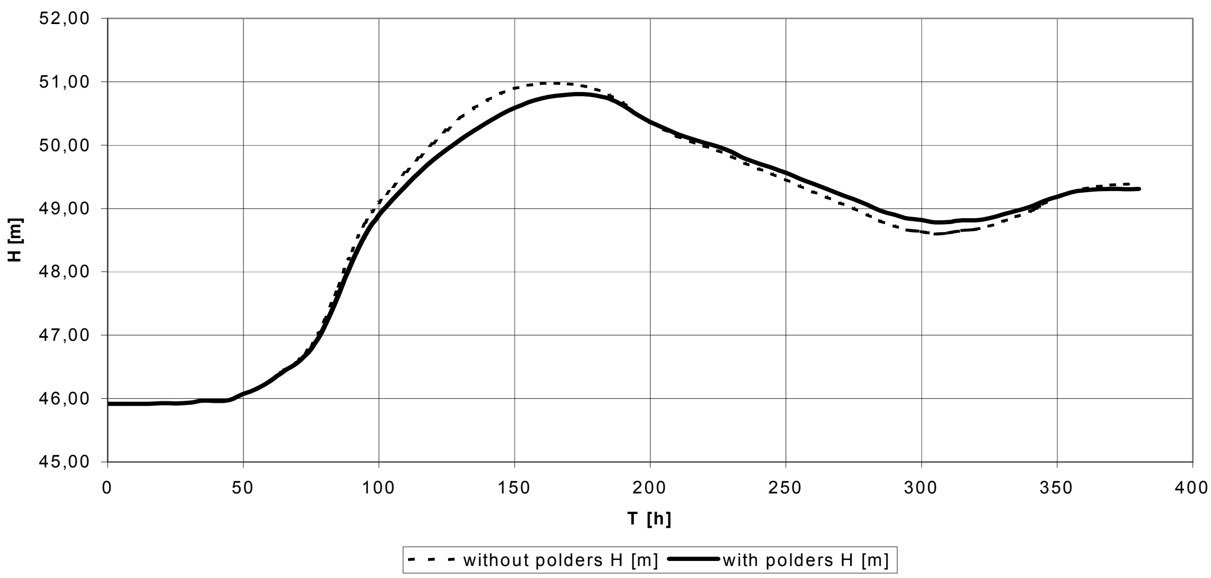


Figure 5.11 Water level comparison with and without polder, Bonn

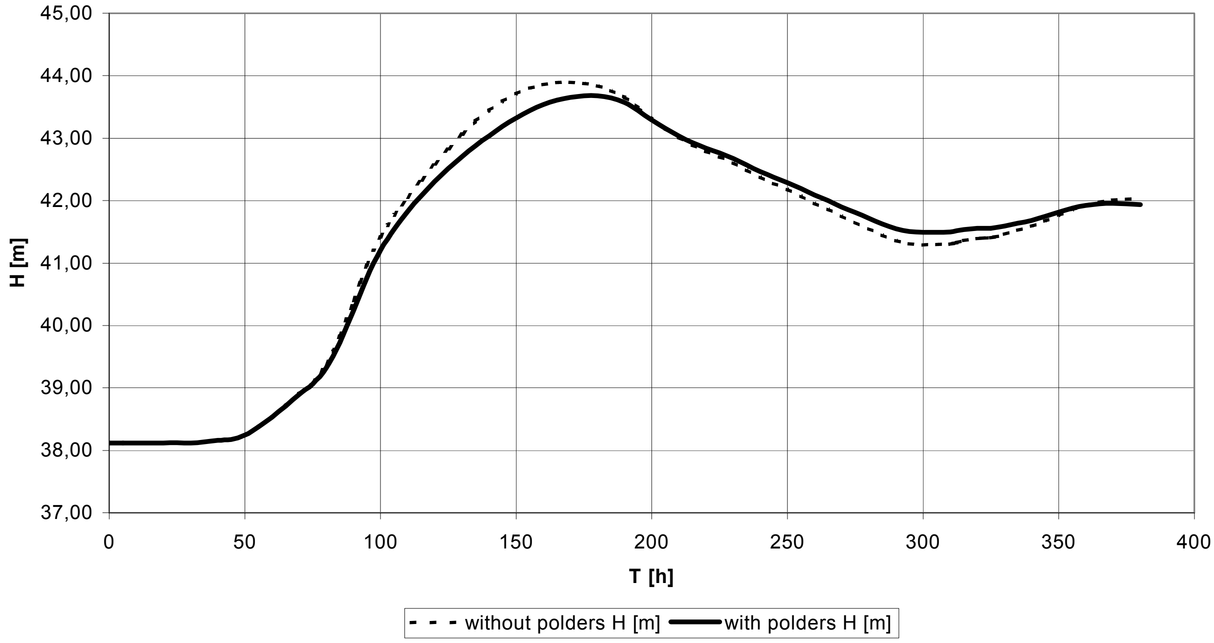


Figure 5.12 Water level comparison with and without polder, Cologne

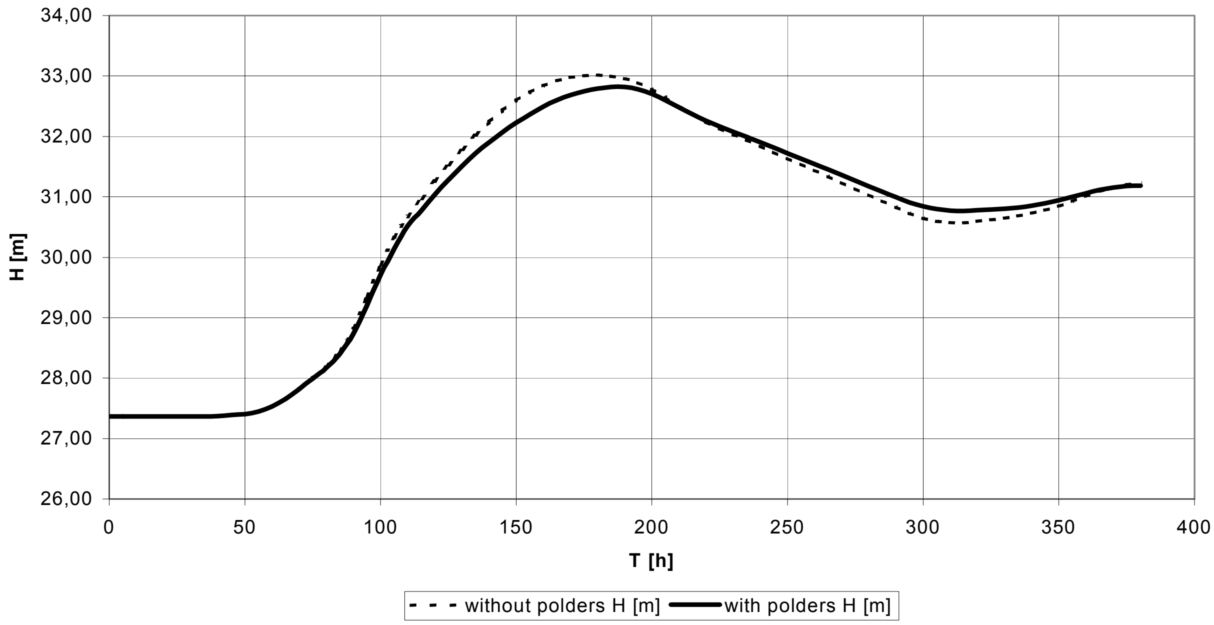


Figure 5.13 Water level comparison with and without polder, Düsseldorf

Gauge	Worms	Kaub	Mainz	Bonn	Cologne	Düsseldorf
ΔH (m)	0,18	0,18	0,14	0,20	0,20	0,18
ΔT (hour)	7,25	9,75	9,25	10,25	11,75	11,50

* Including the polders: Kulturwehr Kehl, Polder Altenheim I+II and Manöver up stream of Iffezheim

Table 5.4 The impact of polders on the Upper Rhine*, flood event February 1999

5.3.2 Conclusions and remarks

Polder systems in the Upper Rhine can help to reduce the peak water level up to 20 cm at the downstream of the gauging stations.

The time where the peak water level appeared is up to 12 hours later in comparison with the case model simulation without polder.

Due to the operation of the polders, the water level at the rising limb was always lower than in the case without polders and the opposite sight is shown at the falling limb.

5.4 Impact of the types of the flood retention polders

In order to assess the effect of the type of polder systems on flood regulation, the comparison between the three following cases were carried out: without polder, with flood polder and with summer polder.

Flood polder means the polder acts as a storage basin connected to the river. It is thus assumed to fill up or empty without any time lag with respects to the river water level. There are two conditions imposed at the end point i and (i+1) of the reach:

a. Water level at both points is assumed equal: $y_i = y_{i+1}$

The continuity condition requires that:

$$Qi = Qi+1 + Q_p$$

$$Q_p = s\frac{\partial y_i}{\partial t} \qquad \text{if} \quad y_i > y_f$$

$$Q_p = 0 \qquad \text{if} \quad y_i < y_f$$

With : y_f : elevation of the bottom of the basin entrance

$S_{(yi)}$: free surface of the basin

b. The free surface is assumed horizontal and water elevation in the basin is equal to the water stage in the river.

$$y_{reservoir} = y_i = y_{i+1}$$

Summer polder: The polder connected with the river by a fix crested weir is called summer polder. Figure 5.14 shows the schematic sketch of a polder controlled with summer dyke.

The calculation of the flow characteristics as for a rectangular weir is based on the classical equations:

Flooded: $$Q = \mu B\sqrt{2g}\,(y_{us} - y_{weir})\,(y_{us} - y_{ds})^{1/2} \qquad (4)$$

Free-flowing: $$Q = \mu B\,\sqrt{2g}\,(y_{us} - y_{weir})^{3/2} \qquad (5)$$

With:

μ = discharge coefficient

B = weir width

y_{us} = upstream water level

y_{ds} = downstream water level

y_{weir} = weir crest elevation

Those equations are satisfied at the end of each time step.

The flood case occurs if:

$$Y_{ds} - y_w < \frac{2}{3}(y_{us} - y_w)$$

There is no discharge if $y_{us} < y_w$. The free flowing case occurs if none of the above conditions is satisfied.

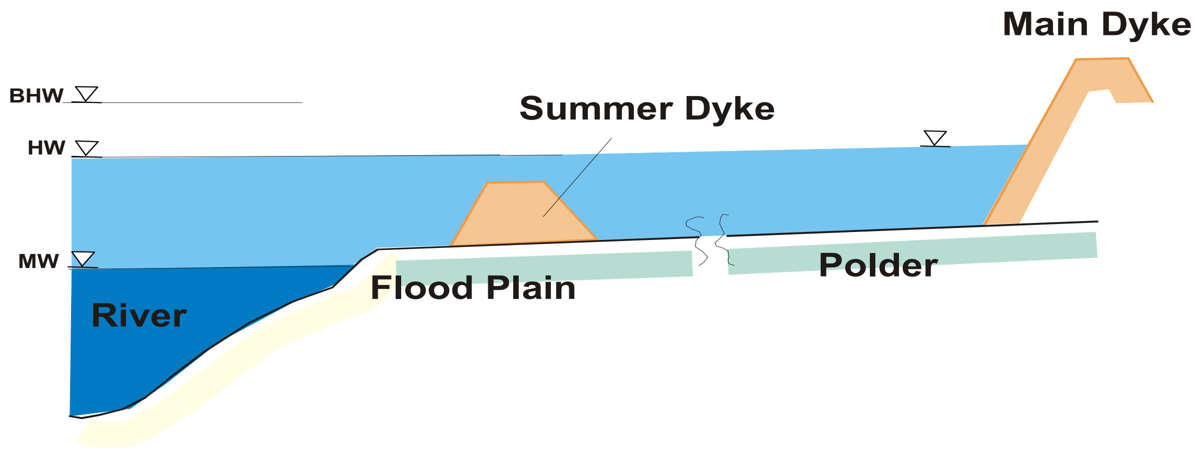


Figure 5.14 Controlled polder with Summer dyke

The above formulation assumes that the weir discharge is not dependent on the approach and exit velocities. The upstream velocity is neglected and there is no head loss between the upstream section and the weir crest. This is valid if velocities are lower than some 1 m/s.

In the flooded case, it is assumed that the kinetic energy between the weir crest and the downstream section is totally dissipated and that the water level is the same at the weir crest location and downstream.

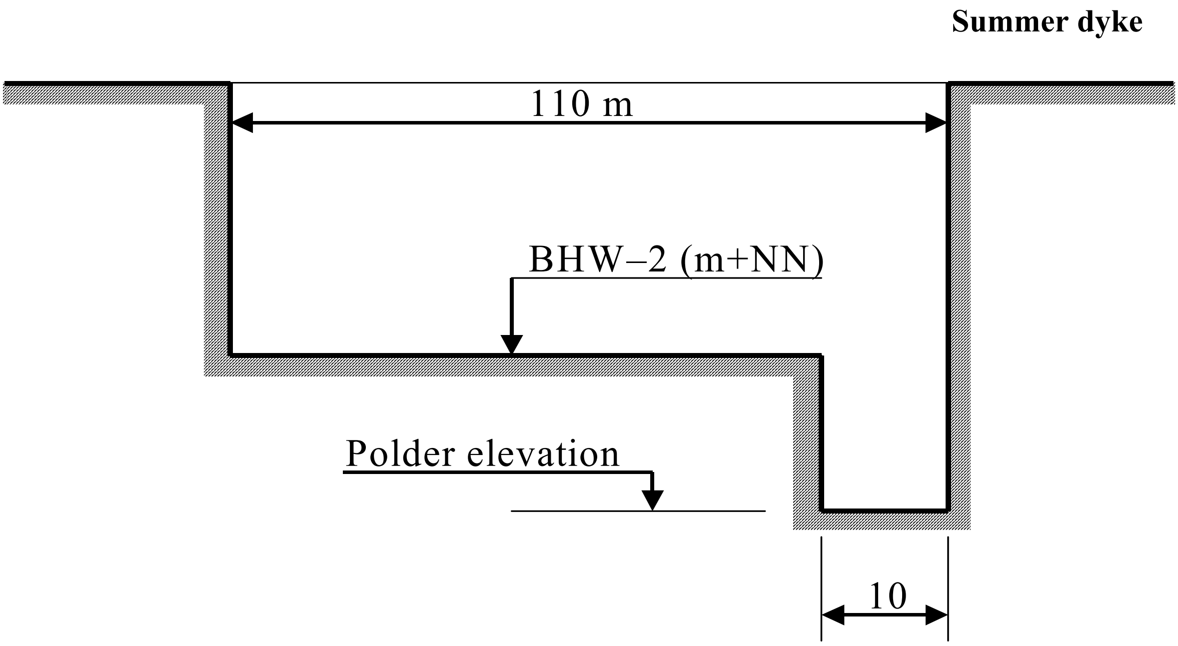


Figure 5.15 The weir cross section of the summer polder

Figure 5.15 shows the computed weir cross section. It is a suggest taken from pre-studying the Lower Rhine with respect to the natural and ecological conditions (Minh Thu, 1996). Based on it, the crest of the weir should be lower than the permitted flood water level BHW (m+NN) by 2 meters and it should have 10 meters with the elevation equal to the elevation of the polder. With this design, it allows the water to come into the polders as soon as it is over Polder elevation. It gives more possibility for recreating the alluvial areas which are an ecological entity with the Rhine river.

The computation was carried out with the flood event of December 1993 for the Lower Rhine with eleven polders as shown in Table 5.5. Figure 5.16 shows the result obtained from simulation. It is very clear that with the construction of a weir connected with the polder (summer polder SP), the impact of the polder system on flood regulation is better than in the case of flood polders (without construction of a flood polder FP) and of course with the case without polder (OP).

Polder	Rhine-km	Area (km²)	Approximately Elevation (m+NN)	BHW (m+NN)
Niederkassel	644,0-665,0	0,35	47,50	51,69
Koeln-Langel	669,2-672,5	5,00	46,00	49,98
Worringer Bruch	705,4-708,5	6,00	39,00	42,99
Monheim	708,2-713,2	2,00	38,00	42,35
Itter-Himmelgeist	723,8-729,0	0,60	35,00	39,57
Illvericher Bruch	750,5-753,5	6,00	30,00	34,23
Muendelheim	767,0-767,5	1,50	28,00	31,54
Orsoyer Land	797,5-803,3	2,20	18,50	25,62
Bislicher Insel	819,0-823,2	11,00	18,50	22,59
Lohrwardt	827,0-834,8	5,00	17,50	21,15
Bylerward	845,0-850,0	7,20	16,00	19,16

Table 5.5 Some characteristics of 11 polders on the Lower Rhine

Further investigation has been done with fourteen flood waves (see Table 5.6) and for the cases without polder, with flood polder (approximately 96.85 km² - the polder Salmorth was not yet taken into account, see Table 2.5) and with 11 summer polders (approximately 46.85 km² - Table 5.5).

The results are shown in Table 5.6. For the flood of December 1993, the water level at the model outflow is approximately 5 cm lower than in comparison with the case flood polder and about 12 cm lower than with the case summer polder. The discharge is reduced approximately 160 m³/s in case of flood polder and approximately 290 m³/s in case of summer polder.

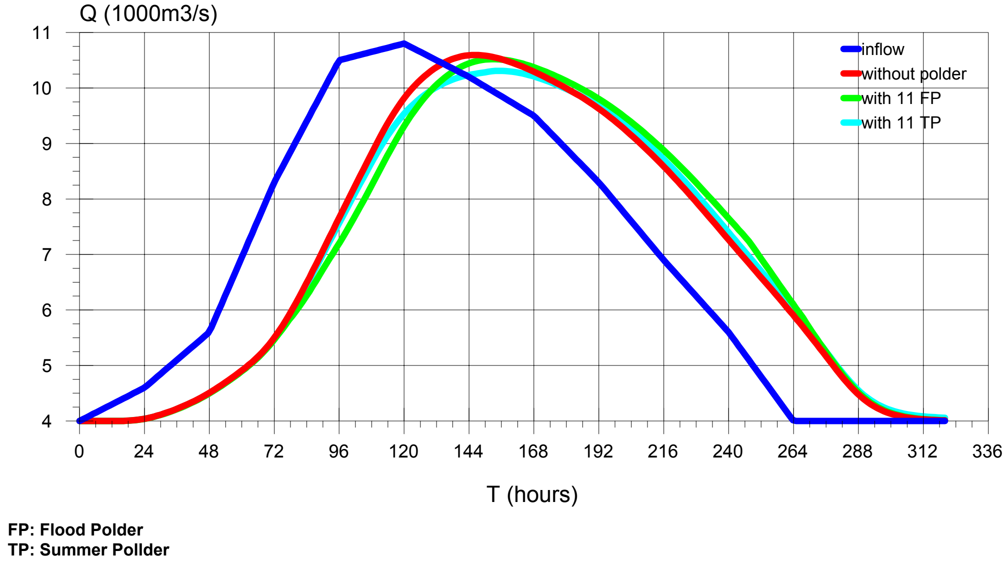


Figure 5.16 The effect of flood controlled structure

Waves	Q_{max} (m³/s)	$Q_{outflow}$			$H_{outflow}$		
		OP	FP	TP	OP	FP	TP
D/J 1925/26	10595	10369	10191	10074	17,39	17.31	17.26
Dec 1993	10800	10594	10428	10308	17.49	17.42	17.37
Apr 1983	9372	9182	9069	9041	16.88	16.83	16.81
Apr 1983-1	5875	5763	5737	5760	15.42	15.41	15.42
Apr 1983-10	8892	8714	8616	8614	16.67	16.67	16.63
Apr 1983-100	11709	11471	11330	11284	17.87	17.81	17.79
M/J 1983	9670	9501	9391	9321	17.01	16.97	16.94
M/J 1983-1	6049	5967	5931	5964	15.50	15.49	15.50
M/J 1983-10	9175	9016	8916	8889	16.80	16.76	16.75
M/J 1983-100	12082	11869	11731	11678	18.04	17.98	17.95
M/A 1988	9415	9299	9227	9158	16.93	16.90	16.86
M/A 1988-1	5902	5836	5819	5835	15.45	15.44	15.45
M/A 1988-10	8933	8824	8760	8834	16.72	16.69	16.67
M/A 1988-100	11764	11616	11527	11534	17.93	17.89	17.89

Table 5.6 The result of computation with HQ – waves

Table 5.6 continue:

OP: Without retention measures (polders)

FP: The polders act as flood storage volume only (without control structures

TP: Summer polders (with control structures)

5.5 Conclusions and remarks

The polder with control measures has better effects on flood regulation in comparison with the polder without once.

Polder systems in the Upper Rhine may help to reduce the peak of water level locally and also down stream of the gauging stations by up to 20 cm. The time where the peak water level appears is up to 12 hours later in comparison with the model simulation without polders on the flood event of February 1999.

Polder systems on the Lower Rhine may help to reduce the flood peak of the flood event December 1993 up to 300 m³/s, and the delay time when the peak discharge appears by up to 10 hours in comparison with the case without polder system.

6 Polder Grietherbusch

Besides the use for studying the effects of flood regulation measures along the river, the HN-Model of the river Rhine is also used for investigating the effects of the operation of the polders themselves along the river where necessary.

Following the contract with the Ministry of Environment, Regional Planning and Agriculture of State North Rhine-Westphalia (MURL), study of Polder Grietherbusch on the Lower Rhine is selected as one example.

6.1 Approach

Polder Grietherbusch is situated on the right bank of the Rhine between Rhine km 842.50 and Rhine km 847.50. The polder extends in maximum about 4 km from the Rhine bank towards inland and consists of three single polders (Lower Polder, Upper Polder and Grietherbuscher Polder) which are separated by overflow dams and over flowing reach (e.g. passage DN 500) among themselves and to the Rhine. Into these overflow dams the hydraulic connection links (regulated and unregulated overflow weirs, sluices,etc.) are integrated. Towards the inland the polder is separated by the main dyke, which runs mostly along the Bienener Old Rhine.

The total area of the polder amounts to approx. 1,200 ha. Figure 6.1 shows the layout of the entire polder area and the adjacent Rhine. The polder surface is predominantly used for grassland agriculture and there is a set of farms which are

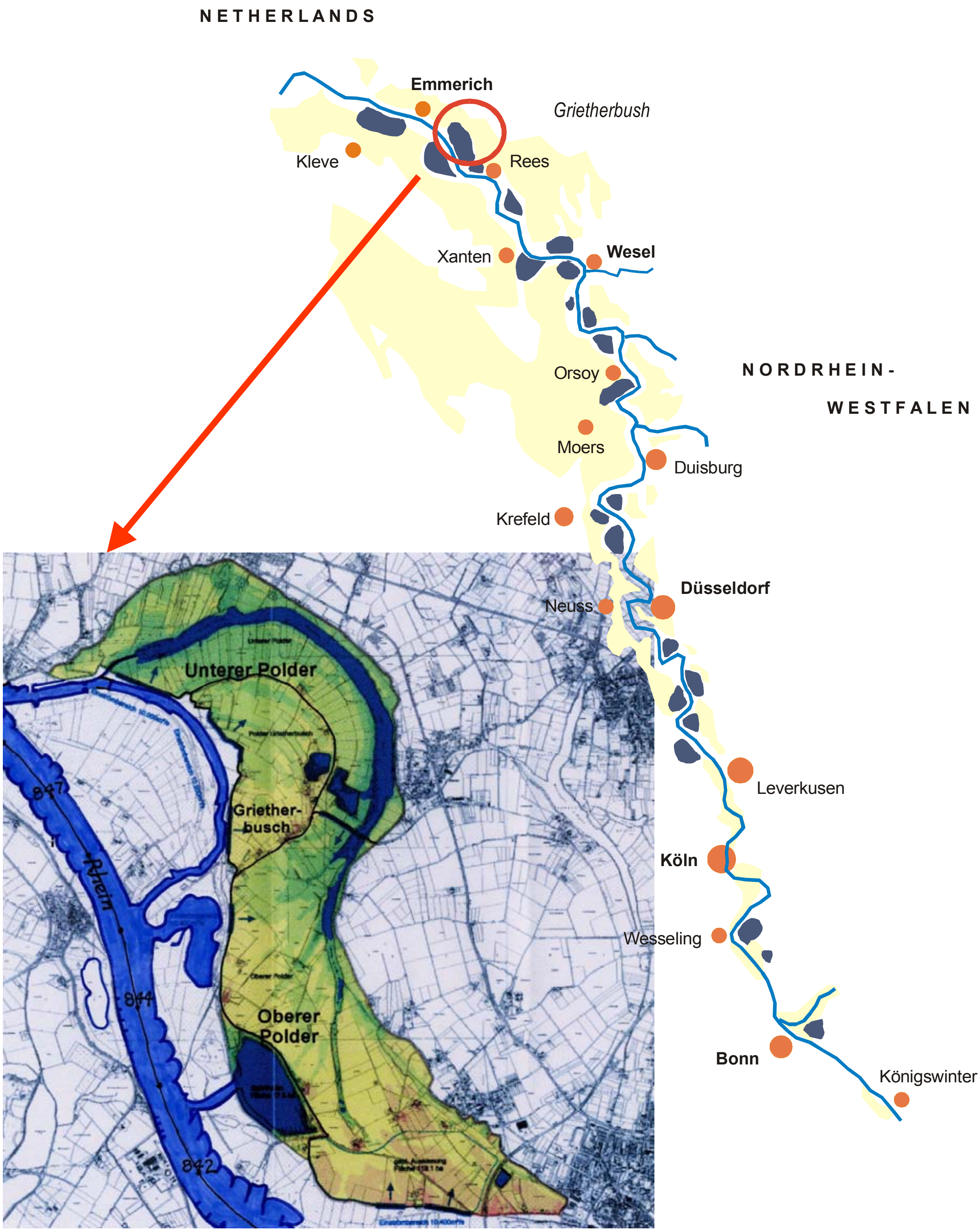


Figure 6.1 Layout plan of polder Grietherbusch

settled on flood free ground. The area is generally flat and scarcely structured, apart from the Old-Rhine arms opened for gravel pits.

There are two old Rhine arms going through the polder, the Bienener Old Rhine and the Grietherorter Old Rhine which is situated next to the river. While the Grietherorter Old Rhine, which is situated outside of the overflow dam is heavily silted up both in its underflow and especially in its head flow and has no surface water connection to the Rhine. In addition, because it is situated higher than the water level of the Rhine at mean discharge, a flow is generally not given.

The polder is equipped with summer-dykes which separate it from the Rhine and represent the boundaries of the partial polders among themselves. The contour lines of the summer-dykes are not uniform, so that the crests of the lower situated dykes are overtopped earlier in the case of flood than those of the higher situated dams. Various control structures are integrated into the summer-dykes such as sluices with sliding gates, stop logs or stem gates or also tube passages.

Based on the already available investigations for the HN-Model of the river Rhine, an optimum flooding strategy as well as the necessary structural measures for polder Grietherbusch are developed. The target was to combine a protection of the polder surface during smaller floods with an optimal retention effect. At the same time the ecology of the area should be preserved or improved where it was possible. The work was executed in close co-operation with the Schulze Engineer GmbH, Düsseldorf.

6.2 Methodology

For the simulation and optimisation of the in and outflow conditions, an exact knowledge of the water-surface levels was necessary for the polder Grietherbusch. One part of the HN-Model of the river Rhine was used for investigating these information. Different elements for the description of the topology of the respective system can be built on the model using CARIMA aspects. There are one-dimensional river sections which connect nodal points (transverse profiles) and quasi two-dimensional elements which are composed of connected cells, as well as retention areas, which are not flown through and whose water level communicates directly with the river. Quasi 2-D currents are simulated as (1-D) currents through so-called cells which can be connected among themselves. Contrary to many other processes both the local and the convective accelerations are considered, so that this procedure can be used also with temporally fast variable processes (e.g. waves due to hydro power station operation).

Since with the available HN-model Rhine which has been used, the profile distances of 1000 m were too large for the necessary accuracy, these had to be compressed to 100 m. The river-sections necessary for these calculations extend from approx. Rhine-km 835 to Rhine-km 852. First of all, stationary water-level calculations were executed for different discharges. With the help of this, water level and discharge relations could be determined for practically every point of the examined Rhine section. On the basis of these data and the comparison with the contour lines of the summer-dyke the boundary conditions for the polder inflow could be determined.

After creation of a model containing the Rhine section, the flood plain and the polders, the unsteady calculations were executed, with which the intake and discharge of the polder, the distribution between the three partial-polders as well as the respective water levels as a function of the time could be obtained. From this, the necessary improvement of the management of the polder could be determined, which resulted in the necessary modifications of the structures.

6.3 Model calibration

6.3.1 Construction of the model

For the available investigations the following documents were used:

° HN-Model Rhine from km-835 to km-852

° “Deutsche Grundkarte” M 1:5,000

° Rhine transverse profiles km 840.000 – 850.000 (100 meter distance)

°Summer-dykes system including constructions within the area of the polders

° Flood lengthen profile of the Lower Rhine M 1:100,000 / 50

° “Deutsches Gewässerkundliches Jahrbuch“ (1993)

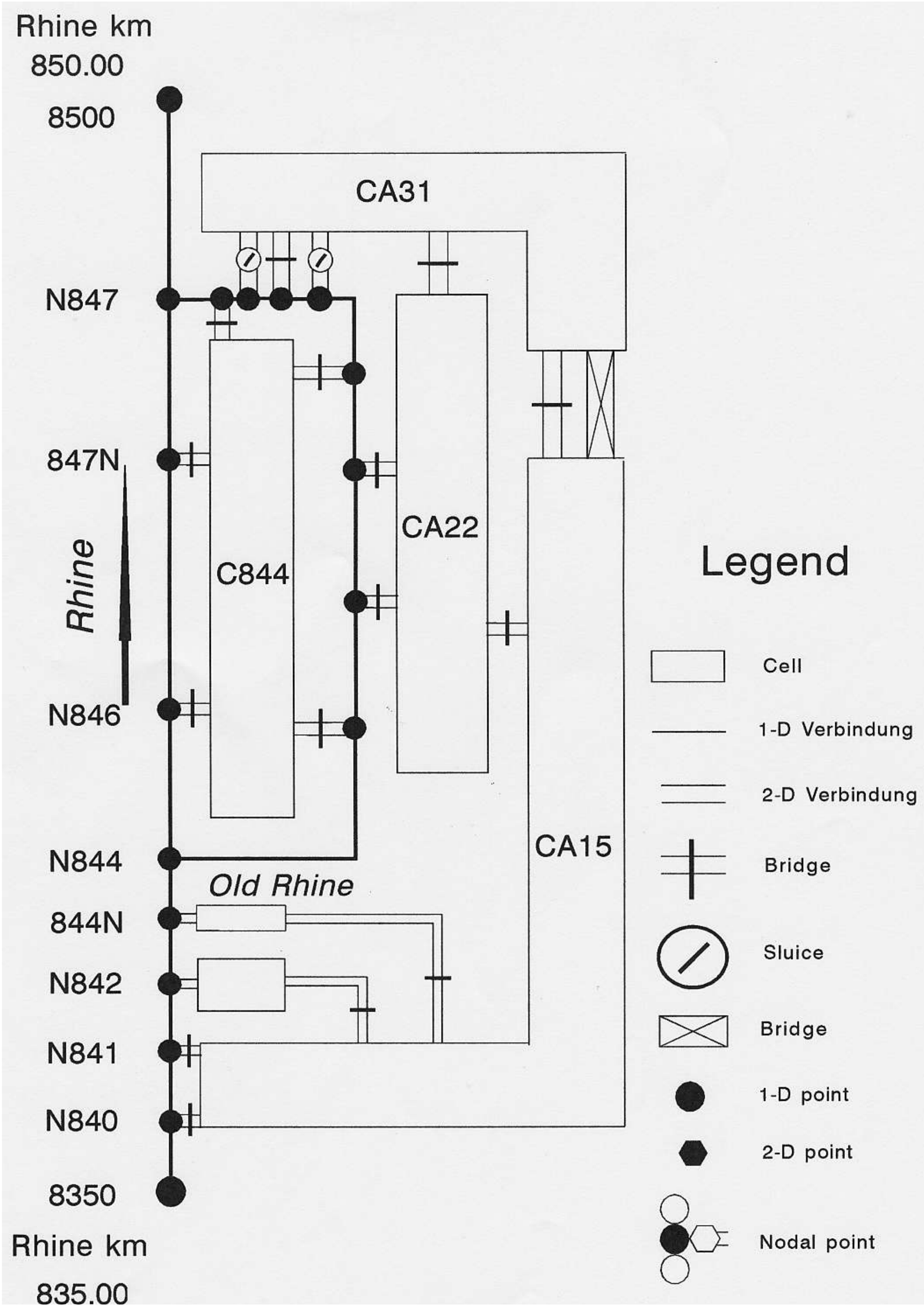


Figure 6.2 The model construction of the polder Grietherbusch

The topology of the model of the polder Grietherbusch used for the available calculations is represented in Fig. 6.2. The system covers primarily the Rhine between km 835.000 and km 850.000, whereby within the particularly important range between km 840 and km 850 the transverse profiles are integrated with a distance of 100 m between them and the transverse profiles of the others are only considered every 1000 m. The Grietherorter Old Rhine is connected to the Rhine at km 844 and km 847 while the flood plain which is situated between them is defined as cell. The three polders (Grietherbuscher Polder, Lower Polder and Upper Polder) are likewise defined as cells, whereby the Lower Polder is connected to the Grietherort Old Rhine with the Grietherbusch sluice and the Flooding sluice and is furthermore connected to the Upper Polder via the bridge on the road K19, where separated the Upper polder and the Lower polder. The summer-dykes surrounding the polders are defined as fixed weirs with overflow. The further items as the sports port at km 842 and the quarry pond at km 844 are attached to the Rhine.

The substantial polders are summarized in the Table 6.1.

Polder	Area* (km^2)	Volume* (10^6 m^3)	Middle elevation (m+NN)
Grietherbuscher	1,76	3,60	15,60
Lower Polder	3,89	11,80	14,60
Upper Polder	5,19	13,70	16,00

* related with the maximum water level of the polder

Table 6.1 Areas and volume of the polder Grietherbusch

The development of polder volume following with the water level can be seen in Fig. 6.3. The data was obtained from State Environment Agency Krefeld, Nordrhein-Westfalen (Staatliches Umweltamt STUA Krefeld).

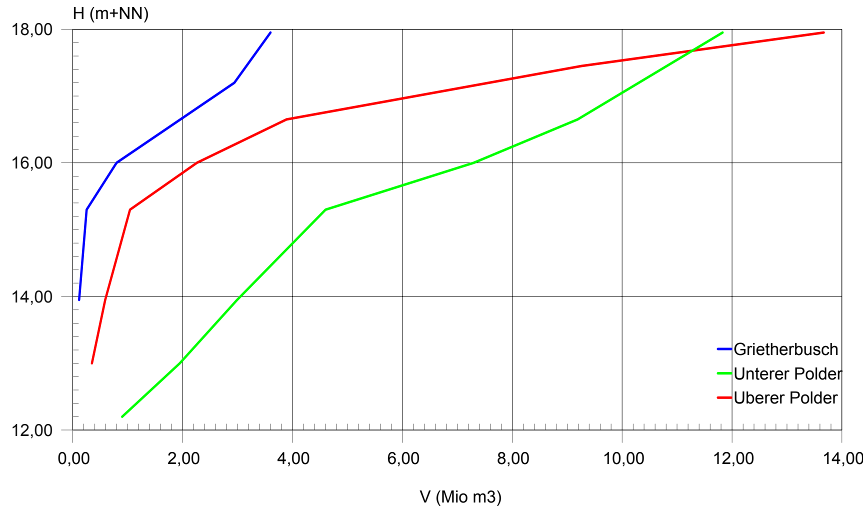


Figure 6.3 Polder volume, Grietherbusch

Generally the summer dykes existing in the area do not have constant crest elevations. Therefore middle decisive length and elevations were determined for the hydraulically effective overflow reaches which are summarized in Table 6.2.

Construction	Length (m)	Crest (m+NN)
Old Rhine–Lower Polder	600	17.30
Grietherbuscher-Lower Polder	2000	17.20
Lower –Upper Polder (K-19)	500	17.60
Old Rhine-Grietherbuscher	700;500	17.50; 17.55
Grietherbuscher-Upper Polder	500	17.30
Rhine-Upper Polder (K-18)	300	17.90

Table 6.2 Characteristic of some overflow reaches

On the available model only the most important structures were considered. These are summarized with the hydraulically relevant dimensions in the following table (Table 6.3).

Construction	Width (m)	High (m)	Elevation (m+NN)
Grietherorter Sluice	4.04	3.00	11.67
Weir DN 500	0.50	0.50	13.30
Flood Sluice	80.20	-	16.00
Bridge	5.00	5.10	11.90

Table 6.3 Some construction characteristics

6.3.2 Boundary conditions

The flood of December 1993 was taken as the upstream boundary condition of the model after an agreement with Public Environment Agency Krefeld (Staatliches Umweltamt STUA Krefeld). For the steady flow calibration the water level along the Rhine with Q = 10.800 m³/s was used. The stage discharges at gauging station Emmerich (Rhine km-851,90) were used as downstream boundary condition (see Table 6.4).

Q (m³/s)	720	1001	1801	2553	3200	4061
H (m+NN)	8,28	8,96	10,37	11,46	12,30	13,26
Q (m³/s)	4761	5191	6000	6805	7507	8295
H (m+NN)	13,97	14,37	15,02	15,57	15,94	16,34
Q (m³/s)	9009	9991	10824	11678		
H (m+NN)	16,67	17,08	17,40	17,71		

Table 6.4 The stage discharges, Emmerich

6.3.3 Model calibration

On the previous calibration, the HN-Model Rhine has been calibrated with very good agreement between computed and measured water level. In this simulation, the profiles have been chosen for every 100 m length that is why the calibration should be done again.

In the present case the observed water levels of the flood from December 1993 (Q = approx. 10.800 m³/s) was considered as the calibration water level, since also the further calculations are based on this event. In Fig. 6.4 the Rhine water levels between km 835 and km 852, calculated with a steady discharge of 10.800 m³/s, were confronted with the ones observed in nature. For the calculation Strickler coefficients were set as before both for the river bed and for the flood plain (see Table 3.3) . As can be seen, with this combination – incidentally already used with comparable investigations for the river Rhine - the measured water level is quite well achieved. The partially existing deviations are about 10 cm. In the nature observations of this difference can already be determined from the water levels on the right and the left bank of the Rhine (about 20 cm).

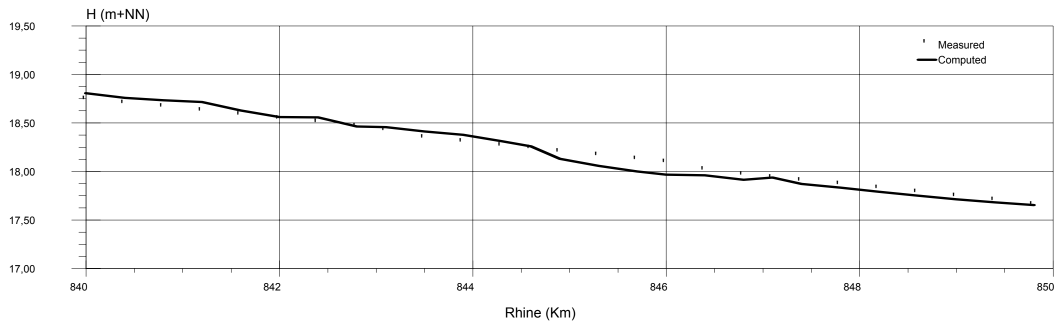


Figure 6.4 Model calibration, Grietherbusch – 1993 flood event

6.4 Model simulation – Variation 33

For the unsteady calculations the flood wave from December 1993 was taken as a basis. This wave is characterized by the peak discharge of approx. 10.800 m³/s with the hydrograph represented in Fig. 6.4. As can be taken further from Fig. 6.4, at Rhine km 847 a peak water level of approx. 17,93 m+NN corresponds to the chosen discharge.

In the following it is assumed that, at the beginning the Upper Polder and the Lower Polder indicate a pre-filling at the water level position of 13.20 m+NN, and Polder Grietherbusch with the level of 13,80 m+NN. After pre-filling the control devices (Grietherbuscher sluice, Flood sluice and passage DN 500) are closed, until the wave vertex is exceeded and the emptying of the polder begins.

Target of the flood retention measures is in general to reduce the peak of the flood wave as far as possible. That means the max. supply to a polder should occur at the time of the peak of the wave. In case of a polder flooded by over flowing it follows that the polder may be filled at this time only by rushing over dike when the wave vertex occurs (see Fig. 6.6).

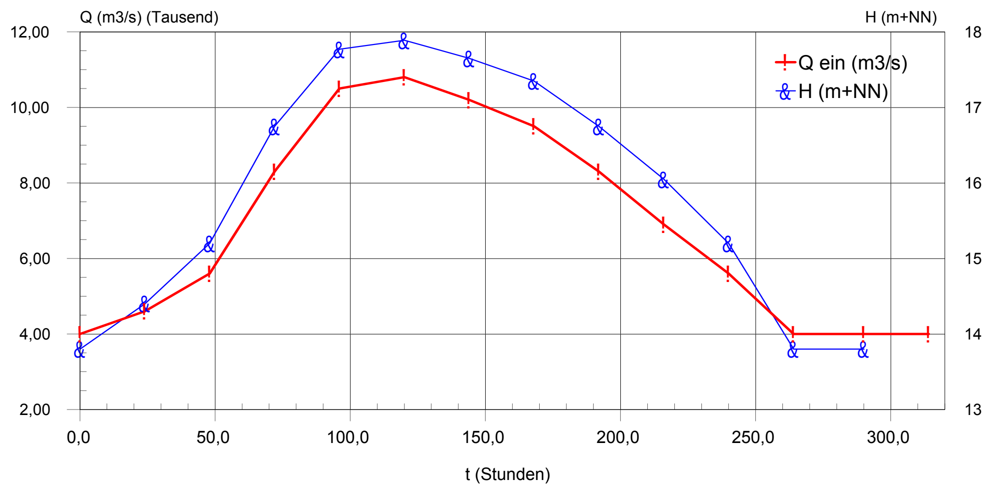


Figure 6.5 HQ – December 1993, Rhine km-847

The amount of discharge q per 1m length is calculated by formula 6.1

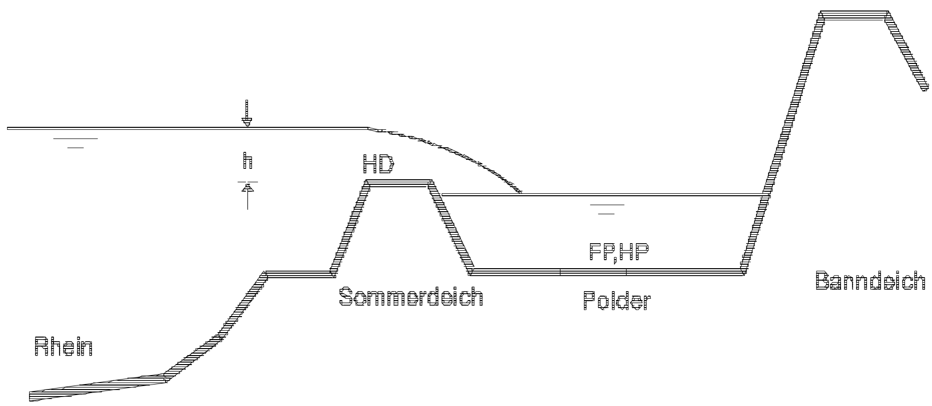


Figure 6.6 Schematisation of the water filling into polder over an overflowing reach

$$q = \frac{2}{3}\mu\sqrt{2g}h^{\frac{3}{2}} \tag{6.1}$$

and the volume V of the flow into the polder per 1 m weir length is

$$dV = \int_{t1}^{t2}\frac{2}{3}\mu\sqrt{2g}h(t)^{\frac{3}{2}}\,dt \tag{6.2}$$

Where

μ: Overflow coefficient

g: Gravity coefficient

t1: Time at beginning of polder filling

t2: Time at which the peak discharge occurs

If the maximum supply occurs with the wave vertex, the water level in the polder may cross the crest of the overflow dam but only insignificantly. That means, up to this point the volume of water flows into polder has to correspond with the existing volumes between the crest of overflow dam and polder's bottom. Therefore the goals must be, the overflow dams and other control structures should be equip for regulating the inflow in such away that the conditions are complied with the design wave. It is clear that a complete filling of the polders up to the vertex level of the water level in Rhine for this case is not possible.

6.4.1 Variation 33

After many different simulation tests, a remark suggestion was finally compiled, which should consider the following criteria:

• Beginning of the filling discharge into polders with a Rhine discharge of approx. 10.000 m³/s

• Beginning of the filling in the order Lower polder - Upper polder and Grietherbuscher Polder

• Achievement of a clear discharge reduction within the area of the wave vertex

• Use if possible the entire potential volume for the retention

• Avoidance of harmful flow rates within the polder

In order to achieve these above conditions, the following measures for the overflowing dams were made:

• Design of the overflowing dams between Old Rhine and Grietherbuscher Polder at a critical Rhine discharge of approx. 10.000 m³/s

• Design of the overflowing dams between Old Rhine and Lower Polder at a critical Rhine discharge of approx. 10.200 m³/s

• Extension of the overflowing dams between Rhine floodplain and Upper Polder and vice versa at a critical Rhine discharge of approx. 10.400 m³/s

• The Overflowing dams between the polder are maintained unchanged.

After investigation of some different variations, the variation 33 finally resulted in the best compromise regarding the above demands. The distribution of the assumed crest of the summer dike for the remark suggestion (variation 33) are represented in Fig. 6.7.

Here should be noted that the HN - Model Rhine only consider on the horizontal crested weirs, so that the certain simplifications were necessary. In the computations, the inclination parallel to the water level of the Rhine should be taken into account. For the variation 33, the assuming characteristic of the overflowing dams are summarized in following table (Table 6.5).

Overflowing dam	Length (m)	Crest (m+NN)
Old Rhine–Lower Polder	600	17.60
Grietherbuscher-Lower Polder	2000	17.20
Lower –Upper Polder (K-19)	500	17.60
Old Rhine-Grietherbuscher	700,500	17.80, 17.85
Grietherbuscher-Upper Polder	500	17.30
Rhine-Upper Polder (K-18)	300, 700	18.65, 18.20

Table 6.5 Some data for an overflowing dams, Polder Grietherbusch

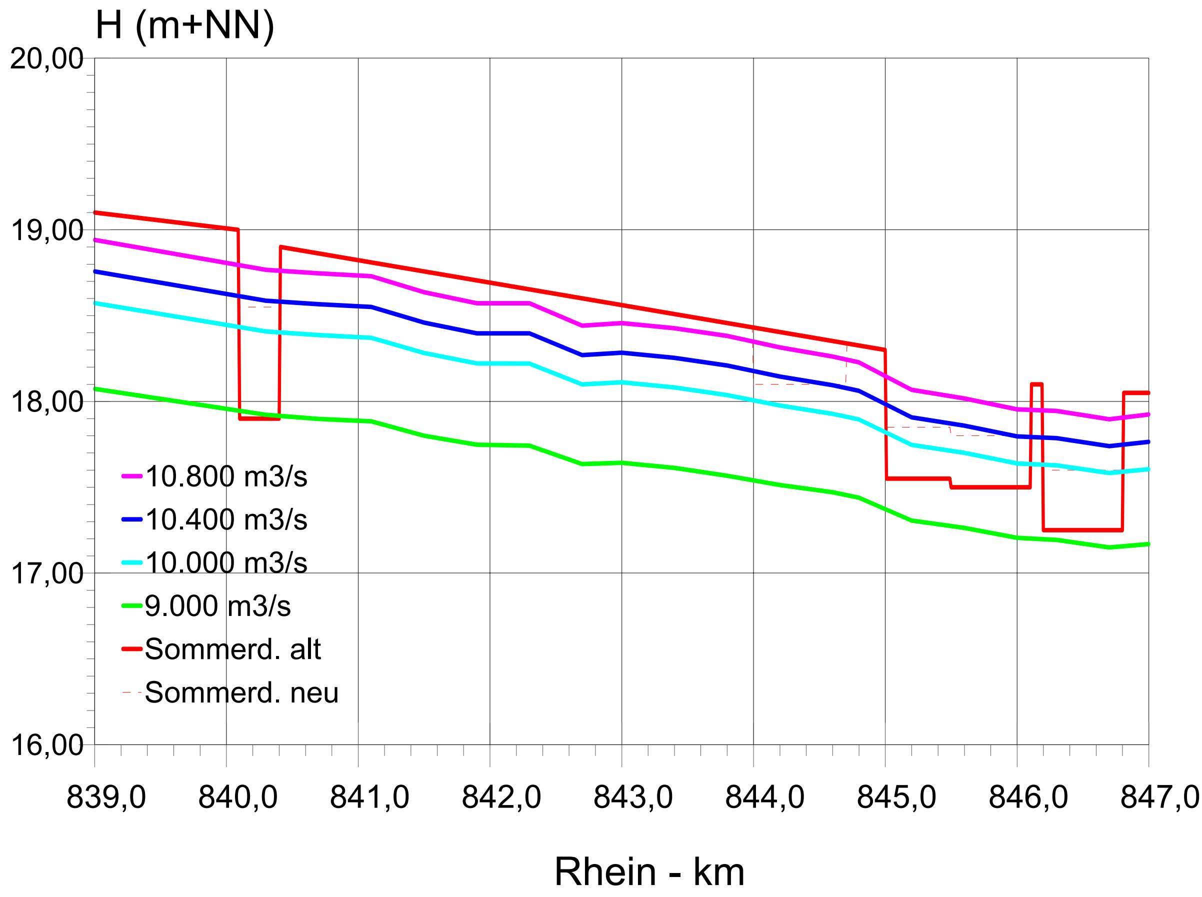


Figure 6.7 Water level and summer dike discharge, variation 33

Figure 6.8 represents the results of the calculations for the variation 33, and one can see from Figure 6.8, a reduction of the Rhine discharge over the entire vertex area of the HQ wave taken place, which leads to an amount of approx. 200m³/s at the point in time T = 120 h.

Additionally the filling takes place as desired from the Lower polder (Figure 6.9). The filling begins with the Lower polder at the point T = 95 h with a Rhine discharge of approx. 10000 m³/s and a starting filling of 13.20 m+NN (Figure 6.10) over the overflow dam at Rhine km 846.5.

The max. water level is achieved at the point T = 140 h at the elevation 17,76 m+NN, from which for the Lower polder a retention Volume of approx. 9 millions m3 may be achieved (see Figure 6.3).

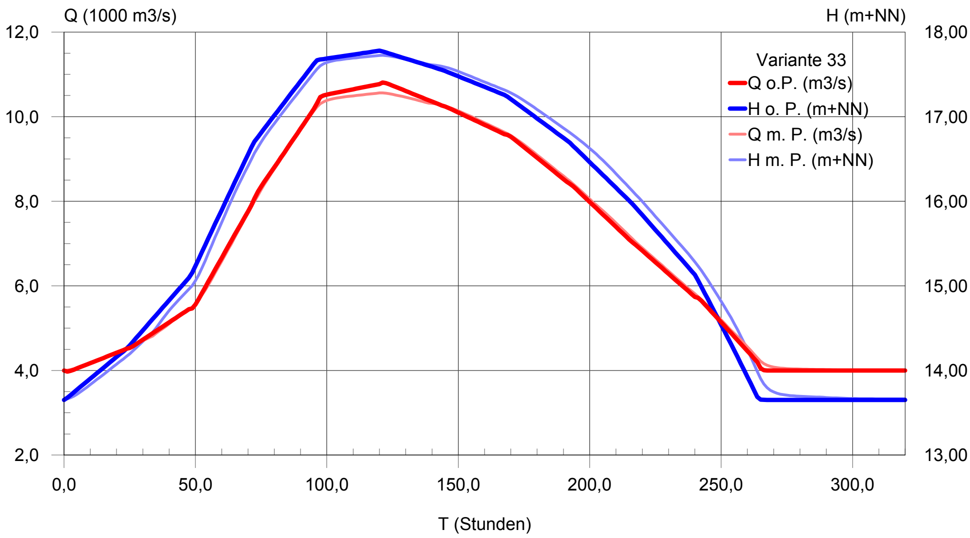


Figure 6.8 Model out flow comparison, variation 33

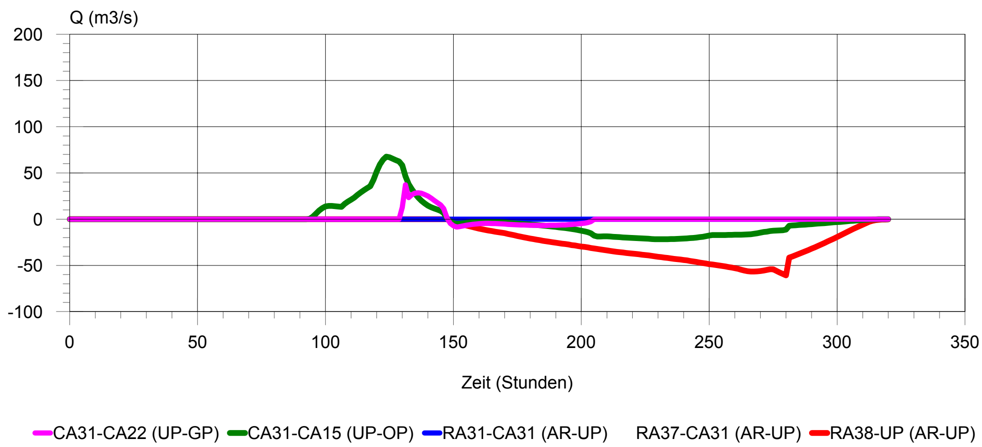


Figure 6.9 Filling discharge at Lower polder , variation 33

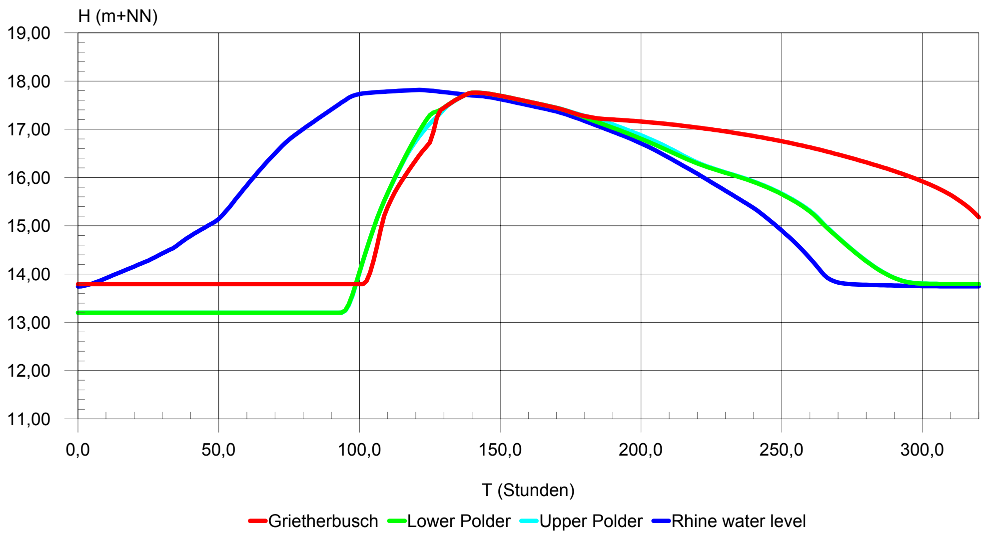


Figure 6.10 Polder water level, variation 33

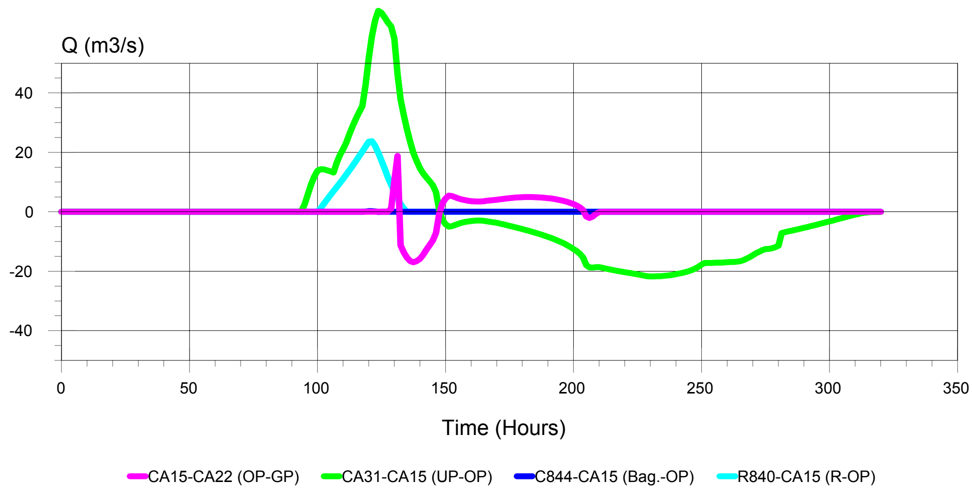


Figure 6.11 Filling discharge, Upper polder, variation 33

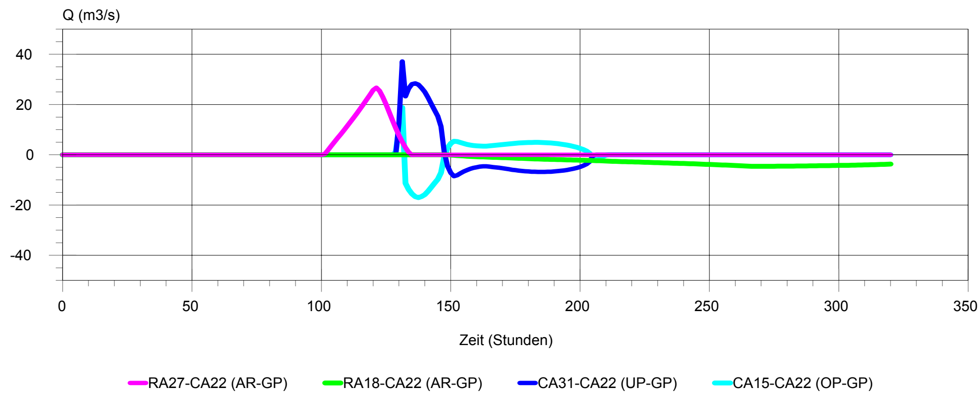


Figure 6.12 Filling discharge, Grietherbusch polder, variation 33

The filling discharge into the polders begins from Lower polder over the summer dike at the Rhine km-846,5, the time T = approx. 95 h (Fig. 6.10), the Rhine discharge Q = 10.000 m³/s and the initial water level of the polder of 13.20 (m+NN). The maximum water level of the polder appears at the time T = approx. 140 h with the level of 17.76 (m+NN), see Fig.6.10, with the volume of approx. 9 millions m³ (see Fig. 6.2).

The following is the filling discharge into the Upper polder. At the beginning, the water flows under the bridge at the road K19 (that run between the Lower polder and Upper polder), the time T = approx. 95 h, the Rhine discharge Q = approx. 10.000 m³/s and the initial water level of 13.20 (m+NN). At the time T = approx. 110 h and the Rhine discharge of 10.400 m³/s, the filling discharge begins over the summer dike at the Rhine km-840 and km-844. At this time the water level in the polder is approx. 15.70 (m+NN). The maximum polder water level reaches 17.76 (m+NN) at the time T = approx. 140 h with the volume of approx. 11.4 millions m³.

The filling of Grietherbuscher polder begins over the summer dike from the Rhine km-845 to km-846, at the time T = approx. 100 h and a starting filling of the polder water level of 13.80 (m+NN) and the Rhine discharge of approx. 10.200 m³/s. When the water level in the Lower polder reaches the level of 17.20 (m+NN), approx. at the time T = 120 h, the filling discharge from Lower polder into Grietherbuscher polder over the summer dike begins. The maximum polder water level reaches 17.76 (m+NN) at the time T = approx. 140 h with the volume of approx. 3.2 millions m³.

The total retention volume of the three polders amount therefore for the variation 33 with consideration of the respective pre-filling approx. 24 millions m³.

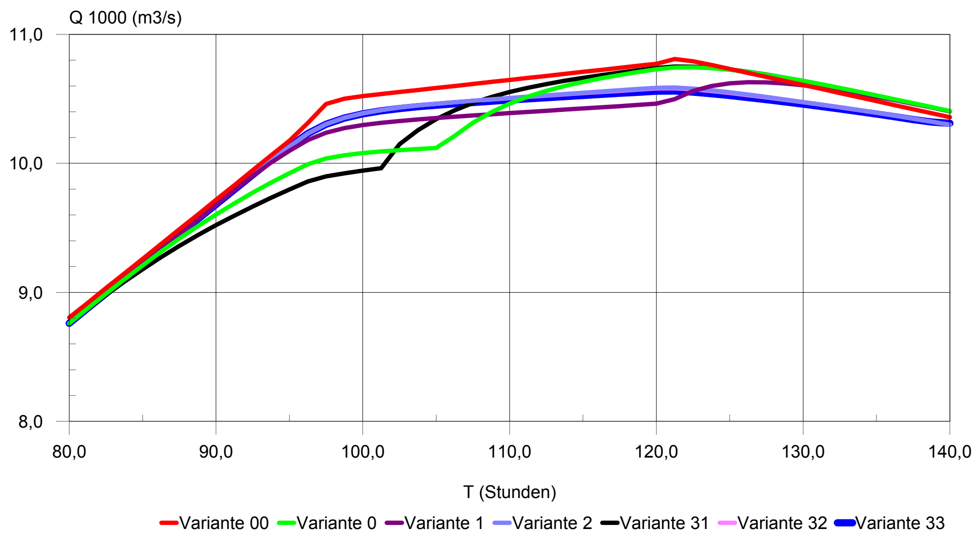


Figure 6.13 Discharge comparison, variation 33

Fig. 6.13 indicates the discharges at the downstream of polders Grietherbusch at the Rhine km 848 in the vertex area of the flood wave of December 1993 for the most important examined variations. Herein the radically differences are recognizable clearly in the wave process with different flooding strategies.

In the case of early flow (variation 0, variation 31) the discharge in the front part of the wave vertex is strongly reduced (Figure 6.13) while the actual vertex discharge is reduced only little, since the polder is filled at this time already and works therefore only as tide flood polder. This type of the flow effectuation has no strong reduction of the discharge point, leads however after experiences with other calculations to a relatively strong delay of the wave propagation.

In the case of relatively late flow (variation 2, variation 33) it is possible to reduce the discharge over the entire vertex area so that the actual flood peak can be clearly reduced. But the delay effect is smaller in this case, according to experiences. Additionally, the usable retention volume is slightly smaller, since the polder may be not completely filled at the wave of the flood peak. However the advantages of an effective reduction of the discharge within the entire vertex area are very important and in addition, the later flow affects the use of the polder area opportune(Goebel, 1997) .

Table 6.6 is summery results obtained from the simulations.

No.	Points	Construction	Rhine-km	Width (m)	Heigth (m)	Overflow begin (m³/s)	Direction	q_{max} (l/sm)
1	RA37-CA31	OldRhine-Lower Polder	846,50	600	17,60	10.000	RA37→CA31 RA37←CA31	246 30
2	RA27-CA22	OldRhine-Grietherbuscher P.	846,00	700	17,80	10.200	RA27→CA22	38
3	RA18-CA22	OldRhine-Grietherbuscher P.	845,30	500	17,85	10.200	RA18→CA22	10
4	C844-CA15	Rhine-Upper Polder	844,50	300	18,20	10.400	C844→CA15	0,8
5	N840-CA15	Rhine-Upper Polder	840,00	700	18,65	10.400	N840→CA15	34
6	CA31-CA15	Lower P.-Upper P.	845,00	500	17,60		CA31→CA15 CA31←CA15	31 11
7	CA31-CA22	LowerP.-Grietherbuscher P.	845,00-846,50	2.000	17,20		CA31→CA22 CA31←CA22	19 4
8	CA15-CA22	UpperP.-Grietherbuscher P.	845,00	500	17,30		CA15→CA22 CA15←CA22	10 30

Table 6.6 Some characteristics of flow through the connection construction of polder Grietherbusch

6.4.2 Conclusions and remarks

Based on the above investigations, an optimal flow strategy as well as the necessary measures for polder Grietherbusch have been compiled in the available study for the polder. The objective was to connect here as large as possible the protection of the polder surfaces with smaller flood event with an optimal retention effect. At the same time, the ecological priority of the area should be reserved or to be increased where possible.

After discussion with the client (STUA Krefeld), a remark suggestion was finally compiled, which considers the following criteria:

- Beginning of the filling at a Rhine discharge of approx. 10000 m³/s
- Beginning of filling in the order Lower - Upper - Grietherbuscher polder
- Achievement of a clear discharge reduction within the area of the wave vertex
- Use if possible the entire potential volume for the retention
- Avoidance of harmful flow rates within the polder

Around these targets regarding the overflowing reach, the following measures are suggested:

- Design of the overflowing reach between Old Rhine and Lower polder for a critical Rhine discharge of approx. 10.000 m³/s
- Design of an overflowing reach between Old Rhine and Grietherbuscher polder for a critical Rhine discharge of approx. 10.200 m³/s
- Extension the overflowing reach between Rhine floodplain and Upper polder and design at a critical Rhine discharge of approx. 10.400 m³/s
- The Overflowing reaches between the polders and among themselves are maintained unchanged.

In such a way one obtains relatively flow delay and it is possible in contrast to the present status to reduce the discharge over the entire vertex area so that the actual flood peak is clearly reduced. However the usable retention volume is slightly smaller than in the present status, since the polder may be not completely filled with the run of the flood wave. The maximum water level is achieved at the point in time T = approx. 140 h and at the level of 17,76 m+NN, from which the total retention volume of the three polders for the variation 33, with consideration of the respective pre-filling, is about 24,6 millions m3.

7 Conclusions and Remarks

7.1 Conclusions

A hydrodynamic – numerical model of the river Rhine (HN-Model Rhine) has been developed that simulates the 1993 flood on the Rhine River from Maxau to Lobith with good agreement. Calibration of the model was carried out and computed water levels were within the target error of plus or minus 0,10 m in steady flow simulation. In the unsteady flow simulation, the peak discharges were never exceeding 300 m³/s and the time when the peak discharge appeared at the gauging stations never greater than 6 hours.

The model was verified using data from the floods of 1988 and 1999. With those simulations the model also obtained very satisfactory water levels. The differences between computed and measured water levels were always smaller than 0,10 m in both flood event simulations and the time when the peak water levels appeared were almost the same.

The model required accurate estimation of un-gauged inflows from tributaries for both calibration and verification simulation in order to obtain the exactly delay times from the gauging station to the confluences on the Rhine River.

The effects of floodplain restoration measures along the Rhine with respect to flood regulation in case of flood event 1988 were small while during this time not all the floodplain restoration measures were in implementation and not all the existing ,,polders'' in operation. The effects were clearer downstream of the river reach.

The effects of floodplain restoration measures on the Lower Rhine showed a higher consequence downstream of the river. In case of flood event 1993, at the gauge Emmerich the computations resulted in a reduction of 300 m³/s discharge and the time when the peak discharge appeared was approximately 12 hours later.

In case of flood event 1999 with the activation of the ,,polder system'' on the Upper Rhine, the water levels on the Lower Rhine at the gauging stations were reduced up to 20 cm and the time delay were up to 12 hours.

The effects of polders on flood regulation have clearly increased in case of the polders with flood control devices (e.g. flood controlled gates, etc.).

Besides using for the investigation the whole river system with imposed changes, the HN-Model Rhine also can be used for studying separate reaches of the river for many purposes. For example, the studying of the effects of polders themselves with different flowing strategies along the river into flood regulation.

The results obtained from the model can be used for different engineering works. They are also the boundary conditions for 2-D, 3-D or physical models. And the water levels obtained from simulation run are very important data for the application of GIS on water resources management.

7.2 Remarks

Knowing that the river will respond to any human intervention, the fundamental principle applied is that modification at one point must not be allowed to create a problem elsewhere. It is important that action undertaken in the rivers´ upper reaches is coordinated with that undertaken in the lower reaches. Therefore, to supplement the landscape planning of the river Rhine, a number of integrated studies of the river and its tributaries should be performed to identify which measures for increasing river capacity will be possible and necessary in the future and where such measures should be implemented.

* HN-Model of the river Rhine is a simple river flow recommendation for the aims of management and restoration of floodplain ecosystem study.

* HN-Model Rhine is an analysis of types of river restoration and of the roles they are playing in their implementation.

* HN-Model Rhine contributes to the development of a scientific methodology for determining the flow characteristics for many engineering works.

* HN-Model Rhine creates effective links between the scientific understanding of the functioning of flood plain areas (riparian ecosystems) and the institutional mechanisms by which river management for conservation and restoration occur.

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