Policy Analysis of Water Management for the Netherlands

Vol. IX, Assessment of Impacts on Shipping and Lock Operation

J. G. Bolten

August 1981

N-1500/9-NETH

Prepared for The Netherlands Rijkswaterstaat
This note was prepared with the support of The Netherlands Rijkswaterstaat under Contract No. WW-256.

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PREFACE

For some time the Netherlands has had a problem with water quality, particularly salinity, eutrophication, and thermal pollution. Moreover, the future demand for fresh water is expected to exceed the supply. The growing demand for the limited supply of groundwater is leading to increased competition among its users: agriculture, industry, nature preserves, and companies that supply drinking water. The supply of surface water is sufficient except in dry years, when there is competition not only among such users as agriculture, power plants, and shipping, but also among different regions.

Facing such water management problems, the Dutch government wanted an analysis to help draft the first national water management law and to select the overall water management policy for the Netherlands. It established the Policy Analysis for the Water Management of the Netherlands (PAWN) Project in August 1976 as a joint research project of Rand (a nonprofit corporation),\(^1\) the Rijkswaterstaat (the government agency responsible for water control and public works),\(^2\) and the Delft Hydraulics Laboratory (a leading Dutch research organization).\(^3\)

The primary tasks of the PAWN project were to:

1. Develop a methodology for assessing the multiple consequences of water management policies.
2. Apply it to develop alternative water management policies\(^a\) for the Netherlands and to assess and compare their consequences.
3. Create a Dutch capability for further such analyses by training Dutch analysts and by documenting and transferring methodology developed at Rand to the Netherlands.

The methodology and results of the PAWN project are described in a series of publications entitled Policy Analysis of Water Management for the Netherlands. The series contains the following volumes:

- Volume I, Summary Report (Rand R-2500/1)
- Volume II, Screening of Technical and Managerial Tactics (Rand N-1500/2)
- Volume III, Screening of Eutrophication Control Tactics (Rand N-1500/3)
- Volume IV, Design of Long-Run Pricing and Regulation Strategies (Rand N-1500/4)
- Volume V, Design of Managerial Strategies (Rand N-1500/5)
- Volume VA, Methodological Appendices to Vol. V (Rand N-1500/5A)
- Volume VI, Design of Eutrophication Control Strategies (Rand N-1500/6)
Volume VII, Assessment of Impacts on Drinking-Water Companies and Their Customers (Rand N-1500/7)
Volume VIII, Assessment of Impacts on Industrial Firms (Rand N-1500/8)
Volume IX, Assessment of Impacts on Shipping and Lock Operation (Rand N-1500/9)
Volume X, Distribution of Monetary Benefits and Costs (Rand N-1500/10)
Volume XI, Water Distribution Model (Rand N-1500/11)
Volume XII, Model for Regional Hydrology, Agricultural Water Demands and Damages from Drought and Salinity (Rand N-1500/12)
Volume XIII, Models for Sprinkler Irrigation System Design, Cost, and Operation (Rand N-1500/13)
Volume XIV, Optimal Distribution of Agricultural Irrigation Systems (Rand N-1500/14)
Volume XV, Electric Power Reallocation and Cost Model (Rand N-1500/15)
Volume XVI, Costs for Infrastructure Tactics (Rand N-1500/16)
Volume XVII, Flood Safety Model for the IJssel Lakes (Rand N-1500/17)
Volume XVIII, Sedimentation and Dredging Cost Models (Rand N-1500/18)
Volume XIX, Models for Salt Intrusion in the Rhine Delta (Rand N-1500/19)
Volume XX, Industry Response Simulation Model (Rand N-1500/20)

Four comments about this series of publications seem appropriate. First, the series represents a joint Rand/Rijkswaterstaat/Delft Hydraulics Laboratory research effort. Whereas only some of the volumes list Dutch coauthors, all have Dutch contributors, as can be seen from the acknowledgments pages.

Second, except where noted, these publications describe the methodology and results presented at the final PAWN briefing at Delft on December 11 and 12, 1979. For Rand, this briefing marked the beginning of the documentation phase of the project and the end of the analysis phase. Rand and the Rijkswaterstaat (RWS) considered the results to be tentative because (1) some of the methodology had not become available until late in the analysis phase, and (2) the RWS planned to do additional analysis.

Third, the RWS is preparing its Nota Waterhuishouding, the new policy document on water management scheduled for publication in 1982, by combining some of the PAWN results from December 1979 with the results of considerable additional analysis done in the Netherlands with the PAWN methodology. Because the understanding gained in the original analysis led to improvements in the data—and, in some instances, the models—used to represent the water management system in the additional analysis, the reader is hereby cautioned that the numerical results and conclusions presented in the PAWN volumes will not always agree with those presented in the Nota Waterhuishouding or its companion reports. (It has not been possible to indicate such differences in the volumes
since they are being written before the Nota is published. Thus, the present series of publications puts primary emphasis on documenting the methodology rather than on describing the policy results.

Fourth, Vol. II through XX are not intended to stand alone, and should be read in conjunction with the Summary Report (Vol. I), which contains most of the contextual and evaluative material.

The present study, Vol. IX in the series, considers the potential consequences of water management policies for inland shipping. These consequences include the costs and benefits to both domestic and international shipping on open waterways and canals, and at locks. International shipping is particularly important to the Dutch economy and to Dutch relations with other European nations. As a result, this volume should be of interest to government officials as well as policy analysts, especially those with responsibility for water management or inland shipping operations.

NOTES

1. Rand had had extensive experience with similar kinds of analysis and had been working with the Rijkswaterstaat for several years on other problems.

2. The Rand contract was officially with the Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging (Directorate for Water Management and Water Movement), but numerous other parts of the Rijkswaterstaat contributed to the analysis.

3. Delft Hydraulics Laboratory research was performed under project number R1230, sponsored by the Netherlands Rijkswaterstaat.

4. Each water management policy involved a mix of tactics, each a particular action to affect water management, such as building a particular canal or taxing a particular use. Four kinds of tactics were considered: building new water management facilities (infrastructure) or applying various treatments to the water (called technical tactics); using managerial measures (called managerial tactics) to change the distribution of water among competing regions and users; and imposing taxes or quotas to affect the quantity or quality of water extracted or discharged by different users (called price and regulation tactics, respectively). A mix of tactics of the same kind is called a strategy. Thus, the overall policy could be conceived as a combination of technical, managerial, pricing, and regulation strategies.
SUMMARY

S.1. BACKGROUND

The objective of the PAWN project was to provide information to assist the Dutch government in choosing a preferred water management policy. In this study we have developed alternative policies and the methodology for comparing them in terms of how they affect the nation as a whole and the various user groups. Inland shipping is one of the primary user groups.

Shipping is important to the Netherlands, and Europe as a whole, for two reasons: (1) transport on the Rijn and Maas is a vital link between the inland industrial areas and the North Sea ports of Rotterdam, Antwerp, and Amsterdam; and (2) shipping is a major carrier for domestic goods, especially sand and gravel and agricultural products. In 1976, inland shipping carried 64 percent of the international goods and 22 percent of domestic goods transported in the Netherlands, for a total of 260 million metric tons. Most of this was bulk cargo (ores, sand and gravel, oil products), for which shipping has a relative advantage over other modes.

Water management policies can have important consequences for shipping operations and the shipping industry. By changing the navigational characteristics of the shipping network (e.g., water depths or number of locks) or its operation, policies change travel times and distances for ships. These changes affect shipping costs, for both Dutch and foreign carriers and industry.

S.2. APPROACH

In our analysis we have considered water management policies to be composed of four types of tactics.1 These are:

- Technical--modifying or adding to the existing water management infrastructure.2
- Managerial--changing the policies for managing the existing infrastructure (i.e., distributing the water).
- Pricing--imposing new prices on use or discharge of water.
- Regulation--imposing regulations on use or discharge of water.

The first two types of tactics affect the supply of water; the last two affect the demand for water by the various users. Shipping operations are most concerned with the first two types, although they will also be influenced by large changes in consumption. To evaluate how tactics affect shipping costs, one must define the situation, determine ship traffic on the network under the given circumstances, then assess the impacts on that traffic from the applied tactics. In
practice, this calculation of cost changes can be simplified by the use of loss functions for both low water and lock delay losses. In the analysis, these functions were used by the water distribution model (DM) and managerial strategy design model (MDSM) to calculate the shipping losses for any given situation. All these models needed to know or calculate was the shipping depth on major waterways and the flows through various canals and associated locks.

Certain impacts on shipping cannot be described by loss functions. We investigated the change in long-run fleet requirements using a proxy related to Rijn flow and a model based on the low water loss function analysis. Major network tactics were considered individually to evaluate those consequences not related to low water losses or delays at highlands locks. Finally, we looked at the shipping industry and markets, to determine how these might be affected by the direct impacts of alternative water management policies.

S.3. SHIPPING COSTS

There is a fundamental problem in defining how much it costs to ship goods. Existing shipping prices do not provide enough information, because they are difficult to determine, vary with market conditions, do not exist in certain market sectors, depend on many unknown factors, and reflect capital expenses of shipping. Prices may not accurately present the true marginal costs of alternative policies.

Actual shipping costs are more appropriate. They consist of two components, fixed and variable costs. Fixed costs include: (1) investment and financing expenses, (2) depreciation, and (3) some fraction of labor, maintenance, administration, and insurance costs that is independent of the ship's activity level. Variable costs, on the other hand, include: (1) fuel and oil, (2) lock, harbor, canal, and loading or unloading fees, and (3) that part of labor, maintenance, administration, and insurance costs that is associated with activity. In practice, separating these costs can be difficult, but it is necessary for accurate comparison of alternative policies.

Cost separation is necessary because of the distinction between short-run and long-run costs. The short run can be defined as a time that is too short for the fleet or water management infrastructure to change. In the short run, only variable (operating) costs will be affected. The long run, on the other hand, allows investment decisions to be made and carried out, so that fixed costs can also change. In PAWN, the screening analysis included long-run costs, but generally neglected the long-run shipping costs of tactics because they were small. Only short-run costs are relevant in managerial strategy design, but impact assessment included both short-run and long-run costs. In the shipping analysis, we normally considered only the variable or operating costs, investigating long-run costs through the fleet proxy.
S.4. LOW WATER LOSS FUNCTIONS

Adequate water levels are vital to shipping. If water depths are not sufficient, ships cannot carry their maximum loads, but must travel with less cargo to reduce their drafts. This means more trips and higher operating costs for transporting a given amount of goods. Policies which change flows and water levels on the network will affect shipping depths for various waterways and routes. We developed low water loss functions as a means for calculating the shipping costs of such changes.

Developing these functions required a complete description of shipping operations (domestic and international) in the Netherlands and Western Europe for 1976 and 1985 contexts. To obtain this information, we commissioned a study of shipping operations by the major inland shipping organizations in the Netherlands.5

In the study, the shipping organizations developed a full description of shipping operations and carrier behavior during both normal and low water periods. They then used models to predict shipping operations in the future context. Using these normal water periods as a reference situation, they ran a series of cases with varying Rijn flows, Maas depths, and combinations of water withdrawals from the Waal (at Tiel) and IJssel (at Refde and Denter). These runs determined how many trips (or ships) would be necessary to carry an average amount of cargo under the given conditions, and what the operating costs of these trips would be.

To use these results in developing the low water loss functions, we devised a system of critical points. Every link of the shipping network has a most shallow point that determines the maximum draft that ships can have on that link. Considering a route as a series of links, we can see that each route will have such a minimum point, the overall minimum of all links on the route. We identified a set of five major locations (critical points) that have variable depths affected by water management tactics, and that limit the depths for ships involved in a large fraction of the total transport. These five locations are:

- Northern Rijn near the mouth of the Ruhr.
- Southern Rijn between Keulen and Karlsruhe.
- Maas (minimum depth of all sections in the Netherlands).
- IJssel between Doesburg and the Twenthekanaal.
- Waal between Weurt and Gorinchem, the minimum of the two sections: Weurt to St. Andries and St. Andries to Gorinchem.

The shipping study considered several thousand combinations of origins and destinations for cargo. Assigning routes to the ship traffic between each combination, we determined the set of critical points passed by each route and grouped the routes using these critical point sets. This gives a total of about twenty aggregated routes (including
those which pass no critical points), of which seven can be considered major. The remaining routes can be combined to form a fixed shipping cost term.

PAWN tactics change flows on waterways and the shipping depths at the critical points. Each route will have its limiting depth for any situation, the minimum depth of the critical points on the route. With the shipping study results, one can calculate the costs per route for each study run. Plotting these shipping costs against the corresponding minimum critical point depth for the route, we can generate a low water loss function for each of the seven major shipping routes.

These curves can be used to find shipping costs for any given set of circumstances, provided that we know the shipping depths at the critical points. Using various data sources, we derived equations which give the shipping depths at critical points as a function of the appropriate flow rates. We also derived equations for the immediate depth reduction caused by withdrawals from the Waal and IJssel. Using these equations, the DM and MSDM could calculate the appropriate shipping depths at all critical points for any time period in any case.

There is an additional cost associated with low water. When fleet capacity falls short of that needed to carry all available cargo, some goods must be delayed and stored until water levels rise. Using shipping study information, we calculated cost functions that could be used like the low water loss functions to determine storage costs for any given situation.

S.5. LONG-RUN FLEET REQUIREMENTS

Low flows on the Rijn and Maas, with or without withdrawals, can cause the fleet to be too small to carry all goods and can lead to large storage costs or potential problems for industry. However, the size and composition of the shipping fleet vary from year to year as old vessels are retired and new vessels introduced. The Dutch government has little control over the situation, and frequently the fleet is far from that which would be optimal given the existing demand for ship transport. Excess capacity can mean a weak industry, through low rates and unemployed ships and crew. Insufficient capacity can mean excessive shipping rates, delay of goods, and disruption of industry during low water periods.

Water management policies will change the supply and demand for water in the nation, thereby affecting shipping depths. If these changes persist, they effectively change the fleet capacity. Over the long run, the fleet will have to adjust to the changes, to maintain the relation between supply and demand for transport. These adjustments will change the number and distribution by size and type of vessel, and thus the total fixed costs of the fleet. Specifying an optimal fleet would be quite difficult, because cargo and water conditions vary through the year, seasonally and randomly, and from year to year.
Fortunately, it is not necessary to specify an optimal fleet in order to investigate how water management policies will affect the required fleet size.

To avoid having to define an optimal fleet, we chose to determine how the existing fleet would have to be scaled to meet long-run changes. We selected a fleet proxy, specifically, the fleet required to carry an average amount of cargo a certain percentage of the time. This percentage should be defined in terms of all water flows and levels in the network. In practice, defining these water conditions can be difficult; it is much easier to use the distribution of Rijn flows at Lobith as the basis of our proxy criterion. Thus, we would compare the fleet needed under different policies to carry an average week’s goods during all weeks with Rijn flow greater than or equal to that for the criterion value.

As our basic criterion, we selected the 10-percent dry decade (flow will be greater 90 percent of the time). To apply this proxy to the analysis, we needed only to choose an appropriate decade in one external supply scenario. This decade had to have the proper Rijn flow and occur during the growing season, to ensure that the water management policies directed toward agriculture would be properly considered in the analysis. Using the shipping study results as a reference, we then developed a model to calculate the required fleet for any given situation, as defined by the vector of five critical point depths. This model was then used to determine the necessary shipping fleet in the selected decade for each alternative case.

S.6. LOCK ANALYSIS

Although ship locks ultimately benefit shipping by maintaining fixed and adequate depths on waterways, ships are delayed in passing through them. Under normal conditions, therefore, locks are operated to minimize these delays. However, water management concerns can often change operation policies to the detriment of shipping.

In the lowlands area of the Netherlands, locks frequently separate fresh from tidal salt water. They reduce salt intrusion, allow maintenance of fixed water levels on the fresh side of the lock, and often reduce freshwater contamination of the salt water. As these locks are used, however, some salt passes through them to contaminate the fresh water. The amount of contamination depends on many factors, including lock dimensions, saltwater concentration, relative water levels, and the number of lock cycles.

At many locks this contamination may be acceptable. The flow of fresh water out of the lock or nearby sluices may be sufficient to dilute the salt and carry it back to sea. At other locks, however, the resulting salt concentrations are objectionable, and additional measures are necessary to reduce salt intrusion. These measures can be separated into technical and managerial tactics.
Technical tactics change the lock characteristics by adding anti-salt technology. Managerial tactics change lock operation policies by flushing the lock complex with fresh water, reducing the number of lock cycles, or using intermediate doors and small lock chambers to reduce salt intrusion per cycle. Both technical and managerial tactics have costs. The technical measures have investment and operating costs, and the managerial measures increase ship delays and freshwater losses.

In the same way, locks in the highlands areas of the Netherlands have water management problems. These locks are used to maintain adequate depths along canals with minimum flows. Passing ships through a lock, however, transfers water from the high to the low water side. Also, locks are often old and have significant leaks through closed doors. Under normal conditions these water losses are not important. When dry conditions prevail, however, these transfers may cause an undesirable loss of water needed upstream to maintain shipping depths or meet the demands of other users.

Just as with lowlands locks, the problems can be attacked with either technical or managerial tactics. Again each type of tactic has its associated costs. However, because water loss is important only during dry periods, technical tactics may be less appropriate. They have high investment costs for their relatively infrequent use.

We investigated technical and managerial tactics at both salt-fresh and fresh-fresh lock complexes, using simulation techniques. For the lowlands locks, we developed a lock operation model to simulate the passage of ships under varying managerial tactics. We analyzed eleven lowlands locks in the Netherlands, developing a series of loss function curves for each lock. These curves specified the reduction in normal salt intrusion that can be achieved for a corresponding increase in normal delay and energy costs through use of technical and managerial tactics. The curves are based on different levels of investment in anti-salt technology at the lock complex.

In the highlands lock analysis, we used a mathematical model of lock operation instead of the computer simulation and limited the managerial tactics to restricting operating hours. In this way, we could calculate both lock delay times and water use as functions of the number of lock cycles, given a specified technology. Using this procedure, we investigated several important canals and locks in the Southeast Highlands area of the Netherlands. For these locks, we determined and plotted delay cost versus water loss for each combination of technical and managerial tactics, choosing the lower envelope of these points as the set of possible efficient tactics.

S.7. MAJOR NETWORK TACTICS

For some major technical and managerial tactics, shipping costs will not be limited to low water and lock delay losses. These tactics may require changes in ship routing or other operations, and therefore
they become more difficult to analyze. However, when carriers change their behavior, it must be to reduce costs. Our initial estimates of costs will thus represent an upper bound for the actual results.

In considering these tactics, one must be careful to include only those costs not covered by the low water and lock delay loss functions, and to include all costs that may arise from interactions between tactics. Most of these latter costs could be calculated by the DM.

Many tactics could be eliminated after preliminary study, as having only negligible costs for shipping. Certain tactics could not be studied completely because they were too complex. These tactics included closing the Oude Maas and Nieuwe Maas and canalizing the IJssel. In these cases, however, we could eliminate the tactics during the screening analysis, because they did not provide sufficient benefits to overcome even their investment costs. For the remaining tactics, which we analyzed in more detail, the shipping costs were generally much less than the investment and operating costs.

Tactics may also affect shipping safety. However, the preliminary analysis of accidents did not yield useful quantitative results. Insufficient data and problems inherent in accident prediction made it impossible to develop useful models. Moreover, the water management policies do not affect those variables that are most important in determining ship accident rates. As a result, safety considerations were not included in the final analysis.

S.8. MARKET ANALYSIS

We have not discussed the problem of how carriers and shippers will react to cost changes. One would need to understand the structure and operation of the shipping industry and transport markets. It is necessary to know how cost changes would be passed on, how government policies might affect behavior, and how carriers and shippers would behave under the circumstances.

Unfortunately, the industry and market are particularly complex and difficult to understand. Both domestic and international shipping markets are characterized by large amounts of private, unregulated transport under contracts that include different rates and provisions for low water rate increases. The situation is complex and information is limited. Consequently, we could not obtain more than a superficial knowledge of these markets and could not investigate the effects of PAVN cost changes on the behavior of carriers and shippers. Knowing, however, that the fleet using Dutch waterways is international, and that these cost changes do not fall only on Dutch vessels, we could determine the fraction of total costs that related to Dutch carriers. This figure makes it possible to consider the effects of such cost changes on the Dutch shipping industry.
Using data from the low water loss function study and other sources, we estimated this fraction to be about 62 percent for low water losses and lock delays. This fraction did not vary significantly between shipping study runs or contexts.

5.9. RESULTS AND CONCLUSIONS

The impact assessment phase of the analysis used the DM to compare alternative cases. These cases were composed of promising policies combined with standards and requirements, and system and scenario assumptions. The promising tactics included:

- MAXTACS—a set of the 9 dominant surviving major network tactics.
- Groundwater extraction quotas, charges, and priority.
- Drinking water company pricing at marginal costs.
- A set of 45 promising waterboard plans to improve regional surface-water distribution.
- Three alternative network managerial strategies.

The alternative policies were compared under varying agricultural groundwater and surface-water sprinkling levels and three external supply scenarios: (1) DEX, an extremely dry year, (2) 1943, a moderately dry year, and (3) 1967, an average year. A base case was chosen to represent approximately the current situation in a 1985 context. The other cases were compared to this base in terms of their relative costs and benefits for all users.

With respect to shipping, the impact assessment results led to several important observations:

- Total shipping losses are only 20 percent of shipping costs in DEX, and fall to 7 percent in 1943.
- In all cases, the change in shipping losses is less than 10 percent of base case losses in DEX, and less than 1 percent in 1943.
- The alternative policies have no apparent impact on the size of the long-run fleet.
- Dredging costs are always small in comparison with other shipping costs.
- Some policies that damage shipping in a DEX year benefit it in 1943.

We also considered the sensitivity of benefits to variations in surface water and groundwater sprinkling, managerial strategy, and groundwater quotas, priorities, and charges. These results showed:
Highlands lock losses are important only in DEX, and are affected only by groundwater sprinkling policy.

The waterboard plans considerably increase shipping losses, particularly if surface-water sprinkling is not limited.

MAXTAGS benefits shipping, reducing shipping losses by almost 10 percent in the DEX scenario, and more than offsetting the losses caused by introducing the waterboard plans and increased surface-water sprinkling.

Managerial strategies are relatively unimportant to shipping costs, but either the NSDM or Velsen strategy would benefit shipping in dry years, under nominal conditions. When the system is stressed, however, these policies hurt shipping in comparison with the nominal RWS managerial strategy.

Increased surface-water sprinkling damages shipping in extremely dry years, but affects it only negligibly when water conditions improve.

Large increases in groundwater use can significantly increase shipping costs, especially if agriculture has priority.

Restricting groundwater use through quotas benefits shipping, no matter who has priority for groundwater use.

If industry has groundwater priority, imposing a groundwater charge damages shipping; if agriculture has priority, it benefits shipping.

Considering these observations, one can conclude that none of the alternative policies has a very strong impact on shipping costs. Four possible explanations for this result are:

1. Tactics that might impose high costs on shipping were eliminated in the screening analysis.
2. Shipping and other users do not always compete for water, because shipping is a nonconsumptive user.
3. Low water losses for shipping do not increase significantly until depths become extremely low.
4. Shipping losses are determined predominantly by Rijn and Maas flows, and water management tactics can only vary these flows and losses by relatively small amounts.

In other than the driest years, shipping is not seriously affected by any of the proposed tactics. Similarly, requirements for the fleet in the long run do not change. As a result, the RWS should not be apprehensive about the effects of future water management policies, if they are careful in making their decisions. Certain actions, however, appear to benefit shipping. These are:

- Dredging the Waal below withdrawal points to remove sandbars before they interfere with shipping operations.
- Improving the Merwedekanaal for transporting water north from the Waal to reduce withdrawals at Tiel.
• Incorporating MAXTACS, if groundwater and surface-water sprinkling increase dramatically.
• Changing the current managerial strategy to use IJsselmeer rather than Waal water for augmenting Noordzeekanaal flows.

By choosing reasonable policies, the Dutch should be able to protect domestic and international shipping from severe consequences when they make future water management decisions.

NOTES

1. A tactic is defined as a single action that can be taken to improve water management. A strategy is a combination of tactics of one particular type, and a policy combines strategies of the four types.

2. The water management infrastructure consists of the waterway network in the Netherlands and all structures and equipment associated with it. This would include not only canals, locks, weirs, and pumping stations, but also such things as pipelines and bridges over waterways.

3. For the purposes of this investigation, a loss function specifies the cost to shipping associated with a particular action (or condition), in a given context.

4. We also studied possible price and regulation tactics that could be applied to the shipping industry, but concluded that they were either unnecessary or not relevant to the basic problem.

5. These organizations were the Dienst Verkeerskunde (DVK) of the Rijkswaterstaat (RWS), the Nederlands Vervoerswetenschappelijk Instituut (NVIT), and the Economisch Bureau voor het Weg- en Watervervoer (EBW).

6. In this report, we will refer to highlands locks as fresh-fresh locks and to lowlands locks as salt-fresh locks. Although there are fresh-fresh locks in the lowlands, we did not consider any of them in the analysis.
ACKNOWLEDGMENTS

This study could not have been completed without the assistance of many people. It would be impossible to mention them all. Although we will acknowledge the contributions of certain individuals and organizations, others undoubtedly also deserve our gratitude.

J. W. Pulles, the Dutch project leader of PAWN, was instrumental in developing and maintaining successful working relationships with the inland shipping organizations in the Netherlands. Through his efforts, we were able to obtain essential information and cooperation. J. Koenis and J. Dijkman of the Waterloopkundig Laboratorium both participated in the lock analysis and developed the framework for calculating salt intrusion through locks.

Personnel at the Dienst Verkeerskunde-Hoofdsefdeling Scheepvaart, of the Rijkswaterstaat, under the direction of C. Kooman, supplied invaluable data and analysis, and helped us to understand the complexities of inland shipping operations in Europe. We are also indebted to the personnel of the Nederlands Vervoerswetenschappelijk Instituut and the Economisch Bureau voor het Weg- en Watervervoer for their efforts in conducting the shipping cost study on which much of this analysis was based.

B. F. Coeiler, Project Leader of PAWN at Rand, provided broad guidance throughout the project, as well as very helpful administrative support.

This study benefited substantially from the contributions of several colleagues at Rand. J. H. Bigelow and G. H. Fisher made many constructive comments that led to improvements in the substance and presentation of the material. R. C. Critton, who served as Rand reviewer for this report, provided numerous suggestions to ensure that it would be clear, accurate, and complete.

Our sincere thanks to E. T. Gernert, Managing Editor of PAWN at Rand, and her colleagues in the Publications Department for their care in guiding our study to press; to N. C. Moll for her editorial acuity in reading the manuscript; and to M. P. Dobson for painstakingly incorporating corrections.

Even though we were heavily dependent on other people's contributions, we take sole responsibility for any errors that appear in this volume.
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GLOSSARY

ACB: Administratief Centrum voor het Beroepsvervoer (Netherlands Administrative Center for Commercial Transport)
BD: biochemical oxygen demand
CBS: Centraal Bureau voor de Statistiek (Netherlands Central Bureau of Statistics)
CEN: Conference of European Ministers of Transport
CI: chloride ion
cm: centimeter
Com: commercial ship traffic
m³: cubic meter
m³/s: cubic meter per second
decade: ten-day period (three decades per month)
DEX: extremely dry year (external supply scenario)
Dfl: Dutch florin (guilder)
DM: millions of Dutch florins
Df: thousands of Dutch florins
DHL: Delft Hydraulics Laboratory
DM: water distribution model
dm: decimeter
DVK: Dienst Verkeerskunde (shipping branch of the RWS)
EBW: Economisch Bureau voor het Weg- en Watervervoer (Netherlands Economic Bureau for Road and Water Transport)
EEC: European Economic Community (Common Market)
hr: hour
Int: international
kg: kilogram
km: kilometer
LC: load capacity
m: meter
MAXTAGS: combination of nine dominant promising network tactics
min: minute
MLC: mean load capacity
mil: million
mm: millimeter
MSDM: managerial strategy design model
NAP: normal mean sea level at Amsterdam
Nat: national
No: number
NVI: Nederlands Vervoerswetenschappelijk Instituut (Netherlands Institute of Transport)
PAWN: Policy Analysis for the Water Management of the Netherlands
pct: percent
P/R: price and regulation (tactics)
Rec: recreational ship traffic
RID: Rijksinstituut voor Drinkwatervoorziening (Netherlands Institute for Drinking Water Supply)
RW: Rijkswaterstaat
TLC: total load capacity
ton: metric ton (1000 kilograms)
w: week
Chapter 1
INTRODUCTION

1.1. BACKGROUND

The Netherlands is a wet country that normally has more than enough fresh water to meet all demands. As a consequence, water management has never been an important problem. This situation changed, however, in 1976, when both precipitation and river flows were below normal for much of the spring and summer. The result was agricultural damage in some areas, and a dramatic drop in the level of the IJsselmeer, the main Dutch surface water reservoir. For the first time, the Dutch government began to realize that it might have to worry about water management in the future.

In an average year, the supply of fresh water to the Netherlands can be broken down as follows [1.1]:

- Rijn--69 million m³/year (63 percent)
- Precipitation--30 million m³/year (27 percent)
- Maas--8 million m³/year (7 percent)
- Small rivers--3 million m³/year (3 percent)

This supply will vary considerably from year to year, however, and is not evenly distributed throughout the year. In general, more than half of the total river flow occurs during the winter and spring months, when demands for water are lower than during the summer and fall.

It is much more difficult to characterize the demand for fresh water. The primary uses, in roughly descending order of consumption, are:

- Salinity and pollution control (by flushing) in agricultural water distribution systems.
- Salinity control in the Nieuwe Waterweg (to protect water supplies for agriculture from salt intrusion at Rotterdam).
- Level control in reservoirs and distribution systems (to offset evaporation losses).
- Agricultural sprinkling.
- Industrial consumption.
- Drinking water company consumption (domestic and commercial users).
- Environmental demand.

It is clear that the dominant uses are to control either the quality or quantity of water available for agriculture. Again, this
consumption is not uniformly distributed across the country, but is concentrated in the lowlands areas where surface water distribution systems are most developed and salt water intrusion threatens groundwater quality. Note that shipping and power plants do not appear on the list of consumers. Neither of these industries consumes water, although they both require it in their normal operations. In this sense they exert demands for water levels or flows in various parts of the waterway network.

Although there is generally more than enough fresh water to meet the demands of all users, the quality or distribution of this water may not always be adequate. Industry and drinking water companies have been consuming increasing amounts of groundwater in recent years, because the quality of the Rijn has deteriorated and demands have grown. Also, many agricultural areas in the Netherlands do not have good access to surface water supplies. As a result, to avoid suffering crop losses when rainfall is inadequate, they must either increase groundwater withdrawals or improve surface water distribution systems. Both remedies have costs for other users. The competition for groundwater supplies is increasing, and both environmental groups and farmers are concerned about falling levels. Similarly, more consumption of surface water in these areas could cause problems for shipping during dry periods, because withdrawals from major waterways reduce depths and water available for lock operations. Both of these effects increase shipping costs.

We have seen that there are already competing demands for water during dry periods, and that this competition will only increase as demands rise in the future. With the normal seasonal and annual variations in water supplies, these growing demands create the possibility of water management problems for the Netherlands. As a result of the shortages in 1976, and in expectation of future problems, the Netherlands Rijkswaterstaat (RWS) decided to begin developing a water management program. This program would establish new policies to be used when supplies were not adequate to meet expected demands.

Unfortunately, water management problems are complex and cannot be easily or quickly solved, if approached comprehensively. To do a thorough investigation, one must consider many factors, including all potential sources of supply and demand. The major components of the problem that should be included are:

- Surface water supply and demand by category (with statistical variations).
- Groundwater supply and demand.
- Short-run and long-run problems and policies.
- Water quantity (shortage and excess) and quality (salinity and pollution).
- Alternative policies to increase supply or reduce demand.
- Important user groups that will be affected by policies.
These many complicating elements make the problem difficult to handle in any reasonably comprehensive manner. To assist the Dutch government in preparing future reports and legislation, the RWS provided research funds to The Rand Corporation to study water management problems in the Netherlands. The goals of this research, which began in April 1977, included:

- Develop a set of promising water management policies and assess the consequences of these policies for the country, considering water quantity, quality, and salinity.
- Develop appropriate methodologies for designing these policies and assessing their consequences (impacts).
- Use the results of this analysis to assist the Dutch government in formulating water management policies and legislation.

The PAWN project considered six primary user groups: agriculture, power plants, shipping, industry, drinking water companies, and the environment. Although inland shipping operations do not consume water, they are directly affected by water management decisions and policies. Actions which benefit other user groups could have adverse consequences for shipping and its many customers. This report discusses how alternative water management policies would affect the shipping industry, and explains how the methodology to evaluate these effects was developed. The final chapter summarizes the results of the study and draws some conclusions about the importance of inland shipping in water management decisions.

1.2. SHIPPING AND WATER MANAGEMENT POLICY

Inland shipping is a major industry in the Netherlands for two primary reasons. First, the Netherlands occupies an economically and geographically important position in Europe; it lies on the North Sea at the mouths of the Rijn, Maas, and Schelde rivers. Inland shipping forms a vital transportation link between the major harbors of Rotterdam, Amsterdam, and Antwerp and the industrial areas of Germany. Ships from many nations carry raw materials and finished goods across the Netherlands on a complex network of rivers and canals. Second, for several reasons shipping costs are relatively low, particularly for bulk goods, when compared with other modes of transport [1,2]. Accordingly, ships carry a large fraction of the building materials (sand and gravel), agricultural products, coal, ores, and oil products transported in the Netherlands.

Because shipping is such a major industry, one that could be particularly affected by water management decisions, we should consider in more detail the interactions between shipping operations and water management problems.
Shipping operations are important to two aspects of the water management problem—quantity and salinity. Although shipping does not consume water in a true sense, it requires certain minimum flows to maintain adequate depths on waterways, and minimum delays for passage through locks. These requirements represent demands that affect the distribution of water in the shipping network.

The relationship between shipping and water management does not have to be adverse. Certain actions that benefit shipping (by increasing or maintaining depths on waterways) can also benefit water management. A primary example is the Neder-Rijn canalization [1.1]. This EWS project involved constructing weirs and locks on the Neder-Rijn and Lek at Driel, Amerongen, and Hagestein. The location of these weirs can be seen in Fig. 1.1, which also shows the primary waterway system of the Netherlands.

These weirs, in particular the one at Driel, can be used to control the distribution of Rijn flow among the three branches: the IJssel, Neder-Rijn, and Waal. When the weirs are lowered into the water, they reduce the flow profile and increase resistance to flow. By adjusting the height of the weirs, both flow and water depth on the Neder-Rijn can be regulated. This regulation improves navigation on the IJssel, Pannerdensche Kanaal, Neder-Rijn, and Lek, while permitting larger flows on the IJssel. The additional IJssel flow can be used to maintain the IJsselmeer level and provide water for agriculture in the North.

Shipping operations can, however, create problems for water management. At ship locks in the highlands areas of the Netherlands, lock operations require certain minimum flows in the canals. If this water is needed for other uses, including maintaining canal depths for shipping, the losses through locks can be a management problem. This problem can be important on the canals in the southeast area of the Netherlands, particularly the Julianakanaal.

Lock operations and harbor improvements can cause important water management problems by increasing water salinity [1.1]. Locks between fresh and salt water, such as the sea locks at IJmuiden, near Amsterdam, can be a major source of salt contamination. Similarly, when navigation channels or port facilities are widened and deepened, saltwater intrusion can dramatically increase. Harbor improvements in the Rotterdam area have caused extensive riverbed erosion upstream on local waterways. The improvements and erosion have enabled the salt water of the North Sea to penetrate much farther inland than before. This penetration increased salt concentrations at freshwater inlets, the most important of which is the inlet at Gouda. The same problem has occurred or will occur at other locations in the country where port or harbor facilities are enlarged.

Just as shipping actions can affect water management problems, so can water management policies affect shipping. Various measures have been suggested for reducing the salt contamination problem at Rotterdam.
Weir Location

a -- Driel
b -- Amerongen
c -- Hagestein

Fig. 1.1 -- Location of weirs on the Neder-Rijn
These measures include limiting the depths of some waterways, and closing others under adverse conditions, such as low Rijn flows. Such closures could dramatically affect shipping operations in the area, forcing vessels to reroute (if possible), and increasing costs and congestion on other waterways.

In addition to major projects such as waterway closures, water management actions can affect shipping operations in other ways. These include:

- Modifying flows and water levels in rivers and canals changes the amount of cargo that ships can carry, affecting their costs.
- Withdrawing water from major waterways can reduce levels downstream and lead to future problems from sandbank formation.
- Changing the infrastructure may force ship traffic to reroute, thus increasing costs.¹
- Restricting lock operations to reduce freshwater loss or salt intrusion increases delays for ships using the locks.
- Changing withdrawals and water distribution policies may also have long-run implications for the size of the shipping fleet needed to carry all cargo.
- Modifying the network or the amount of ship traffic can affect shipping safety and the probability of accidents.

An additional complication arises because the shipping fleet operating on Dutch waterways is European, not solely Dutch. To investigate possible market effects of policies, it may be desirable to determine how shipping costs and benefits are divided between Dutch and other carriers and the various industries that ship goods in Europe.

The above effects are not, of course, independent. For example, ships that modify their routes may encounter different minimum depths, and will cause increased congestion and time delays for vessels on the new routes. Similarly, time delays for all ships will become longer as the number of ships on the network grows. This becomes important if water levels fall and more ships are needed to carry a given amount of goods. We must consider such interacting effects where they are important to the problem.

1.3. WATER MANAGEMENT POLICIES

Many solutions have been proposed for Dutch water management problems. In the PAWN analysis, we have considered these suggested policies to be composed of different types of tactics. If we define a tactic as a single action that can be taken to improve water management, we can group potential tactics into the following four general categories:
- 7 -

- Technical--modifying or adding to the existing water management infrastructure.
- Managerial--changing the operation of given infrastructure.
- Pricing--placing a tax or fee on water use or discharge.
- Regulation--establishing a quota or other regulation on water withdrawal, use, or discharge.

The first two types of tactics directly affect the supply of water to the country and its various regions. Price and regulation tactics, on the other hand, are meant to influence the demand for water. Inland shipping should be most affected by technical and managerial tactics, because they change the characteristics and operation of the water distribution system.

As shipping operations do not directly consume water, few price or regulation tactics would apply directly to the industry. However, these tactics applied to other users will change the amounts of water withdrawn, discharged, or required in the different areas of the country. Water distribution and availability, thus shipping conditions, will change as price and regulation tactics are applied to other users.

If a tactic is a single action, a strategy can be defined as a combination of actions (tactics) of one particular type. Thus we can have technical, managerial, price, and regulation strategies. A combination of strategies, ultimately a combination of tactics, forms a water management policy.

1.4. APPROACH

The overall approach used in the PAWN project is described in Vol. I. Within this framework, our investigation of inland shipping was based on the following procedure.

1.4.1. Define Reference Cases

Reference cases form the basis for all calculations and comparisons of impacts. Defining these reference cases involves specifying:

1. Characteristics of the shipping network and related infrastructure.
2. Size, composition, and characteristics of the shipping fleet.
3. Distribution of goods shipped in a given time period, by origin and destination, vessel type and size, and fraction of loading.
4. Fraction of shipping costs which apply to Dutch vessels.

We defined two such contexts for analysis, an observed 1976 and a predicted future year (1985).
1.4.2. Determine Shipping Scenario

The costs and benefits of a policy will depend on the environment in which it operates. Because we do not know the nature of the future environment, we examine policies in a number of different possible states, called scenarios. A scenario is a description of the world at a given time, either in the past or at some hypothetical future date. For purposes of analysis, it considers the major influences on the cost and performance of policy alternatives. In the shipping analysis, the relevant variables consist of the external supply of water, the amount of dredging permitted downstream of withdrawal points, and the context year.

1.4.3. Assign Ships to the Network

For any particular scenario, it is necessary to determine the number and types of ships that may be affected by alternative tactics. In the 1976 context, ship counts were available to provide this information. When such data did not exist, as in the future context, we used models to provide traffic information.

1.4.4. Assess Impacts of Tactics

Identifying and calculating the costs to shipping of alternative tactics constitute a multistage process consisting of the following steps:

1. Modify the shipping network as necessary to reflect the tactic under consideration.
2. Assume the distribution of ships on the network does not change.
3. Calculate changes in shipping costs from all causes associated with the tactic.
4. Investigate changes in routes or ship traffic if water levels are changed or costs (from step 3) are large. 
5. Determine the direct effects of cost changes on the shipping industry.

In practice, we do not have to follow this exact procedure for every policy considered. By separating the analysis into types of impacts, and developing loss functions for some of these impacts, we can avoid detailed analysis of tactics and scenarios that do not significantly change the shipping network. In most cases, these loss functions will give shipping costs directly, when we specify the context, scenario, and water distribution in the network.

In this study, the emphasis has been on shipping impacts related to the quantity of water available. Water management policies can also
affect water quality and salinity. Careful consideration shows that these tactics would affect shipping only as they changed the quantity or distribution of water. Salinity or quality changes would not influence shipping operations. Moreover, because inland ships are not important polluters (except by accident), additional regulations to reduce their discharges would serve no purpose. Accidental spills depend on shipping safety, which was considered to be part of the analysis.

1.5. COMPONENTS OF THE ANALYSIS

It was desirable to separate the analysis into six distinct components or types of impacts. Loss functions could be developed for two of the impacts: low water losses and lock delays. Calculating these losses for each policy would be virtually impossible by any other means. With the loss functions, however, the distribution model (DM) and managerial strategy design model (MSDM) could quickly determine the appropriate losses for any case.

The other impacts could not be handled in this manner. Instead, it was necessary to calculate the costs or benefits of each impact individually for each relevant tactic. The six components or impacts, including low water losses and lock delays, follow.

1.5.1. Low Water Loss Functions

As water levels (thus maximum allowable ship drafts) change on the shipping network, ships may not be able to carry their normal loads. This restriction will affect the number of ships (i.e., loaded trips) required to carry a fixed amount and distribution of goods. Low water loss functions specify the cost of shipping goods as a function of the depths on major waterways.

1.5.2. Lock Loss Functions

To conserve freshwater losses or prevent salt intrusion through a lock, one must either invest in additional equipment or restrict lock operations. Lock loss functions specify the delay costs to shipping at a lock, as a function of the water loss (consumption) or salt intrusion through the lock. In general, water loss is the primary concern at highlands locks; salt intrusion and water loss are both important at lowlands locks which separate fresh and salt water.

1.5.3. Long-Run Fleet Proxy

Water management policies have implications for the size of the shipping fleet needed in the long run. Persistent withdrawals, changes in the shipping network, water distribution policies, and lock operation rules may mean that more ships will be needed to carry a
given amount of cargo. A long-run fleet proxy can be used to compare these effects of alternative water management policies.

1.5.4. Direct Effects of Major Network Tactics

Major changes to the water management infrastructure may directly affect shipping operations in ways not revealed by the loss functions or long-run fleet implications. Every proposed tactic of this type must be investigated to determine what type of effects will occur and how large they will be. Changes in shipping safety and accident probabilities are included in this analysis.

1.5.5. Direct Effects of Price and Regulation Tactics

These tactics directly affect carriers, their equipment, and their operations. However, several factors severely limit the use of such tactics with respect to shipping operations. Therefore, they were considered only in general terms and are discussed in App. H.

1.5.6. Market Analysis

Dutch vessels represent only a fraction of the fleet operating on European waterways. To compare national costs and benefits for the different segments of the economy, one must know what fraction of total shipping costs applies to Dutch vessels and their customers.

1.6. ORGANIZATION OF THE VOLUME

The remainder of this volume discusses the data, methodology, results, and conclusions relevant to each aspect of the study. Chapter 2 describes inland shipping operations in the Netherlands and their importance to Western Europe. Chapter 3 considers shipping costs and the problem of defining what cost elements should be considered in the analysis.

Chapters 4 through 8 describe the various components of the study. Chapter 4 explains the need for the low water loss functions, and presents their development. Chapter 5 considers the implications of water management policies for the size of the shipping fleet in the long run. It describes the selection of an appropriate proxy measure for the long-run fleet, and explains the methodology used to estimate the values of this proxy for the alternative policies. Chapter 6 discusses the general problem of lock analysis. It compares the situations at highlands and lowlands locks, describes the models used in the study, and discusses the development of highlands and lowlands lock loss functions. Chapter 7 explains the general methodology for estimating the impact of major changes in the shipping network and its operation. It discusses the most important of these modifications.
The final two chapters are concerned with the shipping industry and transport market, and the general results and conclusions of the study. Chapter 8 discusses the structure of the industry and market, explaining how difficult it is to determine direct and indirect effects of changes in shipping costs. Chapter 9 summarizes the results of the analysis, and presents observations and conclusions about the relationship between shipping and water management policies.

Several appendixes are included to add supporting material for the main text. Appendix A presents information about shipping costs as described in Chap. 3. Appendix B discusses in detail the development of the low water loss functions, and includes complete results. Appendix C explains the use of low water loss functions in estimating a probability distribution for shipping losses. In App. B, we describe the development of the long-run fleet model. Appendix E describes the lowlands lock analysis models, and App. F presents the results of the highlands lock analysis. The safety and accident study is considered in App. G, and App. H explains why price and regulation tactics were not applied directly to the shipping industry. Finally, App. I derives a procedure for evaluating the net benefits of water management policies.

NOTES

1. In the PAWN study, we have chosen to use Dutch spelling for all Dutch geographical features and place names. The only exceptions to this rule are The Hague, the North Sea, and the Netherlands. Thus, for example, Rhine becomes Rijn and Meuse becomes Maas.

2. The Rijkswaterstaat is an agency of the Ministry of Traffic and Public Works in the Netherlands. It is responsible for water control (including dikes, dams, bridges, pumping stations, etc.), and maintenance and construction of waterway and highway facilities at the national level.

3. Throughout the study we will refer to the system of waterways in the Netherlands and Northwestern Europe as a network. Those waterways that carry ships form the shipping network. In a network, the individual waterway branches are called links, and the junctions of waterways (links) are known as nodes. The water management infrastructure consists of the waterway network and all structures and equipment associated with it. This includes not only canals, locks, weirs, and pumping stations, but also such things as pipelines and bridges over waterways.

4. For reasons discussed in Chap. 4, the low water loss function analysis did not include route changes. They were considered, however, in more localized studies, such as the Spui closure, water transport through the locks at Wijk bij Duurstede, and reduced flow through the Lateraalkanaal.

5. In practice, these effects could not be calculated, because we could not obtain necessary information about shipping markets and the structure of the industry.
6. For the purposes of this investigation, a loss function specifies the cost to shipping associated with a particular action (condition), in a given context.

REFERENCES


Chapter 2
INLAND SHIPPING

2.1. GENERAL OPERATIONS

Inland shipping is a significant industry in the Netherlands, for both geographical and economic reasons. The location of the Netherlands, on the North Sea at the mouths of the Rijn, Maas, and Schelde rivers, means that its system of waterways can serve as a vital link between the industrial areas of inland Europe and the ports of Rotterdam, Amsterdam, and Antwerp. This is shown in Fig. 2.1, a map of the primary inland waterways of Northwestern Europe.

Shipping is also important for economic reasons. It is a primary mode of transport for certain domestic industries, particularly agriculture and construction. Shipping companies, as well as shipbuilding and ship repair activities, are a declining, but still important, source of employment. Moreover, shipping and the economic activities that it makes possible are a prime factor in the growth and vitality of the North Sea port cities and inland industrial areas. Table 2.1 shows the position of shipping relative to the other competing modes of transport for international goods. Clearly, ships are the primary inland means of moving goods between the Netherlands and other European countries.

Table 2.2 shows the distribution of domestic transport by mode, for the years 1966 and 1976. Several important conclusions emerge from this information. First, shipping carries a smaller fraction of the total domestic transport than it does of the international transport. Second, the relative performance of the shipping industry (product of distance and cargo) exceeds the relative tonnage carried. This implies that ships are used more often for long distance hauling. Finally, during the ten years between 1966 and 1976, shipping declined in importance.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cargo (mil tons)</th>
<th>(pct)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner shipping</td>
<td>166.2</td>
<td>64</td>
</tr>
<tr>
<td>Pipeline</td>
<td>42.0</td>
<td>16</td>
</tr>
<tr>
<td>Road(a)</td>
<td>38.6</td>
<td>15</td>
</tr>
<tr>
<td>Rail</td>
<td>11.9</td>
<td>5</td>
</tr>
<tr>
<td>Air</td>
<td>0.2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>258.9</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

SOURCE: Ref. 2.9.
(a) Does not include trade with Belgium and Luxembourg.
Fig. 2.1 -- Primary inland waterways of Northwestern Europe
### Table 2.2
DOMESTIC GOODS TRANSPORT BY MODE FOR 1966 AND 1976

<table>
<thead>
<tr>
<th>Mode</th>
<th>Tons (mln) (pct)</th>
<th>Ton-km (mln) (pct)</th>
<th>Tons (mln) (pct)</th>
<th>Ton-km (mln) (pct)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
<td>81.0 23</td>
<td>7,403 39</td>
<td>94.1 22</td>
<td>7,132 29</td>
</tr>
<tr>
<td>Rail</td>
<td>14.5 4</td>
<td>2,126 11</td>
<td>5.8 1</td>
<td>1,076 4</td>
</tr>
<tr>
<td>Road</td>
<td>255.4 73</td>
<td>9,234 49</td>
<td>336.5 77</td>
<td>16,671 67</td>
</tr>
</tbody>
</table>

**Total** 350.9 100 18,763 99 436.5 100 24,879 100

**Source:** Ref. 2.7.

Not only did ships carry relatively less cargo, but they carried it shorter distances. The increasing fraction of total performance for road transport indicates that trucks are being used more for many of the longer trips for which ships were previously employed.

Shipping has probably become less important because costs have risen more in the shipping industry than in other transport modes. The choice of transport mode is normally based on several factors: total transport costs, time, reliability, safety, and load characteristics. A 1975 RWS committee investigated shipping operations and the shipping industry in the Netherlands [2.4]. The committee found that, as of 1972, for bulk goods, with 15 km of terminal transport at both ends, inner shipping cost less than road transport for distances greater than 75 km. Without terminal transport, the cost was less than road transport for distances greater than only 20 km. For other goods, with terminal transport, the cost was less for distances more than 195 km, and without terminal transport it was always less expensive to ship the goods. These conclusions apply to normal loads of 20 tons for trucks and 500 tons for ships.

Unfortunately, we do not have the same information for 1976. Transport authorities generally believe, however, that shipping costs have increased faster than trucking costs in recent years. This would explain why ship transport has decreased, especially for longer routes.

Transport by ship has its disadvantages also, the most important being slowness. Interest costs or process flexibility problems may limit how long a customer can wait for goods. These factors are less important for bulk goods, such as sand and gravel, because they have less value, and bulk goods are the primary ship cargo. Because the total transport of these materials fluctuates from year to year, the decline in ship transport may only be temporary and due to such a phenomenon.

We have mentioned that shipping is particularly important to agriculture and construction activities. It is also important to other industries, as indicated by the data in Table 2.3, which shows
Table 2.3

INLAND SHIP TRANSPORT BY TYPE OF GOODS FOR 1976

<table>
<thead>
<tr>
<th>Commodity Group</th>
<th>Domestic</th>
<th></th>
<th>International</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tons</td>
<td>Ton-km</td>
<td>Tons</td>
<td>Ton-km</td>
</tr>
<tr>
<td>Agricultural products</td>
<td>6.6</td>
<td>639</td>
<td>8.0</td>
<td>3,704</td>
</tr>
<tr>
<td>Other food products</td>
<td>6.0</td>
<td>608</td>
<td>11.2</td>
<td>4,304</td>
</tr>
<tr>
<td>Solid fuels</td>
<td>1.0</td>
<td>94</td>
<td>10.2</td>
<td>3,586</td>
</tr>
<tr>
<td>Oil and oil products</td>
<td>9.6</td>
<td>853</td>
<td>27.6</td>
<td>10,171</td>
</tr>
<tr>
<td>Ores and metal wastes</td>
<td>0.5</td>
<td>48</td>
<td>33.2</td>
<td>8,440</td>
</tr>
<tr>
<td>Metals</td>
<td>0.8</td>
<td>79</td>
<td>12.2</td>
<td>5,217</td>
</tr>
<tr>
<td>Minerals (sand/gravel)</td>
<td>64.5</td>
<td>4,151</td>
<td>47.7</td>
<td>12,700</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>2.2</td>
<td>364</td>
<td>5.1</td>
<td>2,309</td>
</tr>
<tr>
<td>Chemical products</td>
<td>1.9</td>
<td>226</td>
<td>7.8</td>
<td>2,994</td>
</tr>
<tr>
<td>Others</td>
<td>0.9</td>
<td>70</td>
<td>3.3</td>
<td>1,077</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>94.1</strong></td>
<td><strong>7,131</strong></td>
<td><strong>166.2</strong></td>
<td><strong>54,503</strong></td>
</tr>
</tbody>
</table>

SOURCE: Refs. 2.7, 2.9.

The goods carried by inland shipping in 1976. In domestic transport, sand and gravel are clearly the primary commodities, although agricultural and food products and oil are also important. In international transport, the cargoes have a more even distribution. Oil products and ores are much more important, because of the transport from Rotterdam up the Rijn to German industries.

In the complex network of rivers and canals, the Rijn, with its three Dutch branches, the Waal, IJssel, and Neder-Rijn, is by far the primary waterway. It forms the basic route for raw material transport from the ports on the North Sea to the large inland manufacturing areas. It also carries smaller amounts of coal, sand, and gravel from Germany back into the Netherlands. Table 2.4 indicates how much Rijn shipping dominates the inland navigation statistics.

The dominance of Rijn shipping is greater than the table implies. The total transport includes goods in transit across the Netherlands; these goods are therefore counted both as incoming and outgoing. A large fraction of the transport across the Belgian border consists of cargoes which are either loaded or unloaded in Germany, France, or Switzerland. These goods are thus also transported on the Rijn.

Table 2.5 and Fig. 2.2 should also clarify the distribution of ship traffic. They show the primary Dutch inland shipping ports, in terms of total cargo handled during 1976. It is clear from this information that the Rotterdam area (Rotterdam, Europoort, and Vlaardingen) dominates Dutch shipping, leaving Amsterdam a poor second. If Dordrecht and other areas near Rotterdam are included, the situation becomes even more extreme.
Table 2.4

INTERNATIONAL INLAND SHIPPING BY BORDER CROSSING POINT FOR 1976
(million tons)

<table>
<thead>
<tr>
<th>Border Crossing</th>
<th>Incoming</th>
<th>Outgoing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>German border</td>
<td>42.6</td>
<td>79.6</td>
<td>122.2</td>
</tr>
<tr>
<td>Rijn (Lobith)</td>
<td>41.5</td>
<td>77.0</td>
<td>118.5</td>
</tr>
<tr>
<td>Other</td>
<td>1.0</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Belgian border, east</td>
<td>9.5</td>
<td>10.8</td>
<td>20.3</td>
</tr>
<tr>
<td>Maas points</td>
<td>9.3</td>
<td>10.9</td>
<td>19.3</td>
</tr>
<tr>
<td>Other</td>
<td>0.1</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Belgian border, west</td>
<td>20.4</td>
<td>30.3</td>
<td>50.7</td>
</tr>
<tr>
<td>Kreekraksluizen</td>
<td>11.8</td>
<td>16.0</td>
<td>27.8</td>
</tr>
<tr>
<td>Other</td>
<td>8.6</td>
<td>14.3</td>
<td>22.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>72.4</td>
<td>120.8</td>
<td>193.2</td>
</tr>
</tbody>
</table>

**SOURCE:** Ref. 2.6.

**NOTE:** Totals do not agree with other tables of international shipping because transit goods are counted as incoming and outgoing.

---

Table 2.5

CARGO SHIPMENT AT PRIMARY PORTS FOR INLAND SHIPPING IN 1976
(million tons)

<table>
<thead>
<tr>
<th>Location</th>
<th>Loaded</th>
<th>Unloaded</th>
<th>Total</th>
<th>International</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotterdam</td>
<td>74.26</td>
<td>20.36</td>
<td>94.61</td>
<td>72.59</td>
</tr>
<tr>
<td>Amsterdam</td>
<td>7.39</td>
<td>6.21</td>
<td>13.60</td>
<td>5.85</td>
</tr>
<tr>
<td>Europoort</td>
<td>9.90</td>
<td>1.15</td>
<td>11.05</td>
<td>6.22</td>
</tr>
<tr>
<td>Hoege en Lage Zwaluwe</td>
<td>2.18</td>
<td>5.62</td>
<td>7.80</td>
<td>0.21</td>
</tr>
<tr>
<td>Muiden</td>
<td>6.70</td>
<td>0.30</td>
<td>6.99</td>
<td>0.17</td>
</tr>
<tr>
<td>Dordrecht</td>
<td>3.30</td>
<td>2.68</td>
<td>5.98</td>
<td>1.91</td>
</tr>
<tr>
<td>Vlissingen</td>
<td>2.85</td>
<td>2.33</td>
<td>5.17</td>
<td>2.06</td>
</tr>
<tr>
<td>Hellevoetsluis</td>
<td>4.29</td>
<td>0.59</td>
<td>4.89</td>
<td>0.05</td>
</tr>
<tr>
<td>Terneuzen</td>
<td>2.40</td>
<td>2.18</td>
<td>4.58</td>
<td>2.91</td>
</tr>
<tr>
<td>Vlaardingen</td>
<td>2.79</td>
<td>1.74</td>
<td>4.53</td>
<td>1.34</td>
</tr>
<tr>
<td>IJmuiden</td>
<td>3.20</td>
<td>1.26</td>
<td>4.46</td>
<td>1.51</td>
</tr>
<tr>
<td>Utrecht</td>
<td>0.61</td>
<td>3.61</td>
<td>4.21</td>
<td>1.16</td>
</tr>
<tr>
<td>Made en Drimmelen</td>
<td>3.96</td>
<td>0.05</td>
<td>4.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Maastricht</td>
<td>2.09</td>
<td>1.71</td>
<td>3.79</td>
<td>1.87</td>
</tr>
<tr>
<td>Heel en Panheel</td>
<td>3.24</td>
<td>0.12</td>
<td>3.36</td>
<td>1.61</td>
</tr>
<tr>
<td>Megan e.a.</td>
<td>2.99</td>
<td>0.01</td>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Delfzijl</td>
<td>1.80</td>
<td>1.15</td>
<td>2.95</td>
<td>1.18</td>
</tr>
<tr>
<td>Wessem</td>
<td>2.60</td>
<td>0.26</td>
<td>2.86</td>
<td>0.87</td>
</tr>
<tr>
<td>Zuidrecht</td>
<td>0.49</td>
<td>2.26</td>
<td>2.75</td>
<td>0.89</td>
</tr>
</tbody>
</table>

**SOURCES:** Refs. 2.7, 2.8.
Annual Cargo

- Less than 5 million tons
- 5 - 10 million tons
- 10 - 15 million tons
- More than 15 million tons

Fig. 2.2 -- Primary Dutch inland shipping ports
We can only conclude the following from this discussion: Although the network and shipping operations in the Netherlands are extensive, transport is dominated by traffic along the Rijn, particularly between Rotterdam and the inland industrial areas. Shipping on the Maas and shipping to Amsterdam are also significant, but small by comparison. For this reason, comparing the shipping costs in alternative policies should show that the cost changes are relatively unimportant unless they involve changes to the Rijn or its branches. Similarly, if shipping costs from policies are important, they will probably have international implications that must be considered.

2.2. INTERNATIONAL ASPECTS

Europeans have long recognized the strategic importance of the Rijn. Its ship traffic and transport are regulated under the Convention for Rijn Navigation, signed at Mannheim on October 17, 1868. This treaty between Belgium, France, Germany, Great Britain, the Netherlands, and Switzerland guarantees free navigation on the Rijn and its branches in the Netherlands. It also establishes a Central Commission, which has jurisdiction in most matters relating to navigation on the river.

The major provisions of the convention guarantee free navigation for all vessels, including those not registered in the member states. Ships and their crews, however, must be certified annually by a member country. The convention also requires that the waterway channel must be maintained, and that all obstructions to navigation must be avoided. Channel maintenance has been interpreted to mean preservation of a certain minimum depth and width at a specific (low) river flow.

These restrictions are important for Dutch water management. The depth reductions that result from withdrawals at Tiel and St. Andries might be interpreted as impeding free navigation. Tactics which involve closing waterways in the Rotterdam area would not be subject to treaty constraints. To date there have been no significant international repercussions from the Dutch water management decisions, but the possibility exists.

2.3. SHIPPING NETWORK AND INFRASTRUCTURE

The primary shipping network in the Netherlands is shown in Fig. 2.3. The network consists of a variety of open waterways (river branches, lakes, and sea arms), as well as canals and canalized rivers, whose levels are controlled by locks and weirs. Although the open waterways offer relatively unrestricted travel, ships must pass through a series of locks on the canals and canalized rivers. The locks maintain desired water levels along the canals.

As a rule, locks are also located where it is necessary to keep fresh and salt water separated. In most cases, these locks also maintain a fixed or controlled level on the freshwater side, avoiding tidal influence. The major exception to this rule is the Nieuwe Waterweg in
Fig. 2.3 -- Primary Dutch inland shipping network
the Rotterdam area. There, to avoid interference with shipping, only freshwater flow is used to prevent salt intrusion. Normally, this flow is sufficient to keep the salt from moving too far inland.

The assembly of waterways (open and canals), weirs, locks, pumps, bridges, and all other equipment associated with the network is defined as the infrastructure. Most of the additional equipment has some effect on shipping, as shown in the following examples:

- When weirs are used, ships must pass through locks, causing delays.
- Pumping stations may redistribute water in a manner that affects waterway depths (thus determining load factors) or restrict lock operations.
- Bridges (fixed and movable) limit ship heights; in addition, movable bridges often cause delays because of constraints on opening times.
- Harbors (loading and unloading points) may restrict ship speeds in passage or create congestion which slows traffic and increases the probability of accidents.
- Customs stations at borders delay ships and cause congestion.

All of the above are examples of what must be considered in defining the shipping network. Each section of waterway has its specific characteristics, including dimensions, current velocity, type of infrastructure present, and other factors affecting ship passage. The analysis required a complete specification of the shipping network. Without this, we could not have determined shipping costs or evaluated how alternative policies affected shipping operations.

2.4. NETWORK FLOWS AND DEPTHS

A primary characteristic of each part of the network is its depth. In canals and canalized rivers, the depth is controlled by locks and weirs, and is not clearly related to the flow. In open waterways, flow and depth are closely related. In this analysis, the Rijn and its branches were the most important waterways. To use low water loss functions, we must be able to calculate the waterway depths that correspond to known flows.

The problem of developing relationships between flows and depths is discussed more fully in Chap. 4. Note, however, that the Rijn flow as it enters the Netherlands does not uniquely determine the flows on the Waal, Ijssel, and Neder-Rijn. The weir at Driel is used to change the normal water distribution between branches. The operating policy for this weir is an important variable in water managerial policy. This policy is discussed fully in Vol. V and Vol. XI.
2.5. SHIPPING FLEET AND VESSEL CHARACTERIZATION

The shipping fleet operating in the Netherlands cannot easily be described. Although most domestic transport involves Dutch vessels, ships from all of Western Europe carry cargo on the international routes. Ships operating on the Rijn must be licensed and registered, but very little is known about other foreign vessels. Even if reliable registration data were available, it would not be possible to determine how many of these ships would participate in the international transport when needed (during low water periods). Chapter 4 discusses this problem when it considers fleet capacities and low water shipping losses.

The lack of adequate registration data only aggravates a situation already present in the known fleet; vessels vary greatly in age, size, load capacity, and virtually every other characteristic. It is particularly difficult to classify the fleet under any reasonable system, but our analysis required that we do so. Vessels range in size from small ships with load capacities of a few metric tons to large barge combinations with capacities of more than 10,000 tons. Lengths vary from 15 m to 200 m; breadths vary from 3 m to 23 m; and maximum loaded depths vary from 1 m to more than 4 m. Although other characteristics, such as maximum velocity, are more consistent, the overall result is enormous diversity.

There are other important variations among vessels. The fleet can be classified by type, as well as size. In addition to the most common dry cargo ships, there are tankers, concrete carriers, motorless towed ships, and assemblies of barges rigidly secured to special pushing vessels. The number of towed ships has decreased steadily during recent years, replaced by larger self-propelled ships and the multiple barge assemblies, called push/tows.

The four barge push/tow combinations are the largest vessels on the inland waterway system. With lengths of up to 200 m, widths of 23 m, and maximum loaded drafts of more than 4 m, they have capacities of up to 12,000 tons. Only the major waterways can accommodate them, but they have become particularly popular for Rijn transport.

Recent trends in ship construction, as well as the age diversity in the fleet, can be seen in Table 2.6. This table shows the distribution by type of ship and period of construction for the active Dutch fleet. Recent construction activity has concentrated on larger, wider, and more efficient vessels, particularly dry cargo push/tow barges. It is also clear that construction of towed barges has ceased, and that the rapid growth of motor vessel production during the 1960s has also slowed. This indicates that there may be too many of these ships, especially tankers, and that the push/tow combinations are the most efficient means of transport.

Although we would like to classify vessels by type (dry cargo, tanker, barge, etc.), we must also be able to aggregate them by size. In the current systems, this is based on load capacity, which is highly
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6,416</td>
<td>3,739</td>
<td>530</td>
<td>527</td>
<td>3,818</td>
<td>3,184</td>
<td>68</td>
<td>28</td>
</tr>
<tr>
<td>Unknown</td>
<td>13</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Before 1900</td>
<td>251</td>
<td>97</td>
<td>1 (a)</td>
<td>250</td>
<td>96</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<tr>
<td>1940-1949</td>
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<td>192</td>
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<td>Before 1900</td>
<td>44</td>
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<td>-</td>
<td>43</td>
<td>36</td>
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<tr>
<td>1900-1909</td>
<td>171</td>
<td>166</td>
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<td>1</td>
<td>167</td>
<td>164</td>
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</tr>
<tr>
<td>1910-1919</td>
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<td>125</td>
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<td>(a)</td>
<td>113</td>
<td>124</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>1920-1929</td>
<td>223</td>
<td>256</td>
<td>-</td>
<td>-</td>
<td>202</td>
<td>252</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>1930-1939</td>
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<td>84</td>
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<td>-</td>
<td>55</td>
<td>78</td>
<td>19</td>
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<td>7</td>
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<td>6</td>
<td>1</td>
</tr>
<tr>
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<td>4</td>
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<td>8</td>
<td>12</td>
<td>22</td>
<td>7</td>
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<tr>
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<td>28</td>
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<td>-</td>
<td>15</td>
<td>48</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>1970-1976</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Push Barges</td>
<td>378</td>
<td>594</td>
<td>37</td>
<td>56</td>
<td>341</td>
<td>538</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>Before 1900</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1900-1909</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1910-1919</td>
<td>4</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>4</td>
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<td>6</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1940-1949</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>1950-1959</td>
<td>12</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1960-1969</td>
<td>122</td>
<td>211</td>
<td>28</td>
<td>37</td>
<td>94</td>
<td>174</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1970-1976</td>
<td>229</td>
<td>349</td>
<td>9</td>
<td>20</td>
<td>220</td>
<td>330</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Total: 7,515, 5,104, 573, 598, 6,770, 4,449, 172, 57

SOURCE: Ref. 2.8.

NOTE: Load capacity is expressed in thousands of metric tons.
(a) Less than 1,000 tons.

correlated with ship length. The relationships between breadth and
draft, and ship length, are not so strong, but these characteristics are
less important in determining load capacity.

In 1954, the Conference of European Ministers of Transport (CEMT)
established a system of waterway classification based on the sizes of
the largest ships that could use the waterways. This system of waterway and ship classification originally consisted of five classes, but it has been enlarged to seven by addition of one class at each end. The system is shown in Table 2.7, which includes the accepted mean characteristics for each size of vessel. The table also shows the total length of Dutch waterways of each class (1975), and load capacity limits for each ship. These limits were developed by the European Economic Community (EEC).

Table 2.7

CENT CLASSIFICATION SYSTEM OF EUROPEAN INLAND WATERWAYS

<table>
<thead>
<tr>
<th>Class</th>
<th>Length (m)</th>
<th>Breadth (m)</th>
<th>Depth (m)</th>
<th>Load Capacity (tons)</th>
<th>Waterway Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Variable Dimensions</td>
<td>2.2</td>
<td>150</td>
<td>80-250</td>
<td>989.3</td>
</tr>
<tr>
<td>I</td>
<td>38.5</td>
<td>3.0</td>
<td>2.2</td>
<td>300</td>
<td>250-400</td>
</tr>
<tr>
<td>II</td>
<td>50.0</td>
<td>6.6</td>
<td>2.5</td>
<td>600</td>
<td>400-650</td>
</tr>
<tr>
<td>III</td>
<td>67.0</td>
<td>8.2</td>
<td>2.5</td>
<td>1000</td>
<td>650-1000</td>
</tr>
<tr>
<td>IV</td>
<td>80.0</td>
<td>9.5</td>
<td>2.5</td>
<td>1350</td>
<td>1000-1500</td>
</tr>
<tr>
<td>V</td>
<td>95.0</td>
<td>11.5</td>
<td>2.7</td>
<td>2000</td>
<td>1500-3000</td>
</tr>
<tr>
<td>VI</td>
<td>185.0</td>
<td>22.8</td>
<td>3.3</td>
<td>9000</td>
<td>3000-</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 2.4.

(a) Draft when fully loaded.
(b) Within the Netherlands.

The objective of the CEMT system was to permit classification of the European waterway network. A waterway is assigned to a specific class if no vessel of the next higher class can use it. Class restriction may arise from water depths, as well as limiting dimensions at a lock or bridge. The classification of the Dutch shipping network is also shown in Fig. 2.4.

The CEMT system was not convenient to use in the analysis, however. Most of the available data did not divide ships by class. Moreover, a large part of the information and reference material provided by DVK uses a different system. This system, also used by other shipping organizations in the Netherlands, is presented in Table 2.8. The table includes, in addition to standard dimensions, mean values for horsepower and the maximum drafts at various load factors for each class. These characteristics may vary considerably within classes, and distributions for this variation can be developed when necessary. The primary difference between this and the CEMT system is in the description of push/tows. The DVK has used classes 6 and 7 to separate the two barge push/tows from the four barge push/tows.

The DVK scheme has an additional benefit. Through an extensive study of ship traffic data, personnel at the DVK determined that the distribution of ships by size class passing a point depends on the mean load capacity of those ships. This approximate relationship
Fig. 2.4 -- CENT classification of Dutch waterways
holds well under normal circumstances, and the basic distribution is shown in Table 2.9. Modified distributions have also been developed to reflect limitations imposed by waterway size class. We used this information in the analysis when no observations of ship sizes were available.

Table 2.8
DVK STANDARD SHIP CLASSIFICATION SYSTEM

<table>
<thead>
<tr>
<th>Size Class</th>
<th>Load Capacity</th>
<th>Length (m)</th>
<th>Breadth (m)</th>
<th>Full Depth 85% (m)</th>
<th>Full Displacement (tons)</th>
<th>Empty Displacement (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>125</td>
<td>50-199</td>
<td>25.0</td>
<td>4.6</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>1</td>
<td>325</td>
<td>200-449</td>
<td>39.0</td>
<td>5.1</td>
<td>2.3</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>550</td>
<td>450-749</td>
<td>50.0</td>
<td>6.6</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>925</td>
<td>750-1149</td>
<td>67.0</td>
<td>8.2</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>1350</td>
<td>1150-1549</td>
<td>80.0</td>
<td>9.5</td>
<td>2.6</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>2000</td>
<td>1550-2349</td>
<td>95.0</td>
<td>11.5</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>4100</td>
<td>2550-4999</td>
<td>175.0</td>
<td>11.4</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>8800</td>
<td>5000-</td>
<td>185.0</td>
<td>22.8</td>
<td>3.2</td>
<td>2.8</td>
</tr>
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</table>

SOURCE: Ref. 2.3.

Table 2.9
STANDARD SHIP FREQUENCY DISTRIBUTION

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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>100.0</td>
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<tr>
<td>160</td>
<td>82.5</td>
<td>17.5</td>
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<td></td>
<td></td>
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<tr>
<td>200</td>
<td>62.5</td>
<td>37.5</td>
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<td></td>
</tr>
<tr>
<td>240</td>
<td>42.5</td>
<td>57.5</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>20.0</td>
<td>73.0</td>
<td>7.0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>350</td>
<td>17.5</td>
<td>62.5</td>
<td>16.0</td>
<td>4.0</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>15.4</td>
<td>54.2</td>
<td>20.9</td>
<td>9.0</td>
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<td>43.4</td>
<td>26.1</td>
<td>13.0</td>
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<td>0.9</td>
<td></td>
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<td>36.7</td>
<td>27.0</td>
<td>17.0</td>
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<tr>
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<td>6.0</td>
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<td>9.0</td>
<td>6.4</td>
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<td>1.6</td>
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<td>4.5</td>
<td>14.5</td>
<td>25.0</td>
<td>25.0</td>
<td>16.5</td>
<td>7.2</td>
<td>2.8</td>
<td>4.5</td>
</tr>
<tr>
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<td>12.5</td>
<td>25.0</td>
<td>24.5</td>
<td>18.0</td>
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</tr>
<tr>
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<td>10.5</td>
<td>25.0</td>
<td>23.5</td>
<td>20.0</td>
<td>7.0</td>
<td>3.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 2.3.
2.6. RECREATIONAL BOATING

In addition to the commercial ship traffic, an ever increasing number of recreational vessels use the waterway system. Recreational boating is strongly seasonal, lasting from May through September, peaking in July. Although the primary areas for recreational traffic are Friesland and Zeeland, it can be found on virtually every waterway in the country.

Recreational vessels make their presence felt most strongly at locks, where they can dramatically increase congestion and the consequent delay times for all vessels during peak hours. Chapter 6 considers this problem in more detail. Recreational motorboats and sailing vessels are also present, however, on the major commercial waterways. There the most important problem is the danger of accidents. Pleasure craft are smaller and more difficult to see, have relatively inexperienced operators, lack radar and radio units, and may be present in large numbers. Congestion would probably be worse, however, if the obvious dangers did not cause smaller vessels to avoid operating on the larger commercial waterways.

Although recreational vessels compete with and affect commercial shipping operations, and are, in turn, affected by water management policies, we have chosen not to consider them specifically in the analysis for two reasons. First, recreational traffic is strongly seasonal, and is concentrated in weekend and vacation periods, when the volume of commercial traffic is reduced. This minimizes the interaction between the two types of vessels. Second, although recreational boaters may suffer lock delays or increased operating costs from tactics, the costs should be small and particularly difficult to evaluate. Commercial costs will be much larger (for tactics with significant costs) in most cases. The only exception may be at salt-fresh locks, which are considered in Chap. 6.

Recreational boating is growing at a rapid rate throughout the Netherlands, however. As a result, it is possible that at some time in the future our assumptions will no longer be valid. Should this occur, a revised and expanded analysis would be necessary.

2.7. SCENARIO AND REFERENCE CASES

The PAWN study compared the consequences of alternative water management policies. A policy cannot be evaluated in a vacuum, however; we must define the world in which it is being considered. This means the system in which the policy operates, as well as the external environment--those forces outside our control that influence the system and its operation.

In order to describe and model the system, it is necessary to make certain assumptions. System assumptions specify inherent characteristics of the world for the models used in the analysis. In PAWN, many of the important assumptions were related to agriculture, economic conditions, and power
plants. Those that pertain to shipping will be discussed as they become important to the study.

The external environment for the analysis is described by the scenario assumptions. They specify the outside factors affecting the system, those variables that are uncertain or whose values must be determined by forces outside the control of water management decisionmakers. When we study inland shipping, describing the scenario is a primary problem.

Water management policies will affect shipping operations and costs. But to determine how, and how much, shipping will be affected, we must be able to characterize shipping operations in a reference situation. But how do we define the reference situation? Clearly, shipping operations and total shipping costs will depend on many factors, including the following:

- Amount and type of cargo to be carried by ships and other modes.
- Where the cargo originates and where it is to be delivered.
- Character of the shipping fleet.
- Nature of the shipping network.
- Shipping cost coefficients.
- Availability of water (flows and depths) in rivers and canals.
- Ship traffic distribution on the network.

The first five elements in this list will be a function of the time frame that we are considering. They depend on social and economic conditions, as well as on existing plans by various public and private organizations. In this sense, they are either completely or partially outside the control of water management or shipping authorities in the Netherlands. These variables have been combined into a scenario component called the context, which specifies conditions in the reference year for the analysis.

The availability of water in the shipping network is primarily a function of precipitation and flows in rivers entering the Netherlands. Unlike context variables, rainfall and river flows are primarily random and not dependent on time frame. Consequently, these elements have been combined into an independent component of the scenario, external supply. When investigating water management policies, we must consider them in a particular context with a specified external supply of water.

The last variable on the list, the distribution of ship traffic on the network, will be a function of both the context and external supply. Among other factors, it depends on how much cargo needs to be carried between each origin and destination and how much water is available to ships on the potential routes. Consequently, it cannot be considered as a scenario component, but must be determined by the various models used in the study.
One additional scenario component must be mentioned. When water is withdrawn from the Waal, sedimentation will increase downstream of the withdrawal point. The resulting sandbar can either be left in place or removed by dredging. Because the decision as to whether or not to dredge may involve factors not under the control of water management authorities, we have included it as a scenario variable.

2.7.1. Context

The contexts chosen for the shipping analysis were 1976 and an indefinite future year, 1985. We selected this year because it had frequently been used in recent studies and was close enough to be reasonably described. For each context year, we specified the basic structure of shipping operations, namely:

- Characteristics of the shipping network.
- Size and distribution by class and type of the Dutch and total shipping fleets.
- Distribution of goods shipped between all pairs of points (origin-destination pairs) by type of commodity.
- Size and type of vessels used in carrying each commodity between each origin and destination.
- Normal maximum load factors for each commodity, by type and size class of ship for each origin-destination pair.

Theoretically, one can completely specify the structure for the 1976 context. In reality, this is not possible. In many cases one must make assumptions and use other shipping models to specify all information.

Even if all of the above information is available, we still must know what routes the ships follow. Some ship counts are available from various government organizations, but the data are usually limited in time or aggregated over an entire year [2.1.2.2]. In either case, seasonal variations are lost, and we must make assumptions about traffic levels. Ship counts by themselves do not establish the particular routes used; more detailed analysis is required. This normally means using large traffic distribution models to find minimum cost routes for each origin-destination pair. We will discuss this problem in more detail in Chap. 4.

Every problem in specifying the 1976 context is magnified in the 1985 situation. Without shipping data, it is necessary to rely completely on various types of models to predict the shipping structure. These models range from econometric systems for the entire EEC to simple trend equations and expert judgment. For various reasons, the same procedures cannot be used for each component of the analysis, and one must be satisfied with the best available information.
The least difficult aspect of this problem, and the one in which a consistent approach is possible, is the shipping network. Major projects normally require long periods for planning, financing, and construction. For this reason, large infrastructure changes can be predicted, especially for shipping. Modifications usually come as the result of a problem in the network. One can say, therefore, with some certainty, what the shipping network will look like in ten years. It will look like today's network, with the addition of changes currently planned and under construction, and others now under consideration.

For the other parts of the context, however, prediction is not as simple. The 1985 context for the low water loss functions and long-run fleet analysis is based on a shipping cost study produced by the DVK of the NVI, the Nederlands Vervoerswetenschappelijk Institut (NVI), and the Economisch Bureau voor het Weg- en Watervervoer (EBW) [2.5]. The predictions of goods production and distribution, as well as mode selection, were made by the NVI and EBW for an earlier study commissioned by the EEC. Table 2.10 compares the projections for 1985 total cargo shipment with the data for 1976.

The remaining parts of the context for these sections of the analysis were projected by using trend equations tempered by expert judgment. More complete descriptions of this process can be found in [2.5].

A related, but somewhat different, source of information was used in determining the context for the lock analysis. Total traffic (in terms of load capacity) at the locks was taken from [2.4]. These predictions were also made by the NVI and EBW for an earlier study of 1985 shipping. They should be, therefore, reasonably consistent with the 1985 context for the low water loss functions. Actual ship traffic at the locks came from existing trends in average ship sizes at each lock complex. For the remainder of the analysis, we selected the 1985 context from one of the above sources, using additional reports whenever necessary.

Table 2.10

<table>
<thead>
<tr>
<th>Component</th>
<th>1976</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>94.116</td>
<td>119.265</td>
</tr>
<tr>
<td>International (in)</td>
<td>43.523</td>
<td>74.040</td>
</tr>
<tr>
<td>International (out)</td>
<td>93.793</td>
<td>176.286</td>
</tr>
<tr>
<td>International (through)</td>
<td>28.877</td>
<td>28.283</td>
</tr>
<tr>
<td>Total</td>
<td>260.309</td>
<td>395.874</td>
</tr>
</tbody>
</table>

SOURCES: Refs. 2.1, 2.7, 2.8.
2.7.2. External Supply

There are unlimited numbers of possible external supply scenarios, if one specifies Rijn and Maas flows and the pattern of precipitation over space and time. The PAWN project selected four such supply scenarios, as described in Vol. II. The large number of variations does not present any serious problem in this study, because of the loss function approach to low water and lock delay costs. These loss functions can be used with all external supply scenarios, as the DM and NSDM automatically calculate the appropriate losses from water conditions on the shipping network.

Loss functions are not appropriate to the rest of the shipping analysis, particularly in the study of major technical and managerial tactics. For most of these tactics (discussed in Chap. 7), we used 1976 data in the cost calculations, thus building the 1976 external supply characteristics into the analysis. The probable errors should be small and biased toward a worst-case analysis. Because 1976 was extremely dry, the number of ships on the network would have been greater than normal, and greater than that expected for all but the driest external supply scenarios, and thus total shipping costs should be higher.

A complete discussion of the construction of external supply scenarios can be found in Vol. II. We will also briefly describe the selected scenarios in Chap. 9.

2.7.3. Dredging and Sedimentation

When water is withdrawn from the Waal at Tiel or St. Andries, a sandbank begins to form downstream. If the withdrawals are large or persistent (or both), this sedimentation will accumulate sufficiently to reduce maximum allowable ship drafts in future years. Such reductions mean increased shipping costs, through low water losses. One alternative to the future costs is to dredge the extra sediment, either during or after the withdrawals. This scenario variable states whether dredging is permitted.

NOTES

1. Although the Rijn has three branches in the Netherlands, the Waal, IJssel, and Neder-Rijn/Lek, the IJssel is not included under the treaty. It does not connect the Upper Rijn directly with the North Sea. Free navigation on the Rijn is also guaranteed by provisions of the Congress of Vienna (1815) and the Treaty of Versailles (1919).

2. A river is canalized by constructing a series of weirs and locks to control flows and water levels. When the weirs are open, water
flow and ship traffic are unrestricted. Closing the weirs, to modify the flow and maintain the water level, forces shipping to use the adjacent locks.

3. For any ship, we shall define the ratio of cargo weight to total load capacity as the load factor. Because cargo type varies, load factors can sometimes exceed 1.00, although they usually average about 0.85.

4. A complete specification of the Dutch shipping network was provided by theDVK of the RWS. The European shipping network description was developed jointly by the DVK, the BBW, and the NVI in their study of shipping costs for the PAWN project.

5. With completion of the link between the Rijn and Danube, ships from Eastern European nations will be able to use the Rijn. Shipping authorities in the Netherlands and other Western countries fear an influx of government-subsidized vessels that will depress shipping rates and adversely affect the industry. The provisions of the Act of Mannheim, however, do not allow shipping authorities to discriminate against the ships of any nation.

6. The active fleet differs from the registered fleet. Many of the older and smaller ships are not in condition to sail profitably. They may be registered with the government, but are tied up at docks and have not carried cargo during the previous year. It is likely that many of them are used as temporary structures and will not sail again.

7. This correlation is for single-hull vessels only. In push/tow combinations, barges may be attached side by side, thus doubling capacity for a particular length. This creates no practical problems, if we are careful to remember the distinction.

8. Hydrological authorities in the RWS have indicated that there would probably not be a sedimentation problem for withdrawals at other locations, either because of river depth or because the river water does not carry much sediment. These locations include: Gorinchem, on the Waal; Deventer and Eefde, on the IJssel; and sites on the Amsterdam-Rijnkanaal and Lek.

REFERENCES


2.4. Rijkswaterstaat, Varendennota (Note on Waterways), The Hague, October 1, 1975.


Chapter 3

SHIPPING COSTS

Although we have mentioned the importance of shipping costs, we have not defined them. Defining and determining the costs of shipping may seem relatively simple, but it is not. Problems arise in even deciding what types of costs should be included, to say nothing of the difficulty of estimating cost coefficients, once the decision has been made.

3.1. COSTS AND PRICES

The first basic question that must be faced is whether to use shipping costs or prices when evaluating the effects of water management policies. Ideally we should use both. Shipping costs represent the direct effects of policies on shipping operations, just as prices indicate how these costs are passed on to the industry's customers. This approach is difficult, however, because the industry is complex and reliable information is limited.

The Dutch and European inland shipping markets are complex, consisting of several distinct sectors. Very little detailed information about these markets is available, particularly information about price determination and price structure. Prices vary with type of commodity, route, length of contract, water levels, and other factors. For any particular commodity, an enormous number of prices may exist. These prices are not always determined by pure supply and demand interaction; government regulations affect some, and much of the transport is done by companies carrying their own goods.

As a result of these circumstances, any analysis using prices becomes extremely difficult; price information is not available or reliable. This problem will be considered when we discuss industry and market structure in Chap. 8.

Determining actual shipping costs would not be any easier, except that the NVI and EBW have studied the problem extensively in recent years. One objective of these studies has been to create a basis for price setting in regulated sectors of the market [3.1]. In the investigations, they calculated costs for many vessel types and sizes. They used these results to estimate cost coefficients as a function of vessel characteristics.

Using this type of cost information, it should be possible to quantify the impacts of water management policies, in terms of the cost changes experienced by the carriers. This will give the direct effects of policy alternatives. The indirect effects will depend on how these costs can be passed on to consumers (of shipping services), which is considered later.
3.2. FIXED AND VARIABLE COSTS

Shipping costs can be separated into two components, although the distinction can be difficult to make in many cases. These are fixed and variable (operating) costs. In discussing how policies affect shipping costs, we must be careful to define which costs are being considered.

Fixed costs are those that do not vary over a short time and are independent of the activity level of the shipping fleet. In other words, they do not vary whether ships are actively engaged in transport or are tied up at a dock awaiting cargo. These costs include (1) investment and finance expenses, (2) depreciation, and (3) that fraction of labor, maintenance, administrative, and insurance costs that is independent of activity level.

Variable costs must then change in the short run and depend directly on the activity level of the fleet. They include (1) fuel and oil, (2) dock, harbor, canal, and loading or unloading fees, and (3) that part of labor, maintenance, administrative, and insurance costs that is associated with shipping activity.

It may sometimes be difficult to determine whether a specific cost item is fixed or variable. Hull maintenance is probably a fixed cost, although engine maintenance is more logically variable. But other elements of the total maintenance costs are more difficult to classify in this manner. Similarly, some crew members, such as the captain, may be considered as part of the fixed cost, and other personnel might be hired for a particular trip. If the entire crew is hired on a monthly basis, the distinction blurs. Such problems arise when considering harbor fees, insurance costs, and other components of the total cost structure.

All shipping costs used in the calculations were obtained from Dutch shipping authorities, after discussion about which elements should be included. In general, we separated costs into fixed and variable classes, in which variable costs included only fuel and oil costs; one-half of repair and maintenance costs; overtime wages; harbor, canal, and lock fees; and various administration costs. All other expenses were considered to be fixed costs.

3.3. TIME HORIZON AND APPROACH

Time horizon is a primary consideration in calculating all costs, not only shipping. In the PAVN analysis, we considered two different time horizons, short run and long run. We define the "short run" as that period which is too short for changes in the water management infrastructure or the fleet. During this period of a few days to a few months, only water levels and the fleet activity can vary. In contrast, the "long run" is considered to be a time sufficient for
everything to change, normally a period of one year or longer. Investment decisions can be made and carried out for both the fleet and water management system.

The time horizon varies with the stage of analysis on the PAWN project. Management strategy design attempts to determine the optimal management policy, decade by decade, throughout the year, for a given infrastructure. It thus considers only short-run costs and benefits. Impact assessment, however, attempts to assess both short-run and long-run consequences of alternative water management policies. Because this is much more difficult, impact assessment must be confined to a limited number of cases.

By definition, the short-run costs of shipping are only the variable or operating costs for a given fleet. In the short run, no investment in additional ships can be completed. For this reason, short-run activities, such as management strategy design, used variable shipping costs. Moreover, the loss functions and other short-run shipping costs were calculated using variable cost coefficients. We considered long-run costs only in the impact assessment phase, where we were concerned with changes in the size of the shipping fleet, in addition to changes in operating costs.

The PAWN study used a consistent approach to calculate the short-run and long-run costs and benefits for all sectors of the economy. The approach involves determining the market-valued welfare gains and losses that result from applying alternative water management policies. These gains and losses were evaluated by considering the direct effects of policies on the supply conditions in the various sectors of the economy.

The net benefit to society of a water management policy is the sum of the change in consumer surplus and the change in profits to industry. In this framework, shippers are the consumers, and the carriers are the industry. Appendix I discusses this net benefit analysis, and shows that for shipping, so long as all goods can be carried, the net benefit is reduced to the change in the variable costs of shipping operations. If not all goods can be transported, the resulting change in consumption imposes an additional cost on society. We must also be able to estimate the market value of this change.

When some goods cannot be shipped during a particular time period, because of insufficient fleet capacity, the consumers of these goods face a loss. That loss is the opportunity cost of not receiving the goods from their original source during the specified time period. In general, this cost will be the minimum of three alternatives: (1) doing without the goods; (2) obtaining them from another source (mode of transport); and (3) waiting until a later time period (when water levels are higher) to receive them. The third option involves costs for storage and delay, as well as for the eventual shipment of the goods. Note that not all of these three options may be available to any given shipping customer.
As discussed in App. I, one can obtain a lower-bound estimate of the consumption loss by calculating the amount that customers were willing to pay for shipment before the policy was introduced. One can also estimate an upper bound by calculating the amount that customers who have left the market refused to pay after the policy was introduced. Thus if we know the price behavior for each situation, we can estimate the consumption losses.

Unfortunately, we do not have enough information about shipping prices to estimate either an upper or lower bound. In the same way, it is not possible to estimate the costs of either option (1) or option (2) above. This leaves only option (3), which involves storage costs, costs for the eventual shipment, and some amount of delay cost for the customer. The storage costs can be calculated from known information, as can the costs of later shipment. For the delay costs, however, there is no obvious estimate.

As a proxy for the cost of option (3), therefore, we chose to use the sum of calculated storage costs and the cost of shipping the goods under the original conditions, were there sufficient fleet to do so. This shipping cost is somewhat greater than the cost of moving the goods later, when water levels rise and the fleet capacity is sufficient. Under the improved conditions, ships could be more heavily loaded and the cost of shipping a given amount of goods would be less. The net result of using this cost with storage costs is a proxy for delay costs equal to the difference between shipping costs now and later. Under the circumstances, this is neither an upper nor a lower bound, but it is probably the best estimate available.

3.4. SHIPPING COST COEFFICIENTS

Having resolved the questions about the proper definition of shipping costs, we now ask, what are these costs? In practice, how can they be calculated? This section will answer these questions.

The calculation of average shipping costs per trip is based on a standard formula developed by the DBW. The equation is of the form:

\[ C = a \times W + b \times T \]

where \( C \) = variable trip cost (Dfl),
\( W \) = waiting time per trip (hr),
\( T \) = sailing time per trip (hr),
\( a \) = cost of waiting time (Dfl/hr),
\( b \) = cost of sailing time (Dfl/hr).

In this equation, \( a \) and \( b \) are parameters whose values vary with the type and size class of ship, for both variable and total cost calculations.
If we desire the variable costs of shipping, the trip cost $C$ does not include any of the fixed costs of operation. Coefficient $a$ then represents primarily hull maintenance, some insurance costs, variable costs of personnel, and miscellaneous expenses. Coefficient $b$ includes all these costs plus fuel and oil, fees associated with travel, and the remainder of maintenance and repair costs.

If we want to calculate, instead, total costs, the equation must be changed. Coefficient $a$ must reflect all costs of owning and operating a ship which are not clearly travel dependent. It includes depreciation; finance and interest charges; insurance; and some fraction of maintenance and repairs, administrative costs, harbor fees, and wages. Coefficient $b$ covers all of these expenses plus the variable operating costs that it included above. We must add an additional term to the equation, however, to account for idle time. The ship is idle whenever it is waiting to acquire a cargo, or otherwise occupies its normal operating hours with some activity not part of a trip. Thus this additional term should reflect the fixed costs for the average idle time per trip during a year.

Both total and variable cost coefficients have been estimated by type and size class of ship for 1976 and 1985 [3.2]. A summary of the 1976 coefficients is shown in Table 3.1. The complete set of coefficients can be found in App. A.

### Table 3.1A

<table>
<thead>
<tr>
<th>Type</th>
<th>Size Class</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Dry cargo (Nat)</td>
<td>4.70</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>6.70</td>
</tr>
<tr>
<td>Towed</td>
<td>4.24</td>
</tr>
<tr>
<td>Tank</td>
<td>5.94</td>
</tr>
<tr>
<td>Cement</td>
<td>11.60</td>
</tr>
<tr>
<td>Push/tow (a)</td>
<td>0.50</td>
</tr>
<tr>
<td>Push/tow (2)(b)</td>
<td>1.05</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
<td>0.84</td>
</tr>
</tbody>
</table>

**SOURCE:** Ref. 3.2.
Table 3.1B

SAILING COST COEFFICIENTS FOR SHIPPING (1976)
(Dfl/hr)

<table>
<thead>
<tr>
<th>Type</th>
<th>Size Class 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo (Nat)</td>
<td>10.21</td>
<td>21.42</td>
<td>35.29</td>
<td>53.02</td>
<td>73.52</td>
<td>100.47</td>
<td>172.20</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>12.87</td>
<td>24.89</td>
<td>39.12</td>
<td>54.41</td>
<td>75.73</td>
<td>113.05</td>
<td>179.79</td>
</tr>
<tr>
<td>Towed</td>
<td>24.87</td>
<td>28.65</td>
<td>33.23</td>
<td>38.10</td>
<td>43.57</td>
<td>51.24</td>
<td>68.65</td>
</tr>
<tr>
<td>Tank</td>
<td>23.02</td>
<td>38.99</td>
<td>50.66</td>
<td>69.27</td>
<td>90.90</td>
<td>118.17</td>
<td>162.41</td>
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<tr>
<td>Cement</td>
<td>36.07</td>
<td>42.85</td>
<td>51.43</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Push/tow (2)(b)</td>
<td>6.85</td>
<td>8.92</td>
<td>16.55</td>
<td>21.46</td>
<td>32.09</td>
<td>44.02</td>
<td>63.06</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
<td>5.64</td>
<td>7.21</td>
<td>13.29</td>
<td>17.21</td>
<td>24.77</td>
<td>33.30</td>
<td>50.67</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 3.2.

(a) Cost per barge while not attached to pusher unit.
(b) Cost per barge while attached to pusher unit, with total number of barges in parentheses.

3.5. LOCK DELAY COSTS

The formulas for trip cost are somewhat misleading, because not all waiting time for ships has the same cost. When vessels are waiting at locks, their costs differ from when they wait in harbors, for instance. For short delays, ships prefer to leave their engines running, rather than stopping and restarting them. Thus, the costs of lock delays should be logically somewhere between the cost of waiting and moving.

This problem has other complications. Long delays could cause delay costs for the cargo receiver, and may represent an opportunity cost to the carrier, if he could otherwise be actively engaged. This would be strictly true, however, only if the fleet had no excess capacity and if no ships had idle time between loaded trips. If idle time exists, however, additional lock delay does not necessarily keep a carrier from additional revenue. With no idle time, delay costs at locks could be as much as the total costs for a ship, if we consider them to be a fair measure of the prices the carrier might receive in the long run.

This factor was not included in the delay cost calculations, because some excess capacity and idle time exist in the fleet. As a result, delay cost coefficients at locks have been defined as the sum of 75 percent of the waiting cost and 25 percent of the moving cost coefficients, for variable, not total, costs.

NOTES

1. Low water surcharges compound the general problem of determining shipping prices. During low water periods, prices may increase in
those market sectors that have prices. These increases should offset the reduced revenue to carriers from being able to carry less cargo. The price surcharge, and even its use, depends on the market sector and other conditions. For some traffic, set surcharge percentages are added to prices. In other sectors, surcharges are not explicit, but may be incorporated into contracts as higher prices during low water periods. In most cases where surcharges would be important, they are virtually impossible to understand or separate from other price influences.

2. Within the NWS and other Dutch agencies, a "decade" is often defined as a nominal ten-day period. There are exactly three decades per month, however. The first two decades have ten days each, and the last decade has the remaining days in the month.

3. Not all participants in the analysis agreed with this decision to separate variable and fixed costs and to use only variable costs in the short run. The DVK, NVI, and BBW argued that all shipping calculations should be made with total costs, representing the average price of ship transport, based on the normal number of productive hours per ship per year. These organizations felt that we could not adequately determine the fixed costs of additional ships when fleet capacity was insufficient. They argued that it would require far more time and effort than that available to properly consider fleet requirements and construction decisions. As a consequence, the shipping cost study (discussed in Chap. 4) was performed with both variable and total shipping costs, although we used only the variable cost results in our analysis. The study indicates that variable costs are about one-third of total costs under most circumstances.

4. This sum is equivalent to saying the net sum of the change in profits to the producers and profits to the consumers of the goods and services of interest (shipping transport). This and the subsequent discussion of delay costs are summarized from a detailed derivation in Ref. 3.3.

REFERENCES


Chapter 4
LOW WATER LOSS FUNCTIONS

4.1. LOW WATER SHIPPING LOSSES

The shipping industry cannot exist without adequate water levels. Water management policies that change flows and water levels in rivers and canals may significantly affect shipping operations. Low water loss functions were developed to measure the extent of these impacts.¹

The maximum amount of cargo a ship can carry depends on two factors: (1) the ship's capacity for that particular type of cargo, and (2) the minimum depth that the ship will encounter on its route. Only if water depths are sufficient, can it sail fully loaded. If, on the other hand, the minimum depth on the route is less than its fully loaded draft (with keel clearance), the ship must unload enough of its cargo to pass. If it does not reduce its draft sufficiently, it may run aground and cause serious damage.²

When water levels are not adequate to permit full loading, ships must operate at less than full efficiency. They (or additional ships) must make additional trips to carry the same amount of goods. This increases the real cost of shipping, the increase being the variable cost of the extra trips, not the additional total cost for the extra ships. The fixed costs of these ships must be paid, whether or not they make any trips, so long as they exist. The additional trips create only variable costs. It is not important now who pays this additional cost, only that it exists and that someone must pay it.

This is a primary example of how water management policies can be so important to shipping. If a policy changes water distribution extensively, or calls for large and continuing withdrawals from a waterway, it can significantly increase shipping costs for vessels using affected routes. There may, of course, be offsetting benefits for vessels using other routes which have more water as a result of the policy. Under any circumstances, however, we need a method of determining at least the net costs or benefits to shipping operations for any policy affecting water levels.

There are obviously complicating factors in this situation. The shipping network is a complex system of canals, canalized waterways, and open rivers. Normally water levels on canals and canalized waterways (e.g., the Maas and Neder-Rijn) are independent of the flow in those waterways. Lock and weir systems allow the operators to maintain adequate depths for ships. Under extreme dry conditions, however, there may not be adequate water for all users, and the operators must choose between maintaining water levels for shipping and releasing the water to other consumers.
Changes in water depths are most important on open rivers. Reductions in the Rijn flow of a few hundred cubic meters per second (m³/s) can dramatically reduce depths on the Waal and IJssel. Flow changes of this size are not infrequent, and can occur over a period of two or three days. Under these circumstances, a ship that is properly loaded when it begins a long trip on the Rijn may find water depths too shallow by the time it reaches the end of its journey. Uncertainty of this type causes ship operators to load more conservatively, and creates a demand for accurate current minimum depth measurements on open waterways. In most cases, this situation will not be changed much by management policies.

The effect of depth changes depends on many factors. For ships that travel only on canals and canalized waterways, allowable depths and maximum loading may not change. This is true also if the ships are already limited in depth at some point before or after they have passed affected areas. Moreover, smaller vessels may be able to operate with full loads under any circumstances, while the largest push/tows will have to unload cargo frequently when water levels drop.

As an additional complication, most ships do not operate at full load capacity even when water levels would permit this. Differences in material density, sizes of loads, and other variables cause average load factors to be less than 100 percent. The normal maximum load factors vary with the type and size of ship, the type of commodity, and the specific route that the ship follows.

Management policies may also have time-delayed effects on water depths. Large withdrawals from waterways, particularly from the Waal at Tiel (for transport north on the Amsterdam-Rijnkanaal), will cause downstream sedimentation. The resulting sandbar will ultimately reduce shipping depths, although the limiting shallows is located farther downstream. Over time, the sandbar will move downstream and eventually reach the shallow area, where it may remain for several years. The development and duration of the deposit will depend on how much water is withdrawn and for how long, as well as on river flows. This problem will be discussed more fully later in this chapter.

4.2. SHIPPING COST STUDY

In order to develop low water loss functions, one must have a complete description of domestic and international shipping operations in the Netherlands. This is an extremely difficult problem, because the situation is complex. Such a description must include:

1. Distribution of goods transported by ship between all origins and destinations, for all goods loaded or unloaded in the Netherlands, or passing through in transit.
2. Complete characterization of the shipping fleet, including the distribution of ships by size class and type, and the change in load capacities as a function of maximum draft.
3. Specification of the shipping network in the Netherlands and relevant areas of Europe, including relationships between depth and flow for all waterways.
4. Distribution of ship traffic between all origins and destinations, by type and size of ship and type of commodity, including normal maximum load factors.
5. Shipping costs by type and class of ship for all ships.

Theoretically, one could determine the above information for 1976, but the data are generally poor and difficult to obtain. Moreover, such data do not exist for 1985. In any case, the problem requires extensive general knowledge and understanding of European inland shipping.

To obtain this information, the PAWN project commissioned a special study by the major inland shipping organizations in the Netherlands. A coordinating group was formed to discuss and direct this shipping study, and to provide necessary additional information. Appendix B describes the study procedures and results. The study report can be found in Ref. 4.1.

The study involved first developing a description of shipping operations and carrier behavior, based on a detailed examination of shipping patterns during normal and dry periods of the years 1975 and 1976. Second, this description was used as input for a series of computer models which:

- Distributed the ship traffic (for an average week) between all origins and destinations on the network, choosing routes on the basis of minimum trip costs.
- Calculated the additional number of trips required to carry all cargo in a series of cases which varied in Rijn flow, Maas depth, and withdrawals from the Waal and IJssel.
- Determined total and variable shipping costs for each case.
- Estimated storage costs and the amount and type of goods stored for cases in which the fleet size was inadequate.

The study agencies repeated this process for the 1985 context. The context was developed with various models and results from previous work. Cost coefficients for 1985 were also developed by inflating 1975 figures, using varying inflation factors for the different components. Special cases were added to the analysis, to reflect uncertainties in the amount of cargo shipped and in the depth of the Rijn in Germany.

Some basic assumptions were necessary to simplify the study. These assumptions are discussed in App. B. In summary, all routes were assigned to ships on an "all or nothing" basis. That is, if a route had the lowest cost for a particular type of ship, all similar ships with the same origin and destination would use it. This decision was independent of the subsequent cost increases from congestion at locks.
and bridges. Also, in order to simplify the calculations, routes were not altered when water levels changed.

For the most part, these assumptions are reasonable under the circumstances. They might be questionable under extreme low water conditions, but even then, only some of the traffic would have viable alternative routes with lower costs. It would be quite difficult to determine the overall solution to the traffic distribution and routing problem using alternative routes, and it would make subsequent data reduction also much more difficult.

The models also assumed that the fleet was infinitely expandable. Shipping costs were calculated assuming that goods which must be unloaded from one ship could be carried on another identical ship. Restrictions in fleet capacity were considered after the fact outside the models.

The study provided a standard output for each run (alternative case based on Rhine flow, context, and withdrawal rate). This included the distribution of shipping costs on several bases, the used capacity of the Dutch and total fleets, the carried weight and round-trip times for each variety of ship, and the number of trips between aggregated origins and destinations. These results were processed to impose fleet capacity restrictions and calculate cost changes when cargo was shifted. In many cases, the total capacity was not sufficient to carry all goods. Under these circumstances, the goods were stored, and storage costs calculated. This will be discussed later.

4.3. CRITICAL POINTS

The results of the shipping study were not in a form suitable for use in constructing low water loss functions; the information needed further processing before it could be used. As a result, we developed the concept of "critical points" and a procedure for assigning shipping costs to routes or waterways in the network.

Each link of the shipping network has a most shallow point, the point that determines the maximum permissible draft for ships that use the link. There may be more than one point on the link with this minimum depth. The minimum depth will certainly vary between links and waterways, and it will also vary with flow and water level on open rivers. On canals and canalized waterways, the entire link can generally be considered to have the same depth, the minimum depth.

A shipping route can be considered as a series of links in the network. Each route will have a minimum depth, the overall minimum of the minimum depths of all links on the route. It is this overall minimum that will determine the load factor restrictions for ships using the route.

We have identified about ten links in the network which may be important in restricting load factors in shipping operations. These
points that limit the size of ships and their cargoes have been called "critical points." These ten links are shown in Fig. 4.1.

Two of the critical points are located in the Rijn in Germany, one near the mouth of the Ruhr and the second between Cologne and Karlsruhe. The Rijn is canalized in the area of the second critical point, so we need not specify its location more exactly.

Being canalized, the Maas has several possible critical points. It consists of a series of canals and weir ponds, the levels of which are controlled by regulating discharges through the weirs. Although other factors may intervene, normal policies of weir control yield roughly the same depth for shipping on all sections of the river. When depth variation exists, we have defined the limiting depth to be the minimum depth of all sections in the Netherlands. In the analysis, we have considered the Maas to be one critical point, with a depth equal to this minimum.

It is also difficult to define a unique critical point on the Waal, but for different reasons than on the Maas. The problem is that the location of the limiting depth varies with the flow on the river. During low flows without major withdrawals, the limiting depth is normally either slightly upriver or downriver of Tiel. These two locations have about the same depth, so we can conveniently assume that the critical point is always below Tiel. When withdrawals are made at Tiel, the limiting depth will be below the withdrawal point. It is possible to shift the limiting depth farther downstream, if substantial withdrawals are made at St. Andries. We assumed for the analysis that the Waal had one critical point, that being the minimum of the depths below Tiel and St. Andries.

The IJssel has potentially four critical points. This occurs because the critical point may move as the flow changes, substantial withdrawals can be made at more than one location, and ship traffic along its length is not uniform. For the PARN study, however, it was possible to limit consideration to one of the critical points, the point farthest upstream, including the entrance to the Twentekanaal. A large fraction of the ship traffic on the IJssel does not pass more than the first two critical points; but these points have the same depth under virtually all conditions, even when withdrawals are made. For these reasons, the first critical point can be used for IJssel shipping, without incurring other than negligible errors in calculating shipping losses.

Critical points are also located at the beginning of the Neder-Rijn and on the Pannerdenschke kanaal. These were eliminated from final inclusion in the analysis for several reasons. The Neder-Rijn has very little traffic, compared with the traffic passing other points, and was thus not included. The Pannerdenschke Kanaal was combined with the IJssel critical point. Most shipping using the Pannerdenschke Kanaal continues up the IJssel, and almost always the IJssel depth will be less. The IJssel will thus determine the critical depth for this shipping.
It should be clear that the depths at critical points will not always limit all of the traffic passing them. There will frequently be locations outside the Netherlands or off the main routes that will be more shallow than the critical locations. This will be true for much of the traffic using the canal systems in Germany, Belgium, France, and the Netherlands. We will discuss the implications of this situation later.

4.4. SHIPPING ROUTES

Ships carry goods between the point where they load their cargo (origin) and where they deliver it (destination). The path that a ship follows on the network between these two points is called its route. When we consider all shipping operations concerning the Netherlands, there are hundreds or thousands of possible routes for the ships involved in transport. Each route will pass a particular combination of critical points (including none), depending on which parts of the network it uses.

The size of the ship and the load it can carry will be determined by the depths at the critical points that it passes. It is also possible, as we have mentioned, that the depth may be limited by some waterway on its route that is not a critical point. Under any circumstances, however, it will not be able to carry any load greater than that permitting it to pass the critical points on its route. In particular, its size and load will be limited by the minimum depth for the combination of critical points that it passes.

It is possible to group all shipping routes by the combinations of critical points that they pass. All routes that do not pass any critical points would be grouped together, as would all routes which passed any given set of points. This procedure reduces the hundreds or thousands of routes to a manageable number of groups; the maximum number of groups is the number of combinations of critical points. Given the final 5 critical points, this maximum number is 31, although in practice there are only about half this many groups with any routes in them.

For the purposes of the analysis, these groups can be considered to be aggregated shipping routes. PWN water management policies affect low water shipping costs in terms of how they change the depths at the critical points in the shipping network. Each aggregated route will have its own set of critical points (including the set with none) and its own minimum depth (smallest critical point depth) for any given situation. Thus, information on how much the shipping costs change for each route, as their minimum critical point depths change, may be used to determine the desired low water loss functions.

4.5. SHIPPING COST CURVES

Using the system of critical points described above and the detailed results of the shipping cost study, one can define a shipping cost
curve for each of the shipping routes. This curve gives the variable cost of shipping an average week’s goods on that route as a function of the limiting depth on the route. Appendix B discusses the procedure in detail.

When water is plentiful and water levels high, the limiting (critical) depth will be large. This permits large ships to pass with full loads. As water levels decline and the critical depth is reduced, ships will have to carry less cargo in order to pass the critical points on the route.

The consequences of this situation are that ships will have to make more trips to carry all goods on the route. Also, other ships may be found to carry the remaining goods. In either case, the result is more trips by loaded ships and correspondingly higher transport costs for a given amount of goods.

We need not know now who is paying the extra shipping costs. They may fall on the ship operators, or on those paying for the transport, depending on contract terms and market factors. They may also fall on the government, if some general provision exists for compensating shippers for their losses. It is only important to recognize that the existence of low water imposes an additional real cost on shipping a given amount of goods.

We must remember that the increased shipping costs stem from the operating costs of the additional trips (or ships), not from any change in the fixed costs of the fleet. Any extra ships required must also exist during high water periods, if they are to be available for use when water levels are low. Thus the fixed costs of these ships must be paid at all times, not just when they are in use during low water periods.

In the analysis it was not necessary to consider all aggregated shipping routes. In calculating the costs for all routes, we found that many routes were negligible in comparison with the major routes. In fact, it is possible to use only the seven most important routes and still include a large fraction of the total cost, and almost all of the variation in costs due to changes in water levels (critical depths). The remaining routes can then be combined with the routes not passing any critical points, to be considered as a fixed term in shipping costs.

The major shipping routes are shown in Figs. 4.2 to 4.8. Table 4.1 gives the unique set of critical points passed by each route. Table 4.2 compares total variable shipping costs with the costs of the major routes. It was derived by taking a simple mean and standard deviation over the cases reported in the shipping cost study. It is clear from this information that these seven routes represent shipping costs in the Netherlands very well.
Fig. 4.2 -- Upper Rijn - Waal shipping route
Fig. 4.3 -- Lower Rijn - Waal shipping route
Fig. 4.4 -- Maas - Waal shipping route
Fig. 4.5 -- Lower Rijn - IJssel shipping route
Fig. 4.6 — Maas - IJssel shipping route
Fig. 4.7 -- Upper Rijn - IJssel shipping route
Table 4.1

CRITICAL POINTS ASSOCIATED WITH THE MAJOR SHIPPING ROUTES

<table>
<thead>
<tr>
<th>Route</th>
<th>Upper Rijn</th>
<th>Lower Rijn</th>
<th>Waal</th>
<th>Maas</th>
<th>IJssel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Rijn - Waal</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower Rijn - Waal</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maas - Waal</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Lower Rijn - IJssel</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Maas - IJssel</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Upper Rijn - IJssel</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Waal - IJssel</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 4.2

COMPARISON OF SHIPPING COSTS IN BOTH CONTEXTS
(Dflm/wk)

<table>
<thead>
<tr>
<th>Item</th>
<th>1976</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Values</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17.66</td>
<td>30.67</td>
</tr>
<tr>
<td>Major routes</td>
<td>14.50</td>
<td>24.68</td>
</tr>
<tr>
<td>Fixed routes</td>
<td>3.16</td>
<td>5.98</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3.16</td>
<td>5.26</td>
</tr>
<tr>
<td>Major routes</td>
<td>3.05</td>
<td>4.78</td>
</tr>
<tr>
<td>Fixed routes</td>
<td>0.11</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 4.9 shows the low water loss function for an important route, the Upper Rijn - Waal traffic. The shape of this curve is typical of all seven routes, although the magnitude of the costs varies considerably. The remaining loss functions, for both 1976 and 1985 contexts, are included in App. B.

It is not difficult to explain the general shape of the loss function curves. For high flows and depths, all ships which can use a certain route are able to proceed fully loaded over a large range of critical point depths. This situation has the minimum shipping cost, one which is independent of water levels beyond a certain depth. As water levels decline, the largest ships must begin to carry less cargo. Because these ships are a small part of the fleet, the cost increase is relatively small at first.

As water levels continue to decrease, the larger ships must carry progressively less cargo, and some of the smaller ships on the route begin to be affected. The number of additional trips required also increases more than proportionally, because the extra ships cannot carry as much cargo as they could at higher water levels. As this process continues, more and more smaller ships will be involved, and the larger ships will have to carry a smaller and smaller fraction of
their normal cargo. At the same time, extra trips become increasingly less efficient in carrying the extra cargo. As a result, the costs accelerate as the critical depth on the route decreases. This gives the characteristic shape to the loss function curves.

Two problems deserve mention. First, what happens if the fleet is too small to carry all the cargo? This can occur for low flows and large withdrawals. Under the circumstances, it is necessary to store some of the goods until there is sufficient water for them to be transported. Storage costs will be discussed in the next section. Second, what is the optimum size of the fleet? How many ships are necessary to carry all of the goods? What level of fixed costs for unused ships are we willing to pay, to have them ready for use during low water periods? The tradeoffs between fleet size alternatives will be considered in Chap. 5.

4.6. DELAY AND STORAGE OF GOODS

As water levels and critical depths decrease, because of low flows or large withdrawals, there may not be enough ships to carry all of the goods that need transporting. Under these conditions, the extra cargo will have to be stored or moved by another method. The NVI and EBW shipping cost study found that other transport modes had small ability to expand in the short run [4.1]. Consequently, storage becomes the only reasonable alternative for goods that cannot be carried, shipping them later when water levels rise sufficiently to make adequate capacity available.

As discussed in Chap. 3, there are three components to the total cost of not being able to ship goods. First is the actual cost of storing the goods until they can be transported. Second is a delay cost to the receiver of the goods, the cost to his business of not having the goods when desired. Third is the cost of shipping the goods at a later time, under other water level conditions. This last cost is largely offset, of course, by not having to pay to ship the goods now. Ideally, we would like to have some estimate of all three cost components.

The earlier discussion concluded that we can probably use, as a proxy for the total cost of delayed goods, the calculated storage costs plus the cost of shipping them under the original conditions (though technically they cannot be transported). This approach was used in the analysis in the following manner.

The shipping cost study assumed that certain goods would be stored when fleet capacity was exceeded. These goods were food and agricultural products for dry cargo ships; oil products for tankers; and ores (including coal) for push/tow. Using this assumption, the study calculated costs for all cases in which storage was necessary. The shipping study cases included both these calculations and the cost of shipping stored goods under the given conditions. Incorporating
the storage costs into the loss functions required relating these costs to the critical point depths. The analysis, described in App. B, found that the storage costs (for both contexts) can be well described as the sum of two functions, one a function of the critical depth on the IJssel, and the other a function of the critical depth on the Waal. The storage cost component curves for the 1976 context are shown in Fig. 4.10. Note that the total storage cost for a given situation will be the sum of the costs from the two curves. Although they are plotted on one graph, the curves are independent. Each curve relates to the critical point and critical point depth on the appropriate waterway (not an entire shipping route). The curves for the 1985 context are included in App. B.

These storage calculations are clearly only a rough approximation to the real situation. Which commodities are actually stored will depend on several factors, including:

1. The relative distribution of available ships and cargo to be transported.
2. Existing contracts between carriers and industry.
3. Profitability in the various transport sectors.
4. Cost and availability of storage facilities.
5. Delay costs for goods, expressed as the willingness of shippers to pay increased rates for transport.9

Appendix B discusses several potential weaknesses in the cost calculation and allocation procedures. It also considers how these weaknesses might affect the results of the study.

4.7. DEPTHS AT CRITICAL POINTS

To use the low water loss functions, we must be able to calculate the depths at all critical points for any given situation. These depths will depend on the flows, water levels, and withdrawals on the appropriate parts of the network. Because of continuous changes in the riverbed, there is no linear relation between river flow and minimum shipping depth in a river. The relation depends also on the rate of increase or decrease of river flows, as there is a memory effect. However, by considering flow and depth data for an extended period, one can develop approximate and relatively simple functions for the depths on the Rijn, Waal, and IJssel, as well as for the effects of withdrawals on these waterways.9

Specific functions for the Maas do not exist, however, because it is canalized. The depth on its various sections depends on the amount of water available, which in turn depends on the supply and demand for water along the waterway. This information is used by the DM in its water balance calculations, from which it determines the depth on each segment. We then assume that the limiting depth is the minimum of the shipping depths of the segments.
Fig. 4.10 -- Storage cost functions (1976)
The basic relationships between flow and depth are presented below. These equations do not include the depth on the Upper Rijn, because we could find no linear equation. The curve giving Upper Rijn shipping depth as a function of flow is presented in Fig. 4.11. These relationships were developed from the data in Ref. 4.1. Details of the derivations can be found in App. B. Note that these depths are shipping depths, not actual water depths, because they include a keel clearance allowance.

\[
\begin{align*}
\text{Lower Rijn} & \quad D_{lr} = 8.7 + 0.014 \times F_{lr} \\
\text{Waal (Tiel)} & \quad D_{wt} = 6.0 + 0.023 \times F_{wt} \\
\text{Waal (St. Andries)} & \quad D_{ws} = 12.9 + 0.018 \times F_{ws} \\
\text{IJssel} & \quad D_{ij} = 3.4 + 0.092 \times F_{ij}
\end{align*}
\]

where \(D\) = minimum shipping depth (dm),

\(F\) = flow before withdrawals (m\(^3\)/s).

---

![Graph](image-url)  

**Fig. 4.11 -- Upper Rijn critical depth**
There are simple functions of the Rijn flow at Lobith for the critical point depths at the two locations on the Rijn outside the Netherlands. Although these relationships are approximate, they should be valid so long as the conditions defined in the study remain true. Future construction or improvement of the Rijn in Germany could mean these functions must be revised. The critical point depth on the IJssel, ignoring withdrawals, is also a simple function of flow in the appropriate section.

For the Waal, the shipping depth calculation was more difficult, because there are two withdrawal locations, Tiel and St. Andries. The critical point depth is the minimum of the depth at these two points. Neither point dominates, as certain flow and withdrawal combinations can make either point more shallow. The basic equations for the shipping depths at Tiel and St. Andries were developed in the same manner as that for the IJssel. Note that the flow on the Waal at St. Andries is not equal to the flow at Tiel, because of withdrawals and discharges on the Waal between the two points.

Functions describing the reduction in water depths resulting from withdrawals on the Waal and IJssel were developed from data in Refs. 4.1 and 4.2 and information derived from computer models. These simplified equations are shown below; details of the derivation are presented in App. B. The computer models were programs that calculated the effects of a series of flows and withdrawals on the Waal at Tiel and St. Andries.

\[
\begin{align*}
\text{IJssel} & \quad dD_{ij} = 0.10 \times (Q_e + 0.5 \ Q_d) \\
\text{Waal (Tiel)} & \quad dD_{wt} = 0.03 \times Q_{wt} \\
\text{Waal (St. Andries)} & \quad dD_{ws} = 0.053 \times Q_{ws} - 0.00126 \times F_{ws}
\end{align*}
\]

where \(dD\) = reduction in depth (dm),
\(Q\) = withdrawal rate (m³/s),
\(Q_e\) = withdrawal rate at Eefde (m³/s),
\(Q_d\) = withdrawal rate at Deventer (m³/s),
\(F\) = flow before withdrawal (m³/s).

For Tiel, we used the results of one model and information in Ref. 4.2 to derive the formula for the water level reduction caused by withdrawals. The result does not include sedimentation effects, which will be discussed later. At St. Andries, we used only the computer program results to derive the approximate equation for the depth reduction.

Development of a depth reduction function for IJssel withdrawals was more difficult, although it was based on the shipping study input data.
Two problems made the derivation difficult. First, the input data had been rounded to one digit, because the calculations were uncertain. Second, the two potential withdrawal sites were separated and affected different amounts of ship traffic. For these reasons, it was necessary to develop an approximate formula for the withdrawal effects. The approximation does not change the analysis results, however, as discussed in App. B. These equations are reasonable for withdrawal rates up to 100 m³/s at Tiel, 50 m³/s at St. Andries, and 20 m³/s at Deventer and Eefde.

4.8. DREDGING AND SEDIMENTATION

We have been discussing the immediate costs to shipping from water management policies, but some delayed costs must also be considered. When water is withdrawn from a river or canal, sedimentation may occur downstream from the withdrawal point. If the sedimentation is large, it will cause future reductions in critical depths, thereby increasing shipping costs. It is these future costs that we must consider.

The sedimentation process can be roughly described as follows. When water is withdrawn, flow and water velocity downstream of the withdrawal point are reduced. This decreases the ability of the river to carry sand. Also, the withdrawn water may have a smaller sand content than the river as a whole. As a result, the concentration of sediment in the remaining water increases as its capacity to carry that sediment decreases. Because of this, sand drops out of the water to form a bar downstream of the withdrawal location. So long as water is being removed from the river, the bar will continue to grow.

The importance of the sandbar will depend on the circumstances. For the IJssel, the sandbar should not be large enough to merit further consideration. On the IJssel, the river depth is relatively large close to the withdrawal points. Moreover, the critical points are located so far downstream that the sandbar would require several years to reach them. As a consequence, the chances are large that the sandbar will be swept away before it can cause problems. This is not true on the Waal, where sedimentation problems are more critical.

When withdrawals are made from the Waal at Tiel or St. Andries, sedimentation begins immediately. It causes no reduction in critical depth at first, however, because the actual critical points are farther downstream. Over time, however, if the sand is not removed, the sandbar will extend downstream (if withdrawals continue) or be swept downstream by the flow. After several months, it will reach the critical points and begin to reduce shipping depths. Under normal circumstances, it will take several years for the sand to be carried far enough downstream to clear the critical points and restore the original shipping depths.

There is clearly a future cost to shipping associated with current extractions. We cannot actually calculate this cost, because (1)
river hydrology is complex, (2) future flows will affect the sandbar, (3) ship transport will vary, and (4) future water levels will affect the importance of the depth reduction. The cost of the sandbar depends on the difference in shipping depths with and without it, and this depends on future flows. If water levels are always high, the bar will have little effect; if they are low, the sedimentation cost will be quite high. The actual cost will thus depend on the flow pattern during its entire existence.

For obvious reasons no one can say at any time what the future flow patterns will be. One can only look at the frequency distribution of Waal flows and attempt to calculate an expected shipping cost based on the predictions for future shipping. We did this to develop two sedimentation loss functions shown in Fig. 4.12, using a 10-percent discount rate over the life of the sandbar. The sedimentation and dredging cost analyses are discussed in Vol. XVIII.

It is not necessary to accept the future costs of sandbank formation. A reasonable alternative may be to remove the sediment by dredging before it reaches the critical point downstream of the withdrawal location. This could be less costly than allowing the bank to form and disrupt shipping.

![Graph showing sedimentation loss functions for 1976 and 1985.](image)

Fig. 4.12 -- Sedimentation loss functions
The choice between dredging and sedimentation losses depends on several factors, such as availability of dredgers, wall conditions, relative costs, safety, and interference with shipping operations. In PAWN, we have assumed that it should always be possible to dredge downstream of St. Andries. At Tiel, however, there may be problems in dredging under certain conditions, and thus we have developed both the sedimentation loss function and dredging cost functions for that location.

NOTES

1. In this and subsequent discussions, we will use the term losses to indicate those shipping costs which are affected by changes in water levels or flows in the network. Consequently, the low water loss functions could be converted to cost functions simply by adding a large constant term. With this definition, changes in shipping losses are also changes in shipping costs, and we will use the terms more or less interchangeably.

2. The necessary keel clearance for most ships is larger than one would normally expect. As ships move through the water, their motion causes a lowering of water levels in the immediate vicinity. This makes it possible for passing ships to ground each other, as occasionally happens. In recent years, one ship which ran aground on the IJssel became lodged sideways in the channel, completely blocking traffic for several days.

3. The careful reader may wonder why such rapid changes in Rijn flow do not to some extent invalidate the shipping analysis in the PAWN project, which used a 10-day period (the decade) as its basic time step. We feel that such flow changes are not a problem for several reasons. First, the variations are roughly proportional to the magnitude of the flow, so the largest variations occur at high flows, where they do not affect shipping costs. At low flows, where shipping costs are most sensitive, flow variations are much smaller. Second, the most rapid changes are flow increases; reductions of a significant amount generally occur more slowly and affect ships making long trips on the Rijn. Third, the low water loss functions are roughly linear over any given short segment. As a result, the shipping costs during a decade should approximately average out to those appropriate to the mean flow conditions.

4. These organizations, as mentioned earlier, were the DVK of the RWS, the NVI, and the EBW.

5. Although the graphs are drawn as smooth curves, they consist of a series of points with inherent scatter. This scatter arises from computational approximations, in part, but primarily from the aggregation process used in creating the major routes. It is caused by the variation in limiting depths between different routes. This variation occurs for part of the traffic because of canal and other waterway restrictions away from the critical points.

6. It can be argued that there are several reasons to neglect storage costs under these circumstances, but we chose to accept and use the costs calculated in the shipping cost study.
7. Although storage costs were used in the analysis, the DM did not accumulate them over time. In other words, goods were stored only one decade, because the DM could not calculate the unused fleet capacity for a given situation. This calculation is necessary if goods are to be removed from storage as water levels increase, but it is difficult to do. Fleet capacity depends on how many ships are available (by type and size), including those not fully loaded, and how much cargo they can carry under the circumstances. The capacity of these ships is a function of the type of cargo available, shipping depths on the network, and the travel times required for the stored goods, among other factors. To do the overall calculation in a reasonable way would require a sophisticated and complex procedure which could not be developed during the analysis. It is unlikely, however, that the results are seriously in error. For reasons discussed in App. B, the storage costs calculated in the shipping study may be much too high; thus the two errors would be offsetting to some unknown degree.

8. Discussions with shipping authorities at the DVK have revealed that the fleet capacity was adequate for international transport during the extremely dry periods of 1976. Shipping prices increased by a factor of three, but ships were available to those customers who were willing to pay.

9. The critical point depth will decrease by 1.0 cm for every centimeter reduction in water level, as a first approximation. Levels will not fall uniformly along a waterway, however, as the flow drops, because of irregularities in the channel. This may cause the actual critical point to shift position with flow.

10. The keel clearance allowance is not constant across all ship classes; it is greater for larger ships and push/tows. Keel clearances do not affect the flow-depth derivations, because the relationships are based on shipping depth data from the cost study. These data already incorporate compensation for keel clearance. The depths should not be used for other purposes, therefore, without careful consideration.

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Chapter 5
LONG-RUN SHIPPING FLEET

5.1. GOVERNMENT POLICIES AND THE SHIPPING FLEET

The shipping fleet is not a stable entity from year to year. Rather, it constantly changes in size and composition, as older vessels are retired and new vessels constructed. Additions to the fleet are built and financed by private industry, based on its expectations about supply and demand for shipping transport. The shipping fleet will not always be appropriate, therefore, for many reasons, including the following:

- Construction decisions are not coordinated.
- Time lags occur in the construction process.
- Industries prefer to avoid the risks of not having sufficient transport capacity.
- Vessels have long useful lives, and will not likely be removed from the fleet if not immediately needed.
- Transport rates have been too low for many carriers to recover their investment costs, but high enough to cover operating costs.
- Demand for ship transport fluctuates with economic conditions, water levels, and other influences.

When the demand for transport is not in equilibrium with the supply, the resulting price adjustments will adversely affect either the shipping industry or its customers.

During recent years the fleet has consistently been too large, given the demand for shipping transport. Many small, old, and inefficient ships remain active, and the supply of tankers far exceeds the demand. Among the reasons for this situation are:

- Many large, efficient vessels have been constructed recently.
- Many commodities such as peat and coal, previously carried in the small ships, are no longer transported.
- Government influence on shipping rates has kept older vessels operating.
- Economic recession and rising energy costs have reduced all transport, particularly that of oil products.

The Dutch government has assumed part of the responsibility for maintaining a desirable fleet size and composition. Officials desire to preserve a healthy Dutch shipping industry for economic reasons and to avoid future dependence on foreign fleets. Unfortunately, the Dutch
government cannot control the size or character of foreign fleets, and can exert only limited influence over the domestic fleet.

The government can influence the fleet in some ways, however. In recent years it has conducted programs to induce owners to scrap or replace old and small ships. Also, the shipbuilding industry receives subsidies which affect the price of new vessels. Finally, through control of rates in certain sectors of the transport market, the government can make shipping either more or less profitable for the carriers.

Government policies are not always well coordinated, however, and sometimes have opposing effects. Price control in part of the market can keep vessels operating which other regulations are trying to remove. Overall, however, fleet capacity has declined recently, especially among the older and smaller ships. This is clear from the data in Table 5.1 that show fleet capacity by size class for recent years. Table 5.2 gives the capacity as a function of construction year, also supporting the conclusion. Newer and larger vessels have gradually replaced older and smaller ships in the fleet during the past 8 years. In spite of this success, problems still exist, such as the overcapacity in tankers.

The government can influence the size and composition of the shipping fleet in one other way, although it is an unintentional side effect of water management decisions. Alternative policies will affect water distribution in the network in different ways. In doing so, they will influence the shipping fleet over the long run. If more water is withdrawn from the Waal or IJssel, the fleet will need additional capacity to carry a constant amount of goods on all routes affected by the withdrawals. This capacity will be necessary to offset the reduced loads that existing ships will be able to carry. Other

Table 5.1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>21- 249</td>
<td>216</td>
<td>2700</td>
<td>412</td>
<td>1945</td>
<td>315</td>
</tr>
<tr>
<td>250- 399</td>
<td>2317</td>
<td>760</td>
<td>2325</td>
<td>767</td>
<td>2213</td>
</tr>
<tr>
<td>400- 649</td>
<td>2025</td>
<td>1048</td>
<td>2066</td>
<td>1072</td>
<td>1972</td>
</tr>
<tr>
<td>650- 999</td>
<td>1228</td>
<td>1019</td>
<td>1316</td>
<td>1089</td>
<td>1383</td>
</tr>
<tr>
<td>1000-1499</td>
<td>662</td>
<td>848</td>
<td>708</td>
<td>902</td>
<td>699</td>
</tr>
<tr>
<td>1500-2999</td>
<td>373</td>
<td>719</td>
<td>474</td>
<td>964</td>
<td>459</td>
</tr>
<tr>
<td>3000-</td>
<td>25</td>
<td>90</td>
<td>34</td>
<td>119</td>
<td>44</td>
</tr>
<tr>
<td>Total</td>
<td>9330</td>
<td>4879</td>
<td>8868</td>
<td>5228</td>
<td>8146</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 5.1.

NOTE: LC = load capacity; TLC = total load capacity.
Table 5.2

ACTIVE SHIPPING FLEET BY YEAR OF CONSTRUCTION FOR RECENT YEARS

<table>
<thead>
<tr>
<th>Year Built</th>
<th>1971 MLC No. (tons)</th>
<th>1973 MLC No. (tons)</th>
<th>1975 MLC No. (tons)</th>
<th>1977 MLC No. (tons)</th>
<th>1979 MLC No. (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td>41</td>
<td>220</td>
<td>29</td>
<td>342</td>
<td>25</td>
</tr>
<tr>
<td>-1900</td>
<td>639</td>
<td>399</td>
<td>534</td>
<td>424</td>
<td>391</td>
</tr>
<tr>
<td>1910-1919</td>
<td>1418</td>
<td>441</td>
<td>1246</td>
<td>468</td>
<td>1039</td>
</tr>
<tr>
<td>1920-1929</td>
<td>2308</td>
<td>480</td>
<td>2117</td>
<td>521</td>
<td>1809</td>
</tr>
<tr>
<td>1930-1939</td>
<td>977</td>
<td>476</td>
<td>961</td>
<td>501</td>
<td>908</td>
</tr>
<tr>
<td>1940-1949</td>
<td>327</td>
<td>566</td>
<td>333</td>
<td>603</td>
<td>603</td>
</tr>
<tr>
<td>1950-1959</td>
<td>955</td>
<td>637</td>
<td>989</td>
<td>671</td>
<td>1041</td>
</tr>
<tr>
<td>1960-1969</td>
<td>1181</td>
<td>834</td>
<td>1173</td>
<td>878</td>
<td>1180</td>
</tr>
<tr>
<td>1970-1974</td>
<td>16</td>
<td>688</td>
<td>228</td>
<td>1191</td>
<td>386</td>
</tr>
<tr>
<td>1975-1977</td>
<td>23</td>
<td>2000</td>
<td>40</td>
<td>1875</td>
<td>4</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 5.1.

NOTE: MLC = mean load capacity per vessel.

policies which affect the supply or demand for water may have similar effects by changing the amount or distribution of water in the network. Some waterways (routes) may benefit, while others may suffer over the long run.

The actual change in the fleet may not reflect the change in fleet requirements. Ship acquisition decisions are based on the expectations and perceptions of industry. If industries fear the effects of a policy, they may decide to acquire additional vessels in an attempt to avoid the risk of having insufficient transport capacity. This inclination will be reinforced by government policies or tax regulations that favor such investments. We do not intend to investigate this problem or try to predict industry behavior patterns; rather, we will limit the analysis to determining the actual change in long-run fleet requirements.

5.2. OPTIMAL FLEET SIZE

It is not easy to estimate how management policies will affect fleet requirements in the long run. In the first place, no one has determined what the optimum size or composition of the fleet should be. The problem involves comparing many different costs and benefits in an uncertain environment.

Chapter 3 discussed the fixed and variable costs of shipping. When considering fleet size, we must be concerned with total fixed costs. Ships are expensive to build and own, as Tables 5.3 and 5.4 show. These tables present the annual fixed costs of owning and operating a ship. But these may not be the only costs. If ships cannot be used, because the fleet is too
Table 5.3

ANNUAL FIXED COSTS OF INLAND SHIPS (1976)
(Dfl/yr)

<table>
<thead>
<tr>
<th>Type</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo</td>
<td>39.7</td>
<td>56.5</td>
<td>71.8</td>
<td>98.8</td>
<td>118.9</td>
<td>144.4</td>
<td>216.0</td>
</tr>
<tr>
<td>Tanker</td>
<td>104.0</td>
<td>189.3</td>
<td>258.1</td>
<td>342.5</td>
<td>408.4</td>
<td>477.9</td>
<td>613.3</td>
</tr>
<tr>
<td>Tow barge</td>
<td>30.8</td>
<td>44.3</td>
<td>54.9</td>
<td>63.7</td>
<td>71.4</td>
<td>80.9</td>
<td>100.7</td>
</tr>
<tr>
<td>Push/tow(a)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>195.7</td>
<td>197.6</td>
</tr>
</tbody>
</table>

SOURCE: Private communication from the NVI and EBW.
(a) Push/tows include barges and pushers at the following ratios:
   Class V: 8 barges per pusher
   Class VI: 9 barges per pusher
   Class VII: 10 barges per pusher

Table 5.4

ANNUALIZED INVESTMENT COSTS OF INLAND SHIPS (1976)
(Dfl/yr)

<table>
<thead>
<tr>
<th>Type</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo</td>
<td>35.0</td>
<td>45.0</td>
<td>80.0</td>
<td>110.0</td>
<td>150.0</td>
<td>190.0</td>
<td>300.0</td>
</tr>
<tr>
<td>Tanker</td>
<td>75.0</td>
<td>100.0</td>
<td>150.0</td>
<td>190.0</td>
<td>225.0</td>
<td>310.0</td>
<td>500.0</td>
</tr>
<tr>
<td>Tow barge</td>
<td>25.0</td>
<td>35.0</td>
<td>50.0</td>
<td>65.0</td>
<td>90.0</td>
<td>115.0</td>
<td>180.0</td>
</tr>
<tr>
<td>Push/tow(a)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>107.5</td>
<td>136.7</td>
</tr>
</tbody>
</table>

NOTE: These results were derived from NVI and EBW information on the costs of new vessels.
(a) Push/tows include barges and pushers at the following ratios:
   Class V: 8 barges per pusher
   Class VI: 9 barges per pusher
   Class VII: 10 barges per pusher

large, the crew must be otherwise employed or paid. The potential monetary and social costs of the unemployment make it undesirable to have many ships lying idle for long periods of time.

On the other hand, the costs of not having a sufficient fleet may be large. During low water periods, large amounts of cargo may not be delivered. Even if these goods can be stored, substantial storage and delay costs will accumulate. A recent survey has indicated that these costs may often be high, particularly if shipping is restricted for more than a few weeks and other transport cannot be found \[5.5\]. Because low water periods frequently last more than a month, an inadequate fleet could seriously disrupt industrial operations.

Assume that we have some measure of control over the character of the fleet. How does one determine what fleet size and composition are desirable (if not optimal)? The two primary influences on fleet
requirements are obvious: (1) how much cargo must be carried, and (2) how much water is available. In addition to the normal variations in water flows, seasonal and economic fluctuations change the amounts of commodities that must be carried. Should we determine the fleet needed in the most extreme case—the lowest water levels and highest cargo loads expected? The probability of this occurrence is low, so the fleet would be unreasonably expensive. It would be much larger than needed in any but the most extreme circumstances, but industry would never be threatened by lack of transport.

Specifying any fleet requires establishing criteria for water levels and the amount of goods carried. In the loss function shipping study, cargo levels were specified for an average week. Cargo patterns should be seasonal, under normal water conditions. To verify this expectation, we can look at monthly cargo data for recent years, presented in Table 5.5.

Seasonal variations are clearly evident in the data, but other fluctuations are also present. Monthly percentages are below average (8.33) during the winter months, when weather conditions reduce construction activities, and holidays limit transport. July is also low, because many industries, particularly construction, schedule vacations then. August through November have above average shipping, probably because industries make up for vacations, and agricultural products, primarily sugar beets and potatoes, are transported then.

Looking at the average monthly fractions, we find that the maximum variations are only +11 percent and -20 percent from the mean. The above average months are more important, if we want to avoid delay and storage problems in sizing the fleet. If variations between years are random, or caused by irregular events, they should not be important. We could always add a fixed percentage to our nominal cargo to account for them.

Table 5.5
MONTHLY PERCENTAGE OF ANNUAL CARGO SHIPMENTS IN RECENT YEARS

<table>
<thead>
<tr>
<th>Month</th>
<th>1974</th>
<th>1975</th>
<th>1976</th>
<th>1977</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>7.91</td>
<td>8.42</td>
<td>7.89</td>
<td>7.50</td>
<td>7.88</td>
</tr>
<tr>
<td>February</td>
<td>7.42</td>
<td>8.27</td>
<td>6.60</td>
<td>7.09</td>
<td>7.34</td>
</tr>
<tr>
<td>March</td>
<td>8.29</td>
<td>8.37</td>
<td>8.90</td>
<td>9.30</td>
<td>8.72</td>
</tr>
<tr>
<td>April</td>
<td>7.96</td>
<td>8.87</td>
<td>8.58</td>
<td>8.73</td>
<td>8.54</td>
</tr>
<tr>
<td>May</td>
<td>9.35</td>
<td>8.39</td>
<td>8.45</td>
<td>8.74</td>
<td>8.73</td>
</tr>
<tr>
<td>June</td>
<td>8.54</td>
<td>9.09</td>
<td>8.87</td>
<td>9.38</td>
<td>8.97</td>
</tr>
<tr>
<td>July</td>
<td>7.43</td>
<td>6.55</td>
<td>6.39</td>
<td>6.26</td>
<td>6.66</td>
</tr>
<tr>
<td>August</td>
<td>9.28</td>
<td>8.42</td>
<td>8.99</td>
<td>9.16</td>
<td>8.96</td>
</tr>
<tr>
<td>September</td>
<td>8.46</td>
<td>8.24</td>
<td>9.32</td>
<td>8.85</td>
<td>8.72</td>
</tr>
<tr>
<td>October</td>
<td>9.70</td>
<td>9.05</td>
<td>9.59</td>
<td>8.59</td>
<td>9.23</td>
</tr>
<tr>
<td>November</td>
<td>8.59</td>
<td>8.32</td>
<td>8.79</td>
<td>8.74</td>
<td>8.61</td>
</tr>
<tr>
<td>December</td>
<td>7.06</td>
<td>8.01</td>
<td>7.83</td>
<td>7.65</td>
<td>7.64</td>
</tr>
</tbody>
</table>

SOURCE: Refs. 5.3, 5.4.
Having looked at cargo variations, we should consider the flow patterns on the Rijn. Table 5.6 shows the decade mean discharges at Lobith for the years since 1930. The maximum variations from the mean of 2165 m³/s are +760 m³/s and -566 m³/s, during February and October, respectively. In general, flows are above average from December through April, average or slightly below from May to August, then well below average until late November.

This information confirms that the most critical time for the fleet is during the fall months, particularly September and October. At that time, water levels are lowest and the demands on the fleet highest. These conditions make a reasonable alternative for specifying the size and composition of the shipping fleet. The fleet would again be conservative, but less so than the worst-case fleet discussed above. This combination of water level and cargo conditions occurs at least once a year, rather than only rarely.

Approaching the problem in a different way, one could select the fleet large enough to carry an average week's goods during a specified percentage of the time. Ideally, this percentage would be based on the distribution of water levels throughout the country. Assume that a particular set of water levels exists now, and that we can specify the fleet required under these conditions. If this situation is worse for shipping than what occurs 90 percent of the time, we have defined a 90-percent fleet. This fleet can carry an average week's goods all but 10 percent of the time. By varying the percentage, we have a basis for comparing the relative fleet costs with the probable storage and delay costs.

Table 5.6

<table>
<thead>
<tr>
<th>Decade</th>
<th>Flow (m³/s)</th>
<th>Decade</th>
<th>Flow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January I</td>
<td>2415.7</td>
<td>July</td>
<td>2179.7</td>
</tr>
<tr>
<td>II</td>
<td>2503.8</td>
<td>II</td>
<td>2092.7</td>
</tr>
<tr>
<td>III</td>
<td>2593.0</td>
<td>III</td>
<td>2115.9</td>
</tr>
<tr>
<td>February I</td>
<td>2625.4</td>
<td>August</td>
<td>1918.7</td>
</tr>
<tr>
<td>II</td>
<td>2925.5</td>
<td>II</td>
<td>1857.4</td>
</tr>
<tr>
<td>III</td>
<td>2652.0</td>
<td>III</td>
<td>1856.1</td>
</tr>
<tr>
<td>March I</td>
<td>2606.5</td>
<td>September</td>
<td>1775.3</td>
</tr>
<tr>
<td>II</td>
<td>2366.0</td>
<td>II</td>
<td>1653.0</td>
</tr>
<tr>
<td>III</td>
<td>2546.4</td>
<td>III</td>
<td>1619.6</td>
</tr>
<tr>
<td>April I</td>
<td>2482.2</td>
<td>October</td>
<td>1609.0</td>
</tr>
<tr>
<td>II</td>
<td>2362.7</td>
<td>II</td>
<td>1629.9</td>
</tr>
<tr>
<td>III</td>
<td>2327.6</td>
<td>III</td>
<td>1640.6</td>
</tr>
<tr>
<td>May I</td>
<td>2176.8</td>
<td>November</td>
<td>1764.1</td>
</tr>
<tr>
<td>II</td>
<td>2147.0</td>
<td>II</td>
<td>1865.4</td>
</tr>
<tr>
<td>III</td>
<td>2059.7</td>
<td>III</td>
<td>2196.7</td>
</tr>
<tr>
<td>June I</td>
<td>2062.1</td>
<td>December</td>
<td>2383.7</td>
</tr>
<tr>
<td>II</td>
<td>2171.0</td>
<td>II</td>
<td>2345.5</td>
</tr>
<tr>
<td>III</td>
<td>2182.6</td>
<td>III</td>
<td>2190.6</td>
</tr>
</tbody>
</table>
Defining the fleet for an average amount of cargo simplifies the basic problem. No longer do we have to deal with a probability distribution combining variations in goods shipment with natural changes in Rijn and Maas flows. Such a distribution might be difficult to estimate, particularly because water levels and cargo shipments are not independent. If low water restricts ship drafts and causes capacity problems, the amount of cargo shipped may well vary with water levels.

5.3. STUDY ASSUMPTIONS AND PROCEDURE

5.3.1. Proxy Definition and Selection

In the long-run fleet analysis, there was no attempt to determine the optimum size and composition of the shipping fleet. No one has succeeded in doing this, and it was not within the scope of the overall water management problem. Rather, the problem was to estimate how the alternative policies and scenarios would affect fleet capacity requirements in the long run. This problem can be addressed more easily, because one can specify any reasonable fleet, and then investigate how that fleet must be expanded under different circumstances. To do this, we have chosen a proxy for the long-run fleet, and investigated how the value of that proxy is affected by alternative policies and scenarios.

Considering the available data, the obvious choice for a basic fleet is the fleet used in the low water loss function study. We can use the same information to study how the fleet size and composition are affected by changes in water conditions in different cases. Aside from simplifying the problem, this choice ensures that the loss functions and fleet analysis are based on consistent data and assumptions.

As the specific proxy, we selected that fleet necessary to carry the average cargo (in a context year) 90 percent of the time, based on the Rijn flow at Lobith. Ninety percent was chosen as the basic proxy, because the NVI and EBW used this figure in designing the 1985 fleet in their study [5.2]. The sensitivity of fleet size to the proxy criterion will be discussed later.

Having selected this approach, we must determine what water level and flow conditions correspond to a particular proxy percentage. What defines the conditions that are worse for shipping than what occurs 90 percent (or X percent) of the time? Because the distribution network and infrastructure are so complex, an exact solution does not exist. A natural approximation is available, however. We can easily determine the Rijn flow at Lobith which will be exceeded 90 percent of the time. This flow can be found statistically from existing discharge data and is given in Table 5.7. This table shows the Rijn discharges (averaged over a decade) that correspond to various values of the proxy criterion.

To begin the analysis, we selected the corresponding Rijn flow for the specific criterion percentage. We then chose, for each scenario, the
Table 5.7
CORRESPONDENCE BETWEEN PROXY CRITERION VALUES AND RIJN DISCHARGES

<table>
<thead>
<tr>
<th>Proxy (pct)</th>
<th>Rijn Discharge (m³/s)</th>
<th>Proxy (pct)</th>
<th>Rijn Discharge (m³/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0</td>
<td>1917.5</td>
<td>85.0</td>
<td>1232.6</td>
</tr>
<tr>
<td>60.0</td>
<td>1705.5</td>
<td>90.0</td>
<td>1098.0</td>
</tr>
<tr>
<td>70.0</td>
<td>1512.0</td>
<td>95.0</td>
<td>951.0</td>
</tr>
<tr>
<td>75.0</td>
<td>1422.0</td>
<td>98.0</td>
<td>831.2</td>
</tr>
<tr>
<td>80.0</td>
<td>1319.0</td>
<td>99.0</td>
<td>775.5</td>
</tr>
</tbody>
</table>

decade with Rijn discharge closest to this flow, provided it occurred during the growing season. This restriction ensured that water management policies directed toward agriculture would affect the water distribution during the decade. Alternative policies could then be compared by determining the required fleet during the appropriate decade in each case.

5.3.2. Long-Run Fleet Model

Appendix D describes the fleet model and the procedure used to develop and apply it. For now we will only discuss the model in general terms, summarizing how it operates and what output it produces.

It was intended that the fleet model should predict the shipping fleet required to carry all cargo under a given set of conditions. The general characteristics of the shipping network and operations were based on the DVK, NVI, and EBW shipping study. Water conditions by decade were found from DM results for the various alternative cases. These water conditions were specified to the fleet model as a vector of shipping depths at the five critical points used in the low water loss functions.

To calculate the required fleet, the model uses specific case results from the shipping study [5.2]. It interpolates between the runs to obtain the fleet needed for the given vector of critical point depths. To make the interpolation, it uses information about the distribution of load factors (by ship type and size) as a function of maximum allowable draft. The interpolation yields the number of ships required on the major shipping routes included in the low water loss functions. To account for the fixed shipping routes, it adds the fixed route ships from the selected shipping study cases.

These calculations determine the number of ships required to carry all cargo under the specified conditions. Because these ships vary in type and size class, we cannot easily compare results between cases. For example, suppose one policy causes a more shallow IJssel but deeper Waal than another policy. The total number of ships in each case might be the same, but the distribution by size and type would be quite different. The ships that normally use the IJssel are smaller
than Waal ships and include fewer tankers and push/tows. We can look at the distribution of ships by type and class for each case, but we also need a common denominator to compare model results for different policies.

This common denominator is, of course, money. Tables 5.3 and 5.4 show the annualized investment and annual fixed costs of operation for typical ships by type and size class. The model used this information to calculate the total annualized fixed costs for the fleet in each case. Comparing these costs gives a valid measure of the fleet requirement differences between cases.

For some purposes, we may desire to compare the costs of the Dutch part of the fleets. To do this, however, we must make two simplifying assumptions. First, we assumed that Dutch and foreign ships in the fleet have similar characteristics and costs. Second, we assumed that the ratio of Dutch to foreign ships (by type and class) would remain constant as the fleet expands and contracts. This latter assumption is reasonable if the fleet owners in all countries have similar incentives for building or retiring vessels. For now this appears to be true.

In summary, then, the model calculates, for each vector of critical point depths, the following information:

- Required Dutch and total shipping fleets by type and class of ship.
- Annualized investment costs for Dutch and total fleets.
- Annual fixed costs for Dutch and total fleets.

Adding the annualized investment and annual fixed costs gives the total annualized fixed costs of owning the fleet. This number was used to compare the long-run implications of alternative water management policies.

5.3.3. Sensitivity to Other Variables

After selecting a proxy for the long-run fleet analysis, we still have important questions to answer. First, how will the variations between alternative cases be affected by the value of the proxy criterion? This value is directly related to Rijn flow. When the value is low, the corresponding Rijn flow must be high, and the fleet will be sufficient during a smaller fraction of the year. Under these circumstances, variations in management policies may not seriously affect the shipping depths on the network or the required fleet. If the proxy is high, and the corresponding Rijn flow low, the same policy alternatives may dramatically change shipping depths, causing a much larger variation in fleet size.
The second question is whether specifying a Rijn discharge adequately characterizes the water conditions. Other variables might have to be included, such as the IJsselmeer level and net precipitation. Variations in these conditions could change water distribution and affect fleet sizes for a given Rijn flow. Should this be true, we must also specify these conditions when we discuss the proxy value for various alternative cases.

It is not difficult to see how net precipitation could affect water conditions. If the decade under consideration is wet (high precipitation), less water will be withdrawn for agricultural purposes. Not only will this leave more water in the network, it may also change the flow distribution, because agricultural demand for water is not uniform across the country. The IJsselmeer level can have similar consequences. If the level is high, agricultural demands will not draw water north on the IJssel. This may change weir operation at Driel and withdrawals at Tiel and other locations.

The water distribution policy will also affect water conditions for a given Rijn flow. Changing operating rules for the weir at Driel or the withdrawal policy on the IJssel and Waal would significantly affect the relative depths on the major waterways, especially when Rijn flows are low. In the PAWN analysis, we considered two primary managerial policies, the nominal RWS policy and the designed MSDM policy. These policies have the same basic objectives, but differ in method, and we would expect them to affect the value of the proxy.

If variations in net precipitation and IJsselmeer level do not significantly change the proxy value for a given Rijn flow, we can feel more confident in using the proxy as defined. If, however, it is sensitive to one or more of these variables, we must incorporate more information into our model and analysis. This problem could be studied using the fleet model and the simplified version of the strategy design model. With these models it is possible to calculate the proxy fleet for different criteria, varying the IJsselmeer level, net precipitation, and distribution policy. Tables 5.8 and 5.9 present the results of this analysis.

Table 5.8

<table>
<thead>
<tr>
<th>Conditions</th>
<th>RWS Strategy</th>
<th>MSDM Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Dry/low IJsselmeer</td>
<td>1540.4</td>
<td>1657.1</td>
</tr>
<tr>
<td>Dry/high IJsselmeer</td>
<td>1540.4</td>
<td>1637.3</td>
</tr>
<tr>
<td>Wet/low IJsselmeer</td>
<td>1540.4</td>
<td>1636.8</td>
</tr>
<tr>
<td>Wet/high IJsselmeer</td>
<td>1540.4</td>
<td>1636.8</td>
</tr>
</tbody>
</table>
Table 5.9

EFFECT OF PROXY CRITERION ON LONG-RUN FLEET COSTS USING KWS STRATEGY
(Total annualized fixed cost in Dflm/yr)

<table>
<thead>
<tr>
<th>Item</th>
<th>25</th>
<th>20</th>
<th>15</th>
<th>10</th>
<th>5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijn discharge (m³/s)</td>
<td>1422</td>
<td>1319</td>
<td>1233</td>
<td>1098</td>
<td>951</td>
<td>831</td>
</tr>
<tr>
<td>Dry/low IJsselmeer</td>
<td>1529.1</td>
<td>1540.4</td>
<td>1559.3</td>
<td>1657.1</td>
<td>1779.5</td>
<td>2039.9</td>
</tr>
<tr>
<td>Dry/high IJsselmeer</td>
<td>1529.1</td>
<td>1540.4</td>
<td>1556.5</td>
<td>1637.3</td>
<td>1714.1</td>
<td>1880.4</td>
</tr>
<tr>
<td>Wet/low IJsselmeer</td>
<td>1529.1</td>
<td>1540.4</td>
<td>1556.5</td>
<td>1636.8</td>
<td>1703.9</td>
<td>1824.9</td>
</tr>
<tr>
<td>Wet/high IJsselmeer</td>
<td>1529.1</td>
<td>1540.4</td>
<td>1556.5</td>
<td>1636.8</td>
<td>1703.9</td>
<td>1824.8</td>
</tr>
</tbody>
</table>

From the results shown in the tables, one can see that:

- Fleet requirements increase little until the criterion value approaches 90 percent. Beyond this value, the fleet increases at an accelerating rate, under extremely dry conditions, but only at a roughly linear rate when conditions are less extreme.
- For a criterion value less than 90 percent, net precipitation and IJsselmeer level are unimportant.
- With a normal IJsselmeer, net precipitation is not important until the proxy criterion reaches 95 percent.
- Under all but the most extreme conditions, the required fleet depends only on the proxy criterion and management strategy.
- Management strategy becomes important for combinations of dry conditions with high criterion values.
- With high lake levels, management policies do not differ until the proxy criterion is well above 90 percent.
- If net precipitation is positive, no difference exists for any criterion value or IJsselmeer level.

We can generally conclude that fleet cost is moderately sensitive to an increase in the percentage of Rijn flows for which the fleet is to carry all the goods with no delay. But, large variations in the net precipitation and IJsselmeer level conditions have little influence on fleet cost, and management strategy has only slightly greater effect. It is important to note that the low IJsselmeer level is an extreme situation that has not been observed in the past and should not be weighed heavily in this discussion.

These are welcome observations, for they show that using Rijn discharges as a proxy criterion is adequate to specify water conditions under all but the most extreme circumstances. Thus we should be able to use the proxy to compare the relative long-run impacts of alternative water management policies. External conditions should not significantly affect the comparisons of fleet requirements.
NOTES

1. Under one breakdown regulation for inner shipping, in force from January 1, 1976, until January 1, 1979, the government paid carriers (not industries using their own ships) from 20 to 112.5 Dfl per ton of capacity to scrap their ships and terminate business. Small businesses would also receive an additional general subsidy for stopping. Another law, in force until January 1, 1978, paid subsidies to any shipowner willing to scrap his vessel. This subsidy could be used to obtain a replacement. Subsidies varied from 16 to 60 Dfl per ton, paid from a fund supported by the government and shipowners. Under both plans, tankers received higher subsidies because of the excess capacity. The German and Belgian governments have developed similar programs.

2. As presented here, fixed costs do not include depreciation and interest, which are included in the annualized investment cost.

3. The annualized investment cost is a means of expressing the total (lump sum) investment cost of an item as a stream of equal annual future payments. One interpretation of this cost is that the investment is financed with borrowed funds, and the loan is paid off with equal annual payments over the life of the item. The annualized investment is the annual payment. Total investment cost can be converted into annualized cost with a capital recovery factor (CRF). The CRF depends, of course, on the useful life of the equipment and the interest rate. It is defined by the following formula:

\[ CRF = \frac{i \times (1 + i)^n}{(1 + i)^n - 1} \]

where CRF = capital recovery factor,
\( i \) = annual interest rate (decimal),
\( n \) = useful life (years).

The annualized investment cost is the product of the investment cost and the capital recovery factor. For the fleet, we assumed a useful life of 50 years and an interest rate of 10 percent. Under these conditions, the annualized investment cost is almost exactly equal to 10 percent of the total investment. This approach implicitly assumes that each investment is replaced at its initial cost (less salvage value) as soon as it reaches the end of its useful life. In other words, another loan is taken out at that time to replace the item.

4. Any method of estimating the required changes in the long-run fleet will have its weaknesses and limitations. We feel that our proxy is a reasonable choice, given the data and time constraints. A thorough analysis would require a long and comprehensive investigation of fleet characteristics, shipping markets, and the structure of the industry. After we had completed our analysis,
however, another approach to the problem was suggested by the DVK, NVI, and BBW. Unfortunately, we do not know enough about this approach to be able to comment on either its theoretical validity or difficulty of application.

5. We agree with Dutch shipping authorities that separating the Dutch fleet from the total has little practical meaning. Vessels can move freely between countries, and determining actual ownership can be difficult. However, the Dutch fleet is a natural reference for two reasons. First, we can assume it consists of all vessels registered and active in the Netherlands. Second, we know very little about vessels from other countries, except those that register for Rijn transport. We can then discuss long-run effects on the Dutch fleet and assume that the relevant European fleet will react in the same manner. This should be reasonable for policies affecting the major trade routes, particularly since the major countries are members of the EEC and frequently have similar policies with respect to inland shipping.

6. No one knows what will happen to the shipping fleet or transport market when the Rijn and Danube are connected early in the 1980s. Aside from generating additional cargo for the Rijn, the connection will enable Eastern European ships to enter the existing market. The incentives for the owners of these vessels may be quite different from those for the Western European carriers.

REFERENCES


Chapter 6

LOCK ANALYSIS

6.1. BACKGROUND

Throughout history, inland shipping in Europe has depended on the use of locks. Locks ultimately benefit shipping operations by maintaining adequate depths on waterways. In the lowlands, locks isolate freshwater lakes and canals from the influence of tides in the North Sea. Throughout the country, locks maintain desired depths on canals and canalized rivers without requiring large flows. Because depths on these various waterways can be controlled, many ships can use the waterways at any time, when this use might otherwise have been limited to high tide or high flow conditions.

Just as they benefit shipping, locks also serve two primary water management purposes. In the lowlands, the salt-fresh locks separate salt water from fresh water, reducing salt contamination of the fresh water and fresh contamination of the salt water. In the highlands, primarily, by maintaining water in canals at different desired levels, locks conserve large amounts of water that can be used for other purposes.

Although shipping ultimately benefits from the existence of locks, carriers do not like to use them. Ships passing through a lock take more time than they would if the lock were not there. This delay comes from the time waiting to enter the lock, as well as the time spent within the lock during the cycle. Such delays cost carriers money, because ships consume fuel while waiting, and crew members may have to be paid for more hours. Because delays lead to higher operating costs, carriers seek to avoid or minimize them whenever possible.

Unfortunately for shipping, water management problems generally increase delays at locks. Although ship operators prefer locks to be cycled quickly and frequently, to minimize delays, water management interests frequently require the opposite. Conserving water or reducing salt intrusion may cause lock cycles to be longer and less frequent.¹

Because of this conflict between shipping and water management at locks, we found it necessary to analyze lock operations. This analysis investigated the consequences of various tactics used at locks, and developed lock delay loss functions for lowlands (salt-fresh) and highlands (fresh-fresh) locks.² These loss functions specify the additional delay costs to ships from the use of various technical or managerial tactics at these locks. The costs are given in terms of either the corresponding reduction in water consumption (highlands locks) or the change in salt intrusion (lowlands locks) resulting from use of the specified tactics. The highlands loss functions were used in
all phases of the PAWN analysis, but the lowlands loss functions were used only by the MSDM.

6.2. LOCK OPERATION

We can describe the operation of a lock with the help of the diagrams in Fig. 6.1. Figure 6.1A shows a view looking down on a typical modern lock, and Fig. 6.1B shows a side view of the lock during a cycle. Ships approaching the lock from either direction will moor while waiting to enter the lock. When the lock is empty and open, the ships enter and tie up inside the lock, until all ships have entered or the lock is full. The doors are then closed and the water level within the lock raised or lowered until it equals that of the waterway on the opposite side. When these levels have been equalized, the doors are opened and the ships leave. The lock can then be cycled back in the other direction in the same manner.

A lock complex consists of one or more locks arranged in parallel at a particular location. Ships approach the complex from both directions to be locked through. Normally the lock operator will direct these ships to an appropriate lock. The choice of the operator will be based on ship and lock dimensions, lock availability, queue lengths, weather conditions, and safety. Ships tie up to wait until they can enter the lock and be cycled through.

During normal operations, ships enter locks in their order of arrival at the lock, with exceptions to facilitate packing the lock for maximum capacity. If the queue of waiting ships is too long, and the lock fills in either direction, additional ships must wait a complete lock cycle before they can pass.

During lock operation, managerial policies in force at the complex determine how the lock will be cycled. Among the many alternative policies that may be in force are:

- Using the smallest suitable lock for an arriving ship, even though this lock may not be the next available.
- Requiring a particular minimum queue length before cycling a lock.
- Setting a maximum waiting time for ships during low traffic periods, to reduce lock cycles while avoiding unfair delays for waiting ships.
- Using intermediate doors to reduce chamber size.\(^3\)
- Limiting cycles during high tide periods.

It is clear that combinations of one or more tactics can also be used. Most of these policies will increase delay times, but they decrease the number of lock cycles and total water volume exchanged, thus reducing salt intrusion and freshwater loss.
Fig. 6.1A -- Modern Dutch ship lock

Fig. 6.1B -- Side view of lock with canal water levels
6.3. WATER MANAGEMENT PROBLEMS AT LOCKS

6.3.1. Lowlands Locks

Three water management functions have priority at lowlands (salt-fresh) locks: (1) preventing salt water from contaminating the fresh water, (2) isolating the fresh water from tidal influence, and (3) preventing fresh water from contaminating the salt water. Although saltwater intrusion must always be considered at salt-fresh locks, tidal influence and freshwater contamination may be unimportant at certain locations. Some salt-fresh locks do not border on the North Sea, but rather connect fresh water with brackish canals or waterways such as the Noordzeekanaal and Nieuwe Waterweg. Similarly, only at certain locations, including the Volkerak and Philipsdam, must fresh water be conserved and prevented from contaminating the salt water outside the lock. This contamination could cause undesirable environmental changes in the saltwater body.

The mere presence of a lock does not prevent salt intrusion. Salt water will pass the lock anyway, for two reasons. First, when the lock opens to the salt side, salt water will mix with the fresh water in the lock chamber. When the lock subsequently opens to the fresh side, the salt water in the chamber can then contaminate the fresh water. Second, when the saltwater level is higher than the fresh, salt water will be used to bring the levels to equilibrium during the locking process. The greater the level difference, the greater the amount of salt water that will enter the chamber. This water will mix in the chamber and be discharged to the fresh side during the next return cycle. How much salt enters the fresh water is a complex problem, depending on relative water levels, mixing characteristics, and other factors. As salt enters the fresh water, however, it diffuses back into the freshwater body, spreading the contamination.

At many salt-fresh locks the salt intrusion caused by this mixing process may be acceptable. The flow of fresh water out of the lock and nearby sluice dilutes the salt and carries it back out to the sea. Salt concentrations in the fresh water away from the lock do not become objectionable.

But these concentrations are objectionable at other locks, as may be the loss of fresh water. Under these circumstances, additional measures are needed to further reduce the salt contamination and freshwater loss. These additional measures can be divided into two categories, technical and managerial. Technical tactics change the infrastructure or equipment at the lock, and managerial tactics change the operation of this equipment or of the lock itself.

6.3.1.1. Technical Tactics. Many possible technical tactics can be applied to locks. These vary from adding equipment to existing locks to completely replacing a lock with one of an improved type. Although these tactics reduce the interchange between fresh and salt water, they accomplish it in different ways with different effectiveness. Similarly, the tactics also have different investment and operating
costs, and different effects on shipping. The tactics that we considered originally, discussed in Refs. 6.1, 6.2, and 6.3, are:

- Brush lock—maintains salt separation with a large brush across the fresh side opening.
- Elevator lock—raises and lowers an elevator-like chamber holding salt water to preserve separation.
- Excavation and selective withdrawal system—collects the intruding salt water in a pit on the fresh side of the lock, later pumping this water back out to the salt side.
- Kreekrak system—uses special construction to exchange fresh and salt water inside the lock chamber during the cycle. This system may also be designed to conserve fresh water.
- Membrane lock—uses a membrane-enclosed salt basin to support ships while pumps exchange fresh and salt water.
- Pneumatic barriers—produce air bubble screens across either or both lock entrances to retard mixing between fresh and salt water.
- Salt-box lock—uses a salt basin below the lock sill level to support ships while pumps exchange the fresh and salt water inside the chamber.
- Terneuzen system—collects salt water in an excavation at the fresh gate and selectively recirculates it with pumps or gravity flow using natural level differences while the inner lock doors are open. This system may also conserve fresh water.

We chose to eliminate most of the above tactics for various reasons. Some were experimental and had not been proven in practice. Others were dominated by remaining tactics which were both less expensive and more effective. The surviving technical tactics were pneumatic barriers, excavation and selective withdrawal, and the Kreekrak system.

Pneumatic barriers or bubble screens can improve salt rejection at locks for relatively low cost. As described in Ref. 6.2, the system pumps air into the water to create a barrier. The air is blown into the water through pipes lying on the lock bottom near the doors. The air forms an air-water mix with lower density than the water. It thus rises to form a continuous upward convection current at the entrances of the lock, before escaping at the surface. The current creates a barrier to the mixing of salt and fresh water. These barriers can be installed at one or both entrances to a lock. If installed at both entrances, the system is about twice as effective as it is at only one entrance. In either case, the barriers have no adverse effect on ship passage.

Excavation and selective withdrawal systems use a pit excavated on the freshwater side of the lock complex. Salt water entering through the chamber, being more dense than fresh, will collect in the pit, from which it can be later pumped back out to the salt side of the
lock. This system, therefore, does not prevent the salt from passing through the lock; rather it prevents the salt from diffusing back into the freshwater body. As with the pneumatic barriers, the system does not adversely affect ship passage through locks. However, although it is quite effective at reducing salt intrusion, under normal operating conditions it requires about 30 percent more fresh water than a lock operating normally (but with much higher salt intrusion).

Kreekrak system locks are specially constructed to minimize mixing of salt and fresh water within the lock chamber. Utilizing the density difference between fresh and salt water, and boundary layer effects, these locks exchange salt water for fresh within the chamber during the leveling process. They simultaneously remove salt water from the bottom and add fresh water at the top during the cycle. The fresh and salt water are kept separate through careful design and controlled inlet and outlet conditions. In systems with freshwater regain, fresh water is also exchanged for salt water during the return cycle. This process saves about 40 percent of the freshwater loss, but increases salt intrusion by a factor of ten. A complete description of this system can be found in Ref. 6.3, but Fig. 6.2 shows a schematic representation of the cycle, both with and without freshwater regain. Although the system works effectively, the complex cycle requires more time than a normal lock, thus increasing ship delays.

In the preliminary screening analysis, during which we selected these tactics, we determined the following rules:

- Air bubble screens can be added to any lock that does not have them, except Kreekrak system locks, which do not need them.
- Excavation and selective withdrawal systems can also be added to any lock.
- Kreekrak systems will be used where they now exist or are planned, but will not be considered at other existing locks. Installation at these locations would be much more expensive, but no more effective, than an excavation and withdrawal system.

6.3.1.2. Managerial Tactics. Given the existing salt intrusion technology at a lock complex, one can change salt intrusion and water loss by using tactics which manage the operation of the lock. We can classify these tactics into four general groups, all of which concern different parts of the lock operation procedures.

1. Use existing salt intrusion technology. Although a lock may be equipped with certain technology, the operators may choose not to use it. If the costs of using the technology exceed the costs of salt intrusion, the technology should be left idle. Even locks with the Kreekrak system can be used
Without Regain

With Regain

F -- Fresh water
S -- Salt water
B -- Brackish water
Ω -- Natural flow
←→ -- Ship entry/exit

Fig. 6.2 -- Kreekrak system operation with and without regain
normally, saving pumping costs and delay time for ships.

2. **Flush lock.** By increasing the flow of fresh water through the lock or an adjacent sluice, authorities can reduce the amount of salt water that remains on the fresh side. Although this tactic does not affect shipping, it quickly becomes inefficient, as flushing water removes salt less effectively as the rates increase.

3. **Reduce lock cycles.** Salt intrusion depends on the number of lock cycles. Reducing the number of cycles should reduce salt intrusion, although this will increase delay times for ships. Many specific types of tactics can be designed to reduce lock cycles, including:

   - Requiring a specific number of ships (or fraction of lock capacity) in the lock before cycling.
   - Scheduling lock cycles by time, rather than by ship arrival.
   - Requiring ships to wait a specified time before being passed through the lock.
   - Closing the lock during certain periods, such as at high tides.

Combinations of these tactics can also be used, to try to equalize delay times for ships arriving during high and low traffic periods.

4. **Reduce salt intrusion per cycle.** These tactics do not reduce the number of lock cycles, but instead reduce the salt intrusion per cycle. They include:

   - Using the smallest lock at a complex, when safety permits.
   - Closing lock doors whenever ships are not entering or leaving locks.
   - Using intermediate doors in locks, when possible, to reduce chamber volume.

These tactics do not significantly increase ship delay times, and may often reduce them, because smaller chambers can usually be cycled more quickly than larger chambers.

Ship operators prefer tactics which do not increase their delay times, those which do not reduce the number of lock cycles. However, under most conditions, salt intrusion cannot be decreased sufficiently without resorting to restrictions on lock usage and ship passage. In our analysis, for instance, we assumed that the group 4 tactics would always be used. If salt intrusion is a significant problem, group 1 tactics do not apply. Thus, if large amounts of flushing water are not available, and they will not be under dry conditions, only lock use restrictions remain.
6.3.2. Highlands Locks

The primary water management problem at these fresh-fresh locks is the loss of fresh water through the lock. Two sources contribute to this loss: leakage through the lock doors, and the normal consumption of water in the locking process. Lock leakage depends only on the condition of the lock, but normal consumption depends on the dimensions of the lock, the number of lock cycles, and the water level difference across the lock.

Under normal circumstances, canal flows far exceed water consumption by locks. During dry conditions, however, this situation may be reversed; the net flow in the canal may be less than lock losses, when standard operating policies are used. This situation will cause water levels to drop in the canal, endangering shipping operations. To maintain water levels, water management authorities must either curtail lock consumption or reduce other water uses. How much water consumption should be reduced for each consumer clearly depends on the relative costs to each party.

We must note that water lost through one lock is obviously available for lock usage downstream. Considering the sources and losses of water between locks and determining which locks dominate the problem, we can balance the water consumption on the waterways in an area. The DM does this by using operating rules derived from the lock loss functions, low water loss functions, and demands for other uses in the area. Volume XI describes this process in detail. The resulting water balance, in dry conditions, will normally require water consumption restrictions at locks on the Maas, Julianskanaal, and other highlands waterways.

Assuming that water consumption at highlands locks must be reduced, how can this be accomplished? Several types of tactics are available, and these can again be classified as either technical or managerial. Technical tactics include modifications or additions to the lock infrastructure, and managerial tactics affect lock operation or use of the infrastructure.

This problem differs in one major way from the salt intrusion problem at lowlands locks: at highlands locks water losses become important only during extremely dry periods. For this reason, technical tactics to solve the problem may be less practical, because the benefits may not accrue often enough to justify the cost of the new or improved technology.

6.3.2.1. Technical Tactics. Technical tactics at highlands locks can be separated into four groups, as follows:

1. Plug leaks in lock doors. This can be done either temporarily or permanently, and may save as much as 2 m³/s at some locks. It does not interfere with shipping operations.

2. Pump back water. Water pumped from the low side to the high side of the lock can be reused. Pumping facilities for
this operation can vary from permanent stations to temporary barges anchored in one lock of the complex [6.5, 6.6]. By occupying one lock, these barges increase delay times for shipping, whereas permanent pumping stations would not.

3. Intermediate storage ponds. These ponds can be constructed at a level intermediate between the canal levels on the two sides of the lock. Water released from the lock when cycling down can be saved and used to partially fill the lock on the return cycle. Without pumping, these ponds can save almost half the normal consumption, at the cost of increased cycle times and lock delays.

4. Synchronous operation. When a complex has two locks, the water discharged from one lock can be used to fill the other. This operation requires that the locks be cycled in opposite directions at the same time. Like the storage pond, this process can save almost half the normal consumption, with a longer cycle time and much longer ship delays (because locks are no longer operated independently).

One can easily show that using two locks in series, instead of one, to drop a given distance will also save water. The second lock will use the water from the first, reducing consumption by one-half, in a manner analogous to the use of an intermediate pond. This does not affect the analysis except at Linne and Roermond on the Maas, where carriers have a choice between the Maas and the Lateraalcanal. We will discuss this problem later in the chapter.

6.3.2.2. Managerial Tactics. The managerial tactics that can be used at lowlands locks can be used at highlands locks, with the exception of flushing, which is clearly inappropriate. The remaining tactics can be described as follows:

1. Use existing technology. Because technology such as facilities for synchronous locking or intermediate storage ponds increases ship delay times, it should not be used when flows are adequate.

2. Reduce the number of lock cycles. Unlike salt intrusion, freshwater consumption is reduced proportionally to the reduction in lock cycles. Many tactics will do this, including reducing opening hours or days, requiring a minimum number of ships per cycle, specifying a minimum waiting time, or forming combinations of different tactics.

3. Reduce consumption per cycle. As with lowlands locks, this includes using intermediate doors (where available) and the smallest lock suitable for waiting vessels.

Carriers obviously prefer tactics of type 3, because these do not add to their delay times. However, many lock complexes have only one lock and no intermediate doors, so these tactics have limited value for highlands locks. Almost always, lock operating hours or cycles must be
reduced to decrease water consumption. Examples of what may be necessary during drought periods can be found in Ref. 6.5, which discusses the tactics applied to the Julianakanaal and Maas during 1976.

6.4. SELECTION OF LOCKS

In the PawN analysis, we investigated only a small fraction of the locks in the Netherlands. The NM and MSDM included only those lowlands (salt-fresh) locks which might have important salt intrusion or freshwater loss problems. The eleven locks selected are shown in Fig. 6.3. As the figure shows, most of the locks separate freshwater bodies from the North Sea. The two exceptions are the locks at Spaarndam, on the Noordzeekanaal, and the Parksluizen, on the Nieuwe Maas near Rotterdam. Both the Noordzeekanaal and Nieuwe Maas have much higher salt concentrations than the freshwater canals behind the locks. The locks at Kreekrak and the Philipsdam were included because they border on a future fresh Zoommeer, one of the primary scenario variables in the analysis.

Certain canals in the highlands area of the Netherlands are important shipping and water distribution links. These canals are shown in Fig. 6.4. This figure indicates with dashed lines the canals that we included in the analysis, as well as the relevant locks. We will discuss these canals and locks in more detail in Sec. 6.6.2.

6.5. MODEL DESCRIPTION

The basic analysis problem is the same for both highlands (fresh-fresh) and lowlands (salt-fresh) locks: to determine how technical and managerial tactics affect ship delays and water management problems at locks. We solve this problem by simulating the passage of ships through the locks under different sets of tactics, using the results to calculate salt intrusion, water loss, and delay costs to shipping. This information is used to develop loss functions for lock operation. In the study we considered using alternative analytical models for the lock analysis. We decided, however, that they were not appropriate because of the variety of managerial tactics and the variability in ship arrival rates at the locks.

Figure 6.5 shows the basic form of the lock analysis model. The salt-fresh model shown can be converted to a fresh-fresh version by replacing the lock salt model with a calculation of freshwater consumption. The overall model consists of a lock operation model and a lock salt model. Lock and ship traffic characteristics and technical tactics determine the model parameters. The lock operation model simulates the passage of ships over a predetermined period, using operating policies based on input managerial tactics. The model passes the results of this simulation to the lock salt model, which calculates salt intrusion, water loss, and delay and energy costs. The complete lock model program is described in detail in App. E.
Lock Complexes
1 -- Delfzijl
2 -- Den Helder
3 -- Den Oever
4 -- Harlingen
5 -- Ljouwden
6 -- Kornwerderzand
7 -- Kreekraksluizen
8 -- Parksluizen
9 -- Philipsdamsluizen
10 -- Spaarndam
11 -- Volkeraksluizen

Fig. 6.3 -- Lowlands salt-fresh locks
Fig. 6.4 -- Highlands canals and locks
Fig. 6.5 -- Lock analysis model
For the highlands (fresh-fresh) lock analysis, we changed the model in two ways. We replaced the salt model with a simple calculation of freshwater loss through the lock. Also, we substituted a simplified model of lock operations for the complex computer simulation model. This simplified model used the same basic approach but substituted an aggregated calculation for the ship-by-ship simulation process. The aggregated model is developed and described in Ref. 6.4.

6.5.1. Lock Operation Model

The lock operation model simulates the operation of a typical lock complex. It passes a series of ships which arrive at random intervals, based on observed traffic patterns at the lock. It simulates the passage of these ships through the various locks of the complex, using operating rules based on actual lock operation procedures and managerial tactics selected for the analysis. It records the passage of vessels and transfers this information to the salt model for the remaining calculations. The program is written in the Simscript II.5 language for use on an IBM 3032 computer.

6.5.1.1. Characteristics of Ship Traffic. For each complex, we must have a description of the ship traffic using the locks. This description includes:

- The distribution of vessels by size class, type, and load.
- The arrival pattern for ships by direction during the week.
- Seasonal variations in the characteristics of ship traffic and its arrival patterns.

We used this information (obtained from the RWS and lock operations) with standard ship characteristics and the descriptions of the locks in the complex to calculate the following parameters:

- Mean entry and exit times for ships using each lock.
- Mean delay cost per ship per hour for the complex.
- Mean number of ships required to fill each lock chamber.
- Fraction of total ship traffic associated with recreation.
- Mean displacement volume per ship for each lock chamber.

The methods used for these calculations are described in Ref. 6.4. Because the characteristics of the ship traffic may vary by season, we used monthly traffic data to partition the year into groups of months which had roughly equal traffic. For each of these groups, we calculated a separate set of lock parameters based on the appropriate distribution of ships in the traffic data.

6.5.1.2. Characteristics of Lock Complex. The analysis procedure also required a description of the locks and sluices in each lock
complex. This description included the number and layout of locks, their dimensions, water levels by season on each side of the complex (including tidal range), normal hours of operation, and average times required to open and close lock doors and equalize water levels. This information was used in calculating the lock parameters for passing ships, energy costs of operation, and parameters for the salt intrusion and water loss calculations (discussed in App. E).

6.5.1.3. Lock Simulation. During the simulation process, the computer program operates on a series of randomly arriving ships. These ships have both a size class and direction of travel. Using this information, the program assigns each ship to a queue, based on lock and ship size, lock availability, and existing queue lengths. After this assignment, the program schedules a lock cycle, guided by the managerial policy selected for the simulation.

Even though a lock cycle may be scheduled at a particular time, the cycle need not take place. The lock may be closed (in the process of cycling) or open in the wrong direction. If this occurs, the program instructs the lock to cycle as soon as possible. When the cycle can begin, the ships enter the lock, the lock closes, and a lock opening is scheduled after an appropriate time. This time depends on the lock characteristics and the number of ships in the lock. After the lock opens, the ships leave the system and the program records the cycle, the number of ships passed, and the cumulative delay times. The lock can then be cycled back in the opposite direction, if a cycle has been scheduled.

In this manner the program proceeds through the specified simulation period, corresponding to the operating hours of a given number of weeks. During this period, the program stops after each day to pass summary information to the lock salt model, which calculates and saves the salt intrusion, water loss, and costs for the day. Summary information transferred between programs for each day includes:

- Ship delay costs.
- Number of lock cycles per chamber.
- Number of times intermediate doors were used in each lock.
- Mean time lock doors were open for each lock.
- Mean displacement volume of ships per cycle for each lock.
- Energy costs per day.
- Recreational vessel delay per day.

At the end of the simulation, the program calculates final statistics for the entire period, using the daily results.

During the simulation process, the program automatically incorporates certain managerial tactics. It gives preference to the smallest suitable lock, although this lock may not be the next available. It also assumes that lock doors will always be closed (to minimize water exchange), except when ships enter or leave the chamber.
program can choose to use intermediate doors in locks, if ship traffic
levels are suitable and waiting ships can be accommodated in the
smaller chamber. We supply as input a sequence of hours during the
simulation when mean ship arrival rates are small enough to permit
using the doors. During these periods, the program determines if the
intermediate chambers will accommodate the queued ships. This
procedure approximates the conditions under which lock operators use
intermediate doors. Although it is only a rough approximation, a more
exact procedure would have been far too complex for the purpose of
the model.

The results of the lock simulation process can be plotted as delay
cost for ships against managerial tactic. Figure 6.6 gives an example
of these results. It shows the average delay time per ship versus the
minimum number of ships in queue before the lock can be cycled. The
results are based on the Volkerak locks during the late summer and
early fall period. The figure also shows the mean number of lock
cycles per day as a function of the tactic selected. These results
show that the number of cycles can sometimes be reduced significantly
without a corresponding increase in ship delay times.

6.5.2. Lock Salt Model

The salt model program calculates salt intrusion at a lock complex using
the daily results of the simulation program and the selected technical
tactics. These calculations are based on equations developed from an
equilibrium analysis of the entire lock complex, including sluices. We
can describe the model using the schematic diagram of a lock complex
shown in Fig. 6.7. Referring to the figure, we see that salt enters the
system (defined from point P) through the locks and in the flushing
water. Salt leaves the system through the sluice, carried out by the
flushing water, and by diffusion back along the waterway. Water enters
the system through the lock and in the flushing process, and leaves the
system through the lock and the sluice. The model considers both salt
and water balances in the system in calculating salt intrusion and
freshwater gain (or loss) as a function of flushing rate on the
waterway.

The type of technical tactic considered determines the specific
equations used in the analysis. These equations and the development
and calibration of the salt model are described in App. E.

In making its calculations, the salt program requires various input
data and parameters. These include:

- Lock characteristics, including water levels.
- Menu of technical tactics applied at the locks.
- Range of appropriate flushing rates.
- Salinity information on both sides of the lock complex and in
  the flushing water.
- Coefficients describing the effectiveness of the technical
tactics for salt prevention and freshwater consumption.
Fig. 6.6 -- Typical results for lock operation model: Volkeraksluizen
The program combines this information with the specific results provided by the lock simulation model to calculate:

- Salt intrusion and saltwater intrusion.
- Increase in salt concentration over background concentration on the fresh side of the lock complex.
- Freshwater loss through the locks or sluices.
- Net water gain (or loss) to the system.
- Daily costs for investing in and operating the lock technology.

All results but the daily cost information depend on the flushing rate through the complex. Therefore, all calculations are performed for a range of flushing rates appropriate to the complex.

6.5.3. Highlands Lock Model

In the highlands analysis, we used a simplified version of the basic lowlands lock model. This version involved substituting an aggregate simulation calculation for the ship-by-ship simulation program, and replacing the salt program with a simple water loss calculation. We used this simplified model because we did not have adequate time, money, or input data to justify using the complete simulation program, which would be the preferred procedure. The general model and procedure are described in Refs. 6.4 and 6.5. The model differs from the lowlands model in several important ways.

6.5.3.1. Lock Capacity. In the highlands version of the model, we calculate most parameters in the same way as in the lowlands model. However, we can define lock capacity in a different manner. In addition to the static chamber capacity, it can also mean the number of vessels that can be passed through the lock (in both directions) during a fixed time period (nominally one week). Defined in this manner, lock capacity depends on the following characteristics:

- Mean entry and exit times for ships passing through the lock.
- Time required to open and close lock doors, and to raise or lower the water level.
- Mean static capacity of the lock chamber.
- Number of operating hours per week.

The capacity can be calculated from the formula:

\[ C = 2 \times n \times H \times (60/T) \]

where \( C = \) lock capacity (ships/wk),
\( n = \) static chamber capacity (ships),
\( H = \) number of hours, and
\( T = \) operating days.
\( H = \) operating hours (hr/wk),
\( T = \) total time for a complete lock cycle (min).

This equation involves several important assumptions, namely:

- Static chamber capacity is the same in both directions.
- Ship traffic is roughly the same in each direction.  
- Ships can maneuver as well at night as during the day.

If any of these assumptions do not hold, corrections to the weekly capacity must be made. During the analysis, the only correction necessary was to reduce lock capacity during night hours. Based on the discussion in Ref. 6.6, we multiplied these hours by 0.95 to account for the reduced visibility around the lock.

Although capacity is expressed as a number of vessels per week, it is really a function of the maximum number of times the locks can cycle. If an average cycle requires one hour (complete round trip), then at most 24 cycles per day are possible. Cycle length depends on the number of vessels passing through the lock, for each vessel requires a certain amount of time to enter and exit. As the average number of ships per cycle increases, the average cycle time increases, and the maximum number of cycles per day decreases.

6.5.3.2. Ship Delay Time. Now that we can calculate the capacity of the locks in a complex, we need to be able to determine the corresponding delay times for ships. In the lowlands analysis, the computer program automatically calculated the delay times for each ship. In this work, however, we must develop another method.

According to Kooman and De Bruijn [6.4], the time a ship requires to pass a lock can be separated into three components. These are:

- Locking--time spent entering, exiting, and waiting inside the lock chamber during the cycle.
- Waiting--time between when a ship arrives at the lock complex and the lock becomes available for ships to enter.
- Delay--additional waiting time if a ship cannot enter the lock at first opportunity because the queue is too long.

Locking time is given by

\[
\begin{align*}
t_s &= T_b + 0.5 \times t_u \times (n + 1 + \text{Var}(n_k)/n)
\end{align*}
\]

where
\( t_s = \) mean locking time (min),
\( T_b = \) lock operating time (min),
\[ t_u = \text{mean exit time per ship (min)}, \]
\[ n_k = \text{number of ships in a given cycle}, \]
\[ n = \text{mean number of ships per cycle}. \]

In this equation, the lock operating time is that required to open and close the lock doors and equalize water levels. The exit time is that between the completed exit of successive vessels from the lock. If we assume that the number of ships per cycle can be described by a Poisson distribution, this equation reduces to

\[ t_s = T_b + 0.5 \times t_u \times (n + 2) \]

The reader will note that the subscripts used in this and subsequent equations are not intuitive. They agree, however, with those used by Koeman and De Brujin in their derivations, and are derived from Dutch equivalents of appropriate English terms.

The equation for mean waiting time depends on the number and type of locks at the complex and the operating procedure. For \( N \) parallel and identical locks, operated independently, the equation is

\[ t_w = \frac{T_c}{N + 1} \]

where \( t_w = \text{mean waiting time (min)}, \)
\[ T_c = \text{mean total time per complete cycle (min)}, \]
\[ N = \text{number of locks}. \]

The total time per complete cycle is that required for all ship entry and exit and lock operation in one complete cycle (including return). If the locks are not identical, but are operated independently, the equations for two and three locks become:

Two locks
\[ t_w = \frac{T_{c1}}{2} - \frac{T_{c1}^2}{6T_{c2}} \]

Three locks
\[ t_w = \frac{T_{c1}}{2} - \left( \frac{T_{c1}^2}{1/T_{c2} + 1/T_{c3}} \right) + \frac{T_{c1}^3}{12T_{c2}T_{c3}} \]

where \( t_w = \text{mean waiting time (min)}, \)
\[ T_{ck} = \text{mean total time per complete cycle for lock } k \text{ (min)}. \]
If the locks are not operated independently, as in synchronized locking, the equations or effective cycle times must be modified accordingly.

The delay time is the additional waiting time caused by an excess of ship traffic at the lock. It depends on the ratio of traffic to lock capacity and the arrival pattern of ships at the lock. Although it is potentially the largest and most important component, this delay time is the most difficult to calculate.

Fortunately, Koeman and De Bruijn were able to devise a relatively simple method of dealing with this problem [6.4]. Using a series of simulations at locks with different arrival patterns, they developed three standard curves of delay time as a function of the ratio of traffic intensity to lock capacity. Each curve corresponds to a different type of ship arrival pattern, and all locks in the Netherlands can be assigned to an appropriate type. This assignment could be obtained from shipping network information. These delay time curves are presented in Fig. 6.8.

With these delay time curves and the equations for the other parts of the total passing time, it was possible to calculate the total delay time and cost at any lock complex. The delay cost coefficients were weighted averages based on the distribution of ship traffic at the lock. Further discussion of cost coefficients can be found in Chap. 3 and App. A.

6.5.4. Water Loss Calculation

The last part of the model was a simple calculation of water loss through the lock. This could be determined from lock dimensions, water levels, leakage rates, and the number of lock cycles per week for each lock. The equation for the water consumption summed over all locks at a lock complex is

\[
W = \sum_{i=1}^{N} \left[ \frac{C_{Y_i} \times V_i}{604,800} + \frac{C_{Y_i} \times T_{c_i} (L_{0_i} - L_{C_i})}{604,800} + L_{C_i} \right]
\]

where \( W \) = total water consumption \((m^3/s)\),
\( N \) = number of locks at complex,
\( C_{Y_i} \) = number of complete lock cycles for lock \( i \) \((cycles/week)\),
\( V_i \) = volume of water released per cycle for lock \( i \) \((m^3)\),
\( T_{c_i} \) = mean total time per complete cycle of lock \( i \) \((min)\),
Fig. 6.8 -- Lock delay time curves
\[ L_{O_i} = \text{leakage rate during operation of lock } i \ (m^3/s), \]
\[ L_{C_i} = \text{leakage rate of lock } i \text{ when lock is not operating } (m^3/s). \]

Note that the volume of water released per cycle assumes no ships are in the lock.

The calculation of ship delay times and water loss may be affected by the tactics used at locks. Two technical tactics, however, will not cause important changes in the calculations. Pumping back water does not directly affect either ship delays or water consumption, unless the pumps occupy a lock chamber. This will be considered further in Sec. 6.8. Similarly, repairing lock doors to reduce leakage rates will change water consumption but not affect ship delays.

On the other hand, using intermediate storage ponds or synchronous operation will influence both delays and water loss. Intermediate ponds increase lock operating time and thus the total time per cycle, while reducing the effective volume of the lock. Synchronous operation of parallel locks also reduces the effective lock volume, but has a more complicated impact on ship delays. In addition to increasing the operating time and total time per cycle for each lock, it prevents the locks from being operated independently. Thus, two locks operated synchronously with a given total cycle time look like one lock with a cycle time half as long. As a result, the calculation of mean waiting time must be adjusted accordingly.

Managerial tactics will also change the calculation of delay times and water consumption. Deciding whether or not to use existing lock technology to conserve water need not be discussed here, as it falls under the above discussion of technical tactics. Reducing the number of lock cycles will directly reduce water consumption. It also changes ship delays by (1) increasing the mean number of ships per cycle, (2) increasing the total time per complete cycle (because more ships enter and leave per cycle), (3) changing the time between lock cycles (if locks stand idle), and (4) reducing the weekly lock capacity. The reduction in weekly lock capacity will increase the delay time component of total passing time.

Finally, choosing to use the smallest lock chambers at a complex (including intermediate doors) will directly influence the relative number of cycles per chamber. It will also change the mean number of ships per lock cycle and thus the mean total time per cycle for the different locks. This tactic could be difficult to incorporate into the delay calculations, because lock preference implies that locks are not cycled independently. This was no problem in the analysis, however, for two reasons. First, in most cases, preference is not possible. Locks either have no intermediate doors, or else traffic is too heavy to permit such flexibility. Second, when capacities exceed ship traffic, one can look at extreme situations (e.g., always use one chamber or the other) to find bounds on the feasible combinations.
6.6. ANALYSIS PROCEDURE AND RESULTS

6.6.1. Lowlands Locks

Prior to using the lock analysis program for a lock complex, we had to complete the following preliminary steps:

- Describe the lock complex, including existing salt intrusion technology, layout, cycle times, and hours of operation.
- Describe the ship traffic by hour, day, and month during 1976, including the distribution by type, size class, load, and direction.
- Determine seasonal variations in ship traffic and separate the annual traffic into representative seasons, assuming that ship traffic does not change when technical or managerial tactics are imposed.
- Calculate model parameters and mean ship traffic levels for each season.
- Generate a ship arrival pattern over the week, giving the mean number of arrivals by direction per operating hour.

With this information it is possible to generate a random arrival stream of ships for each season. We assumed a Poisson distribution imposed on the pattern of arrival rates through the week, and assigned a size class to each ship, using the distribution for ships passing through the lock complex. Knowing the mean number of arrivals per week, we created arrival streams of at least 1,000 ships for each season.

The program was run for each season, using various managerial tactics. The technical tactics appropriate to each complex were included in every run. Because these technical tactics do not normally affect the lock simulation, we could in practice separate the two models. Accordingly, a run with a particular managerial tactic would provide salt intrusion calculations for all technical tactics used at the lock. In addition, the results of the simulation could be saved for subsequent sensitivity analysis with the parameters in the salt calculations. We could not do this for the Kreekrak systems, however, because the lock cycle times vary with the specific operation cycle of the lock. We had to rerun each simulation every time we changed the cycle at either the Kreekraksluizen or Philipsdamsluizen.

The results of the series of runs at a lock complex were expressed as salt intrusion, water loss, and costs per day for each managerial tactic combined with all appropriate technical tactics. These results were then processed and put in an appropriate form for the MSDM. Part of this procedure required defining a nominal situation for each lock, assuming:
• No investment in salt intrusion technology at the lock.
• No use of existing salt intrusion technology.
• Nominal managerial tactics with no imposed delays.
• Nominal range of flushing rates.

The nominal managerial tactic is to pass ships as they arrive, waiting only if another vessel is within 5 minutes of arriving. The nominal situation should represent a worst case for salt intrusion during a particular season at the selected lock complex. Using this nominal case, we can specify a function for lock losses in two parts:

• Nominal salt intrusion at the lock as a function of flushing rate on the waterway.
• Reduction in this salt intrusion that could be achieved for a corresponding increase in investment, delay, and energy cost.

To facilitate using these results in the MSDM, we separated them by level of investment in salt intrusion technology. The reductions in salt intrusion for each managerial tactic were stated as a fraction of the nominal rate of intrusion. Because these fractions were almost independent of flushing rate, for a given combination of technical and managerial tactics, we could plot the mean reduction fraction against the sum of delay and energy costs. This considerably simplified the analysis in the MSDM, as described in Vol. V.

Table 6.1 and Figs. 6.9 and 6.10 show typical loss functions derived from the lowlands lock analysis for the Volkerak locks during late summer in 1976. Table 6.1 contains the nominal salt intrusion. Figure 6.9 shows the reduction in salt intrusion and the corresponding ship delay plus energy cost for one technical tactic (level of investment in salt intrusion technology). Figure 6.10 shows the corresponding curves

<table>
<thead>
<tr>
<th>Flushing Rate (m³/s)</th>
<th>Salt Intrusion (million kg Cl⁻/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>6.11</td>
</tr>
<tr>
<td>10.0</td>
<td>5.25</td>
</tr>
<tr>
<td>15.0</td>
<td>4.51</td>
</tr>
<tr>
<td>20.0</td>
<td>3.88</td>
</tr>
<tr>
<td>25.0</td>
<td>3.30</td>
</tr>
<tr>
<td>30.0</td>
<td>2.87</td>
</tr>
<tr>
<td>35.0</td>
<td>2.46</td>
</tr>
<tr>
<td>40.0</td>
<td>2.12</td>
</tr>
<tr>
<td>45.0</td>
<td>1.82</td>
</tr>
<tr>
<td>50.0</td>
<td>1.56</td>
</tr>
</tbody>
</table>
Fig. 6.9 -- Loss function for Volkerak locks: Salt intrusion reduction with single air bubble screen
Fig. 6.10 -- Loss function for Volkerak locks: Salt intrusion reduction with different tactics
for all technical tactics considered at the lock. For each technical
tactic, we plotted the results for all managerial tactics, then drew an
evelope curve. This can be seen in Fig. 6.9, which shows both the
points and curve. Figure 6.10 shows only the curves. The envelope
curves should represent combinations of the managerial tactics selected
for the analysis.

The complete results of the lowlands lock analysis are too voluminous
to present in this report. The calibration results, however, have
been included in App. E.

In general, only ship traffic in the 1976 context was used in the lock
analysis. The reasons for this restriction were:

- The DM used only the calibration data for salt intrusion in
  its runs. It did not design strategies or select tactics at
  lowlands locks.
- In the early NSDM analysis, we recognized that salt intrusion
  was not sufficiently important to cause the model to select
  other than the nominal tactic at each lock. The benefits of
  reducing salt intrusion did not exceed the increased costs of
  alternative technical and managerial tactics.
- Projections of 1985 ship traffic at the selected locks were
  incomplete. For most locks we had no predictions for either
  commercial or recreational traffic in 1985.

For these reasons we did not feel that the need justified the time and
expense required for a complete 1985 context analysis. We did, however,
investigate the 1985 context at the Kreekrak and Philipsdam locks.
These locks were selected because there are projections for their 1985
traffic, and because saltwater and freshwater problems at these locks
are important for scenarios with a fresh zoomeer.

To investigate these locks, we used RWS estimates of traffic growth
between 1972 and 1985, and assumed the same traffic patterns in 1985
as in 1976. These patterns were scaled by the increase in overall
arrival rates. We also assumed that seasonal traffic patterns at both
locks would remain constant.

The analysis showed that salt intrusion through the locks increased
proportionally to the increase in traffic. This can be seen in Table
6.2, which shows the 1976 and 1985 salt intrusion results for the two
lock complexes. The ship traffic at the Kreekrak locks increased by
24 percent, and that at the Philipsdam locks by 45 percent. The
increase in salt intrusion at the locks is very similar.

The reader will notice that no flushing rates are given in the table.
These rates cannot be varied, because neither location has a sluice.
With a Kreekrak system, freshwater loss (flushing rate) cannot be
varied, but is fixed at the normal consumption of the lock. Thus it
depends on the ship traffic, and whether freshwater regain is used
during the cycle.
Table 6.2
SALT INTRUSION AT KREEKRAK AND PHILIPS DAM LOCKS IN BOTH CONTEXTS
(million kg Cl\textsuperscript{-}/day)

<table>
<thead>
<tr>
<th>Location</th>
<th>Period</th>
<th>1976 Regain</th>
<th>1976 No Regain</th>
<th>1985 Regain</th>
<th>1985 No Regain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philipsdam</td>
<td>Jan - Feb</td>
<td>0.897</td>
<td>0.105</td>
<td>1.448</td>
<td>0.166</td>
</tr>
<tr>
<td></td>
<td>Mar, Nov - Dec</td>
<td>1.025</td>
<td>0.119</td>
<td>1.435</td>
<td>0.167</td>
</tr>
<tr>
<td></td>
<td>Apr - May</td>
<td>1.076</td>
<td>0.125</td>
<td>1.507</td>
<td>0.175</td>
</tr>
<tr>
<td></td>
<td>Jun - Jul</td>
<td>1.094</td>
<td>0.128</td>
<td>1.532</td>
<td>0.179</td>
</tr>
<tr>
<td></td>
<td>Aug</td>
<td>1.153</td>
<td>0.128</td>
<td>1.552</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>Sep - Oct</td>
<td>1.135</td>
<td>0.124</td>
<td>1.527</td>
<td>0.177</td>
</tr>
<tr>
<td>Kreekrak</td>
<td>Jan - Feb</td>
<td>0.260</td>
<td>0.030</td>
<td>0.344</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>Mar - Aug</td>
<td>0.291</td>
<td>0.032</td>
<td>0.379</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>Sep - Oct</td>
<td>0.306</td>
<td>0.034</td>
<td>0.406</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Nov - Dec</td>
<td>0.291</td>
<td>0.032</td>
<td>0.379</td>
<td>0.040</td>
</tr>
</tbody>
</table>

These results indicate that, as a first approximation, the 1985 salt intrusion numbers could be approximated by scaling the 1976 results by the anticipated increase in ship traffic. This approximation would be valid if ship traffic does not closely approach lock capacity. The results would not be linear, however, if traffic is comparable to the lock capacity in 1976, because increasing the traffic would not increase lock cycles or salt intrusion. Instead, it would only increase delay times for ships. Under these circumstances it is even less likely that the NSDM would select any managerial or technical tactics to reduce salt intrusion. Applying these tactics would only increase costs even more than in 1976, when the tactics were not profitable anyway.

6.6.2. Highlands Locks

The lock model as applied to highlands locks does not allow using a variety of managerial tactics. Instead, tactics are limited to considering either the total number of lock cycles or operating hours per day for each lock. The RWS used the latter policy during low flow periods in 1976 [6.5]. Restricting operating hours at a lock is equivalent to restricting the number of lock cycles during the week. Reducing the number of cycles reduces the lock’s water consumption proportionally. Water use can also be decreased by using smaller locks, if traffic permits, or locks with smaller leakage losses during operation.

Figure 6.11 is a typical example of the results at a lock complex. In the figure, each point represents a specific combination of lock cycles per day for the locks at the given location. In this case, point A corresponds to 24 cycles per weekday and 10 on Sunday for each lock at Maasbracht. For this number of cycles, the locks have a maximum capacity determined by the maximum number of ships per chamber.
Fig. 6.11 -- Typical loss function for a highlands lock
during a cycle. Knowing the ship traffic and lock characteristics, we can calculate the mean number of ships per cycle, the various components of total passing time, and thus the delay cost per week for point A. In the same way, we can calculate the water consumption at the complex for the given number of cycles. The results of these calculations give us enough information to plot point A on the graph.

By repeating the same process for other possible combinations of lock cycles, we can generate the remaining points in the figure. Technical and other managerial tactics can easily be incorporated. It is only necessary to change the appropriate lock parameters in the equations before proceeding with the analysis. The appropriate range for the number of lock cycles will quickly become apparent from the delay time results. As the number of cycles approaches the lower limit, delay times increase rapidly.

When an appropriate set of points has been determined and plotted, it is only necessary to draw a smooth envelope curve, as shown in the figure. This curve represents the set of the most efficient combinations of tactics at the complex. However, it will obviously include only those tactics actually incorporated into the analysis.

Water pumping or recirculation is one technical tactic that may lie outside the analysis. Unless the pumps actually occupy a lock chamber, the tactic does not directly affect lock operations, only the amount of water available. Therefore, it should instead be included as part of the overall analysis of the waterway under consideration. There it will represent a horizontal and vertical shift of the entire loss function curve and a reduction in water available downstream.

During the analysis, we separated the highlands canals into different segments, as shown in Fig. 6.4. These segments were defined by the intersections of canals in the network. This division facilitated incorporating the results into the overall project work. As the figure indicates, the canal segments consist of a series of lock complexes of varying configurations and dimensions. To simplify the analysis, the locks on each segment were classified into types, based on lock dimensions and characteristics and ship traffic. We selected one lock of each type for detailed analysis, as described above, generating a delay cost versus water loss curve for the lock type. Using these curves, we could estimate loss functions for each canal by adding the delay costs (at each flow rate) for the appropriate number of locks of each type on the canal. The canal sections, locks, and lock characteristics are shown in Table 6.3.

Although all Maas locks were initially considered, the analysis included only those on the Julianakanaal and the Lateraalkanaal-Maas sections of the waterway. Because the flow of the Roer River enters the Maas at Roermond, water balance problems are not important downstream of this point.

Although the 1976 context was used in this analysis, we also developed ship traffic projections for 1985 on the Julianakanaal. These were


Table 6.3

DESCRIPTION OF HIGHLANDS CANALS AND LOCKS

<table>
<thead>
<tr>
<th>Canal/Lock Complex</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Drop (m)</th>
<th>Volume (m³)</th>
<th>Traffic (ships/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zuid-Willemsvaart 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sluis 0</td>
<td>124.2</td>
<td>26.4</td>
<td>2.05</td>
<td>6722</td>
<td>281</td>
</tr>
<tr>
<td>Sluis 2</td>
<td>52.6</td>
<td>20.2</td>
<td>2.08</td>
<td>2210</td>
<td>405</td>
</tr>
<tr>
<td>Sluis 3</td>
<td>52.4</td>
<td>19.9</td>
<td>1.99</td>
<td>2075</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 4</td>
<td>52.5</td>
<td>20.0</td>
<td>2.05</td>
<td>2152</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 5</td>
<td>52.4</td>
<td>20.2</td>
<td>2.18</td>
<td>2307</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 6</td>
<td>52.4</td>
<td>19.8</td>
<td>2.21</td>
<td>2293</td>
<td>141</td>
</tr>
<tr>
<td>Zuid-Willemsvaart 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sluis 7</td>
<td>52.4</td>
<td>20.3</td>
<td>1.60</td>
<td>1702</td>
<td>240</td>
</tr>
<tr>
<td>Sluis 8</td>
<td>52.6</td>
<td>14.0</td>
<td>2.00</td>
<td>1473</td>
<td>221</td>
</tr>
<tr>
<td>Sluis 9</td>
<td>52.4</td>
<td>20.6</td>
<td>1.93</td>
<td>2083</td>
<td>218</td>
</tr>
<tr>
<td>Sluis 10</td>
<td>52.6</td>
<td>22.0</td>
<td>2.01</td>
<td>2326</td>
<td>229</td>
</tr>
<tr>
<td>Sluis 11</td>
<td>52.6</td>
<td>11.4</td>
<td>2.50</td>
<td>1499</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 12</td>
<td>52.5</td>
<td>21.1</td>
<td>2.03</td>
<td>2249</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 13</td>
<td>52.5</td>
<td>20.6</td>
<td>1.69</td>
<td>1828</td>
<td>230</td>
</tr>
<tr>
<td>Zuid-Willemsvaart 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sluis 15</td>
<td>65.0</td>
<td>15.5</td>
<td>4.66</td>
<td>4696</td>
<td>(a)</td>
</tr>
<tr>
<td>Sluis 16</td>
<td>70.0</td>
<td>15.8</td>
<td>2.18</td>
<td>2411</td>
<td>186</td>
</tr>
<tr>
<td>Wilhelminakanal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sluis 1</td>
<td>120.0</td>
<td>14.0</td>
<td>4.55</td>
<td>7644</td>
<td>160</td>
</tr>
<tr>
<td>Sluis 2</td>
<td>65.0</td>
<td>16.0</td>
<td>2.50</td>
<td>2600</td>
<td>89</td>
</tr>
<tr>
<td>Sluis 3</td>
<td>65.0</td>
<td>16.0</td>
<td>2.50</td>
<td>2600</td>
<td>88</td>
</tr>
<tr>
<td>Sluis 4</td>
<td>65.0</td>
<td>16.0</td>
<td>2.26</td>
<td>2350</td>
<td>69</td>
</tr>
<tr>
<td>Sluis 5</td>
<td>65.0</td>
<td>8.5</td>
<td>0.00</td>
<td>0</td>
<td>(a)</td>
</tr>
<tr>
<td>Kanaal Wessem-Nederweert</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panheel</td>
<td>153.0</td>
<td>7.5</td>
<td>8.10</td>
<td>9295</td>
<td>443</td>
</tr>
<tr>
<td>Julianakanal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Born</td>
<td>(2) 142.0</td>
<td>16.0</td>
<td>11.35</td>
<td>29160</td>
<td>1108</td>
</tr>
<tr>
<td>Maasbracht</td>
<td>(3) 142.0</td>
<td>16.0</td>
<td>12.25</td>
<td>31470</td>
<td>1108</td>
</tr>
<tr>
<td>Lateraadkanal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neel</td>
<td>(2) 142.0</td>
<td>16.0</td>
<td>6.40</td>
<td>16440</td>
<td>1055</td>
</tr>
<tr>
<td>Maas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linne</td>
<td>260.0</td>
<td>14.0</td>
<td>3.65</td>
<td>13640</td>
<td>330</td>
</tr>
<tr>
<td>Roermond</td>
<td>260.0</td>
<td>14.0</td>
<td>2.75</td>
<td>10280</td>
<td>241</td>
</tr>
</tbody>
</table>

NOTES: Traffic levels shown are mean ships per week during 1976. Numbers in parentheses indicate number of locks.

(a) No ship traffic data available.

necessary for screening particular tactics at Maasbracht. We did not
develop traffic projections for the future context for the remainder
of the highlands locks. Available projections [6.7] indicated that
traffic growth (or decline) would be irregular; that some locks would
have more traffic and some less. In general, however, the growth was
uneven and small. Also, several proposals for extensively improving
the highlands canal system have been put forth. Implementing these
proposals would substantially change ship traffic patterns from what they are today. For these reasons, and because the analysis would have consumed time needed for more urgent problems, the 1976 results were used for the 1985 context.

The results of the analysis can be shown as curves which plot ship delay costs as a function of water consumption for each canal section or lock, whichever is appropriate. Figure 6.12 presents the loss function curves for the locks at Measbracht on the Julianakanaal. The three curves in this figure represent different fractions of the average ship traffic through the lock during 1976. The curves for the other canal segments and locks can be found in App. F.

These curves all have a similar shape. They have a long, relatively horizontal section where costs increase slowly as water consumption falls. At these flows lock capacity far exceeds traffic levels, and ships encounter no appreciable delay time in passing. As water use decreases, however, lock capacity falls to the point where delays become important and costs rise. The costs accelerate as flows through the lock continue to decrease, until lock capacity no longer exceeds ship arrival rates. When this occurs, a lengthening queue will form as more ships arrive faster than they can be locked through.

The flow at which lock capacity equals traffic levels is a minimum requirement to avoid formation of this queue. When flows through the lock must be reduced below this level for an extended period, estimating delay costs becomes problematic. We have difficulty defining what constitutes actual delay time, and can no longer assume that ship traffic levels are unaffected by lock operation policies. When ships must wait more than one week, it is doubtful that they make the same number of trips as they would under normal conditions.

Falling water levels present an additional complication. When the diminished flow causes restrictions at locks, particularly on the Julianakanaal, it will also cause water levels to drop, further impeding ship traffic. Water levels and flows will also be reduced on alternative routes, however, so we cannot readily estimate how ship operators will react. To say the least, ship traffic will not remain at normal levels, and ships will certainly look for alternative routes whenever possible.

There are few options for dealing with this situation. We assumed that ships which were delayed more than one week had delay times equal to their normal operating hours per week. In addition, if ships arrive uniformly throughout the week, the average ship will wait only one-half week if it cannot pass. To account for the uncertainty about traffic, we assumed that each week was independent, i.e., that reductions in ship traffic would offset the accumulating delay times at locks.

When ship traffic on the Julianakanaal is severely limited, normal industry operations will be affected. The costs of this interference may be extremely high for those industries that rely on shipping for
Fig. 6.12 -- Loss functions for Maasbracht at three traffic levels (1976)
transport of their raw materials or finished products. In our analysis we have not included these costs specifically, although they were included in the overall investigation of the Julianakanaal. We did not include industrial costs in the analysis of the other locks in the highlands. No estimates of these costs were available, and interference with these locks is less frequent and serious than it is on the Julianakanaal.

6.7. LATERAALKANAAL ANALYSIS

The Lateraalkanaal and the Maas through Linne and Roermond form parallel paths for ships and water in the middle of Limburg. This is shown in Fig. 6.13. For several reasons, the situation is particularly complex and requires a different approach from the rest of the highlands locks. Shipping operations there involve route choice for most of the traffic, but the routes have different numbers of locks and overall time delays.

Under normal circumstances, ship traffic on the Maas prefers to use the Lateraalkanaal. The distance traveled is less and only one lock complex must be passed, rather than the two at Linne and Roermond. Thus total travel time is considerably less on the canal. Ships which use docking facilities or have business in Linne and Roermond are generally the only traffic using the Maas in this area.

When water shortages occur on the Maas, it becomes necessary to limit lock operations. As previously mentioned, two locks in series will use only about one-half as much water as one lock operating over the same total level drop. The water that the first lock uses in dropping one-half the distance can be used again by the second lock. For this reason, when total flow through the parallel branches is limited, lock operations on the Lateraalkanaal are restricted first. The limited Maas flow can be used more efficiently through Linne and Roermond.

As lock operations are restricted, it becomes increasingly more difficult to pass through the Lateraalkanaal. Delays at the lock increase exponentially as capacity is reduced. At some point the delays will become equal to the delay encountered on the Maas (through Linne and Roermond), so ships should be indifferent between the two routes. This situation creates problems in the analysis.

The procedure used for other locks is based on the assumption that ship traffic remains known and constant. When alternative routes are available, the problem involves optimization, as ships will logically divide between the routes in a manner which equalizes delay times. If delays on one route are longer than on the other, ships will move from the longer to the shorter, reducing one and increasing the other until they equalize.

We solved this problem in the following way. Using the general procedure discussed earlier for other locks, we developed and plotted
Fig. 6.13 -- The Maas and Lateraalkanaal
curves describing the total delay on the Lateraalkanaal or the Maas as a function of ship traffic, for a given water consumption on each branch. These curves correspond to the functions:

\[
D_L = f_L(F_L, I_L)
\]

\[
D_M = f_M(F_M, I_M)
\]

where \( D \) = delay time (min),
\( F \) = flow rate (m\(^3\)/s),
\( I \) = ship traffic (vessels/wk).

The problem constraints on traffic and water flow are given by

\[
F_L + F_M = F_{\text{total}}
\]

\[
F_L \geq F_{L\text{min}}
\]

\[
F_M \geq F_{M\text{min}}
\]

\[
I_L + I_M = I_{\text{total}}
\]

\[
I_L \geq I_{L\text{min}}
\]

\[
I_M \geq I_{M\text{min}}
\]

where \( F_{\text{total}} \) = total flow through the branches (m\(^3\)/s),
\( I_{\text{total}} \) = total ship traffic (vessels/wk),

and we have specified minimum values for the flow and traffic on each branch. The overall problem is thus to minimize the delay time by

\[
\text{Min}(D_L + D_M) = f_L(F_L, I_L) + f_M(F_M, I_M)
\]

subject to the constraints defined above. Because the delay functions are everywhere convex, this is a convex programming problem. Such problems have been studied extensively in the literature.
The following procedure was used to solve the problem. Given a total flow, we investigated each possible flow division between the two branches. For each division, using the delay time curves from above, we found the ship traffic division that resulted in equal delays (or minimum total delay) on the routes. The solution was the flow division that gave the minimum total delay for the given initial flow. The results of this process are shown in Table 6.4, which includes delay times and total delay cost to shipping. In this table, the flows do not include water loss through lock leaks. When total flow is more than 6 m³/s, it is no longer possible to balance delay times. They are always less on the Lateraalkanaal, because traffic on the Maas is at its lower bound. Thus the optimal solution will involve unequal delays, but still minimum total shipping cost.

We should note that leaks in the locks may change the distribution of flow between the alternate routes. Because the cost curves are relatively flat, however, changes of less than 1 m³/s should not increase total costs by more than 10 percent, until total flow drops below 6 m³/s.

Table 6.4
LOCK DELAYS AND WATER LOSS THROUGH THE LATERAALKANAAL

<table>
<thead>
<tr>
<th>Total Flow (m³/s)</th>
<th>Lateraalkanaal (m³/s)</th>
<th>Maas (m³/s)</th>
<th>Delay Times (min)</th>
<th>Delay Cost (E/hr/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>9.0</td>
<td>1.0</td>
<td>85/147</td>
<td>39.7</td>
</tr>
<tr>
<td>9.0</td>
<td>8.0</td>
<td>1.0</td>
<td>94/147</td>
<td>42.6</td>
</tr>
<tr>
<td>8.0</td>
<td>7.0</td>
<td>1.0</td>
<td>108/147</td>
<td>47.1</td>
</tr>
<tr>
<td>7.0</td>
<td>6.0</td>
<td>1.0</td>
<td>132/147</td>
<td>54.9</td>
</tr>
<tr>
<td>6.0</td>
<td>5.0</td>
<td>1.5</td>
<td>158</td>
<td>64.2</td>
</tr>
<tr>
<td>5.0</td>
<td>4.5</td>
<td>1.5</td>
<td>210</td>
<td>85.3</td>
</tr>
<tr>
<td>4.0</td>
<td>3.5</td>
<td>1.5</td>
<td>270</td>
<td>109.7</td>
</tr>
<tr>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>350</td>
<td>142.2</td>
</tr>
</tbody>
</table>

NOTE: Delay times are shown as Lateraalkanaal/Maas when these times differ.

6.8. INVESTMENT, ENERGY, AND DELAY COSTS

We calculated delay costs for shipping using the distribution of ships by type and class at each lock. The procedure and cost coefficients for these calculations can be found in Chap. 3 and App. A. In addition to the costs of ship delays at locks, however, we had to determine investment costs for salt intrusion technology, and energy costs for lock operation. This section discusses these costs.

6.8.1. Energy Costs

Energy costs for lock operation fall into two categories. The first is the relatively minor cost of operating lock gates. The second is
the much larger costs of pumping either water or air. Water must be pumped at lowlands locks where the Kreekrak system is employed. At highlands locks, water can be pumped back from below to above the lock to permit increased lock usage. Air is pumped in pneumatic barriers at lowlands locks.

We did not include energy costs in the highlands lock analysis. The cost of opening and closing gates is much smaller than delay costs. We considered pumping costs to be external to lock operations, because lock operations are not directly associated with the pumping. It only provides more water that can be used by the lock. These costs can be found in Vol. II.

We included both types of energy costs in the lowlands lock analysis. An investigation of lock door costs led to the development of the following formula for energy costs [6.8,6.9]:

$$CE = 0.0164 \times W \times D$$

where \( CE \) = energy cost per cycle (Dfl),
\( W \) = lock door width (m),
\( D \) = entrance depth (m).

Lock doors can be operated by several different methods, but the data were insufficient to incorporate these variations into our equations. This formula includes all systems.

Pneumatic barriers at locks have energy costs for pumping air into the water. The cost study developed the following formula for the energy cost of a double air bubble screen:

$$CB = 0.1622 \times W \times \exp(0.2191 \times D)$$

where \( CB \) = energy cost per cycle (Dfl),
\( W \) = screen width (m),
\( D \) = screen depth (m).

We assumed the energy cost of a single bubble screen to be half that of a double screen.

Locks with the Kreekrak system use special equipment to separate the salt and fresh water [6.3]. These systems pump all of the water used by the lock, and thus they have large energy costs. A study of these costs yielded the results shown in Table 6.5. Because we used these locks only where they already existed or were planned, the table contains cost information for only two locations.
Table 6.5

ENERGY COSTS PER CYCLE FOR KREEKRAX-TYPE LOCKS
(Dfl/cycle)

<table>
<thead>
<tr>
<th>Location/Lock</th>
<th>No Salt Abatement</th>
<th>No Fresh Regain</th>
<th>Fresh Regain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kreekrak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large lock</td>
<td>2</td>
<td>44</td>
<td>67</td>
</tr>
<tr>
<td>Medium lock</td>
<td>2</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Small lock</td>
<td>2</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Philipsdam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large lock</td>
<td>2</td>
<td>41</td>
<td>62</td>
</tr>
<tr>
<td>Small lock</td>
<td>2</td>
<td>22</td>
<td>32</td>
</tr>
</tbody>
</table>

6.8.2. Investment Costs

Investment costs for highlands lock technology were considered as part of the screening analysis. They are thus discussed in Vol. II. At lowlands locks, however, investments were part of the actual lock technology itself, and are discussed in this section.

Investments in salt intrusion technology were limited to two types of systems—air bubble screens and excavation and selective withdrawal facilities. As explained previously, replacement of existing locks with Kreekrak systems was considered to be unnecessary.

Investment costs for the two systems were again studied in the Netherlands. Costs for the excavation system must be regarded as rough estimates. There are no real data on capital costs of installing such a system at an existing lock. However, with this proviso, the investment costs of salt intrusion technology are presented in Table 6.6.

Table 6.6

INVESTMENT COSTS OF SALT INTRUSION TECHNOLOGY
(Dflm)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Total</th>
<th>Annualized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation and selective</td>
<td></td>
<td></td>
</tr>
<tr>
<td>withdrawal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IJmuiden</td>
<td>50.0</td>
<td>5.26</td>
</tr>
<tr>
<td>Others</td>
<td>25.0</td>
<td>2.53</td>
</tr>
<tr>
<td>Air bubble screens</td>
<td>0.28</td>
<td>0.036</td>
</tr>
</tbody>
</table>

The annualized costs are calculated on the basis of a 10-percent interest rate and lifetimes of 40 years for excavation systems and 15 years for bubble screens. Also, the bubble screen costs are for a double screen system. Single screen systems were assumed to cost 75 percent as much.
6.9. RECREATIONAL VESSELS IN LOCK ANALYSIS

The primary seasonal variations in ship traffic at locks are caused by recreational vessels. During vacation season, ship traffic increases greatly at some locks, particularly in the northern provinces and Zeeland. For some locks, the amount of recreational traffic can be much larger than commercial traffic during summer months. These increases in recreational traffic change not only the amount of ship traffic, but also its characteristics. Many of the parameters in the lock model must be changed to reflect these seasonal variations. Moreover, the increase in overall traffic causes delay times for all ships to increase.

The lock model recognizes the difference between commercial and recreational vessels, and can easily deal with these problems. However, it cannot treat the two types of vessels differently. Even though it knows the fraction of total traffic that comes from recreational ships, and can thus calculate the hours of delay for these ships, it cannot discriminate against either type of vessel. It can only recognize their size and shuttle them toward the smallest appropriate locks in the complex, or use intermediate doors when appropriate.

More information about recreational vessels can be obtained from the results by using several important observations about recreational boating at locks. Commercial and recreational vessels are often naturally separated at locks for several reasons:

- The Volkerak and Philipsdam complexes have separate locks for only recreational boats.
- Some locks, such as the Maas locks and Kreekrak, have very little recreational boating at any time.
- Many other locations, such as IJmuiden and Delfzijl, have small locks generally used primarily by recreational vessels.

In addition, the seasonality of recreational traffic helps to restrict its impact on lock usage. Commercial traffic is relatively constant throughout the year (except during vacations and fall agricultural transport). Thus the difference between summer and winter periods usually indicates how recreation affects lock operations, including both salt intrusion and delay costs for commercial shipping. As an example, the figures in Table 6.7 show the salt intrusion and costs (delay plus energy) for the nominal case at Kornwerderzand during the winter and summer periods. The fraction of recreational traffic varies from 10 percent of the total during winter to over 80 percent during the summer months. It is clear that for this lock, at least, recreation is an important factor in lock operation during the summer.

Using this type of information, one can normally draw at least some conclusions about how recreation affects lock operations. With the lock model, however, we cannot simulate the effects of lock tactics specific to recreation, such as requiring yachts and sailboats to wait
Table 6.7

SUMMER AND WINTER SALT INTRUSION RESULTS AT KORNWERDERZAND

(thousand kg Cl\textsuperscript{-}/wk)

<table>
<thead>
<tr>
<th>Item</th>
<th>November - March</th>
<th>June - August</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial traffic (ships/wk)</td>
<td>104</td>
<td>163</td>
</tr>
<tr>
<td>Recreational traffic (ships/wk)</td>
<td>12</td>
<td>789</td>
</tr>
</tbody>
</table>

Salt Intrusion

Flushing Rate (m\textsuperscript{3}/s)

<table>
<thead>
<tr>
<th>Rate</th>
<th>November - March</th>
<th>June - August</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>175.4</td>
<td>560.0</td>
</tr>
<tr>
<td>20.0</td>
<td>167.6</td>
<td>549.6</td>
</tr>
<tr>
<td>30.0</td>
<td>158.8</td>
<td>525.6</td>
</tr>
<tr>
<td>50.0</td>
<td>141.9</td>
<td>473.4</td>
</tr>
<tr>
<td>75.0</td>
<td>123.0</td>
<td>411.9</td>
</tr>
<tr>
<td>100.0</td>
<td>106.6</td>
<td>357.4</td>
</tr>
<tr>
<td>200.0</td>
<td>59.8</td>
<td>201.2</td>
</tr>
<tr>
<td>300.0</td>
<td>33.6</td>
<td>113.0</td>
</tr>
<tr>
<td>500.0</td>
<td>10.8</td>
<td>35.6</td>
</tr>
</tbody>
</table>

longer than commercial ships. These tactics will have to be investigated with other means, for those locks at which they are interesting. However, we doubt that they will be important at many important locks, because:

- Recreational boating itself is not important at many major locks.
- Even when it is important, it occurs mostly during weekend periods, when commercial vessels normally do not operate.
- Peak periods of recreational boating occur during July and August, generally falling off rapidly in both directions. Thus, the maximum impact of these ships is limited to a short period, and one in which commercial shipping generally declines because of vacations in industry.

For these reasons, we did not feel justified in considering recreation effects on lock operations in more detail, given the time constraints on the overall analysis.

6.10. SUGGESTIONS FOR FUTURE ANALYSIS

The lock analysis model is a flexible and versatile tool for investigating how technical and managerial tactics affect lock operations. The model could be improved, however, or modified to suit other purposes, given suitable time and incentive.

The salt intrusion analysis was restricted by limited time and information on the locking process and salt exchange. A larger and
more comprehensive investigation of salt intrusion could undoubtedly improve the equations. Such a study could also facilitate tailoring the analysis to the individual lock complexes being considered. This is desirable because salt intrusion and diffusion depend strongly on the configuration of the locks, neighboring sluices, and relevant waterways. An expanded analysis would also permit incorporation of additional novel technical tactics that were not sufficiently understood to include in our study.

Similarly, the lock simulation program could be expanded or modified to suit different purposes. If one desired to consider monthly rather than seasonal traffic patterns, it would be necessary to calculate model parameters for at least four times as many cases. This could be avoided by modifying the model. Because arriving ships are characterized by size class, the model could use individual parameters (e.g., entry and exit times or displacement volumes) for these ships, instead of predetermined mean values. This change would facilitate modifying arrival streams to see how lock operations were affected, but it would mean larger core requirements and longer operating time for the model. These requirements would reduce the advantages of the current model for inexpensive analysis of numerous cases.

There might also be reasons to change the treatment of commercial and recreational vessels. As it now stands, the model cannot treat the two types differently. It would be possible, but not necessarily simple, to change the program to discriminate between the two in the simulation process. This would allow the user to apply different managerial tactics to commercial and recreational vessels. We did not incorporate this feature, because it was not needed for the locks considered in the analysis. It would therefore have unnecessarily complicated the program and its development.

Other modifications to the simulation program might be to improve the use of intermediate doors, incorporate a lock filling routine, or allow the use of different tactics at each lock of a complex. As before, these changes would complicate the program and make it more expensive to run, for a probably small improvement in fidelity. Such modifications, however, might be quite reasonable for an extensive study of a particular lock complex where operational procedures and other characteristics are well understood.

NOTES

1. Normally, salt intrusion is reduced by cycling locks (opening and closing lock doors) more quickly. However, adding certain types of technology to reduce salt intrusion may increase the time required for a lock cycle.

2. Throughout this chapter, for convenience we will consider lowlands locks to be salt-fresh and highlands locks to be fresh-fresh. Although fresh-fresh locks are also found in the lowlands, our analysis did not consider them.
3. Operating with an intermediate door can be difficult. At some locks the doors are never used. At others they can be used almost always, because ship traffic is quite low. At most locks which have the doors, however, the situation is between the two extremes. If an operator chooses to use the door in one cycle, one can easily see that he must use it on the return cycle, because the door is closed when the end doors open. This means that the operator must be able to anticipate arrivals in the opposite direction, to avoid having too many ships or too large a ship to lock back through in the reduced chamber. This problem usually limits the value of intermediate doors during high traffic periods or at locks with many large vessels. Only the Kreekraksluizen have an intermediate chamber large enough to accommodate the largest vessels.

4. This tactic has the additional benefit of allowing the lock to cycle only when the saltwater level is low. This factor helps to reduce the amount of salt intrusion per lock cycle, in addition to reducing the number of cycles. Unfortunately, because tidal cycles are long, delay times for this tactic are much longer than for other tactics with almost as much effect.

5. This tactic is included as a technical tactic because special connections and other equipment may be necessary at a lock complex before this procedure is possible. Once the facilities are suitably modified, it then becomes a managerial tactic to choose whether or not to use the procedure.

6. We calculated a weighted mean delay cost coefficient for each complex using the variable cost coefficients described in Chap. 3 and the distribution of ships passing the locks.

7. We calculated this capacity for all chambers, including those in locks with intermediate doors. Because the capacity is defined in terms of mean ships (based on the appropriate distribution), it will vary with direction of travel as well as chamber dimensions and season.

8. We did not use this assumption during calibration, if we knew that the lock in question had been using a different policy.

9. Capacity is maximized if the number of ship arrivals from each direction is equal. If more ships arrive from one direction, the lock must often cycle only partially full in the low traffic direction. For all highlands locks in the analysis, ship traffic could be considered adequately uniform.

10. Simply adding delay costs as a function of canal flow may not be the most valid approximation to actual delay costs along the canal. However, given the distance between locks and the variation in ship velocities, we felt that this was a reasonable method in the absence of other information.

11. This result can be true also if the locks have unequal volumes. In this case the larger lock will have to use fewer cycles than the smaller lock.

12. This will occur in theory, if we assume ship operators have perfect information. In practice, time lags and other problems will interfere with perfect equalization on the routes. The imbalance should not be large, however, because restrictions on lock operations are announced in advance, and experienced ship operators should be able to anticipate them.

REFERENCES


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Chapter 7

IMPACT OF MAJOR NETWORK TACTICS

7.1. GENERAL PROBLEM

This chapter will discuss water management tactics which involve major changes to the infrastructure. Volumes II and XVI describe these tactics and summarize their costs and benefits. Not all of the tactics affect shipping operations. In fact, most of them have virtually no impact on shipping at all. Many of them, however, could have important effects, and thereby warrant detailed investigation. It is those potentially important tactics that we will consider in this discussion.

Modifications to the water management infrastructure and its operation affect shipping primarily by changing the navigational characteristics of the network. Such changes (e.g., increasing the number of locks or reducing water levels and depths) may alter the travel times, distances, and load factors of ships on particular routes. As an example, one proposed tactic is to temporarily or permanently close the Spui, a waterway in the Rotterdam area. As shown in Fig. 7.1, if this waterway were closed, ships would be forced either to reroute or to wait at a lock in the barrier (for barrier designs with locks).

Another tactic that could affect shipping would be to change the level management of the IJsselmeer. Allowing the minimum level to fall 10 cm from the current minimum (to increase the water supply during dry periods) would reduce the depths available for shipping on the lake. This could force some ships to carry smaller loads.

Vessels affected by such infrastructure changes will face increased variable costs, as well as potential changes in the safety of their operations. Under the circumstances, carriers may choose either to continue as before or to modify their operations, in order to decrease their costs (or increase benefits) as a result of the network changes.

This possibility that carriers may change their operations complicates the analysis considerably. In calculating the loss functions described earlier, we assumed that carriers would not change routes, if lock delays increased or water levels fell. This assumption is not strictly true, but, under the circumstances, we can reasonably justify it for almost all important shipping traffic. For network changes, however, carriers may not continue to operate as before. They must alter their routes if waterways are closed, either temporarily or permanently. They may also choose to do so if other major changes take place, depending on how much the tactics change their costs. Thus, when calculating the costs of these tactics, one must consider the possibility of changes in carrier or customer behavior.

This problem can often be avoided by carefully examining the possible alternatives. After calculating how much the navigational changes
Fig. 7.1 -- Location of major waterway closures
might cost shipping, one must decide (1) if carriers had sufficient
reason to alter their operations, and (2) if better alternatives
existed. If their costs did not increase significantly, they had
little incentive to change. Similarly, they would do nothing if no
other reasonable alternatives were available. Careful investiga-
tion of these alternatives can usually eliminate most or all of them as
either impractical or more expensive.

Under any circumstances, whether or not carrier behavior was affected,
the original variable costs constitute an upper bound on the actual
shipping costs of a tactic. If carriers could reduce the costs by
altering their operations, they would do so. If not, then the original
costs were valid. Thus, if the original calculations found the costs
of a tactic to be unimportant, it is safe to assume that the costs
would not be important no matter how carriers changed routes or
behavior.

7.2. PROCEDURE AND ASSUMPTIONS

An important distinction exists between major technical and managerial
tactics. Some managerial tactics did not need to be considered
separately in the analysis. The DM could calculate how they affected
shipping costs by using the low water and lock loss functions. These
functions do not apply to other managerial tactics, however, such as
those which varied water levels in the IJsselmeer and Markermeer.
Such tactics and the technical tactics, which modified the shipping
network, require more detailed analysis.

Chapter 1 described the basic procedure used to assess the impacts of
major technical tactics.1 Within the analysis framework discussed in
Sec. 1.4, impact assessment consists of these steps:

1. Modify the shipping network as necessary to reflect the
tactic being considered.
2. Assume the distribution of ship traffic on the network does
not change.
3. Calculate changes in variable shipping costs from causes
associated with the tactic.
4. Investigate changes in routes or ship traffic if water levels
are affected, or costs (from step 3) are large.
5. Determine the direct effects on the shipping industry.

For the managerial tactics that required analysis, the same procedure
could be used, with one exception. Instead of modifying the network
to incorporate the tactic, one must change water flows or levels on
the network. The shipping costs resulting from these changes can then
be calculated with the loss functions.

Two potential problems developed during the PAWN screening analysis.
First, some shipping costs could be counted twice. When comparing
major network tactics under alternative scenarios, the DM calculated
low water losses and lock delay costs. These costs had to be excluded
from the direct impacts of the tactics. Second, the screening process
considered not only single tactics, but also combinations of tactics.
The true costs of these combinations might include interaction effects
not present in the individual tactics. The DM could account for most
of these interactions in the low water losses and lock delays. By
examining each combination, we could ensure that no important effects
had been missed.

Some of the proposed tactics did not have concrete plans for
implementation. Under these circumstances we were forced to base our
analysis on the best available design information. In some cases this
meant designing a ship lock or channel, or making assumptions about how
the tactic would be used. For this reason, the shipping costs for some
tactics have an inherent additional uncertainty. This should not be
large, however, when compared to the total costs of the tactics.

7.3. MAGNITUDE OF IMPACT

Although the tactics considered in this chapter are called major
infrastructure tactics, not all of them have important effects on
shipping. In fact, many do not affect shipping at all, and others
affect it only slightly. If the effects were negligible, during the
preliminary examination of a tactic, the tactic was not considered
further. We concentrated, instead, on those tactics that could have
important implications for shipping.

It may seem strange that something called a major infrastructure tactic
could have no effect on shipping costs. The cost changes could be
negligible because there is a difference between the water management
infrastructure and the shipping network. Some tactics might alter the
infrastructure for water management, but not affect the network used by
shipping. Thus, constructing pipelines, rerouting polder drainage,
raising dikes, or building pumping stations in dikes will not normally
affect the shipping network or influence shipping costs. The same may
be said for many tactics which help to improve water quality in local
areas or throughout the nation.

Other tactics which do modify the shipping network may not have
significant costs either, for different reasons. If only a small
number of ships are affected, the aggregate cost of a tactic may be
unimportant. Similarly, if the tactic requires changing flows in a
canal or canalized waterway, it may not interfere with shipping
operations at all. Shipping will not be harmed because water depths
in canals are controlled and are independent of flows. Flow
variations may affect water velocities, however, which will alter ship
speeds and travel times. In the PAWN analysis, these changes in flow
velocity were small enough (by constraint) to be ignored. The effects
on ships traveling in opposite directions were largely offsetting,
Finally, one can deal with limited withdrawals from canals and rivers in the same way. In this case, it is necessary to assume that canal levels can be maintained at desired values, and that reasonable engineering at the withdrawal point will eliminate any interference with shipping operations. With these assumptions, we can eliminate from consideration many of the tactics to improve water distribution to the highlands agricultural areas.

7.4. WATERWAY CLOSURE

Several tactics involve closing entire waterways in the Delta area of the Netherlands. These waterways would be closed either permanently (with or without ship locks) or temporarily, when conditions warrant. Waterway closure is especially difficult to analyze, so much so that we could not determine shipping impacts for three of the tactics. These tactics were (1) permanently closing the Oude Maas with a weir and lock, (2) temporarily closing the Oude Maas with caissons, and (3) temporarily closing the Nieuwe Maas with caissons. Only the options for closing the Spui were sufficiently uncomplicated that we could analyze them. Figure 7.1 shows the approximate locations of the closures.

Closing either the Oude Maas or the Nieuwe Maas temporarily or permanently (with locks) would affect thousands of inland ships every year. These ships would face large costs from the consequent lock delays and other problems caused by the increased congestion. These costs can be estimated, because we know something about the characteristics of the inland ship traffic and possible alternative routes.

What could not easily be estimated, however, was the cost to seagoing vessels that use these waterways. The Delta area has an extensive harbor system. Many of these harbors could not be used by larger seagoing vessels while the waterways were closed. These ships require too much depth to have any alternative routes, so closure would cause major delays for many of them. Unfortunately, some of these ships cannot be legally or safely delayed, because they carry hazardous cargoes. Even those that carry more benign cargo would suffer large costs and schedule disruption. Considering the extent of the problem, we did not have either enough time or information to attempt to calculate the shipping costs.

Fortunately, the PAWN screening analysis found that the cost calculations were unnecessary. Assuming no shipping costs whatsoever, the screening analysis found that the benefits of closing either the Oude Maas or Nieuwe Maas did not exceed the investment costs. Adding shipping costs to these results would not make the tactics more attractive. Thus we had no reason to consider them further.

The Spui, a waterway connecting the Haringvliet with the Oude Maas, could be closed in four different ways: permanently, with or without a ship lock, and temporarily, with or without a lock. Although shipping
costs would differ in each case, the basic problem remains the same. When the Spui is closed, ships would either use an alternative route or wait to use the lock (if available). By calculating the costs of these alternatives, one can combine them to determine the total costs of each option. These costs would only depend on the number and distribution of ships using the Spui, and carrier preference for taking the alternative route instead of waiting at the lock. The EWS provided this information for the 1976 context, based on a survey of ship operators [7.1,7.2]. Table 7.1 summarizes the results.

The costs shown in the table require some explanation. They are stated per week for temporary closures and per year for permanent closure cases. Permanent closure costs do not need to be separated by week, because the Spui would be closed every week. It would not be closed every week in the temporary cases, but rather only an average of two or three weeks a year. In this situation, seasonal ship traffic variations could cause the costs to change during the year. As the table indicates, summer costs are higher, because recreational vessels increase lock delay times for all ships during this period. When no lock is provided during the temporary closure, recreation does not interfere with commercial shipping.

| Table 7.1 |
| Shipping costs for Spui closure alternatives |

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost (Dfl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent closure without lock</td>
<td>305.0/yr</td>
</tr>
<tr>
<td>Permanent closure with lock</td>
<td>62.0/yr</td>
</tr>
<tr>
<td>Temporary closure without lock</td>
<td>6.51/wk</td>
</tr>
<tr>
<td>Temporary closure with lock</td>
<td>1.09/wk Mean</td>
</tr>
<tr>
<td></td>
<td>1.74/wk Summer</td>
</tr>
</tbody>
</table>

7.5. IJsselmeer Level

In comparison with the closure tactics discussed above, the management policies for the IJsselmeer level will have a less obvious, but potentially important, effect on shipping operations. Not only will they influence the distribution of Rijn water, but they will also affect shipping on the IJsselmeer itself. These policies control maximum, minimum, and target lake levels during different seasons of the year, thus changing water depths for shipping on the lake. Unless these depths are maintained, carriers may be forced to travel less fully loaded, thereby increasing shipping costs. The analysis had to determine how much total shipping costs would change under each of the alternative policies.

The number of alternative level policies is quite large. Not only can the IJsselmeer level vary throughout the year, but also the levels of the Markermeer and IJmeer can vary. Fortunately, it is not necessary
to consider all policies individually. The DM could calculate how each policy affected water distribution and low water losses. Similarly, how each policy affected IJsselmeer shipping could be calculated with an IJsselmeer loss function. Developing this loss function was the primary problem.

The current IJsselmeer level policy maintains the lake at NAP = 20 cm during the summer and NAP = 40 cm during the winter. Shipping operations have accommodated to this policy, and rely on dredging to maintain channel depths of at least 4 m. With this depth, only the largest ships need ever be concerned about load factors, and few of these ships use the IJsselmeer under normal circumstances.

In this situation, policies which only change maximum or minimum levels slightly should have little effect on shipping. Policies which raise summer or winter levels will benefit only the few larger vessels, by permitting them to load more fully. Policies which reduce lake levels during the year, but maintain them at or above NAP = 40 cm, will not affect current shipping at all. Only those policies which reduce lake levels below NAP = 40 cm will force carriers to adjust their operations.

Before discussing how much these adjustments would cost, we must consider another alternative. If the IJsselmeer can be dredged, to maintain a minimum shipping depth under current conditions, it could be dredged to restore this depth under future level policies. Because this additional dredging does not need to be repeated, it has been included as an investment cost. By investing this amount initially, and continuing at the current level of maintenance dredging, the RWS can avoid the recurring costs of low lake levels.

Assuming that the dredging investment would not be made, we calculated the costs of various alternative lake levels. To do this, we used observations of total ship traffic and the distribution of ships by type and size class on the IJsselmeer and its approaches. Assuming standard ship characteristics, a load factor of 85 percent, and mean trip length of 240 km, we determined how many additional trips would be necessary (and what these trips would cost) if the IJsselmeer depth were reduced. Table 7.2 presents the results for the 1976 context. These costs are low, because few large ships use the affected routes, and because even these ships do not have to reduce their loads very much. Even with pessimistic assumptions, we can see that the costs are probably unimportant.

7.6. IJMEER TACTICS

The IJmeer is a small lake east of Amsterdam at the southern end of the Markermeer. The original plans for the area called for reclaiming most of the Markermeer as a new polder area (the Markerwaard). This area would have provided protection from flooding for Flevoland, to the east. If the Markerwaard is not constructed, it will be necessary to take other measures to increase Flevoland safety.
### Table 7.2

**SHIPPING COSTS OF IJSSELMEER AND MARKERMEER LEVEL CHANGES**

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Cost (Dflt/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease IJsselmeer Minimum Level</td>
<td></td>
</tr>
<tr>
<td>NAP - 40 cm</td>
<td>0.0</td>
</tr>
<tr>
<td>NAP - 50 cm</td>
<td>4.8</td>
</tr>
<tr>
<td>NAP - 60 cm</td>
<td>12.4</td>
</tr>
<tr>
<td>NAP - 70 cm</td>
<td>23.3</td>
</tr>
<tr>
<td>Decrease Markermeer Minimum Level (Separated IJmeer)</td>
<td></td>
</tr>
<tr>
<td>NAP - 40 cm</td>
<td>0.0</td>
</tr>
<tr>
<td>NAP - 50 cm</td>
<td>1.3</td>
</tr>
<tr>
<td>NAP - 60 cm</td>
<td>3.3</td>
</tr>
<tr>
<td>NAP - 70 cm</td>
<td>6.1</td>
</tr>
<tr>
<td>Decrease Markermeer Minimum Level (Connected IJmeer)</td>
<td></td>
</tr>
<tr>
<td>NAP - 40 cm</td>
<td>0.0</td>
</tr>
<tr>
<td>NAP - 50 cm</td>
<td>5.7</td>
</tr>
<tr>
<td>NAP - 60 cm</td>
<td>14.4</td>
</tr>
<tr>
<td>NAP - 70 cm</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Two other problems also affect water management tactics in the IJmeer area. First, Flevoland discharges have increased the salinity of the Markermeer in recent years. If the Markerwaard is not constructed, it may be desirable to reroute these discharges to another body of water. Second, any tactic that modifies the IJmeer configuration must also permit the transport of fresh water between the IJmeer and Amsterdam-Rijnkanaal.

Many alternative tactics and combinations of tactics have been considered for the IJmeer area. These alternatives vary in the following characteristics:

- Salt content of the lake.
- Type and location of dikes.
- Number and locations of locks.

After an extensive investigation, the initial list of potential tactics was reduced to the following, which are illustrated in Figs. 7.2 through 7.9:

1. Raise Flevoland dikes.
2. Raise Flevoland dikes and construct a new canal and pumping station to transport drainage to the IJsselmeer.
3. Raise Flevoland dikes and build a drainage pipeline from Flevoland to Amsterdam.
Fig. 7.2 -- Flevoland dikes
Fig. 7.4 -- Flevoland dikes and drainage pipeline from Flevoland to Amsterdam
Fig. 7.5 -- Short Second Oostvaardersdijk to Marken
Fig. 7.6 -- Long Second Oostvaardersdijk to Durgerdam with syphon and channel from Markermeer to Diemen
Fig. 7.7 -- Drainage channel from Flevoland to Amsterdam
Fig. 7.8 -- Drainage channel from Flevoland to Amsterdam with syphon from Markermeer to IJmeer
Fig. 7.9 -- Drainage channel from Flevoland to Amsterdam with syphon and open connection between Markermeer and IJmeer.
5. Build a long second Oostvaardersdijk to Durgerdam with a syphon and channel from the Markermeer to Diemen.
6. Build a drainage channel from Flevoland to Amsterdam.
7. Build a drainage channel from Flevoland to Amsterdam with a syphon from the Markermeer to the IJmeer.
8. Build a drainage channel from Flevoland to Amsterdam with a syphon and open connection between the Markermeer and IJmeer.

The calculation of shipping costs was confined to these alternatives.

The Dienst Verkeerskunde (DVK) of the RWS did the necessary lock design and shipping cost analysis for both context years [7.3]. Using observed and predicted commercial and recreational ship traffic throughout the year, they designed the locks that would be necessary in each proposed configuration. Given the dikes and locks, they could then calculate the additional delay times and costs at each lock for all ship traffic. The ship traffic levels used in the analysis are shown in Fig. 7.10.

The delay costs vary through the year, because the recreational traffic in the Amsterdam area increases dramatically in the spring and summer. However, the costs can be stated on an annual basis, because the locks would be used throughout the year. Only increased lock delay costs are important, because the alternative tactics do not require any ships to change routes significantly. The delay costs for each separate lock could be combined to determine the total costs for each proposed combination of locks and dikes. Table 7.3 summarizes the variable costs of the IJmeer tactics.

Table 7.3

<table>
<thead>
<tr>
<th>Alternative(a)</th>
<th>1976</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>43.3</td>
<td>57.1</td>
</tr>
<tr>
<td>5</td>
<td>43.3</td>
<td>57.1</td>
</tr>
<tr>
<td>6</td>
<td>256.8</td>
<td>202.0</td>
</tr>
<tr>
<td>7</td>
<td>256.8</td>
<td>202.0</td>
</tr>
<tr>
<td>8</td>
<td>209.7</td>
<td>304.0</td>
</tr>
</tbody>
</table>

(a) Tactics are identified according to the list in the text.

7.7. WATER TRANSPORT PROBLEMS

Under some conditions, it may be necessary to limit withdrawals from the IJsselmeer for flushing the Noordzeekanaal. It then becomes
Symbol | Description
--- | ---
| | Dike (assumed)
| | Lock

Annual Ship Traffic (thousand ships/year)
1976 | 1985
--- | --- | --- | ---
1 | 8.5 | 26.0 | 10.9 | 45.5
2 | 22.8 | 22.8 | 19.1 | 39.9
3 | 30.9 | 3.0 | 31.9 | 5.3
4 | 7.2 | 22.8 | 7.2 | 39.9
5 | 55.9 | 29.7 | 61.7 | 52.0

Fig. 7.10 -- Ship traffic for IJmeer tactics
necessary to transport more water north from the Waal or Lek on the Amsterdam-Rijnkanaal. To reach the canal, however, this water must pass through the ship locks at either the Lekkanaal or Wijk bij Duurzeste. Each location has two locks, one of which must be closed to shipping during water transport. This action imposes additional delay costs on the ships using the locks.

Current RMS policy, to withdraw continuously when taking water from the Waal or Lek, may impose unnecessary delay costs on shipping. Continuous withdrawals require continuous lock closures for water transport. This policy simplifies the problem of informing ship operators about lock restrictions and lock availability, but it also increases delay costs. An alternative policy would be to withdraw and transport more water during the night, leaving the lock open during daylight hours. This alternative could be managed and communicated easily to shippers, yet would reduce delay costs at the locks. We have included this policy in the analysis, but have not studied the problems of putting it into operation.

The DVK calculated the delay costs for these tactics at both lock complexes. They based their work on the ship traffic determined in the low water loss function study, but rerouted the traffic (for each run) to make the distribution correspond more closely to observations at both locks. We reduced their results to an appropriate form by plotting the costs against Waal depth for each run, then fitting a curve through the results. Figure 7.11 shows this curve for the lock complex at Wijk bij Duurzeste.

The costs for water transport through the Lekkanaal locks have not been shown. During the screening analysis, we determined that constructing a water bypass there would be a more practical alternative. Bypass construction would impose no additional cost on shipping, but would leave both locks open to traffic at all times.

7.8. MISCELLANEOUS TACTICS

We have discussed only a few of the major infrastructure tactics that were considered in the analysis. Most of the remaining tactics had no significant shipping costs or benefits that could not be calculated with the low water and lock loss functions. For a few of the tactics, however, special circumstances were important in whether or not shipping costs were calculated. These tactics are shown in Fig. 7.12 and discussed below.

7.8.1. Krimpenerwaardkanaal

This canal would extend from the Lek through the Krimpenerwaard area. It would be used to transport water from the Lek to the Midwest when the salt concentration at the Gouda inlet becomes unacceptable for agriculture.
Fig. 7.11 -- Water transport costs at Wijk bij Duurstede
<table>
<thead>
<tr>
<th>Number</th>
<th>Tactic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Krimpenerwaardkanaal</td>
</tr>
<tr>
<td>2</td>
<td>Kanaal Maarssen—</td>
</tr>
<tr>
<td></td>
<td>Bodegraven</td>
</tr>
<tr>
<td>3</td>
<td>Zwarte Meer Dam</td>
</tr>
<tr>
<td>4</td>
<td>LIssel Canalization</td>
</tr>
</tbody>
</table>

Fig. 7.12 -- Miscellaneous major technical tactics
Constructing the canal would not significantly affect shipping under two conditions. The first is that shipping would not be able to use the canal. If it could, some carriers might prefer the canal to other routes, but the total benefits would be small. The second condition is that water would be withdrawn from the Lek only during low-water periods. If large amounts are withdrawn frequently, sedimentation could reduce depths on the Lek and cause low-water losses.

7.8.2. Kanaal Maarssen-Bodegraven

Like the Krnmpenerwaardkanaal, this canal would be used to transport water to the Midwest area when the Gouda inlet becomes unusable. It would extend from the Amsterdam-Rijnkanaal at Maarsen to the Oude Rijn northwest of Bodegraven.

Unlike the Krimpenerwaardkanaal, this waterway would be available for shipping. Again, however, the benefits would be small, because few ships would use the route. Furthermore, withdrawals would not cause sedimentation problems on the Amsterdam-Rijnkanaal, because the canal water already contains little sediment.

7.8.3. Zwartemeer Dam

The Zwartemeer Dam with ship lock would be constructed between the Zwartemeer and Koteimeer near the mouth of the IJssel. The lock would remain open under most circumstances, closing only to build up or maintain a water level difference between the two lakes, for flood protection. We designed the lock and calculated shipping costs based on observations of the 1976 ship traffic between the lakes. Table 7.4 presents the lock delay costs over the year. Recreational traffic again causes the variation between seasons, although the costs, in general, are negligibly small in comparison with the investment costs. Shipping costs are small, because only an average of 115 commercial and 215 recreational ships per week would be affected.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Cost (Dfl/wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October - April</td>
<td>821</td>
</tr>
<tr>
<td>May and September</td>
<td>759</td>
</tr>
<tr>
<td>June - August</td>
<td>715</td>
</tr>
</tbody>
</table>

7.8.4. IJssel Canalization

Like the waterway closure tactics, IJssel canalization presents a difficult analysis problem, because of design uncertainties and the
possibility that carriers might use alternate routes. Thus we chose
to deal with this tactic in the same manner as the Oude Maas closure:
to assume no shipping cost in the initial screening analysis. If the
tactic proved to be promising under this condition, we could try to
estimate the shipping costs and recalculate the net benefits.

In contrast to the cost calculations, the benefit calculations come
immediately from the low water loss functions on the IJssel routes. By
canalizing the IJssel, you remove shipping depth constraints on that
waterway and provide more water for the Waal. Only the critical depths
in other parts of their routes limit ship loading. Thus, for any given
case, setting the IJssel and Waal depths to large numbers allows the DM
to calculate an estimate of the maximum benefits.

These are maximum benefits, because canalization would place locks on
the river. These locks would delay shipping, producing offsetting
costs. Such costs could be estimated, given a reasonable design for
the required lock complexes. However, as with the major closure
tactics, canalization did not provide adequate expected benefits to
exceed its investment costs.

7.9. SAFETY AND ACCIDENTS

Water management policies may affect shipping safety and the number of
accidents. Tactics which alter the shipping network will certainly
influence navigation in the vicinity of the changes. Waterway
configuration strongly influences the frequency of collisions in the
Netherlands [7.4, 7.5]. We would expect, therefore, that the major
technical tactics could change accident probabilities and overall
shipping costs.

Not only the technical tactics will affect shipping safety, however.
By changing water distribution and levels, managerial tactics will
alter navigation conditions and traffic levels on major rivers and
canals. Although the relationship between accidents and ship traffic
has not been determined [7.4], some dependence should exist. If it
does, shipping safety should certainly be included in designing
strategies and evaluating water management policies. 6

In addition to their obvious effects on costs, shipping accidents have
another important connection with water management. Every accident
that involves toxic or hazardous materials can produce water
pollution. Records indicate that accident-caused spills have occurred
regularly on the Rijn in recent years [7.6]. These spills can
interfere with reservoir operation and water supply. The IJsselmeer,
in particular, could suffer from a major spill on the Rijn [7.7].
As a potential source of spills, shipping accidents become more
significant in water management decisions.

Early in the analysis, we began to investigate the problem of safety
and accidents in inland shipping. The intent was to develop models
that we could use in evaluating the effects of water management
tactics. It soon became apparent that finding relationships on which to base these models would not be easy. Instead, we discovered a series of problems that made further effort appear unwarranted.

Some of these problems that complicate shipping safety analysis are:

- No one systematically collected accident data or reports until April of 1977.
- Daily ship traffic information is scarce or nonexistent.
- Environmental conditions are not well reported when accidents do not occur.
- Insurance companies will not release data on accident costs.
- Accidents happen infrequently, so statistical analysis becomes difficult, even with a large dataset.

As a result of these problems, we chose to do a limited preliminary study to investigate the feasibility of further analysis. Appendix G discusses that study and its results. To summarize the results, we found no strong relationships between shipping accidents and any variables that our policies would affect. Although there are indications that certain relationships might exist, these relationships were either too weak or too uncertain to be useful. Consequently, the accident study was terminated at that point.

By deciding not to pursue the safety analysis, we left unsolved the problem of accidental spills. Shipping accidents are not the only source of spills, but they are the only source which might be affected by water management policies [7.6]. Because the other sources were beyond our control, however, even useful accident models would not have been sufficient to deal with this problem.

NOTES

1. Shipping authorities at the DVK in the Netherlands calculated the shipping costs for some of the major technical tactics. In their analysis, they used the basic procedure that we are discussing here. We studied their ship traffic data, cost coefficients, and methods carefully, to ensure that all results would be completely compatible.

2. This statement is not strictly true for several reasons. If the lake level rises above the current maximum, authorities will need to alter docks, mooring facilities, and ship locks on the lake. We have considered the costs of these changes to be investment rather than shipping costs. Moreover, as lake levels change, cycle times for locks on the IJsselmeer will also change. Such variations in cycle times should not cause high costs, however, because few commercial ships will be affected, and the delays should be short.
3. It can be shown that the delay costs that would be calculated using the total cost coefficients are equivalent to the sum of the variable costs and the fixed cost of the additional fleet required by the tactics. This means that we need not calculate the change in the fleet proxy for impact assessment cases that involve the IJmeer tactics.

4. The incidence of accidents at locks is related to management tactics because lock operation policies will affect traffic congestion. Discussions with lock operators, however, revealed that few serious accidents occur at locks. Ships move slowly there, and lock operators handle the traffic carefully. As luck would have it, however, a serious accident occurred during the PAWN project. A large ship ran into the gates on the sea lock at IJmuiden, causing extensive damage.

REFERENCES


7.7. Claessen, Verontreiniging IJsselmeer Door een Calamiteit (Pollution of the IJsselmeer by a Calamity), Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging, District Noord, No. TWSIJ-91, Lelystad, May 1978.
Chapter 8
MARKET ANALYSIS

8.1. THE NEED FOR MARKET ANALYSIS

We need to understand how the shipping industry is structured and how the transport markets operate in order to address certain questions in the shipping analysis. These questions concern whether, and how, carriers and their customers will react to shipping cost changes. Shipping cost changes lead directly to changes in profits and employment in the shipping industry, and may lead indirectly to new prices for shipping transport. New prices may in turn cause industry to decide to transport more or less cargo in ships. Without understanding how the markets operate, we cannot estimate whether these changes are important. Unfortunately, the shipping markets in the Netherlands and Europe are complex and extremely difficult to study.

The complexity of the industry and markets makes solving this problem difficult. How cost changes affect the shipping industry will depend in part on:

- How well carriers can pass cost increases on to customers.
- How much government subsidies and regulations may offset the cost changes.
- How current shipping revenues compare with costs.
- What alternatives carriers have for improving their situation.

If government subsidies increase, or carriers can alter their operations, to offset cost increases, no change in shipping prices may occur. If prices increase, however, industry may decide to transport less by ship and more by road or rail. This will in turn reduce shipping operations and lead to more changes. We should be able to understand these changes and include them in the analysis.

In understanding the structure of the market and industry, we want to know who actually pays cost increases or benefits from reductions, how they will react, and what effects these reactions cause. More specific questions that must be considered are:

- How is the shipping industry structured?
- How do the shipping markets operate?
- How are freight prices now determined and how would they be affected by changes in shipping costs?
- How do current prices compare with actual shipping costs?
• How will the different sectors of the industry vary in their reaction to cost changes?
• What government subsidies exist for the shipping industry?
• What government policy changes can be expected, and how will they affect the industry?
• How does the current fleet capacity compare with the demand for shipping services?
• What industries ship goods, and who pays transport costs?

What you want to know about the market typically does not equal what you are able to learn. What we discovered about the shipping industry and the sectors of the transport market is described below.

8.2. SHIPPING INDUSTRY

Chapter 2 discussed in general terms the shipping industry in the Netherlands and Europe. Here we will consider the industry and market structure in more detail. This process can be simplified by dividing shipping operations into two components, domestic and international. Before discussing these components, however, we should first describe the fleet.

8.2.1. Shipping Fleet

This discussion will be restricted to the Dutch fleet, because we know very little about the size or characteristics of the fleets in other European countries. The only exception to this is the fleet registered for transport on the Rijn. Even for these ships our knowledge is limited, though, because the fleet can vary from year to year. An unknown number of ships in other countries are available and able to enter the fleet at any time, particularly during low water periods when freight prices rise.

The active Dutch fleet in 1976 consisted of 7,515 ships with a combined load capacity of 5,104,000 metric tons, owned and operated by 5,687 companies. Of this total, 4,991 companies (88 percent) owned one ship. These one-ship companies represented 66 percent of the total active ships, but only 56 percent of the total load capacity of the fleet. We can conclude from this that most shipping companies are small, and that the small companies generally own the smaller ships.

It is also interesting to consider the ships in the active fleet in terms of their participation in domestic and international transport. This information is summarized in Table 8.1, which shows that:

• Approximately the same number of ships operate in both markets as operate in only one or the other together.
• More companies operate in both markets than in only one.
* Companies operating in only the domestic or international market have, on the average, more ships than those in both markets, most of which have only one ship.
* The international market attracts much larger ships than the domestic market.

Table 8.1

<table>
<thead>
<tr>
<th>Transport Market</th>
<th>Companies</th>
<th>Ships</th>
<th>Load Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(tons)</td>
<td>Total (tons)</td>
</tr>
<tr>
<td>Domestic only</td>
<td>1,305</td>
<td>1,915</td>
<td>953,000</td>
</tr>
<tr>
<td>International only</td>
<td>1,167</td>
<td>1,880</td>
<td>1,621,000</td>
</tr>
<tr>
<td>Both</td>
<td>3,215</td>
<td>3,720</td>
<td>2,530,000</td>
</tr>
<tr>
<td>Domestic total</td>
<td>4,520</td>
<td>5,635</td>
<td>3,483,000</td>
</tr>
<tr>
<td>International total</td>
<td>4,382</td>
<td>5,600</td>
<td>4,151,000</td>
</tr>
</tbody>
</table>

SOURCE: Ref. 8.1.

These observations indicate that the smaller one-ship companies operate in whichever market they feel is most profitable. The larger companies, on the other hand, seem to prefer to operate in only one market. This may imply that they have more fixed operations or longer term contracts in their transport. To understand the situation more completely, however, we should look at the two shipping markets.

8.2.2. Domestic Shipping

The domestic shipping market can be divided into four major and two minor sectors, which together accounted for total transport of 94.1 million metric tons in 1976. The four major sectors are (1) private transport, (2) the "special" sector, (3) the shippers' bourse, and (4) the tanker trade. The two minor sectors include regularly scheduled transport and the "campaign" transport of agricultural products during harvest periods. These two sectors will not be considered further. The regular transport is small and has not changed appreciably over the years. The campaign transport has not been carefully regulated or monitored, so accurate data do not exist. In general, it is small, seasonal, and relatively unknown.

Table 8.2 shows the domestic transport by sector during recent years. The four major sectors are separated by a license system and the requirement that a carrier can operate in only one sector at a time. This system was designed to control shipping fleet capacity by limiting how many licenses were issued. In view of recent fleet capacity excesses, we must suspect that it has not always been successful.
### Table 8.2

DOMESTIC TRANSPORT BY SECTOR IN RECENT YEARS  
(million tons)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Private</td>
<td>42.1</td>
<td>37.6</td>
<td>34.8</td>
<td>30.9</td>
<td>39.6</td>
<td>45.9</td>
<td>36.8</td>
</tr>
<tr>
<td>Special</td>
<td>22.6</td>
<td>19.2</td>
<td>16.5</td>
<td>17.1</td>
<td>20.4</td>
<td>18.4</td>
<td>19.4</td>
</tr>
<tr>
<td>Bourse</td>
<td>21.3</td>
<td>20.9</td>
<td>19.2</td>
<td>18.0</td>
<td>19.6</td>
<td>19.9</td>
<td>21.4</td>
</tr>
<tr>
<td>Tank</td>
<td>14.2</td>
<td>14.7</td>
<td>12.9</td>
<td>11.0</td>
<td>11.9</td>
<td>11.3</td>
<td>12.2</td>
</tr>
<tr>
<td>Campaign</td>
<td>1.9</td>
<td>1.9</td>
<td>2.0</td>
<td>1.9</td>
<td>2.0</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Regular</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>102.7</td>
<td>94.8</td>
<td>85.9</td>
<td>79.5</td>
<td>94.1</td>
<td>98.0</td>
<td>92.2</td>
</tr>
</tbody>
</table>

*SOURCE: Ref. 8.2.*  
*NOTE: Column sums may not equal totals because of rounding.*

8.2.2.1. Private Transport. This sector consists of all domestic transport carried by ships either owned or leased for more than one year by the shipping party. Of the total transport in this sector during 1976, more than 90 percent was sand and gravel. In the sand and gravel business, the dealer (wholesaler) usually buys from the producer and then arranges for transport to where the material will be sold. The transport costs account for most of the retail price variation, because producers' prices for these materials do not vary much. As a consequence, many dealers have their own ships or vessels hired on long-term contracts.

Under these circumstances, the shippers (as the carriers) will bear any additional shipping costs imposed by tactics or low water. These costs will probably be passed on to consumers in terms of higher product prices. How easily the dealers can raise prices depends on how much competition exists in the industry. If all dealers in an area are affected, however, then prices will certainly increase.

If transport costs increase on a particular waterway or in a given area, sand and gravel trade in that area may decline. Dealers might prefer to purchase their materials from producers in other areas where costs (production or transport) are lower. Under these conditions, the water management tactics could have an important local effect. This effect could be national, if dealers decide to go to Germany or some other country for their new sources.

8.2.2.2. Special Sector. This sector consists of unregulated transport operating under general licenses. These licenses are issued for transport of specified commodities, either in given regions or for given agencies. Once a carrier has obtained a license, his transport under the license is not further regulated. Contracts in this sector are negotiated for periods ranging from a month to a year. The prices specified in the contracts must be at least as high as certain minimum levels specified by the government.
Of the 20.4 million tons carried in this sector in 1976, almost 98 percent was sand and gravel or other building materials. As in private transport, sand and gravel dealers are the primary shippers in this sector. Here, however, they operate under short-term contracts with independent carriers. Because these carriers have excess capacity, shipping prices have generally been low. Because prices are so low, carriers in this sector probably earn only enough to cover operating expenses, not all of their capital expenses. Also because of the excess capacity, carriers should have difficulty in passing cost increases along to the shippers. As a result, such cost increases would only aggravate the problems of the carriers, but would not cause any changes in shipper behavior.

8.2.2.3. Shippers' Bourse. The shippers' bourse, a transport institution, has been established in various inland shipping towns in the Netherlands. When a shipper has goods to be shipped, he can take them to the bourse. Bourse officials will set a tariff (price) for the shipment and offer the goods to carriers waiting there. The carriers have a priority order based on waiting time. If a carrier accepts the cargo, he must transport it at the stated price. If no carrier agrees to the price, the shipper can negotiate with any of them for transport at some other price. Authorities estimate that 30 percent of the offered cargo is subsequently rejected and carried under negotiated contracts. Of the 19.5 million tons shipped under the bourse during 1976, the primary commodities were agricultural and food products (50 percent) and sand and gravel (30 percent).

Prices set at the bourse are founded on a system of basic tariffs established in 1954 and revised annually to account for inflation. The tariff is based on origin and destination of the goods, route, type of ship, and type of goods. Once the basic tariff has been determined, the price is some percentage of that tariff. This percentage, ranging from 80 to 130 percent, is set by a joint district committee of carriers and industry representatives. They decide on the multiplier value considering the supply and demand for shipping in the district. An additional low water surcharge may be added to this price, but this surcharge has not been used in recent years. Shipping depths on Dutch waterways have been too high and stable to warrant applying it.

The bourse can be blamed for the continued existence of many older and smaller vessels. It provides these weak carriers with transport opportunities and sufficient income to remain in business. Unfortunately, the bourse does not provide enough money for vessel improvement or replacement, as prices are estimated to be only 60 to 70 percent of total shipping costs. Although authorities intend to revise the current tariff system, the revision process may require several years. Under current policy, the authorities are not issuing new licenses for operation in the bourse unless the overall character of the fleet is improved. Improving the fleet means that an old ship must be retired from service when a new one enters. With this requirement, they are attempting to reduce the excess capacity of small and old vessels.
Considering the price-setting mechanism, we would expect that the increased costs caused by water management policies would probably not be passed on. This may no longer apply, however, when a new tariff system is instituted. Even then, however, revisions to the basic tariffs will require at least a year. As a result, the number of cargoes refused will most likely increase. When these cargoes are carried under independently negotiated contracts, carriers should have a better opportunity to pass on increased costs.

8.2.2.4. Tanker Transport. This sector operates basically as a free market, in that no licenses are required for domestic transport. Of the 11.9 million tons carried by domestic tankers in 1976, about 9.5 million tons were carried in vessels owned or leased by the shipper. Thus, only 2.4 million tons were carried under conditions equivalent to those in the "special" sector. Most of this special sector shipping occurs under contract, but some is in a daily market. In the market, large shipping companies deal directly with their customers, while the smaller ones often negotiate through intermediaries.

The tanker fleet has a large excess capacity, roughly estimated at 20 percent. This excess was caused by overinvestment in ships and reduced demand. Prices in this market have decreased over the years to where they are now extremely low. These low prices and excess capacity make it unlikely that carriers could pass on increased costs. Carriers must also worry about competition from rail transport and pipelines.

8.2.3. International Transport

International transport, in contrast to domestic, operates generally in a free market, according to current EEC policy. However, two conditions or exceptions must be mentioned. First, all companies which operate on the Rijn must license both their crews and vessels. These licenses are issued by the Central Rijn Navigation Committee. Second, some goods transported to and from Belgium and France pass through a bourse composed of carriers and industry representatives. The bourse requires no specific licenses, however, for vessels using it, and represents only about 4 percent of the total international transport through the Netherlands.

Table 8.3 summarizes the international transport by commodity group for recent years. From the table we can see that the most important commodities are raw minerals (sand and gravel), ores, and oil products. Most of these materials are transported between the Netherlands and Germany on the Rijn.

International shipping includes many types of contracts with different characteristics. A large, but unknown, fraction of the market could be called private transport, goods carried by industries in ships that they own or lease on long-term contracts. The term length of contracts in the rest of the market varies from one trip to several
### Table 8.3

**INTERNATIONAL TRANSPORT BY COMMODITY GROUP FOR RECENT YEARS**

(million tons)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural products</td>
<td>7.0</td>
<td>6.6</td>
<td>6.7</td>
<td>8.0</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Other food products</td>
<td>8.0</td>
<td>9.5</td>
<td>9.0</td>
<td>11.2</td>
<td>11.7</td>
<td>12.8</td>
</tr>
<tr>
<td>Solid fuels</td>
<td>10.6</td>
<td>13.3</td>
<td>11.4</td>
<td>10.2</td>
<td>12.9</td>
<td>13.6</td>
</tr>
<tr>
<td>Oil and oil products</td>
<td>23.5</td>
<td>23.8</td>
<td>25.1</td>
<td>27.6</td>
<td>29.8</td>
<td>33.7</td>
</tr>
<tr>
<td>Ores and metal wastes</td>
<td>34.2</td>
<td>39.2</td>
<td>34.1</td>
<td>33.2</td>
<td>30.4</td>
<td>33.7</td>
</tr>
<tr>
<td>Metals</td>
<td>14.4</td>
<td>16.5</td>
<td>11.0</td>
<td>12.2</td>
<td>13.5</td>
<td>13.9</td>
</tr>
<tr>
<td>Minerals (sand/gravel)</td>
<td>45.5</td>
<td>46.5</td>
<td>45.2</td>
<td>47.7</td>
<td>51.9</td>
<td>50.1</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>5.9</td>
<td>6.5</td>
<td>4.6</td>
<td>5.1</td>
<td>6.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Chemical products</td>
<td>6.7</td>
<td>7.6</td>
<td>6.8</td>
<td>7.8</td>
<td>7.9</td>
<td>9.0</td>
</tr>
<tr>
<td>Others</td>
<td>4.3</td>
<td>4.2</td>
<td>2.5</td>
<td>3.3</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>160.0</strong></td>
<td><strong>167.8</strong></td>
<td><strong>156.3</strong></td>
<td><strong>166.2</strong></td>
<td><strong>174.7</strong></td>
<td><strong>185.4</strong></td>
</tr>
</tbody>
</table>

**SOURCE:** Ref. 8.3.

**NOTE:** Columns may not sum to totals because of rounding.

months. For short-term contracts, shipping prices fluctuate sharply as water levels change the effective supply of ships and the demand for their services. Under normal conditions, however, the supply exceeds the demand, implying that transport prices may not adequately cover the true costs of carriers. The carriers must also deal with the powerful bargaining position of intermediaries who represent groups of industries. In this situation, most carriers cannot easily pass along cost increases to their customers. Those with longer-term contracts, however, may be able to include some provision for their increased costs during low water periods.

One circumstance favors the carriers, however. Much of the cargo carried in this market is either destined for, or arriving from, seagoing vessels. Because these vessels often have high delay costs, and storage space is limited, shippers may often have little flexibility in their operations. This may cause prices in short-term contracts to be very sensitive to water conditions, and may enable carriers to pass on their true costs to shippers.

### 8.3. CONCLUSIONS

As described above, our study of the shipping market discovered that it is extremely complex and difficult to understand. Before trying to predict how cost changes might affect the market or industry, we would have to know far more about the situation than we were able to learn. Some of the remaining unanswered questions are:

- How much excess capacity actually exists in the fleet, and how is this capacity distributed by ship type?
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- Who owns and operates the ships in international transport?
- How is international transport divided between private shipping, long-term, short-term, and daily contracts?
- How are low water cost provisions included in contracts?
- What is the structure of the price system in international transport?
- How do domestic and international prices compare with total and variable shipping costs?

As this list makes clear, too little is known about the markets for anyone to predict how cost increases might be divided between carriers and shippers. As a result, we made no attempt to make the separation, but rather assumed that all cost changes fell directly on the carriers. This assumption allowed us to calculate the indirect effects on the economy, as described in Vol. X. Although we can make no specific predictions about the market effects of PAMN tactics, we can draw some general conclusions.

The character and capacity of the fleet have changed since 1976. In that year, the fleet had excess capacity in small and old ships. Since then, the government subsidy programs to remove old ships and continued growth in international transport have had two effects. First, many small and old ships have left the active fleet, so that now the largest capacity excess is in the tanker trade. Second, investment in new, larger ships (greater than 650 tons) has continued. These two actions have caused the overall fleet to shrink while becoming more efficient.

We cannot draw any reasonable conclusions about the distribution of domestic transport among the different sectors. As Table 8.2 shows, no trends stand out in the market division between sectors. In recent years, both the special sector and bourse have been threatened with elimination by the government. In each case, however, this did not occur. Instead, the government instituted minimum rates in the special sector and began a study to determine new basic tariffs for the bourse. Under these circumstances, we doubt that the government will take any significant further action in the near future.

One additional policy uncertainty should be mentioned. The EEC is currently studying proposals for instituting a system of user charges on waterways. No system now exists, although carriers must pay small charges for using some provincial or municipal harbors and waterways. If a user charge system were imposed, it would presumably cover at least operation and maintenance costs, if not the marginal congestion and external costs. Even then, however, it could significantly affect shipping costs and modal split choices by industry. This possibility was not included in the analysis, because it was too uncertain and too far in the future.
8.4. DUTCH SHARE

Dutch vessels carry only part of the goods that are transported in and through the Netherlands. Allocating all cost changes to the carriers, as described above, requires that we know what fraction of the total cost changes fall on Dutch carriers. The remaining costs must then fall on foreign carriers. With this information, one could determine the subsequent indirect economic effects inside and outside the country.

Using certain reasonable assumptions, it is possible to calculate the share of low water losses and lock delay losses that apply to Dutch ships. Using information provided in the shipping cost study, we can determine for each study run (1) total variable costs of shipping, (2) required Dutch fleet, and (3) required total fleet. Assuming that the share of costs is proportional to the relative fraction of Dutch ships (by type and size) gives directly the fraction of total cost that applied to Dutch carriers. This fraction was calculated for each shipping study run for both contexts. The Dutch cost fraction varied little between runs or years. The fraction in 1976 was 0.63, and in 1985, 0.61. We chose to use the mean value of 0.62 in the PÅWN analysis.

For the lock delay loss functions, the problem is more difficult. Data are scarce, so approximations were necessary. Where flag counts and goods traffic information were available, these could be used. Where they were not available, we used the low water loss function ratios, unless the locks had predominantly local traffic. In that case, it was reasonable to assume that all ships would be Dutch. Table 8.4 summarizes the results.

<table>
<thead>
<tr>
<th>Lock</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowlands</td>
<td></td>
</tr>
<tr>
<td>Delfzijl</td>
<td>0.78</td>
</tr>
<tr>
<td>Den Helder</td>
<td>0.95</td>
</tr>
<tr>
<td>Den Oever</td>
<td>0.96</td>
</tr>
<tr>
<td>Harlingen</td>
<td>0.97</td>
</tr>
<tr>
<td>IJmuiden</td>
<td>0.48</td>
</tr>
<tr>
<td>Kornwerderzand</td>
<td>0.98</td>
</tr>
<tr>
<td>Kreekrak</td>
<td>0.60</td>
</tr>
<tr>
<td>Parkhuisen</td>
<td>0.90</td>
</tr>
<tr>
<td>Philipsdam (Com)</td>
<td>0.83</td>
</tr>
<tr>
<td>Philipsdam (Rec)</td>
<td>1.00</td>
</tr>
<tr>
<td>Spaarndam</td>
<td>1.00</td>
</tr>
<tr>
<td>Volkerak (Com)</td>
<td>0.69</td>
</tr>
<tr>
<td>Volkerak (Rec)</td>
<td>1.00</td>
</tr>
<tr>
<td>Highlands</td>
<td></td>
</tr>
<tr>
<td>Wilhelminkanaal</td>
<td>1.00</td>
</tr>
<tr>
<td>Others</td>
<td>0.62</td>
</tr>
</tbody>
</table>
Although these methods have weaknesses, they were the only reasonable methods available. However, the best information is available for the most important locks.

NOTES

1. This information comes from an interview with Mr. Bergman of the Department of Transportation of Goods on Waterways, of the Ministry of Traffic and Waterworks.

2. Carriers may also be eligible for general social welfare payments during their unemployed periods. We do not know, however, the conditions for this eligibility, or how many carriers actually receive such benefits.

3. The members of the committee are Belgium, France, Great Britain, the Netherlands, Switzerland, and West Germany.

4. These subsidy programs for ship breakdowns are discussed in the first note to Chap. 5.

5. The value of the fraction increased slightly as water depths increased. We would expect this, because depths for domestic transport would not change very much. As a result, the Dutch fleet would remain more stable than the foreign fleet, which is completely engaged in international transport. The foreign fleet would thus be more subject to changes in flows and depths on the Rijn and its branches.

REFERENCES


Chapter 9
RESULTS AND CONCLUSIONS

9.1. DEFINITION OF POLICIES AND CASES

As we have discussed previously, a water management policy is composed of tactics from each of the four types: technical, managerial, price, and regulation. When this policy is combined with a set of standards and requirements, system assumptions, and scenario assumptions, it becomes a case for impact assessment. Because policies are composed of promising tactics from the screening analyses, we should briefly describe which tactics survived the analyses and were incorporated into policies. Figure 9.1, a map of the Netherlands and its waterway network, can be used for reference. For a complete description of the screening process, see Vols. II, IV, and V.

9.1.1. Promising Tactics

The price and regulation tactics which survived screening were:

- Groundwater extraction quotas of either 100 percent or 25 percent of the extractable amounts as estimated by the Rijksinstituut voor Drinkwatervoorziening (RID).
- Groundwater extraction charge on industry and drinking water companies of either 0.0 or 0.20 Dfl/m³.
- Drinking water pricing at marginal costs of production.
- Groundwater extraction priority to either industry and drinking water companies or to agriculture.

The last tactic in this group gives priority on extractions under a quota. When agriculture has priority, farmers can drill wells, after which their groundwater use is not restricted. Thus agricultural priority can mean that more groundwater, rather than less, is used in dry years. When industry has priority, its withdrawals are still monitored, but the amount that it can withdraw increases. If industries desire more water, they must generally obtain it from the drinking water companies.

Technical tactics were separated into network tactics and waterboard plans. We will discuss the network tactics first. The promising network tactics were all relatively minor; the major tactics were eliminated in the screening process. Nine of the promising tactics were dominant over the remaining tactics and were incorporated into a group called MAXTACS. This group was considered as a unit in the impact assessment analysis and included:
Fig. 9.1 -- Waterway network in the Netherlands
1. Expand the Twenthekanaal capacity by 15 m³/s.
2. Expand the capacities of the Zuid-Willemsvaart (section 2), Kanaal Wesselom-Nederweert, Noordervaart, and Wilhelminakanaal by 5 m³/s.
3. Maintain portable pumping capacity of 5 m³/s at Maasbracht on the Julianakanaal.
4. Decrease the minimum level of the IJsselmeer and Markermeer in summer by 10 cm (to NAP - 50 cm).
5. Build a pipeline from the Biesbosch to Delfland with a capacity of 8 m³/s.
7. Make the Grevelingen fresh.
8. Institute a new policy for flushing the Markermeer.
9. Increase the throughput capacity of the Van Starkenborghkanaal at Gaarkeuken to 25 m³/s.

Not all of these tactics have important implications for shipping. The last three (7, 8, and 9), for example, should have at most only minor impacts on shipping operations. Similarly, if dredging is used to maintain shipping depths, decreasing the minimum summer levels of the IJsselmeer and Markermeer (4) will not affect ships at all.

On the other hand, two of the tactics have the potential to increase shipping costs. Increasing the capacities of the Twenthekanaal (1) and the canal sections in the Southeast Highlands (2) means that more water may be extracted from the IJssel and Maas for use by agriculture. Although these extractions are not assured, they are most likely to occur during dry periods, when river flows are low and ships need as much water depth as possible.

The remaining three tactics should benefit shipping. As discussed earlier, maintaining portable pumping capacity on the Julianakanaal at Maasbracht (3) gives lock operators the ability to recycle water at the lock. This increases the effective flow available for locking and reduces ship delays during low water periods. Building a pipeline to transport 8 m³/s of fresh water from the Biesbosch to Delfland (5), for use with Midwest agriculture, reduces the demand for water at the Gouda inlet and the potential damage from excess salinity there. Similarly, constructing a groin in the Nieuwe Waterweg (6) also benefits Midwest agriculture as well as shipping. The groin improves flow conditions in the waterway, thereby increasing the efficiency of fresh water in fighting salt intrusion. As a result, a given flow in the Nieuwe Waterweg will provide improved water quality at Gouda; or the same quality can be maintained at the inlet with a smaller flow than previously required. The net result of the pipeline and groin should be less demand for water to fight the salt wedge.

The other technical tactics were the waterboard plans. Waterboards are regional agencies charged with administration and management of water, dikes, sluices, pumps, and other civil engineering works in a polder or polders. They are responsible for water management and
safety within the area. Waterboards are governed by elected boards, chosen by real estate owners in the management area. The waterboard plans are local development projects to improve surface water distribution networks for agriculture. These plans make improved distribution possible, but they do not actually increase surface water use by themselves. We considered a total of 65 plans during screening, of which 46 were retained for further analysis in impact assessment. Most of the plans are located in three areas: the Southeast Highlands, the Delta, and the Northeast Highlands.

PAWN considered three managerial strategies in the final analysis of cases, of which the first was the nominal RWS policy. This policy is a close approximation to the unofficial policy of recent years. It incorporates a specific set of flow-based rules for operating the weir at Driel, minimizes withdrawals from the Waal at Tiel, and maintains a minimum flow of 20 m³/s on the Amsterdam-Rijnkanaal. This water is used to augment flow in the Noordzeekanaal to cool the Velsen power plant at IJmuiden.

The second strategy was the improved policy determined by the MSDM. This strategy satisfies demands for water in the following priority order:

1. Supply water level control requirements for boezems and lakes.²
2. Supply water for agricultural sprinkling.
3. Simultaneously minimize the sum of shipping losses due to low water, dredging cost from sedimentation due to withdrawals at Tiel, and salt damage to agriculture due to the Rotterdam salt wedge, by adjusting the weir at Driel and extractions from the Waal at Tiel.³
4. Use water from the IJsselmeer and Markermeer to cool power plants at Bergum and Velsen on the Noordzeekanaal.
5. Raise lakes to desired levels to meet possible future needs.
6. Use water for flushing salt from boezems, locks, and lakes.

These priorities correspond roughly to the relative economic values of water as determined by the model. Note that for any particular cubic meter of water, these demands do not always compete. Water can often meet more than one demand (e.g., be used for shipping on the IJssel and subsequently for sprinkling), and not all demands apply to some water. This is a priority scheme, in that each cubic meter of water is assigned to the highest priority for which it can be used.

The third strategy selected is called the Velsen policy (VEL). It is a modification of the RWS policy which reduces the minimum flow on the Amsterdam-Rijnkanaal and increases the flow from the IJsselmeer and Markermeer to cool the power plants at Bergum and Velsen on the Noordzeekanaal.
9.1.2. Definition of Cases

We defined the cases for impact assessment by specifying ten different tactic and scenario variables. These were:

- Management strategy.
- Implementation of waterboard plans.
- Incorporation of MAXTACS.
- Level of surface water sprinkling of agriculture.
- Level of groundwater sprinkling of agriculture.
- Groundwater withdrawal quota.
- Groundwater withdrawal priority.
- Groundwater withdrawal charge.
- Sui salt content.
- External water pollution.

Because the last two water quality scenario variables do not affect shipping costs, we will not consider them further. In the impact assessment analysis, we ran cases in the 1985 context with three external supply scenarios: (1) DEX, the extremely dry year, (2) 1943, the moderately dry year, and (3) 1967, the average year. Using the 1985 context stresses the system and provides conditions that should show the maximum differences between policies. This should also be true for shipping, as the 1985 context has much larger commodity transport and a larger, deeper draft shipping fleet than the 1976 context.

Table 9.1 defines the impact assessment cases that we considered in the analysis. The table summarizes both the policies and the external supply scenarios.

Some of the terms in Table 9.1 require further explanation. We consider low sprinkler capacity, both groundwater and surface water, to be the present situation. Medium capacity represents medium plausible growth, and high capacity represents the upper limit on plausible growth in sprinkler capacity.

Case A should be considered the base case, a close approximation to the current situation with respect to the policy variables. The costs and benefits of other cases are compared with case A. The other primary cases are C, D, E, F, and G. All but A have waterboard plans and use the MSUM management strategy. Cases C, D, and G have low groundwater sprinkling, for environmental protection, and C has a quota to further limit groundwater use. This case also includes MAXTACS for surface water quality improvement. Case F is the extreme case, with high sprinkling intensities and a full menu of technical tactics.

The remainder of the cases defined in Table 9.1 are intended to show the sensitivity of policies to changes in various factors. Management strategy can be isolated by comparing cases A, B, and J (under unstressed conditions), and cases H, F, and K (maximum stress on the
### Table 9.1

**DEFINITION OF CASES**

<table>
<thead>
<tr>
<th>Case Strategy Plans</th>
<th>Management Board</th>
<th>Water MAXTACS</th>
<th>Sprinkler Water</th>
<th>Sprinkler Groundwater</th>
<th>Quota Groundwater</th>
<th>Priority Charge</th>
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<td>DEX External Supply</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
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</tr>
<tr>
<td>B1</td>
<td>MSDM</td>
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<td>No</td>
<td>Low</td>
<td>Low</td>
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</tr>
<tr>
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<td>Medium</td>
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</tr>
<tr>
<td>G1</td>
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<td>High</td>
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<td>0.25</td>
</tr>
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<tr>
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<tr>
<td>K1</td>
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<td>Yes</td>
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<td>1943 External Supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>RWS</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
<td>B2</td>
<td>MSDM</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
<td>C2</td>
<td>MSDM</td>
<td>Yes</td>
<td>No</td>
<td>Medium</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
<td>D2</td>
<td>MSDM</td>
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<td>Yes</td>
<td>Medium</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
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<td>MSDM</td>
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<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>1.0</td>
</tr>
<tr>
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<td>MSDM</td>
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<td>Yes</td>
<td>High</td>
<td>High</td>
<td>1.0</td>
</tr>
<tr>
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<td>MSDM</td>
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<td>Yes</td>
<td>High</td>
<td>Low</td>
<td>0.25</td>
</tr>
<tr>
<td>H2</td>
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<td>Yes</td>
<td>High</td>
<td>High</td>
<td>1.0</td>
</tr>
<tr>
<td>J2</td>
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<td>No</td>
<td>Low</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
<td>K2</td>
<td>VEL</td>
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<td>Yes</td>
<td>High</td>
<td>High</td>
<td>1.0</td>
</tr>
<tr>
<td>P2</td>
<td>MSDM</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
<td>1.0</td>
</tr>
<tr>
<td>1967 External Supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>RWS</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>1.0</td>
</tr>
<tr>
<td>B3</td>
<td>MSDM</td>
<td>No</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
<td>1.0</td>
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<tr>
<td>F3</td>
<td>MSDM</td>
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<td>Yes</td>
<td>High</td>
<td>High</td>
<td>1.0</td>
</tr>
<tr>
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<td>MSDM</td>
<td>Yes</td>
<td>Yes</td>
<td>High</td>
<td>Low</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**NOTE:** Groundwater charge is in Dfl/m³.

(a) Industry and drinking water companies.

(b) Agriculture.

Water management system. The effects of increasing surface water sprinkling can be found by comparing cases B, C, D, G, and N, and groundwater sprinkling from cases B, E, F, L, F, and Q. The effects of groundwater quotas, charges, and priority are shown in cases G, P, F, M, L, and Q.
9.2. RESULTS AND OBSERVATIONS

The DM was used for impact assessment, to calculate the costs and benefits to all user groups for each case. For this stage of the analysis, we used the future context with the three primary external supply scenarios: DEX, 1943, and 1967. In this section, we will present these results, which show how shipping would be affected by each of the water management policies under consideration.

9.2.1. Primary Cases

The shipping impacts for the primary cases in the DEX scenario and future context are shown in Table 9.2. The impacts include total variable shipping cost for the reference case; Dutch and total variable low water losses, highlands lock delay losses (for tactics at highlands locks), and dredging costs; and the value of the fleet proxy for the Dutch and total shipping fleets. The table shows total losses for the reference case (A), and net benefits (relative to case A) for all other cases.

<table>
<thead>
<tr>
<th>Item</th>
<th>Case</th>
<th>A1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>E1</th>
<th>F1</th>
<th>G1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipping costs</td>
<td></td>
<td>1814.9</td>
<td>-29.97</td>
<td>4.09</td>
<td>2.46</td>
<td>-20.38</td>
<td>-14.80</td>
<td></td>
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<tr>
<td>Total variable shipping losses</td>
<td></td>
<td>347.44</td>
<td>-29.59</td>
<td>3.85</td>
<td>2.24</td>
<td>-18.10</td>
<td>-14.76</td>
<td></td>
</tr>
<tr>
<td>Low water losses</td>
<td></td>
<td>9.72</td>
<td>-0.11</td>
<td>0.03</td>
<td>0.01</td>
<td>-2.19</td>
<td>0.02</td>
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</tr>
<tr>
<td>Highlands lock delay losses</td>
<td></td>
<td>0.36</td>
<td>-0.27</td>
<td>0.21</td>
<td>0.21</td>
<td>-0.09</td>
<td>-0.06</td>
<td></td>
</tr>
<tr>
<td>Dredging costs</td>
<td></td>
<td>357.52</td>
<td>-29.97</td>
<td>4.09</td>
<td>2.46</td>
<td>-20.38</td>
<td>-14.80</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>215.41</td>
<td>-18.35</td>
<td>2.38</td>
<td>1.39</td>
<td>-11.22</td>
<td>-9.15</td>
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<tr>
<td>Dutch variable shipping losses</td>
<td></td>
<td>5.93</td>
<td>-0.08</td>
<td>0.02</td>
<td>0.01</td>
<td>-1.36</td>
<td>0.01</td>
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<tr>
<td>Low water losses</td>
<td></td>
<td>0.36</td>
<td>-0.27</td>
<td>0.21</td>
<td>0.21</td>
<td>-0.09</td>
<td>-0.06</td>
<td></td>
</tr>
<tr>
<td>Highlands lock delay losses</td>
<td></td>
<td>221.70</td>
<td>-18.70</td>
<td>2.61</td>
<td>1.61</td>
<td>-12.67</td>
<td>-9.20</td>
<td></td>
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<tr>
<td>Dredging costs</td>
<td></td>
<td>2562.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
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<tr>
<td>Total fleet</td>
<td></td>
<td>1758.1</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
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<tr>
<td>Long-run fleet proxy</td>
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<td></td>
</tr>
</tbody>
</table>
As an example to clarify the tables, consider cases D1 and C1 in Table 9.2. In those cases, the shipping benefits have opposite signs. Case D1 has positive numbers in the shipping loss rows, which means that shipping does better than in the base case A1. Shipping losses are reduced by the amounts shown, and thus there is a net benefit. For case C1 the numbers are negative. This means that there is a net increase in shipping losses equal to the amounts shown, and thus shipping does worse. This same relation applies also to the long-run fleet proxy. Positive numbers again mean a smaller fleet is required than in A1.

Considering the primary case impacts shown in the table, we can make some fundamental observations, as follows:

- **Total shipping losses are only 20 percent of shipping costs.**
- In all cases, the change in shipping losses is less than 10 percent of the base case losses and less than 2 percent of the base case costs.
- The selected policies have little apparent impact on the size of the long-run fleet for the 90-percent proxy.
- Highlands lock delay costs do not change significantly except when groundwater use changes strongly.
- Dredging costs are always small in comparison with other shipping costs.

Having looked at the impact of the primary cases in the DEX scenario, we should consider them in a less dry year, 1943. These shipping impacts are shown in Table 9.3.

Looking at these results and comparing them with those in Table 9.2, we discover more about how our promising policies affect shipping costs.

- **Total shipping losses have fallen to 7 percent of costs.**
- The change in shipping losses is less than 1 percent of base case losses and less than 0.1 percent of base case costs.
- Some policies which damaged shipping in a DEX year benefit it in a moderately dry year.
- Highlands lock delay losses have become almost negligible.

We can see that all costs and differences observed in the primary cases under the DEX scenario have been considerably reduced in this scenario. The policies have very little effect on shipping costs, one way or the other. This might be somewhat surprising, because 1943 was not a good year for shipping. As the analysis in App. C shows, 1943 was the eighth driest year since 1930 (hence a 17-percent year). Thus it is interesting that the water management policies have so little effect on shipping in this scenario.

The cases have no effect on the size of the long-run fleet proxy, as before, because the proxy value does not depend on a scenario. As we
Table 9.3
PRINCIPAL CASES:
SUMMARY SCORECARD OF NET BENEFITS FOR SHIPPING
(1943 EXTERNAL SUPPLY)
(Defn)

<table>
<thead>
<tr>
<th>Item</th>
<th>A2</th>
<th>C2</th>
<th>D2</th>
<th>E2</th>
<th>F2</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipping costs</td>
<td>1570.6</td>
<td>-0.05</td>
<td>0.77</td>
<td>0.73</td>
<td>0.52</td>
<td>0.41</td>
</tr>
<tr>
<td>Total variable shipping losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low water losses</td>
<td>113.02</td>
<td>-0.04</td>
<td>0.62</td>
<td>0.58</td>
<td>0.42</td>
<td>0.25</td>
</tr>
<tr>
<td>Highlands lock delay losses</td>
<td>0.12</td>
<td>-0.10</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Dredging costs</td>
<td>0.12</td>
<td>0.09</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>Total</td>
<td>113.26</td>
<td>-0.05</td>
<td>0.77</td>
<td>0.73</td>
<td>0.52</td>
<td>0.41</td>
</tr>
<tr>
<td>Dutch variable shipping losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low water losses</td>
<td>70.07</td>
<td>-0.02</td>
<td>0.38</td>
<td>0.36</td>
<td>0.26</td>
<td>0.16</td>
</tr>
<tr>
<td>Highlands lock delay losses</td>
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<td>-0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Dredging costs</td>
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<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>Total</td>
<td>70.27</td>
<td>0.06</td>
<td>0.52</td>
<td>0.50</td>
<td>0.34</td>
<td>0.30</td>
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<tr>
<td>Long-run fleet proxy</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Annualized fixed cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fleet</td>
<td>2862.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Dutch fleet</td>
<td>1758.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

explained in Chap. 5, the proxy is determined by a specific Rijn flow and decade, so it depends only on the water management policy.

9.2.2. Sensitivity Cases

In addition to the primary cases, many sensitivity cases were included in the analysis. We used these cases to investigate how the impacts changed with respect to variations in:

- Management strategy.
- Increasing surface water sprinkling.
- Increasing groundwater sprinkling.
- Groundwater quota, priority, and charges.
- Rijn salt load.
- Rijn BOD load.
Because the last two variables do not affect shipping costs, we will not consider them in this discussion. The results for the other cases, however, are shown in Tables 9.4A and 9.4B.

To investigate the relative benefits of various components of the alternative policies, we must isolate specific cases. This has been done in Table 9.5, which presents the benefits of specific tactics in the DEX and 1945 scenarios. These benefits can be found by comparing the net benefits in Tables 9.4A and 9.4B for the cases shown in parentheses beside the tactics.

The impact assessment results in Tables 9.3 through 9.5 lead to other observations about how water management tactics and policies affect shipping. It is clear that:

- Highlands lock delay losses are important only in extremely dry years, and are affected only by groundwater sprinkling policy.
- The waterboard plans considerably increase shipping losses, particularly if surface water sprinkling is not limited.
- MAXTACS benefits shipping, reducing shipping losses by almost 10 percent in the DEX scenario, and more than offsetting the losses caused by introducing the waterboard plans and increased surface water sprinkling.
- Management strategies are relatively unimportant to shipping costs, but either the MSDM or Velsen strategy would benefit shipping in dry years, under nominal conditions. When the system is stressed, however, these policies hurt shipping in comparison with the nominal RWS management strategy.
- Increased surface water sprinkling damages shipping in extremely dry years, but affects it only negligibly when water conditions improve.
- Large increases in groundwater use can significantly increase shipping costs, especially if agriculture has priority.
- Restricting groundwater use through quotas benefits shipping, no matter who has priority for groundwater use.
- If industry has groundwater priority, imposing a groundwater charge damages shipping; if agriculture has priority, it benefits shipping.

It is particularly important that none of the alternative policies has a large effect on the long-run fleet for a 90-percent proxy. This result is significant, because the proxy decades were selected from the growing season. During this period, flows are normally low, demands are high, and the alternative policies should show their maximum effects.

The careful reader will recognize that we have not performed a systematic sensitivity analysis in determining the various components of shipping costs. There are several good reasons for this omission. Most of the analysis has been based on the shipping cost study done
<table>
<thead>
<tr>
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<tr>
<td>Shipping costs</td>
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<tr>
<td>Total variable</td>
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</tr>
<tr>
<td>shipping losses</td>
<td></td>
</tr>
<tr>
<td>Highlands lock</td>
<td></td>
</tr>
<tr>
<td>delay losses</td>
<td>9.72</td>
</tr>
<tr>
<td>Dredging costs</td>
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</tr>
<tr>
<td>Total</td>
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</tr>
<tr>
<td>Dutch variable</td>
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</tr>
<tr>
<td>shipping losses</td>
<td></td>
</tr>
<tr>
<td>Highlands lock</td>
<td></td>
</tr>
<tr>
<td>delay losses</td>
<td>5.93</td>
</tr>
<tr>
<td>Dredging costs</td>
<td>0.36</td>
</tr>
<tr>
<td>Long-run fleet proxy</td>
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</tr>
<tr>
<td>Annualized fixed cost</td>
<td></td>
</tr>
<tr>
<td>Total fleet</td>
<td>2862.1</td>
</tr>
<tr>
<td>Dutch fleet</td>
<td>1758.1</td>
</tr>
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</table>
### Table 9.48
SUMMARY OF NET BENEFITS FOR SHIPPING (1943/1967 EXTERNAL SUPPLY) (DM/M)

<table>
<thead>
<tr>
<th>Case</th>
<th>1943</th>
<th></th>
<th></th>
<th>1967</th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>A2</td>
<td>B2</td>
<td>C2</td>
<td>D2</td>
<td>E2</td>
<td>F2</td>
</tr>
<tr>
<td><strong>Shipping costs</strong></td>
<td>1570.8</td>
<td>0.12</td>
<td>-0.05</td>
<td>0.77</td>
<td>0.73</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Total variable shipping losses</strong></td>
<td>113.02</td>
<td>0.03</td>
<td>-0.04</td>
<td>0.62</td>
<td>0.58</td>
<td>0.42</td>
</tr>
<tr>
<td>Low water losses</td>
<td>113.26</td>
<td>0.12</td>
<td>-0.05</td>
<td>0.77</td>
<td>0.73</td>
<td>0.52</td>
</tr>
<tr>
<td>Highlands lock</td>
<td>0.00</td>
<td>-0.10</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Delay losses</td>
<td>0.12</td>
<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
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<td>0.06</td>
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<tr>
<td>Dredging costs</td>
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<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>70.27</td>
<td>0.11</td>
<td>0.06</td>
<td>0.52</td>
<td>0.50</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Dutch variable shipping losses</strong></td>
<td>70.07</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.38</td>
<td>0.36</td>
<td>0.26</td>
</tr>
<tr>
<td>Low water losses</td>
<td>70.07</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.38</td>
<td>0.36</td>
<td>0.26</td>
</tr>
<tr>
<td>Highlands lock</td>
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<td>0.07</td>
<td>0.07</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Delay losses</td>
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<td>0.09</td>
<td>0.09</td>
<td>0.12</td>
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<td>0.06</td>
</tr>
<tr>
<td>Dredging costs</td>
<td>0.12</td>
<td>0.09</td>
<td>0.07</td>
<td>0.12</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>70.27</td>
<td>0.11</td>
<td>0.06</td>
<td>0.52</td>
<td>0.50</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Long-run fleet proxy</strong></td>
<td>2862.1</td>
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<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Annualized fixed cost</td>
<td>2862.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total fleet</strong></td>
<td>1758.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Dutch fleet</strong></td>
<td>1758.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Table 9.5

BENEFITS OF WATER MANAGEMENT POLICIES
(Dflm/yr)

<table>
<thead>
<tr>
<th>Tactic (cases)</th>
<th>External Supply Scenario</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>DEX</td>
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<tr>
<td>MAXTACS (C,D)</td>
<td>34.1</td>
</tr>
<tr>
<td>Waterboard Plans</td>
<td></td>
</tr>
<tr>
<td>Medium sprinkling (B,C)</td>
<td>-32.8</td>
</tr>
<tr>
<td>Low sprinkling (B,N)</td>
<td>-6.4</td>
</tr>
<tr>
<td>Surface Water Sprinkling(a)</td>
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</tr>
<tr>
<td>Low -&gt; medium (B,C)</td>
<td>-32.8</td>
</tr>
<tr>
<td>Medium -&gt; high (D,G)</td>
<td>-18.9</td>
</tr>
<tr>
<td>Groundwater Sprinkling</td>
<td></td>
</tr>
<tr>
<td>Low -&gt; medium (D,E)(b)</td>
<td>-1.6</td>
</tr>
<tr>
<td>Groundwater Quota</td>
<td></td>
</tr>
<tr>
<td>1.0 -&gt; 0.25 (F,G)(c)</td>
<td>5.6</td>
</tr>
<tr>
<td>1.0 -&gt; 1.5 (F,Q)(d)</td>
<td>-15.6</td>
</tr>
<tr>
<td>Groundwater Priority</td>
<td></td>
</tr>
<tr>
<td>Ind -&gt; Agr (F,P)</td>
<td>-34.6</td>
</tr>
<tr>
<td>Ind -&gt; Agr (L,M)(e)</td>
<td>10.3</td>
</tr>
<tr>
<td>Groundwater Charge(f)</td>
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</tr>
<tr>
<td>Ind priority (F,L)</td>
<td>-24.1</td>
</tr>
<tr>
<td>Agr priority (P,M)</td>
<td>20.8</td>
</tr>
<tr>
<td>MSIDM Management Policy</td>
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</tr>
<tr>
<td>Base case (A,B)</td>
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</tr>
<tr>
<td>High stress (N,F)(g)</td>
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<tr>
<td>Velsen Management Policy</td>
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</tr>
<tr>
<td>Base case (A,J)</td>
<td>8.9</td>
</tr>
<tr>
<td>High stress (N,K)(g)</td>
<td>-3.6</td>
</tr>
</tbody>
</table>

(a) Includes waterboard plans necessary to permit increased surface water sprinkling.
(b) Medium sprinkling gives priority to industry/drinking water companies.
(c) Priority changes from industry/drinking water companies to agriculture.
(d) Priority to industry/drinking water companies.
(e) Includes groundwater charge of 0.20 Dfl/m³.
(f) Charge = 0.20 Dfl/m³.
(g) High stress includes waterboard plans, MAXTACS, high surface-water and groundwater sprinkling, 1.0 groundwater quota, and industry/drinking water company priority.

by the DVK, EBW, and NVI. This study employed extensive data collection and analysis, many assumptions and simplifications, and a number of complex models. Primarily because of time and resource constraints, these organizations did not extensively investigate the sensitivity in their results. Consequently, we had no way of knowing how large the errors or uncertainty might be. Similarly, all shipping cost calculations are based on the cost coefficients developed by the NVI and EBW. We did not know the uncertainty in these coefficients
either, much less the direction of possible errors. However, if all coefficients are in error by a given percentage, all subsequent cost calculations will be off by the same relative amount.

In general, we can assume that there were errors of completely unknown size in our input information and parameters. This information was used in several relatively complex models, which added more uncertainty to the analysis. A thorough sensitivity analysis of this situation would have been extremely difficult and time consuming. However, the uncertainty in the calculations does not have a significant impact on the results or conclusions of the PAWN analysis. Shipping costs and benefits are small relative to total benefits in every case. Even if shipping costs were underestimated by a factor of two (representing a very unlikely 100 percent error), it would have little or no effect on the policy conclusions. Under these circumstances it was clear that the limited research time and budget could be better spent on other activities.

9.3. CONCLUSIONS AND RECOMMENDATIONS

We have found that shipping operations do not seem to be seriously affected by the promising policies developed in the PAWN analysis. Four possible reasons for this result are:

1. Tactics that might impose high losses on shipping could be eliminated from consideration because they failed to provide sufficient benefits to justify even their investment costs.
2. Shipping and other users do not always compete for water; many of the benefits to other users come from improved water distribution, increased groundwater use, or consumption of water that shipping has already used or does not need.
3. Low water losses do not increase significantly over a large range of flows and critical depths. Consequently, they become important only at the very low flows found mostly in extremely dry years.
4. Shipping losses are determined predominantly by Rijn and Maas flows, and water management tactics can only vary these flows and losses by relatively small amounts.

In other than the driest years, shipping is not seriously affected by any of the promising tactics considered in the analysis. Most of the alternative policies do not harm shipping in a moderately dry year (one out of six). Even in an extreme year (one out of 100), the damage is limited to a few percent of total shipping costs in the most highly stressed situation.

In the same way, there are no increases in the long-term requirements for the shipping fleet. The fleet proxy value remains remarkably stable with the 90-percent proxy. This should not be surprising, in light of the other results. The policies do not affect shipping very
much except in the driest decades of the driest years, which occur rarely. We might find a significant variation between policies for a higher proxy criterion (Rijn dryness), but this would represent a much larger and more expensive fleet.

Although shippers and carriers should not feel threatened by the results of this analysis, certain actions by the RWS could minimize the damage to shipping from some of these tactics. These actions would include:

- Dredging the Waal downstream of Tiel and St. Andries to remove the sandbars caused by withdrawals.
- Improving the Merwedezaaaima for transport of water north from the Waal at Gorinchem to the Lek, to reduce the amount of water withdrawn at Tiel.
- Changing the current managerial strategy to substitute water from the IJsselmeer and Markermeer for water from the Waal (via the Amsterdam-Rijnkaanaal) for augmenting the flow in the Noordzeekanaal.
- Incorporating MAXTACS, if groundwater and surface water sprinkling increase dramatically in the future.
- Reducing agricultural sprinkling to moderate levels during extremely dry periods.

Considering everything that we have discussed, the Dutch should be able to make water management decisions that do not damage or alarm the shipping industry and other European countries. Inland shipping in the Netherlands can be protected from serious consequences, even during dry periods, by a careful choice of technical, managerial, and other tactics. Reasonable water management policies will not damage the shipping industry or Dutch international relations. Shippers should not have reason to change their current behavior, and other nations should not have reason to blame the Dutch for interfering with international transport.

NOTES

1. Adding pumping capacity to the Merwedezaaaima was found to be a promising tactic with large benefits for shipping, but was not incorporated into MAXTACS. This tactic, which enables water to be transported from the Waal to the Lek, benefits shipping in any situation where correspondingly less water can be withdrawn from the Waal at Tiel. This tactic also provides significant agricultural benefits when combined with the construction of the Lopikerwaard-Zaaima. However, the combination of tactics is dominated by the construction of groins in the Nieuwe Waterweg. Consequently, the Merwedezaaaima tactics were not included in either MAXTACS or the impact assessment analysis. A complete discussion of these tactics can be found in Vol. II.
2. This priority refers to maintaining water levels in lakes, canals, boezems, and ditches throughout the Netherlands. Its ranking is implicit in the results because it was imposed as a constraint in the model.

3. With the current infrastructure, salt intrusion at Rotterdam is determined by the flows on the Lek and Waal. Lek flow depends on the flow in the Neder-Rijn, withdrawals at Tiel, and the flow north on the Amsterdam-Rijnkanaal. This latter flow has a minimum constraint of about 25 m³/s, but more can be required during dry periods. To maintain the Lek and Amsterdam-Rijnkanaal flows, we can either open the weir at Driel (increasing the Neder-Rijn and decreasing the Waal and IJssel flows) or withdraw from the Waal at Tiel. If we open the weir and reduce the amount withdrawn at Tiel correspondingly, we effectively draw water from the IJssel to the Waal. The MSMD uses the cost functions for Waal and IJssel shipping, and for Midwest agricultural damage, with other constraints to determine the optimal policy for any situation.
Appendix A

SHIPPING COST COEFFICIENTS

Chapter 3 discussed how shipping costs per trip could be calculated from an equation of the form:

\[ C = a \times W + b \times T \]

where \( C \) = variable trip cost (Dfl),
\( W \) = waiting time per trip (hr),
\( T \) = sailing time per trip (hr),
\( a \) = cost of waiting time (Dfl/hr),
\( b \) = cost of sailing time (Dfl/hr).

In this equation, the cost coefficients \( a \) and \( b \) vary with the type and size of ship, and include the operating costs of shipping. If we want to consider the total costs of shipping, we must incorporate another term in the equation, as described in Chap. 3.

The 1976 and 1985 variable cost coefficients are shown in Tables A.1 and A.2. The total cost coefficients for the two context years are shown in Tables A.3 and A.4. Note that there are no coefficients for towed barges in 1985; the fleet for that year does not include these ships.
Table A.1

VARIABLE COST COEFFICIENTS (1976)

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<th>Waiting Costs (Dfl/hr)</th>
<th>Type</th>
<th>Class</th>
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<td>0</td>
</tr>
<tr>
<td>Dry cargo (Nat)</td>
<td>4.70</td>
<td>7.17</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>6.70</td>
<td>9.26</td>
</tr>
<tr>
<td>Towed</td>
<td>4.24</td>
<td>6.02</td>
</tr>
<tr>
<td>Tank</td>
<td>5.94</td>
<td>14.91</td>
</tr>
<tr>
<td>Cement</td>
<td>11.60</td>
<td>13.28</td>
</tr>
<tr>
<td>Push/tow(a)</td>
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<td>0.59</td>
</tr>
<tr>
<td>Push/tow (2)(b)</td>
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<td>2.10</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
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<td>1.54</td>
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</table>

<table>
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<th>Sailing Costs (Dfl/hr)</th>
<th>Type</th>
<th>Class</th>
</tr>
</thead>
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<td>Dry cargo (Nat)</td>
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</tr>
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<td>Dry cargo (Int)</td>
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<tr>
<td>Towed</td>
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<td>28.65</td>
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<tr>
<td>Tank</td>
<td>23.02</td>
<td>38.99</td>
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<td>Cement</td>
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<td>42.85</td>
</tr>
<tr>
<td>Push/tow (2)</td>
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<td>8.92</td>
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<tr>
<td>Push/tow (4)</td>
<td>5.64</td>
<td>7.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barge Handling Fees(c) (Dfl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push/tow</td>
</tr>
</tbody>
</table>


(a) Cost per barge while not attached to pusher unit.
(b) Cost per barge when attached to pusher unit, with total number of barges in parentheses.
(c) Cost per barge for loading and unloading in harbors.
Table A.2

VARIABLE COST COEFFICIENTS (1985)

<table>
<thead>
<tr>
<th>Class</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waiting Costs</td>
<td>(Dfl/hr)</td>
<td>Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry cargo (Nat)</td>
<td>9.53</td>
<td>14.21</td>
<td>18.79</td>
<td>23.87</td>
<td>29.15</td>
<td>35.46</td>
<td>51.18</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>13.08</td>
<td>17.97</td>
<td>22.68</td>
<td>27.83</td>
<td>33.15</td>
<td>39.47</td>
<td>55.16</td>
</tr>
<tr>
<td>Tank</td>
<td>11.56</td>
<td>30.36</td>
<td>42.25</td>
<td>54.83</td>
<td>65.66</td>
<td>72.37</td>
<td>88.09</td>
</tr>
<tr>
<td>Cement</td>
<td>23.17</td>
<td>26.32</td>
<td>30.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push/tow (a)</td>
<td>0.85</td>
<td>1.01</td>
<td>1.28</td>
<td>1.53</td>
<td>2.13</td>
<td>3.10</td>
<td>5.30</td>
</tr>
<tr>
<td>Push/tow (2)(b)</td>
<td>1.88</td>
<td>3.76</td>
<td>6.46</td>
<td>8.25</td>
<td>12.22</td>
<td>16.39</td>
<td>24.94</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
<td>1.49</td>
<td>2.74</td>
<td>4.51</td>
<td>5.72</td>
<td>6.73</td>
<td>11.69</td>
<td>17.53</td>
</tr>
</tbody>
</table>

Sailing Costs 
(Dfl/hr)

| Type |  |  |  |  |  |  |  |
| Dry cargo (Nat) | 18.00 | 36.16 | 58.19 | 86.08 | 118.14 | 160.09 | 271.88 |
| Dry cargo (Int) | 22.49 | 41.77 | 64.36 | 88.81 | 122.20 | 179.48 | 285.14 |
| Tank | 39.61 | 68.82 | 89.72 | 120.91 | 154.99 | 196.87 | 266.49 |
| Cement | 64.44 | 75.79 | 90.18 |  |  |  |  |
| Push/tow (2) | 10.29 | 13.65 | 25.22 | 32.68 | 48.85 | 67.03 | 96.16 |
| Push/tow (4) | 8.45 | 10.96 | 20.10 | 26.01 | 37.15 | 53.33 | 76.70 |

Barge Handling Fees(c) 
(Dfl)

| Push/tow | 280.0 | 535.0 | 535.0 | 1107.5 | 1107.5 | 1107.5 | 1197.5 |


(a) Cost per barge while not attached to pusher unit.
(b) Cost per barge while attached to pusher unit, with total number of barges in parentheses.
(c) Cost per barge for loading and unloading in harbors.
Table A.3

TOTAL COST COEFFICIENTS (1976)

<table>
<thead>
<tr>
<th>Waiting Costs</th>
<th>Class</th>
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<tbody>
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</tr>
<tr>
<td>Dry cargo (Nat)</td>
<td>17.19</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>20.92</td>
</tr>
<tr>
<td>Towed</td>
<td>14.12</td>
</tr>
<tr>
<td>Tank</td>
<td>56.92</td>
</tr>
<tr>
<td>Cement</td>
<td>59.01</td>
</tr>
<tr>
<td>Push/tow(a)</td>
<td>2.83</td>
</tr>
<tr>
<td>Push/tow (2)(b)</td>
<td>17.78</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
<td>12.18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sailing Costs</th>
<th>(Dfl/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo (Nat)</td>
<td>23.12</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
<td>27.09</td>
</tr>
<tr>
<td>Towed</td>
<td>34.75</td>
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<tr>
<td>Tank</td>
<td>74.00</td>
</tr>
<tr>
<td>Cement</td>
<td>84.16</td>
</tr>
<tr>
<td>Push/tow (2)</td>
<td>23.58</td>
</tr>
<tr>
<td>Push/tow (4)</td>
<td>16.98</td>
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</table>

<table>
<thead>
<tr>
<th>Barge Handling Fees(c)</th>
<th>(Dfl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push/tow</td>
<td>280.0</td>
</tr>
</tbody>
</table>

*SOURCE:* Ref. A.1.

(a) Cost per barge while not attached to pusher unit.
(b) Cost per barge while attached to pusher unit, with total number of barges in parentheses.
(c) Cost per barge for loading and unloading in harbors.
### Table A.4

TOTAL COST COEFFICIENTS (1985)

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<th>Class</th>
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<th>4</th>
<th>5</th>
<th>6/7</th>
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</thead>
<tbody>
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<td>Dry cargo (Nat)</td>
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<td>35.24</td>
<td>54.52</td>
<td>78.61</td>
<td>108.35</td>
<td>133.92</td>
<td>165.52</td>
<td>248.67</td>
</tr>
<tr>
<td>Dry cargo (Int)</td>
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<td>42.15</td>
<td>64.09</td>
<td>87.48</td>
<td>116.37</td>
<td>145.65</td>
<td>178.40</td>
<td>262.86</td>
</tr>
<tr>
<td>Tank</td>
<td></td>
<td>101.29</td>
<td>174.66</td>
<td>208.86</td>
<td>253.24</td>
<td>288.81</td>
<td>324.17</td>
<td>388.56</td>
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<tr>
<td>Cement</td>
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<td>109.82</td>
<td>137.09</td>
<td>167.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push/tow (a)</td>
<td></td>
<td>4.87</td>
<td>6.31</td>
<td>10.50</td>
<td>13.19</td>
<td>18.97</td>
<td>25.37</td>
<td>35.35</td>
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<tr>
<td>Push/tow (2)(b)</td>
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<td>35.12</td>
<td>44.77</td>
<td>83.21</td>
<td>107.74</td>
<td>160.67</td>
<td>219.17</td>
<td>310.53</td>
</tr>
<tr>
<td>Push/tow (4)(b)</td>
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<td>24.06</td>
<td>30.71</td>
<td>56.52</td>
<td>73.02</td>
<td>108.59</td>
<td>147.91</td>
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<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo (Nat)</td>
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<td>44.32</td>
<td>78.03</td>
<td>120.85</td>
<td>173.13</td>
<td>229.52</td>
<td>299.55</td>
<td>485.98</td>
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<td>87.89</td>
<td>129.17</td>
<td>177.35</td>
<td>234.71</td>
<td>318.42</td>
<td>492.84</td>
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<tr>
<td>Tank</td>
<td></td>
<td>129.33</td>
<td>213.11</td>
<td>256.33</td>
<td>319.33</td>
<td>380.05</td>
<td>448.67</td>
<td>566.96</td>
</tr>
<tr>
<td>Cement</td>
<td></td>
<td>151.09</td>
<td>186.57</td>
<td>227.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push/tow (2)</td>
<td></td>
<td>42.56</td>
<td>53.23</td>
<td>90.40</td>
<td>128.88</td>
<td>192.43</td>
<td>262.72</td>
<td>372.46</td>
</tr>
<tr>
<td>Push/tow (4)</td>
<td></td>
<td>30.65</td>
<td>38.30</td>
<td>71.06</td>
<td>91.98</td>
<td>137.12</td>
<td>187.02</td>
<td>264.92</td>
</tr>
</tbody>
</table>

| Push/Tow              |       | 560.0   | 1110.0  | 1110.0  | 2215.0  | 2215.0  | 2215.0  | 2215.0  |

**SOURCE:** Ref. A.1.

(a) Cost per barge while not attached to pusher unit.

(b) Cost per barge while attached to pusher unit, with total number of barges in parentheses.

(c) Cost per barge for loading and unloading in harbors.

**REFERENCE**

Appendix B

DEVELOPMENT OF LOW WATER LOSS FUNCTIONS

This appendix presents in detail the development of the low water loss functions for shipping. The description includes a summary of the shipping study on which the loss functions are based, and a discussion of the procedures used in converting the study results into final loss functions.

B.1. SHIPPING COST STUDY

The shipping cost study was defined and developed by a special committee composed of personnel from the PAWN project, the Dienst Verkeerskunde (DVK) of the Rijkswaterstaat (RWS), the Nederlands Vervoerswetenschappelijk Instituut (NVI), and the Economisch Bureau voor het Weg- en Watervervoer (EBW). The primary work of the study itself was performed by personnel from the DVK, EBW, and NVI, with assistance from other members of the committee. In this section we will describe the general approach of the study, its primary outputs, and the basic assumptions. A more complete discussion of the study and its results can be found in Ref. B.1.

B.1.1. General Description

The purpose of the study was to investigate and calculate shipping costs for transport of the cargo of an average week in the two years 1976 and 1985. The analysis considered domestic and international transport, including all cargo that entered or exited the Netherlands, even if only in transit.

Shipping costs were calculated for a variety of cases. The cases were distinguished by differences in Rijn flow and water withdrawals on the Waal at Tiel, and the Ijssel at Deventer and Eefde. Also included were three cases specifying reductions in the shipping depth on the Maas. Two sets of costs were computed, total costs (including investment and fixed costs) and variable costs (operating expenses), for each case studied.

The analysis incorporated specifications of the size and composition of the Dutch and international shipping fleets. It included calculations of the type, amount, and cost of storing cargo which could not be transported in those cases in which the fleet capacities were exceeded.

B.1.2. Approach

The approach used by the DVK/NVI/EBW study team is outlined below.
1. **Nature of Shipping Operations.** Data provided by the Centraal Bureau voor de Statistiek (CBS), on shipping during May and June of 1975 and 1976, were used to investigate shipping operations and carrier behavior during high and low flow periods. The purpose of this study was to determine the types of goods carried, the origins and destinations of cargoes, the types and sizes of vessels, and variations in the degree of ship loading.

2. **Basis of Analysis.** The region to be included in the study was specified in terms of 93 districts for loading and unloading cargo (origins and destinations). The shipping fleet was divided into 7 size classes, 4 types, and 27 depth classes. Potential cargoes were partitioned into 14 commodity groups.

3. **Goods Traffic.** The flow of goods for the 1976 context was determined from data provided by the CBS. The goods flow for the 1985 context was derived from a study for the EEC. Predictions were based on a series of models which specify: (a) supply and demand for each commodity group, (b) distribution of goods shipped between all origins and destinations, and (c) the fraction of total shipments transported by ship.

4. **Shipping Fleet.** Registration data for the Dutch and Rijn fleets were used to specify the 1976 shipping fleet. Trend equations and other information were used to develop the description of a 1985 Dutch shipping fleet. The exact size of the 1985 fleet was specified later in the analysis.

5. **Shipping Structure.** On the basis of the transport analysis for 1976 and 1985, the shipping structure for both contexts was specified. This structure describes the number and distribution of loaded trips by ship type, size class, origin, destination, cargo, and normal load factor. In the study, the structure was defined for an average week.

6. **Shipping Networks.** Networks for Northwestern Europe were defined for 1976 and 1985. The networks included relationships between Rijn flow and water depths on the primary rivers and canals.

7. **Required Draft Relationships.** This analysis found functions relating load factor and maximum draft for each type, depth, and size of ship in both fleets.

8. **Water Withdrawal Effects.** EMS models were used to estimate the effect of water withdrawals on shipping depths on the IJssel and Waal. The results included the effects of water level reduction and sedimentation.

9. **Cost Coefficients.** Total and variable (operating) cost coefficients were determined for each type and class of ship for 1976. These costs were adjusted with inflation factors to produce estimates of 1985 coefficients [B.1]. All cost coefficients are shown in App. A.
10. Reference Cases. Based on the shipping structure, models were used to determine the number and distribution of loaded ships on the network for a situation with sufficient water depths in both context years. Canals and canalized waterways assumed their normal depths for these base cases.

11. Flow and Withdrawal Cases. The same models were applied to other cases to calculate the required numbers and distribution of ships by type and size for situations with water level limitations. Each run corresponded to a combination of Rijn flows (800, 1000, 1400, or 2000 m³/s), Maas depth, and withdrawals on the Waal and IJssel. The number of required ships was computed by unloading ships until their drafts were less than or equal to the minimum depths on their routes, loading the remaining cargo onto additional ships of the same type and size.

12. Empty Ships. The number of empty ship trips (backhaul) for each case was estimated from the total number of loaded trips by type and class for each origin and destination. These ships were then added to the network.

13. Ship Traffic. Results from the previous steps were used to calculate ship traffic levels on each link of the network. This information formed the basis for estimating total travel times for all ships, including loading and unloading operations.

14. Shipping Costs. Shipping costs (total and variable) were computed for each run using trip times and the appropriate cost coefficients.

15. Indirect Effects. The required shipping fleet for each case was compared with the existing fleet to determine where capacity restrictions had been exceeded. Where there was too little fleet capacity, costs were calculated for shifting cargo to other vessels or storing it, if no appropriate ships were available. In this calculation, the 1985 fleet size was specified to be that exactly adequate to carry all goods for a Rijn discharge of 1000 m³/s with no withdrawals on the Rijn or IJssel. Rijn flows exceed 1000 m³/s about 90 percent of the time (based on a decade average).

B.1.3. Results

The elemental output of a study run (case) was a trip by a loaded ship. This trip was characterized by five variables, specifically:

- Ship type (4 types).
- Ship size class (7 classes).
- Origin of trip (93 districts).
- Destination of trip (93 districts).
- Cargo type (14 commodity groups).
In addition, each such trip has the following five attributes:

- Number of trips.
- Fraction of trips in Dutch vessels.
- Trip cost (variable or total).
- Round trip time.
- Transported weight.

In presenting the data, the shipping organizations combined the 93 elemental origins and destinations into 14 aggregated areas. In this and subsequent discussions, we will denote the aggregated origins by k, and destinations by l. These will be considered as sets of the elemental origins o and destinations d. In the results, the aggregated areas were:

1. Noord-Nederland (Northern Netherlands)
2. IJssel
3. IJmond (Amsterdam area)
4. Rijnmond (Rotterdam and Europoort area)
5. Oostelijk Noord-Brabant (Eastern Noord-Brabant)
6. Nederlandse Maas (Dutch Maas)
7. Ruhrgebied--Rijn (Ruhr area--Rijn)
8. Ruhrgebied--Kanalen (Ruhr area--canals)
9. Midden-Rijn (Middle Rijn)
10. Boven-Rijn (Upper Rijn)
11. Belgische Havens (Belgian harbors)
12. Belgische Maas (Belgian Maas)
13. Frankrijk (France)
14. Overige (Other, primarily scattered about the Netherlands)

Unless otherwise noted, the term elemental will refer to one of the 93 original districts. Other references to origins or destinations will mean the 14 aggregated areas.

The results of each run (case) were presented as a series of tables, aggregated over different variables. The tables that were used in either the low water loss function or long-run fleet analysis are described below. Unless otherwise stated, all costs will be variable. The primary results for each run included:

- \( SC_{i,j} \) = Cost by ship type i and class j aggregated over origin, destination, and cargo type. See Table B.1 for an example of this output.
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- $C_{k,l}$ = Cost by origin $k$ and destination $l$ aggregated over ship type, class, and cargo type. See Table B.2.

- $LT_{k,l}$ = Loaded trips by origin $k$ and destination $l$ aggregated over ship type, class, and cargo. See Table B.3.

- $DH_{i,j}$ = Utilized capacity of the Dutch fleet by ship type $i$ and class $j$, as total hours per week aggregated over origin, destination, and cargo type. See Table B.4.

- $TH_{i,j}$ = Utilized capacity of the total fleet by ship type $i$ and class $j$, as total hours per week aggregated over origin, destination, and cargo type. See Table B.4.

- $CC_{i,m}$ = Cost by ship type $i$ and cargo type $m$ aggregated over ship class, origin, and destination. See Table B.5.

- $T_{i,j}$ = Mean round-trip time by ship type $i$ and class $j$ averaged over origin, destination, and cargo. See Table B.6.

- $W_{i,j}$ = Mean transported weight by ship type $i$ and class $j$ averaged over origin, destination, and cargo. See Table B.7.

In addition, each run included the total cost of cargo storage and transfer between size classes when fleet capacity was exceeded [B.1].

Table B.1

VARIABLE COSTS BY SHIP TYPE AND CLASS (1976 REFERENCE CASE) (Dfl/
wk)

<table>
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<tr>
<th>Type</th>
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<th>4</th>
<th>5</th>
<th>6/7</th>
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</thead>
<tbody>
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<td>2,348</td>
<td>2,661</td>
<td>2,560</td>
<td>1,324</td>
<td>469</td>
<td>128</td>
</tr>
<tr>
<td>Tow</td>
<td>13</td>
<td>25</td>
<td>51</td>
<td>69</td>
<td>106</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Tank</td>
<td>9</td>
<td>122</td>
<td>146</td>
<td>622</td>
<td>883</td>
<td>709</td>
<td>176</td>
</tr>
<tr>
<td>Push/tow</td>
<td>0</td>
<td>38</td>
<td>16</td>
<td>90</td>
<td>194</td>
<td>528</td>
<td>336</td>
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### Table B.4
VARIABLE COSTS BY AGGREGATED ORIGINS AND DESTINATIONS (1976 REFERENCE CASE)  
[DIRT/WK]

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<th>Origin(a)</th>
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<th>6</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>46.621</td>
<td>1.211</td>
<td>3.996</td>
<td>35.667</td>
<td>0.328</td>
<td>3.047</td>
<td>1.262</td>
<td>36.533</td>
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<td>19.923</td>
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<td>28.162</td>
<td>0.283</td>
<td>32.241</td>
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<td>75.223</td>
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<td>1.280</td>
<td>8.077</td>
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<td>0.0</td>
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<td>25.549</td>
<td>23.274</td>
<td>23.528</td>
<td>32.465</td>
<td>21.772</td>
<td>56.054</td>
<td>49.891</td>
<td>20.870</td>
</tr>
</tbody>
</table>

(a) Origin and destination areas are numbered as in the text.

### Table B.5
LOADED TRIPS BY AGGREGATED ORIGINS AND DESTINATIONS (1976 REFERENCE CASE)  
[TRIPS/WK]

<table>
<thead>
<tr>
<th>Origin(a)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>50.80</td>
<td>1.28</td>
<td>6.05</td>
<td>11.37</td>
<td>0.27</td>
<td>0.98</td>
<td>0.77</td>
<td>15.85</td>
</tr>
<tr>
<td>2</td>
<td>29.11</td>
<td>18.62</td>
<td>2.18</td>
<td>21.08</td>
<td>0.31</td>
<td>0.0</td>
<td>0.96</td>
<td>2.69</td>
</tr>
<tr>
<td>3</td>
<td>51.34</td>
<td>15.70</td>
<td>51.94</td>
<td>24.47</td>
<td>8.83</td>
<td>5.21</td>
<td>12.68</td>
<td>17.83</td>
</tr>
<tr>
<td>4</td>
<td>71.62</td>
<td>40.80</td>
<td>49.68</td>
<td>30.30</td>
<td>87.69</td>
<td>47.39</td>
<td>37.08</td>
<td>120.96</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>0.21</td>
<td>8.16</td>
<td>10.22</td>
<td>3.52</td>
<td>1.13</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>23.00</td>
<td>12.60</td>
<td>32.61</td>
<td>31.49</td>
<td>37.29</td>
<td>31.80</td>
<td>1.53</td>
<td>1.80</td>
</tr>
<tr>
<td>7</td>
<td>77.68</td>
<td>72.00</td>
<td>20.25</td>
<td>110.38</td>
<td>12.60</td>
<td>3.84</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>2.67</td>
<td>1.97</td>
<td>3.60</td>
<td>13.32</td>
<td>14.19</td>
<td>1.30</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>12.20</td>
<td>9.88</td>
<td>13.44</td>
<td>84.04</td>
<td>12.95</td>
<td>6.98</td>
<td>0.04</td>
<td>0.30</td>
</tr>
<tr>
<td>10</td>
<td>26.30</td>
<td>9.19</td>
<td>1.62</td>
<td>7.11</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>11</td>
<td>16.49</td>
<td>12.31</td>
<td>7.95</td>
<td>60.17</td>
<td>31.05</td>
<td>16.47</td>
<td>40.61</td>
<td>34.10</td>
</tr>
<tr>
<td>12</td>
<td>23.60</td>
<td>6.64</td>
<td>8.69</td>
<td>26.23</td>
<td>22.31</td>
<td>32.84</td>
<td>8.62</td>
<td>2.39</td>
</tr>
<tr>
<td>13</td>
<td>13.20</td>
<td>13.14</td>
<td>16.67</td>
<td>25.27</td>
<td>21.58</td>
<td>20.35</td>
<td>32.02</td>
<td>11.77</td>
</tr>
<tr>
<td>14</td>
<td>148.70</td>
<td>14.37</td>
<td>246.32</td>
<td>139.56</td>
<td>66.71</td>
<td>24.40</td>
<td>16.91</td>
<td>8.99</td>
</tr>
</tbody>
</table>

(a) Origin and destination areas are numbered as in the text.
Table B.4

UTILIZED FLEET CAPACITY BY SHIP TYPE AND CLASS (1976 REFERENCE CASE)  
(hr/wk)

<table>
<thead>
<tr>
<th>Type</th>
<th>Class</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dutch fleet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry cargo</td>
<td></td>
<td>19,215</td>
<td>124,527</td>
<td>110,676</td>
<td>63,805</td>
<td>16,953</td>
<td>3,865</td>
<td>1,099</td>
</tr>
<tr>
<td>Tow</td>
<td></td>
<td>1,121</td>
<td>1,391</td>
<td>2,763</td>
<td>3,721</td>
<td>2,709</td>
<td>1,761</td>
<td>2,450</td>
</tr>
<tr>
<td>Tank</td>
<td></td>
<td>628</td>
<td>2,512</td>
<td>2,509</td>
<td>5,571</td>
<td>5,164</td>
<td>4,945</td>
<td>683</td>
</tr>
<tr>
<td>Push/tow</td>
<td></td>
<td>0</td>
<td>2,186</td>
<td>1,317</td>
<td>3,660</td>
<td>5,246</td>
<td>11,933</td>
<td>5,834</td>
</tr>
<tr>
<td><strong>Total fleet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry cargo</td>
<td></td>
<td>19,405</td>
<td>163,993</td>
<td>130,059</td>
<td>90,064</td>
<td>37,734</td>
<td>9,276</td>
<td>1,825</td>
</tr>
<tr>
<td>Tow</td>
<td></td>
<td>1,151</td>
<td>1,669</td>
<td>2,932</td>
<td>3,835</td>
<td>3,949</td>
<td>2,563</td>
<td>2,745</td>
</tr>
<tr>
<td>Tank</td>
<td></td>
<td>631</td>
<td>4,326</td>
<td>4,000</td>
<td>11,866</td>
<td>12,914</td>
<td>8,810</td>
<td>1,518</td>
</tr>
<tr>
<td>Push/tow</td>
<td></td>
<td>44</td>
<td>4,607</td>
<td>1,757</td>
<td>5,885</td>
<td>11,405</td>
<td>25,915</td>
<td>12,748</td>
</tr>
</tbody>
</table>

Table B.5

VARIABLE COSTS BY COMMODITY AND SHIP TYPE (1976 REFERENCE CASE)  
(Drift/wk)

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Type of Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Cargo</td>
</tr>
<tr>
<td>Raw agricultural goods</td>
<td>1,791,100</td>
</tr>
<tr>
<td>Foods</td>
<td>173,494</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>375,727</td>
</tr>
<tr>
<td>Sand and gravel</td>
<td>4,208,664</td>
</tr>
<tr>
<td>Ores</td>
<td>536,315</td>
</tr>
<tr>
<td>Chemical products</td>
<td>271,805</td>
</tr>
<tr>
<td>Steel products</td>
<td>1,053,605</td>
</tr>
<tr>
<td>Agricultural products</td>
<td>123,387</td>
</tr>
<tr>
<td>Coal</td>
<td>477,462</td>
</tr>
<tr>
<td>Crude oil</td>
<td>0,0</td>
</tr>
<tr>
<td>Oil products</td>
<td>103,038</td>
</tr>
<tr>
<td>Cement</td>
<td>256,831</td>
</tr>
<tr>
<td>Building materials</td>
<td>44,544</td>
</tr>
<tr>
<td>Other</td>
<td>410,097</td>
</tr>
</tbody>
</table>

Table B.6

MEAN ROUND-TRIP TIME BY SHIP TYPE AND CLASS (1976 REFERENCE CASE)  
(hr/trip)

<table>
<thead>
<tr>
<th>Type</th>
<th>Class</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo</td>
<td></td>
<td>55.08</td>
<td>73.90</td>
<td>72.12</td>
<td>83.16</td>
<td>100.54</td>
<td>92.45</td>
<td>89.23</td>
</tr>
<tr>
<td>Tow</td>
<td></td>
<td>60.69</td>
<td>66.33</td>
<td>73.50</td>
<td>65.98</td>
<td>115.25</td>
<td>106.01</td>
<td>76.20</td>
</tr>
<tr>
<td>Tank</td>
<td></td>
<td>33.04</td>
<td>54.13</td>
<td>47.49</td>
<td>62.03</td>
<td>69.29</td>
<td>54.09</td>
<td>68.33</td>
</tr>
<tr>
<td>Push/tow</td>
<td></td>
<td>101.64</td>
<td>98.34</td>
<td>100.64</td>
<td>109.45</td>
<td>152.58</td>
<td>135.77</td>
<td>123.67</td>
</tr>
</tbody>
</table>
Table 3.7
TRANSPORTED WEIGHT BY SHIP TYPE AND CLASS (1976 REFERENCE CASE)
(tons)

<table>
<thead>
<tr>
<th>Type</th>
<th>Class 0</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
<th>Class 5</th>
<th>Class 6/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry cargo</td>
<td>131.2</td>
<td>293.4</td>
<td>495.1</td>
<td>802.9</td>
<td>1,089.3</td>
<td>1,516.9</td>
<td>2,584.3</td>
</tr>
<tr>
<td>Tow</td>
<td>97.6</td>
<td>255.7</td>
<td>496.4</td>
<td>757.5</td>
<td>1,140.4</td>
<td>1,859.2</td>
<td>2,576.4</td>
</tr>
<tr>
<td>Tank</td>
<td>142.2</td>
<td>306.6</td>
<td>484.1</td>
<td>846.3</td>
<td>1,145.4</td>
<td>1,745.3</td>
<td>2,313.2</td>
</tr>
<tr>
<td>Push/tow</td>
<td>105.0</td>
<td>295.2</td>
<td>552.2</td>
<td>722.4</td>
<td>1,325.9</td>
<td>1,741.5</td>
<td>2,596.0</td>
</tr>
</tbody>
</table>

B.1.4. Assumptions

The participants made several important assumptions in the study, in addition to those either stated or implied in the summary of the general approach above. These assumptions were:

1. Routes were assigned on an "all or nothing" basis. This means that, for a given elemental origin and destination, if a route had the lowest cost for a specific type and size of ship, all ships of that type and size would use the route, although costs might increase with congestion.
2. Routes for all ships remained unchanged from those in the reference case, even though flows and withdrawals reduced water depths.
3. Stream velocity changes caused by reduced flows were not important to shipping costs.
4. The cargo table remained constant in a given context, thus modal split choices did not change with rising costs.
5. Canals and canalized waterways had constant depth.
6. Keel clearances were 30 cm, except for push/tows, whose clearances varied between 35 and 50 cm.
7. The depth of the Maas was uniform along its length.
8. Locks at weirs on the Neder-Rijn and Maas were always used.
9. Capacity restrictions in the European (total) fleet were the same as those in the Dutch fleet (by type and size of ship).
10. The cost of shipping goods which must be stored was included in the cost for the week in which they were stored. The cost was calculated under the conditions which existed at that time.
11. Dutch ships carry all domestic goods. No Dutch ships (registered in the Netherlands) carry goods only in foreign countries.

B.2. LOSS FUNCTION DEVELOPMENT

This section outlines the procedure used to convert the results of the shipping study into low water loss functions. Certain aspects of this procedure will be discussed further in later sections.
1. Critical Points. The major critical points in the network were determined. These areas are important in limiting ship load factors and have variable depths (as a result of flow variations or PAWN tactics). A preliminary set of ten critical points was specified, as shown in Fig. 4.1. These critical points were:

1. The Upper Rijn in Germany between Bingen and Mainz.
2. The Lower Rijn in Germany between Duisburg and Cologne.
3. The Panmerdersche Kanaal.
4. The Waal between Tiel and St. Andries. This point has the minimum of the depths below withdrawal points at Tiel and St. Andries.
5. The Neder-Rijn between IJsselkop and Driel.
6. The entire Meuse, because it has uniform depth in the study models.
7. The IJssel between Doesburg and the Twenthekanaal entrance.
8. The IJssel between the Twenthekanaal entrance and Deventer.
9. The IJssel between Deventer and Harculo.
10. The IJssel between Harculo and IJsselmmond.

2. Minimum Shipping Depth. The shipping depth was determined at each critical point for each study run, using information provided by the study.

3. Cost Matrices. As part of the study output, we requested variable and total shipping costs by elemental origin-destination pair for two cases in each context. These cases were the reference case and the base case (no withdrawals) for a Rijn flow of 800 m$^3$/s. A route was assigned to each nonzero element of these 93-by-93 cost matrices. These routes were chosen as the minimum cost alternatives from the network description, because the shipping study had neither retained nor provided route information.

Where two or more alternative routes were possible, the cost changes between the two runs (cases) were used to resolve the uncertainty. If the cost for a particular elemental origin-destination pair increased significantly between the reference and 800 m$^3$/s cases, the correct route most likely changed its minimum depth considerably. This criterion was usually sufficient to enable us to choose between possibilities. For future discussion, we will denote the costs from these elemental matrices as $C'_{o,d}$ for elemental origin $o$ and destination $d$.

4. Critical Point Vectors. To each route between elemental origin-destination pairs, we assigned a 10-element vector that specified which critical points the route passed. An element had the value 1 if the critical point was passed and 0 if it was not, with the critical points considered in the order listed above. Thus, a route from the Upper Rijn down the Rijn and IJssel to the IJsselmeer would have the critical point vector (1110001111).

One can consider each unique critical point vector to be a distinct shipping route. Consequently, all elemental routes with the same vector can be considered identical and aggregated in the analysis. In
1976 there were 42 unique vectors, and this increased to 45 in 1985, including the zero vector for all routes passing no critical points.

5. Minimum Shipping Depth per Route. Study information was used to find the minimum shipping depth for each critical point vector for each run of the shipping study.

6. Route Cost Fractions. To develop the loss functions, it was necessary to calculate the costs for each run associated with each shipping route. However, the output cost matrix $C_{k,1}$ was specified in terms of the aggregated origins and destinations, and thus each cost element might represent several routes. Consequently, we had to determine what fraction $f_{k,1,n}$ of the cost $C_{k,1}$ between origin $k$ and destination $l$ applied to each route (critical point vector) $n$. Using the elemental cost matrices $C'_{o,d}$ from step 3 above, it was possible to calculate the fractions for each case (reference and 800 m$^3$/s) in each context. These fractions are given by

$$f_{k,1,n} = \frac{\sum_{o \in k} \sum_{d \in l} C'_{o,d} \times \delta_{o,d,n}}{C_{k,1}}$$

where $\delta_{o,d,n} = \begin{cases} 
1 & \text{if the route between elemental origin } o \text{ and destination } d \text{ corresponds to } n, \\
0 & \text{otherwise.}
\end{cases}$

The values of $f_{k,1,n}$ were not always the same for the two runs in each context. However, because the differences between the reference (high flow) and 800 m$^3$/s (low flow) cases were small, it was reasonable to take the average of the two.

7. Cost per Vector. Using the fractions from the above step, it was possible to calculate the cost $VC_n$ for each critical point vector (route) $n$ for each run from

$$VC_n = \sum_k \sum_l C_{k,1} \times f_{k,1,n}$$

8. Critical Point Reduction. This route cost information indicated that it would be possible to reduce the number of critical points without significantly changing the results. Many of the vectors had negligible costs and could be combined with similar vectors that had much larger costs. The ten critical points were thus reduced to five in the following manner:
a. The two points on the Rijn outside the Netherlands were retained.
b. The Neder-Rijn was eliminated, because the cost for ship traffic using it was small compared with that for traffic on other routes.
c. The Maas was retained.
d. The Waal was retained as the minimum depth of the two withdrawal locations, St. Andries and Tiel.
e. The four points on the IJssel were reduced to one, the area at the entrance to the Twenthekanal. This point is limiting for all but a small fraction of the IJssel traffic, and its depth is affected by withdrawals for the Twenthekanal.
f. The Pannerdensch Kanaal was eliminated because its depth is generally greater than the depth on the IJssel critical point. With the elimination of the Neder-Rijn traffic, it would not be limiting for a significant amount of shipping. The depth for the IJssel critical point was adjusted to account for the cases in which the Pannerdensch Kanaal would limit.

9. Revised Shipping Routes. With only five critical points, shipping routes could be recombined using the reduced vectors. New shipping costs per run could be determined by combining all costs for the original 10-element vectors, which reduced to the same 5-element final vector. Minimum shipping depths were also determined for the remaining revised routes.

10. Major Route Selection. To facilitate computation with the DM and MSIM, the remaining routes were ranked by cost, and the seven most important selected. The remaining minor routes were combined with the fixed cost routes (zero critical point vector) to create a fixed cost term.

11. Shipping Cost Curves. For each major shipping route from the above step, we plotted the cost in a given run against the corresponding minimum critical point depth. Figure 5.1 shows an example of the results for the Upper Rijn - Waal route in the 1976 context. In the figure, each point represents the results of one run of the shipping study. As the figure makes clear, these curves contained some scatter from approximations in the original study and our subsequent processing. To obtain the loss functions, we drew a smooth curve through the points, as shown.

The variable cost loss function curves for all shipping on the seven routes in 1976 are presented in Figs. B.2 and B.3. The 1985 context curves are shown in Figs. B.4 and B.5. The 1985 results are deflated to 1976 prices, as described later, so that all costs are in 1976 Dfl.
Fig. 8.2 -- Low water loss functions (1976)(group 1)
Fig. B.3 — Low water loss functions (1976)(group 2)
Fig. B.4 -- Low water loss functions (1985) (group 1)
Fig. B.5 -- Low water loss functions (1985) (group 2)
B.3. MINIMUM SHIPPING DEPTH CALCULATION

In order to use the low water loss functions in the analysis, we had to be able to calculate the shipping depth at each critical point in the network. This required developing functions relating these depths to flows and withdrawals on the waterways. This section will discuss these functions and their derivation.

B.3.1. Flow-Depth Relationships

The derivations in this section do not apply to the Maas. Because it is canalized, the shipping depth in each section can be controlled, so long as there is adequate water to maintain it. For this reason, it is not possible to derive shipping depths as a function of flow. Instead, the depth in each section of the river was calculated in the DM and NSIM, based on the water balance calculations for each of the sections between lock complexes and weirs. The minimum shipping depth on the Maas was chosen to be the overall minimum depth of the sections.

The basic relationships between flow and depth for the remaining critical points were derived from the input data used in the shipping cost study. These data were available as minimum shipping depths on the various links of the network for the four Rijn flows considered in the analysis (800, 1000, 1400, and 2000 m³/s). This information already incorporated the keel clearance automatically, so it was not necessary to determine corrections for it. The relevant flows at the critical points were calculated using the Rijn discharge and formulas for the water distribution between Rijn branches, given the known weir operating policy.

With this information, one can plot the shipping depth versus flow for each of the critical points. When this was done, it was clear that all but one of the relationships could be closely approximated by linear functions. Table B.8 shows the flow and depth data, and the final functions are given below. The graph for the Upper Rijn is given in Fig. 4.11.

\[
\begin{align*}
\text{Lower Rijn} & & D_{lr} &= 8.7 + 0.014 \times F_{lr} \\
\text{Waal (Tiel)} & & D_{wt} &= 6.0 + 0.023 \times F_{wt} \\
\text{Waal (St. Andries)} & & D_{ws} &= 12.9 + 0.018 \times F_{ws} \\
\text{IJssel} & & D_{ij} &= 3.4 + 0.092 \times F_{ij}
\end{align*}
\]

where \( D \) = minimum shipping depth (dm),
\( F \) = flow before withdrawals (m³/s).
Note again that the flow at St. Andries will not necessarily equal the flow at Tiel, because of withdrawals and discharges between the two locations.

Table B.8
CRITICAL POINT DEPTH AS A FUNCTION OF FLOW

<table>
<thead>
<tr>
<th>Flow (m³/s)</th>
<th>Upper</th>
<th>Lower</th>
<th>Depth (dm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rijn</td>
<td>Rijn</td>
<td>Tiel</td>
</tr>
<tr>
<td>800</td>
<td>602</td>
<td>113</td>
<td>17</td>
</tr>
<tr>
<td>800</td>
<td>619</td>
<td>126</td>
<td>17</td>
</tr>
<tr>
<td>800</td>
<td>636</td>
<td>139</td>
<td>17</td>
</tr>
<tr>
<td>1000</td>
<td>746</td>
<td>169</td>
<td>19</td>
</tr>
<tr>
<td>1000</td>
<td>762</td>
<td>183</td>
<td>19</td>
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<tr>
<td>1000</td>
<td>780</td>
<td>195</td>
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<tr>
<td>1400</td>
<td>1052</td>
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</tr>
<tr>
<td>1400</td>
<td>1058</td>
<td>285</td>
<td>22</td>
</tr>
<tr>
<td>2000</td>
<td>1335</td>
<td>291</td>
<td>24</td>
</tr>
</tbody>
</table>

B.3.2. Withdrawal Relationships

When water is withdrawn from a river, there are two separate factors which reduce the downstream depth. First is an immediate drop in water level caused by the reduced flow downstream of the withdrawal point. This is the effect we are most concerned with here. Second is the delayed increase in bottom height caused by sedimentation downstream. Although this is a potentially serious problem, it has not been considered in the loss function development. Separate sedimentation loss functions have been derived and are discussed in Chap. 4.

On the Waal, we have been concerned with tactics involving large withdrawals at both Tiel and St. Andries. Computer models exist which calculate the effects of withdrawals at these locations. These models were developed by the RWS, and have been used in the sedimentation and dredging analysis for the project (see Vol. XVIII). A summary of the Tiel model and its application can be found in Ref. B.2.

We used information in Ref. B.2 to develop an equation for the water level reduction at Tiel. This equation was then simplified to a linear relationship to facilitate incorporation into the MSDM and DM. The original equation and linear approximation are:

General equation: \[ dD_{wt} = 30 \times F_{wt}^{(-0.345)} \times Q_{wt}/100 \]

Linear equation: \[ dD_{wt} = 0.03 \times Q_{wt} \]
where $dD =$ depth reduction (dm),

$F =$ flow before withdrawals ($m^3/s$),

$Q =$ withdrawal rate ($m^3/s$).

In the flow range of interest, $F_{WT}^{(-0.345)}$ is approximately constant, at least to the accuracy of the other data in the depth calculations.

For the depth reduction at St. Andries, we fit a curve to the results of the computer model. This curve was then approximated with a linear relationship. These equations are:

**General equation:**

$$dD_{WS} = 268 \times Q_{WS}^{0.77} \times F_{WS}/50$$

**Linear equation:**

$$dD_{WS} = 0.0526 \times Q_{WS} - 0.00126 \times F_{WS}$$

where $dD =$ depth reduction (dm),

$F =$ flow before withdrawals ($m^3/s$),

$Q =$ withdrawal rate ($m^3/s$).

For withdrawals on the IJssel at Eefde and Deventer, the problem was more difficult. There are no existing computer models of the process at either location, so only the shipping study input data were available. These numbers were approximate calculations done by the RWS. They were inexact and subject to large rounding errors, because the depth reductions were small in comparison with the size of the depth units. Eliminating the three downstream IJssel critical points caused an additional problem. Withdrawals at Deventer are below the remaining IJssel critical point and should not logically affect its depth.

Using the input data for the study, we developed an approximate relationship for the immediate depth reduction. This equation is:

$$dD_{ij} = 0.10 \times (Q_e + 0.5 \times Q_d)$$

where $dD_{ij} =$ depth reduction (dm),

$Q_e =$ withdrawal rate at Eefde ($m^3/s$),

$Q_d =$ withdrawal rate at Deventer ($m^3/s$).

This equation is independent of the flow on the IJssel, and combines the withdrawals at the two locations. Because of the rounding errors,
the effect of withdrawals at Deventer is not consistent, either alone or in conjunction with withdrawals at Eefde. The multiplier of 0.5 for Deventer considers the net result of the withdrawals and the reduced ship traffic affected by them.

The uncertainty and possible errors introduced by this approximation were not important to the analysis. The maximum withdrawal at Deventer was about 3 m³/s, producing a shipping depth reduction of 0.15 dm. This occurred only in the worst decade of the cases run with the extremely dry external supply scenario (DEX) and should be small compared with other errors in the river depth calculations. The maximum cost associated with this reduction would be about 165,000 Dfl, but the error would most likely be less. Under more normal conditions, the withdrawals and costs are far smaller. Thus the errors in this function should have negligible effects.

B.4. STORAGE AND TRANSFER COSTS

B.4.1. Cost Allocation

The final step in developing low water loss functions was to devise a method of determining storage costs for a general case. Using the storage and cargo transfer costs from the study runs, it is possible to partition the costs into nonlinear functions of the Waal and IJssel minimum shipping depths, using the following procedure:

1. Plot the study run storage costs versus IJssel depth (for each year), connecting points with constant Waal depths.
2. Draw a smooth curve through the points (as well as possible), being careful to maintain the correct slope in each area of the graph.
3. Subtract the storage cost (from the smooth curve) for the appropriate IJssel depth from the calculated storage cost for each run and plot remaining costs against the Waal depths.
4. Draw smooth curves through these points (for each year).

This procedure was selected after preliminary analysis indicated that the process would be reasonable, and that other schemes were not feasible for a variety of reasons. The storage cost curves for 1985 are shown in Fig. B.6. The curves for the 1976 context are presented in Fig. B.7.

Although storage costs are a function of both low Rijn flows and withdrawals on the Waal and IJssel, Rijn flows are undoubtedly most important. In the separation procedure, the IJssel probably draws some of the storage costs that should be assigned to the Waal, because Rijn and IJssel depths are highly correlated, but IJssel shipping is much smaller. However, this is not as important as it might seem, for two reasons. First, withdrawals on the IJssel are relatively small
Fig. B.6 -- Storage cost functions (1985)
Fig. B.7 -- Storage cost functions (1976)
and will not seriously affect storage costs. Second, large errors would only arise if the IJssel depth were small and the Waal depth large. Without IJssel canalization, this situation is infeasible with current and contemplated infrastructure.

B.4.2. Calculation Errors and Cost Accumulation

Section 4.6 discussed the storage assumptions used in the shipping cost study. It also listed some of the factors that would determine which commodities might actually be stored during periods of insufficient fleet capacity. This is an especially important problem, particularly for the 1985 context, which has large storage costs in DEX cases. It is important because the choice of commodity will strongly affect storage costs and how they should be treated in the analysis.

The storage cost coefficients by type of commodity for 1976 and 1985 are given in Table B.9. The table does not specifically identify sand and gravel, however, and it is unlikely that these materials would be included in "remaining products," which have very high costs. It is more reasonable to assume that the costs of storing sand and gravel would be extremely low (if not zero), because they could simply be left in place if not shipped. In contrast, ores are not locally mined, but come in by ship at Rotterdam.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>1976</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil products</td>
<td>0.10</td>
<td>0.17</td>
</tr>
<tr>
<td>Ore</td>
<td>0.02</td>
<td>0.025</td>
</tr>
<tr>
<td>Coal and cement products</td>
<td>0.025</td>
<td>0.045</td>
</tr>
<tr>
<td>Food and agricultural products</td>
<td>0.20</td>
<td>0.35</td>
</tr>
<tr>
<td>Remaining products</td>
<td>0.25</td>
<td>0.425</td>
</tr>
</tbody>
</table>

SOURCE: Ref. B.1.

The shipping study assumed that the following commodities would be stored: (1) food and agricultural products for dry cargo ships, (2) oil products for tankers, and (3) ore for push/tows. They must, therefore, have assumed that sand and gravel would always be carried. It is more likely, particularly in prolonged low water periods, that sand and gravel would be stored whenever possible, and that the higher value products would be transported. This would have several advantages: (1) reducing storage costs, (2) increasing effective storage capacity, and (3) reducing delay costs arising from such problems as spoilage and process interruption. There would be delay costs associated with sand and gravel transport interruption, but it
seems likely that these would be less than the costs for other goods used by industry.

It might be argued that there are other factors than economics that dictate which products are stored. There are several objections to this position, though. Sand and gravel are carried in large amounts in both the domestic and international markets. Within the Netherlands, as we discussed in Chap. 8, these materials are a major commodity in both the "special" and "shippers bourse" sectors. Even though some of the transport capacity for dry cargo might be tied up in longer-term contracts in the various markets, not all of it would be, and contracts are only for one trip under the bourse. Thus, one could reasonably expect that a large part of the fleet that carries sand and gravel would be available to carry other goods during low water periods, particularly if shipping rates are higher for these other products.

If we accept the above arguments that ships are more likely to forgo sand and gravel transport in favor of goods with higher storage and delay costs, how does this affect storage costs? When the storage calculations are revised on this basis, assuming that sand and gravel are stored first, the costs are reduced by almost a factor of ten for the runs in the 1985 context. It would seem, therefore, that the assumptions made in the study are unduly pessimistic, and lead to unrealistically high storage costs.

The uncertainties inherent in the entire storage situation make it difficult to say anything reasonable about storage costs. Consequently, we chose not to revise the storage cost calculations. Moreover, as mentioned in Chap. 4, the DM did not accumulate these costs over time, because it did not prove feasible to develop a model of unused fleet capacity. Such a model would be necessary to remove accumulated goods from storage as water levels improved after a prolonged dry period. We should note that the lack of accumulation could somewhat offset the overestimation of costs. It is difficult to say which would be larger in an extremely dry year, but it is unlikely that the real storage costs would be much higher.

B.5. COST COEFFICIENT INFLATION

The 1985 study runs were made with cost coefficients developed for that year by the NVI and E&W. We chose, however, in PANN, to express all costs in terms of 1976 guilders. It was therefore necessary to deflate the study costs before developing the 1985 shipping loss functions. This was done as follows:

1. The 1976 and 1985 shipping cost coefficients were used to determine inflation factors by ship type i and class j for waiting \( w_{i,j} \) and sailing \( s_{i,j} \) costs. We denote the cost coefficients for waiting and sailing by \( a_{i,j} \) and \( b_{i,j} \).
2. Using the cost data $SC_{i,j}$ and total hours $TH_{i,j}$ by type $i$ and class $j$ of ship for a typical shipping study run (1400 m$^3$/s) in the 1985 context, we calculated mean cost coefficients $m_{i,j}$ from

$$m_{i,j} = \frac{SC_{i,j}}{TH_{i,j}}$$

Comparing these values with the variable cost coefficients, we could estimate the relative fraction of sailing $sf_{i,j}$ and waiting $wf_{i,j}$ hours by solving

$$sf_{i,j} + wf_{i,j} = 1$$
$$a_{i,j} \times wf_{i,j} + b_{i,j} \times sf_{i,j} = m_{i,j}$$

3. A mean inflation factor $im_{i,j}$ can then be calculated by taking an average of the sailing and waiting inflation factors weighted by the relative amounts of sailing and waiting time, as follows:

$$im_{i,j} = wf_{i,j} \times iw_{i,j} + sf_{i,j} \times is_{i,j}$$

4. The overall inflation factor for the run can be estimated as a weighted average of ship type and class inflation factors, where the weights are the variable costs by type and class for the run. The equation for this procedure would be

$$ti = \sum_i \sum_j \frac{im_{i,j} \times SC_{i,j}}{\sum_i \sum_j SC_{i,j}}$$

5. Finally, this inflation factor $ti$ can be applied to each 1985 run in order to reduce the variable costs to approximate 1976 levels.

The shipping study organizations had run a 1985 case using the 1976 cost coefficients during their total cost analysis, in order to
estimate a mean inflation factor. They did not do this for the variable cost cases, however. Otherwise, the above procedure would not have been necessary. The variable cost inflation factor that we calculated (0.558) did not differ substantially from their total cost inflation factor (0.550).

B.6. SUGGESTED IMPROVEMENTS AND ANALYSIS

The discussion of the low water loss functions emphasizes many of the assumptions and simplifications required by budget and time constraints. Were this analysis to be repeated and expanded, it could be improved in several respects, including the following procedures:

- Use incremental loading of ships on the network in the shipping study, rather than the "all or nothing" approach.
- Permit ships to change routes as water conditions change between cases.
- Investigate the foreign fleet to improve its description and incorporation into the analysis.
- Study the storage situation for inland transport, including costs, types of goods stored, availability of facilities, and alternatives.
- Incorporate dynamic features into the shipping models used by the NVI and EBW.
- Integrate the loss function development into the study models.

Some of these changes would be much more difficult than others, but all would contribute to improving the results. Modifications of the study models to calculate shipping costs by route directly for each case would by itself permit generating more accurate loss functions for as many routes as desired. It would also allow the study to consider a larger number of critical points, and would remove a major source of uncertainty in the results.

Given a better understanding of the storage situation, it should also be possible to improve the cost calculations. This would include developing a procedure for calculating unused fleet capacity, in order to properly aggregate storage costs over time. Such aggregation calculations would require a thorough understanding of the types of goods stored, however, to properly match the unused fleet with the goods that it could transport.

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Waal bij Tiel op de Bodemligging, Bepaald m.b.v. een
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Mathematical Model), Nota 76.5, Arnhem, December 1976.
Appendix C

PROBABILITY OF SHIPPING LOSSES

C.1. BACKGROUND

During the PAWN analysis, we needed to develop external supply scenarios (river flows, rainfall, and evaporation) to be used in evaluating potential water management policies. Part of the screening process involved assigning probabilities to these scenarios, in order to obtain a value for the expected annual benefits of tactics. These probabilities were based on agricultural losses from water shortage and excess salinity. They were determined by methods described in Vol. II.

One result of that analysis was cumulative distribution functions for agricultural damage. The functions ranked 47 years (1930-1976) on the basis of their total agricultural losses (shortage or salinity) during the year. These rankings provided a probability location for each year and, by extension, for the external supply characteristics of that year. Thus the rankings could be used to assign probabilities to the scenarios.

The same problem might be posed for shipping losses. Dutch shipping authorities acknowledge that 1976 was an extremely damaging year for shipping operations. No one, however, has attempted to measure the extent of the losses, or to compare them with other recent dry years. Shipping losses depend primarily on river flows, not precipitation and evaporation, so we would not necessarily expect the results to be similar to those for agriculture. An independent investigation of the distribution of shipping losses would therefore be useful, and could provide information on many questions, including:

- How well correlated are losses to agriculture and shipping?
- Do the external supply probabilities derived from agricultural losses agree with those obtained from shipping calculations?
- What level of shipping losses can be expected in any given year?
- What external supply characteristics are most important in determining shipping losses?

Development of the low water loss functions made this type of investigation possible. One can obtain a distribution of shipping losses using the loss functions in conjunction with historical external supply data. With this information, it is possible to assign probabilities to the various external supply scenarios, and to address other important questions about low water shipping losses.
C.2. ANALYSIS PROBLEMS AND PROCEDURES

The analysis used a simplified version of the management strategy design model, which is described in Vol. V. This model was constructed to incorporate the MSDM strategy in the impact assessment analysis. The simplified program accepts values for the Rijn flow at Lobith and distributes the water according to certain rules, based on a selected distribution policy, the demands of agriculture, and a set of parameters describing initial conditions and net precipitation for the decade.

Values for the initial conditions and net precipitation create some uncertainty in the analysis. Water distribution in the network depends on how much water is available for agriculture from sources other than the rivers (primarily precipitation and storage in the IJsselmeer). If there is adequate rainfall or stored water available for use in the northern area of the Netherlands, less flow will be necessary in the Ijssel. On the other hand, if it is a dry period and there is not sufficient water stored in the IJsselmeer, more flow in the Ijssel is needed. In either case, the distribution of water between the Rijn branches, and the resulting shipping costs on all routes, will be affected.

It was not obvious whether the shipping cost distribution should be developed using actual net precipitation and storage data for each year or standardized conditions. Although river flow scenarios have the strongest influence on shipping costs, one cannot ignore the agricultural demands for water. In the end, however, two arguments for standardized conditions decided the question. First, time and data about actual net precipitation and storage were limited. Second, we suspected that, although these factors would affect the results, they would be unimportant except under rare and stressful conditions. The results confirmed this expectation.

The analysis was performed using data on mean Rijn flow per decade for the years 1930 - 1976 and two alternative sets of initial conditions. These alternatives consisted of combinations of wet (+11 mm of net precipitation) and dry (-96 mm) decades with a high initial IJsselmeer level (NAP - 20 cm). We did not include a low initial IJsselmeer level (NAP - 40 cm), because it is a rare condition. The RWS policy for water distribution was used in the initial analysis. The MSDM managerial policy was included later for comparison. Previous work had indicated that the policies did not differ significantly except under extremely dry conditions.

C.3. RESULTS AND CONCLUSIONS

The model output consisted of shipping losses by decade for each of the input years, for each set of initial conditions. The losses were summed over the decades in each year, and order statistics were determined for each of the two sets of output. Comparing these statistics verified that net precipitation was not particularly
important except in extremely dry years. Even then, the order
statistics for the years did not change appreciably, only the total
shipping losses. Table C.1 presents the two sets of results which led
to this conclusion.

When the MS2M distribution policy was introduced into the model, the
results did not change significantly. Again, the order of years was
not affected; only the costs in low flow years with low net
precipitation changed. For the cases with high net precipitation,
both policies gave virtually the same costs. The maximum difference
between them was 16 percent, which occurred in the worst year (1949)
for the dry precipitation scenario. The results for selected years
appear in Table C.2.

The shipping losses for the DEX year were calculated using the same
procedure and the RWS management policy. These are also shown in
Table C.1. Figure C.1 shows the cumulative distribution function of
shipping losses over the 47 (ranked) years. This curve incorporates
the mean values for the RWS distribution policy shown in Table C.1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Net Precipitation (mm)</th>
<th>Year</th>
<th>Net Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- 66</td>
<td>+ 11</td>
<td>Mean</td>
</tr>
<tr>
<td>DEX</td>
<td>121.97</td>
<td>96.85</td>
<td>109.41</td>
</tr>
<tr>
<td>1949</td>
<td>101.62</td>
<td>78.40</td>
<td>90.01</td>
</tr>
<tr>
<td>1947</td>
<td>84.98</td>
<td>65.89</td>
<td>75.44</td>
</tr>
<tr>
<td>1959</td>
<td>60.39</td>
<td>49.13</td>
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<td>1976</td>
<td>49.61</td>
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<td>1953</td>
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<td>1962</td>
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<td>31.16</td>
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<td>1933</td>
<td>27.02</td>
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<td>26.46</td>
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<tr>
<td>1973</td>
<td>18.48</td>
<td>17.88</td>
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<td>1954</td>
<td>18.96</td>
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<td>1942</td>
<td>14.26</td>
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</tr>
<tr>
<td>1969</td>
<td>11.89</td>
<td>11.59</td>
<td>11.74</td>
</tr>
</tbody>
</table>
Table C.2

SHIPPING LOSSES BY WATER DISTRIBUTION POLICY AND NET PRECIPITATION (Dfim)

<table>
<thead>
<tr>
<th>Year</th>
<th>NWS Policy</th>
<th>MSDM Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- 66</td>
<td>+ 11</td>
</tr>
<tr>
<td>1949</td>
<td>101.62</td>
<td>76.40</td>
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<td>1947</td>
<td>84.98</td>
<td>65.89</td>
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<td>1959</td>
<td>60.39</td>
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<td>1976</td>
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<td>1953</td>
<td>50.64</td>
<td>41.51</td>
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<td>1933</td>
<td>27.02</td>
<td>25.90</td>
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<td>18.96</td>
<td>16.92</td>
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<tr>
<td>1932</td>
<td>11.44</td>
<td>11.37</td>
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<tr>
<td>1920</td>
<td>8.77</td>
<td>8.62</td>
</tr>
<tr>
<td>1931</td>
<td>4.24</td>
<td>4.37</td>
</tr>
</tbody>
</table>

The short horizontal line in Fig. C.1 indicates the shipping losses associated with a DEX year. One can see that DEX may be somewhat less than a 1-percent year, rather than the 2-percent year it was for agricultural damages, although the sample of years is too small to determine this with any confidence. Also, although 1976 was very dry, it was by no means the driest year for shipping since 1930. In three years, 1949, 1947, and 1959, shipping would have suffered far more damage. The losses in 1976 were perceived to be more severe, because the fleet was composed of larger, deeper draft vessels than in the earlier years. Hence the actual damage was worse, although the water levels might not have been.

Table C.3 compares the shipping and agricultural damage rankings of all external supply years. It shows that the probabilities agree fairly well except for 1967, which was a wet year for shipping. The difference is caused by high river flows and relatively low precipitation in that year.

Figure C.1 illustrates an interesting result of the analysis; shipping losses never reach zero, but instead approach an apparent minimum value of about 3 Dfim per year. This compares with a median value of 11.5 Dfim and a mean value of 19.3 Dfim per year. It is not difficult to

Table C.3

PROBABILITIES OF ANNUAL LOSSES EXCEEDING THOSE OF THE FOUR CHosen YEARS

<table>
<thead>
<tr>
<th>Type of Loss</th>
<th>DEX</th>
<th>1959</th>
<th>1943</th>
<th>1967</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural shortage</td>
<td>.02</td>
<td>.07</td>
<td>.21</td>
<td>.63</td>
</tr>
<tr>
<td>Agricultural salinity</td>
<td>.02</td>
<td>.09</td>
<td>.13</td>
<td>.57</td>
</tr>
<tr>
<td>Shipping losses</td>
<td>.01</td>
<td>.06</td>
<td>.17</td>
<td>.89</td>
</tr>
</tbody>
</table>
Fig. C.1 -- Probability that shipping losses are exceeded
find reasons for this phenomenon, if we look at the characteristics of river flows and the low water loss functions themselves.

Studying the individual loss function curves, we see that each of them has a distinct minimum shipping cost. The curves approach their respective minimum values at different critical depths, but these depths can be translated into a Rijn flow of about 2000 m$^3$/s. The primary determinant of this flow is the depth on the Upper Rijn. When the flow is less than 2000 m$^3$/s, there will be shipping losses, and the size of the losses will increase rapidly as the flow diminishes. The median Rijn discharge at Lobith is about 1900 m$^3$/s (decade mean), so the flow will be less than 2000 m$^3$/s more than half the time. Under these circumstances, years with zero shipping losses will be extremely rare, to say the least.

The shape of the loss function curves implies that periods of very low water levels will dominate the loss calculations. A year with high average flow, but having a few decades with very low flow, will have higher costs than a year with a more uniform, but lower average flow. The worst years for shipping are those with extended periods of extremely low flow, even though previous and subsequent months may have a high flow.

The shipping fleet has apparently evolved to take advantage of high water levels, at the cost of efficiency in low flow periods. This may have occurred because larger ships are nominally more efficient and relatively less expensive to construct. As a result, however, the shipping industry is vulnerable to extremely low water levels. The fleet must often operate at less than maximum efficiency, and shipping losses occur in even the best of years.
Appendix D

LONG-RUN FLEET MODEL

D.1. GENERAL DESCRIPTION

The long-run fleet model calculates the shipping fleet required to carry all goods (without storage) under a particular set of conditions. Because it is based on the low water loss function study, the goods to be transported are those for an average week of the context year (1976 or 1985). The external conditions are specified as a set of critical point depths on the shipping network.

In addition to the detailed results of the shipping study, the model uses certain supplementary information. This consists of:

- The distribution of ships (by type and size class) on each route of the low water loss functions.
- Normal operating hours per week for each type and class of ship.
- Distribution of ships in the fleet by type, size class, and maximum draft.

The model calculates the required fleet using an incremental procedure based on the shipping study run closest to the given input conditions. The procedure involves comparing the depths at corresponding critical points and modifying the number of ships on each major shipping route to account for changes in load factors caused by the changing critical depths.

D.2. MODEL DEVELOPMENT

This section describes the steps followed in developing the model, and the datasets needed to use it. The next section discusses the procedure that the model follows during its operation.

1. Distribution of Ships. Ship count observations from Refs. D.2 and D.3 were used to develop this distribution by ship type $i$, by ship type $i$, and class $j$ for each major route $r$ in a situation corresponding to the 1976 reference case run of the loss function study. These distributions were later modified using an iterative procedure based on comparisons of the study runs with calculations made using the assumed distributions. This procedure will be discussed later.

2. Loaded Trips per Route. We calculated the number of loaded trips per Route $RT_r$ for each major route $r$ for each study run, using the
study output of trips by origin-destination pair. Assuming that the
trip fractions for shipping routes are the same as the cost fractions
calculated in the loss function analysis (see App. B), we can say

\[ RT'_n = \sum_k \sum_l LT_{k,l} \times f_{k,l,n} \]

where \( LT_{k,l} \) = total loaded trips by origin \( k \) and destination \( l \),
\( f_{k,l,n} \) = fraction of shipping cost between origin \( k \) and
destination \( l \) that applies to route \( n \).

Note that the equation calculates the number of trips per critical
point vector (route) \( n \). As with the shipping costs, these routes were
combined into the major routes \( r \) and a fixed depth component to
determine \( RT_r \). (See Sec. B.2, steps 8 through 10, for a corresponding
loss function procedure).

3. Distribution of Loaded Trips. For each study run, we calculated
the distribution of loaded trips \( tf_{i,j,r} \) per route \( r \), by ship
type \( i \) and class \( j \). This required multiplying the distribution
\( bf_{i,j,r} \) for the reference case run by the ratio of total trips (by
type and class) between the two runs. This can be shown as

\[ tf_{i,j,r} = bf_{i,j,r} \times \frac{TH_{i,j}}{T_{i,j}} \times \frac{T_{i,j}}{T_{i,j}^*} \]

where \( TH_{i,j} \) = total hours by ship type and class (hr),
\( T_{i,j} \) = mean trip time by ship type and class (hr/trip),

and the asterisk (*) indicates values for the reference case. This
procedure changes the reference case run distribution to reflect the
overall changes in the distribution of ships (by type and class)
between it and the run of interest. The same procedure was used to
develop distributions for the 1985 runs, also based on the 1976
distribution.

4. Ships per Route. The actual number of ships required for each
route of each run could then be determined. To do this, we calculated
the number of trips per route \( L_{i,j,r} \) by type and class from

\[ L_{i,j,r} = tf_{i,j,r} \times RT_r \]
This result must then be multiplied by the mean trip times \( T_{i,j} \) for the run and divided by the mean operating hours per week \( H_{i,j} \); thus

\[
S_{i,j,r} = \frac{L_{i,j,r}}{H_{i,j}} \times T_{i,j}/H_{i,j}
\]

The mean operating hours per week are shown in Table D.1.

<table>
<thead>
<tr>
<th>Type</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
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<td>67</td>
<td>69</td>
<td>71</td>
<td>74</td>
<td>83</td>
</tr>
<tr>
<td>Tow</td>
<td>64</td>
<td>65</td>
<td>67</td>
<td>69</td>
<td>71</td>
<td>74</td>
<td>83</td>
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<tr>
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<td>77</td>
<td>86</td>
<td>95</td>
<td>101</td>
<td>106</td>
<td>114</td>
</tr>
<tr>
<td>Push/tow</td>
<td>103</td>
<td>106</td>
<td>111</td>
<td>115</td>
<td>123</td>
<td>132</td>
<td>148</td>
</tr>
</tbody>
</table>

5. Fixed Ships. In this step, we calculated the number of ships per run \( FS_{i,j} \) associated with the remaining fixed routes, the minor and fixed depth routes not included in the low water loss functions. The number of such fixed ships could be determined by subtracting the ships belonging to the major routes from the total number of ships per study run, or

\[
FS_{i,j} = \frac{TH_{i,j}}{H_{i,j}} - \sum_{r} S_{i,j,r}
\]

6. Mean Load Factors. At this point, it was necessary to obtain mean load factors \( mlf_{i,j,d} \) for the fleet as a function of shipping depth \( d \). These load factors are weighted mean values over all ships of the given type and class, and could be determined from data in the study report [D.1].

7. Normal Maximum Load Factors. The mean load factors in the reference case run of the study were assumed to be the normal maximum load factors \( mlf_{i,j} \) (by type and class) for all ships. They could be calculated from

\[
mlf_{i,j} = w_{i,j}/mlc_{i,j}
\]
where \( W_{i,j} \) = mean transported weight in reference case (tons),
\( mlc_{i,j} \) = mean load capacity of fleet (tons).

The mean load capacities of ships in the fleet are shown in Table D.2.

### Table D.2

**MEAN LOAD CAPACITY PER SHIP BY TYPE AND CLASS (1976)**

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<th>Type</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6/7</th>
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</thead>
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<td>2034</td>
<td>3119</td>
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<tr>
<td>Push/tow</td>
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<td>927</td>
<td>1476</td>
<td>2109</td>
<td>2859</td>
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</tr>
</tbody>
</table>

8. **Dutch Fleet.** Using the study results, one can calculate the fraction of Dutch to total ships in the fleet \( DF_{i,j} \), for each run from

\[
DF_{i,j} = DH_{i,j}/TH_{i,j}
\]

where \( DH_{i,j} \) = Dutch fleet hours by type and class (hr),
\( TH_{i,j} \) = total fleet hours by type and class (hr).

9. **Iteration.** To adjust the original reference case distribution of ships by route \( bf_{i,j,r} \), we used the long-run fleet model to predict a known run from the most similar run. Comparing the predictions with the study results provided information for adjusting the original route fractions for each type and class. The routes could be somewhat isolated by predicting Waal and IJssel withdrawal cases (at a Rijn flow of 800 m³/s) from the corresponding cases without withdrawals. The adjusted route fractions were then renormalized and the procedure repeated. It was necessary to do this only once to obtain reasonable reference case route fractions.

This procedure generated all necessary information to operate the fleet model. How the model uses this information will be described next.

### D.3. FLEET MODEL OPERATION

The model operates according to the following procedure.
1. **Read Critical Point Vector.** The model reads the vector of critical point depths for the given period and calculates the corresponding minimum shipping depths for each route.

2. **Study Run Selection.** It selects the most appropriate study run by comparing the critical point depths for the input vector with those in all available study runs. In this procedure, it passes through the critical points in the following order: Lower Rijn, Waal, IJssel, Maas, and Upper Rijn. During each pass, it retains all remaining runs with the minimum difference in the appropriate critical point depth. The process continues until only one run remains or all critical points have been used. If more than one run survives the entire process, the model selects the first run.

This process is designed to select the study run that is most similar to the input situation in terms of critical point depths. The Lower Rijn depth is compared first, because Rijn flow is the most important variable in characterizing a given situation. After that, withdrawals on the Waal are most significant, then IJssel withdrawals and Maas depth. Upper Rijn depth is considered last, but it provides no information not found from the Lower Rijn depth.

3. **Trips per Route.** Having selected a preferred run as a basis for further calculations, the model determines the number of trips per route $L_{i,j,r}^*$ for this basis run, from

$$L_{i,j,r}^* = t_{i,j,r}^* \times R_{i,j,r}^*$$

where the asterisk (*) is used to denote variables for the basis run.

4. **Load Factors.** For both the selected run and the input situation, the model calculates the load factors $l_{i,j,r}$ by type, class, and route from

$$l_{i,j,r} = \min \left[ \text{mlf}_{i,j,d}^*, \text{nlf}_{i,j}^* \right]$$

where $\text{mlf}_{i,j,d}^*$ = weighted mean load factors for the fleet,

$$d_r' = \text{minimum critical point depth on route } r \text{ (dm)},$$

$\text{nlf}_{i,j}^*$ = normal maximum load factor.
5. **Trips per Route for Input Data.** The trips per route $L_{i,j,r}$ for the input situation are calculated by scaling the corresponding trips $L^*_{i,j,r}$ in the basis run by the ratios of corresponding load factors, thus

$$L_{i,j,r} = L^*_{i,j,r} \times \frac{If^*_{i,j,r}}{If_{i,j,r}}$$

6. **Required Ships.** The model calculates the required ships $TS_{i,j}$ for the input situation by first calculating the required ships per route from

$$S_{i,j,r} = L_{i,j,r} \times \frac{T^*_{i,j}}{H_{i,j}}$$

It then sums these ships over the major routes $r$ and adds the number of fixed route ships from the basis case, giving

$$TS_{i,j} = \sum_r S_{i,j,r} + FS^*_{i,j}$$

7. **Total Cost.** The total cost $TC$ of the required fleet can then be found from the annualized investment and fixed cost data of Tables 5.3 and 5.4 as

$$TC = \sum_i \sum_j TS_{i,j} \times \left[ AI_{i,j} + AF_{i,j} \right]$$

where $AI_{i,j}$ = annualized investment cost per ship (Dfl/yr),

$$AF_{i,j} = \text{annual fixed cost per ship (Dfl/yr)}.$$

8. **Dutch Cost.** The cost of the Dutch fleet $DC$ is calculated by scaling the total fleet cost by the ratios of Dutch to total fleet (by type and class) for the basis run. More specifically, this cost is

$$DC = \sum_i \sum_j TS_{i,j} \times DF_{i,j} \times \left[ AI_{i,j} + AF_{i,j} \right]$$
In operation, the model passes through a series of decades with different critical point depths. It prints the results by decade, with all results shown by type and class of ship in the Dutch and total fleets.

REFERENCES


Appendix E

LOWLANDS LOCK ANALYSIS

With contributions by J. P. M. Dijkman, J. P. Koenis, and T. F. Kirkwood

E.1. LOCK OPERATION SIMULATION

This section describes the general procedure that we used in setting up and simulating the operation of lowlands locks. It includes a brief discussion of the simulation model and its operation.

E.1.1. Traffic Generation

We used data for each lock to determine how ship traffic varied in composition and amount throughout the year. With this information, we divided the year into seasons having roughly uniform traffic levels and characteristics. Then we calculated appropriate lock parameters for each season.

Other traffic observations were used to estimate weekly ship arrival patterns by direction for each season. These patterns specify the mean arrival rates per hour (during lock operation) throughout the week. A week consisted only of the operating hours of the lock, collapsed to create a period of continuous operation divided into days. This procedure implies, therefore, that ships which either arrive when the lock is not open, or must wait overnight, are not being delayed.

The arrival rates were scaled to make the weekly totals agree with the seasonal means (by direction). We assumed that arrivals followed a Poisson distribution, with mean arrival rates as determined by the weekly pattern. With this assumption, the time between arrivals has a negative exponential distribution.

For each lock, we calculated how many weeks of traffic would have to be simulated to include 1000 or more arrivals, and expanded the basic arrival patterns accordingly. This information was used to develop a series of random ship arrivals (by direction) for each given period. For each arriving vessel, we determined the arrival time of the next ship in that direction and assigned a random ship class, based on the known size distribution for traffic during each season.

E.1.2. Lock Operation

The model that simulates lock operation proceeds as follows:

1. Initialization. The model reads input data describing the lock complex, ship traffic, and the technical and managerial tactics to be
used in the simulation. It initializes all variables, records when intermediate doors can be used, and sets the schedule for calculating daily results. When this is complete, it begins the simulation and waits for external events (ship arrivals) to occur.

2. Ship Arrival. Ships arrive at the lock complex according to the precalculated pattern. Upon arrival, the model determines the ship size and direction. It assigns each ship to a lock queue, selecting the lock most likely to cycle next, but beginning with the smallest lock that can accept the ship. After this assignment, the model looks at the current managerial tactic to determine when a cycle should be scheduled for that lock, based on the queue length and how long ships have been waiting. All locks are operated independently, unless otherwise specified.

3. Lock Cycle Commencement. When the time arrives for a scheduled lock cycle to begin, the model follows this procedure:

- Determines lock and queue status, canceling or rescheduling the cycle if the chamber is unavailable or the queue empty.
- Looks for another arrival in the same direction within a specified holding time, delaying the cycle if necessary.
- Decides if the lock intermediate door can be used, based on the predetermined traffic pattern and the size and number of ships in the queue.
- Fills the chamber to capacity, if possible, leaving extra ships to wait in the queue for the next lock cycle.
- Records delay times and the number of ships in the lock.
- Schedules the lock to open at a time determined by the normal cycle time and the number of ships in the chamber.

4. Lock Cycle Termination. When the cycle ends and the chamber opens, the passed ships leave the lock and the program. The total passing time per ship is calculated and recorded. The model then determines the status of the queue and decides if a return lock cycle should be scheduled.

5. End of Day. At the end of each day, lock operation is suspended while the model summarizes the results and passes the information to the salt model. The salt model calculates salt intrusion and water loss for the lock complex. The entire procedure at the end of each day includes the following operations:

- Determining the results for each lock chamber, including the number of cycles (full and with intermediate doors), ships passed, and time the lock doors were open.
- Calculating the salt intrusion and water loss for the complex for each technical tactic and flushing rate at the locks.
- Recording delay times and costs for ships passed, and energy costs for the lock cycles.
The salt model and its development are completely described later in this appendix.

6. **Change of Managerial Tactic.** In some runs, the managerial tactic specifying lock operation may be changed during the simulation. These changes are necessary when operations depend on the tidal cycle or vary between night and day.

7. **End of Simulation.** At the scheduled end of the simulation, the model calculates summary statistics for the entire run. It determines daily mean values for lock cycles, ships passed, delay times and costs, energy costs, salt intrusion, and water loss (or gain) through the lock complex. This information is printed for each technical tactic and freshwater flushing rate chosen for the complex.

**E.1.3. Input Data**

The model requires four types of input information. These are:

- Lock complex characteristics.
- Ship characteristics.
- Ship traffic description.
- Technical and managerial tactics.

Table E.1 summarizes the basic characteristics of all lock complexes that we investigated. This information was provided by the lock operators or determined from data provided by the RWS. The characteristics of inland ships (both commercial and recreational) were provided by the DWK, as discussed in Chap. 2. Ship traffic descriptions were used to develop the arrival streams for the analysis. As mentioned above, these came from observations (again provided by the DWK) and lock records. Finally, each simulation run was performed for a specific managerial tactic, but incorporated all possible technical tactics at the lock.¹

**E.1.4. Output Information**

The output of the lock model includes mean daily values (based on the entire simulation period) of the following:

- Lock cycles per chamber (including intermediate chambers).
- Ships passed per chamber.
- Total passing time and time in queue per ship.
- Energy cost per technical tactic.
- Total delay cost for commercial ships.
- Total delay time for recreational vessels.
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<th>W (m)</th>
<th>D (m)</th>
<th>H (m)</th>
<th>H (m)</th>
<th>H (m)</th>
<th>H (m)</th>
<th>H (m)</th>
<th>S (m)</th>
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<td>G-N</td>
<td>1</td>
<td>0.65</td>
<td>9.0</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td>Velsenink</td>
<td>C-L</td>
<td>3</td>
<td>0.65</td>
<td>20.1</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
</tr>
<tr>
<td></td>
<td>C-R</td>
<td>2</td>
<td>0.65</td>
<td>20.1</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
<td>6.30</td>
<td>4.03</td>
</tr>
</tbody>
</table>

NOTES: Lock types: G = commercial; R = recreational; W = no salt intrusion technology; S = single air bubble screen; D = double air bubble screen; K = Kruispeark lock system.
Number: Number of locks of similar dimensions at complex.
L: Length of lock chamber available to shipping; parentheses indicate partitioned chamber length.
W: Length of lock chamber.
D: Depth of lock gate sill on freshwater side.
H: Water depth on freshwater side.
S: Water depth at normal low tide on saltwater side.
H: Water depth at normal high tide on saltwater side.
S: Salt concentration on saltwater side.
S: Salt concentration of flushing water.
Cycle Time: Mean time to operate lock gates and equalize water levels in one-half cycle of lock.
Energy Cost: Cost per half-cycle to operate lock gates and salt intrusion technology.
Normal locks: no technology/no submerged screen/no double bubble screen.
Kruispeark locks: no technology/no submerged screen/one bubble screen.
In addition to the above, the model also provides totals and maximum values for passing time and time in queue, as well as the standard deviation for all results. Other information that can be requested includes a summary of the daily simulation results: number of lock cycles, ships passed, mean displacement volumes, and time of open lock doors for each chamber.

E.2. THE LOCK SALT MODEL

E.2.1. Development of the Analysis Method

The Lock Salt Model calculates salt intrusion and freshwater loss through a lock as a function of the flushing rate, the number of lock cycles, and the technical means used to reduce salt intrusion. Salt intrusion can be specified in two ways, either as an increase in background salt concentration, or as an amount of salt entering through a lock. The first case applies to locks in canals and similar waterways; the second is used for locks on lakes and other open waters.

The locks that we consider, shown in Fig. 6.3, consist of all the major ones that separate salt water and fresh water. We have included the Volkerak locks, although when the Zoommeer is completed these locks will no longer have a difference in salt concentration across them. We have also included the Philipsdam locks, although not yet constructed, because they will be built in the process of completing the Zoommeer.

To develop our Lock Salt Model, we first consider a lock of traditional design in which no attempt is made to prevent salt from passing through the lock. Next, we consider various types of locks designed to reduce this salt intrusion. Because we are concerned with salt intrusion over a 10-day period, we have accounted for the tidal variation of water level by averaging over a tidal period and using this average water level on the salt side of the locks. We neglect any effect of leakage past the doors.

The steps in a simplified lock operating cycle are illustrated in Fig. E.1. The cycle starts with the door on the salt side open and that on the fresh side closed. Ships enter and exit on the salt side. As the lock door stands open, the water in the lock becomes saltier and will become completely salt if the doors are left open long enough. After the ships enter the lock, the door on the salt side is closed, and water is allowed to flow out of the lock to the fresh side by gravity. The flow may be either through a small door in the face of the lock door or through pipes equipped with control valves. The process is continued until the water level in the lock becomes equal to that on the fresh side. This flow of salt water is one of the ways that salt is transferred to the fresh side of the lock. Such salt intrusion could be avoided by using a pump to return the leveling water to the salt side; however, this was not done in the older Dutch locks. (Actually, on most of the locks we consider, the difference in levels is not a large fraction of the depth of the lock, so that this saving in salt intrusion would not be large.)
(1) Ships enter/exit on the salt side:
The door on the salt side has been open long enough for complete displacement of fresh water in the lock by salt water.

(2) Leveling process:
Salt water is allowed to flow out of the lock to the fresh-water side until the water levels on the two sides are equal.

(3) Ships enter/exit on the fresh side:
The door on the fresh side has been open long enough for complete replacement of the salt water in the chamber by fresh water.

(4) Leveling process:
Salt water is allowed to flow into the lock from the salt side to raise the water level in the lock to that on the salt side.

Fig. E.1 -- Simplified lock operating cycle
The door on the fresh side is then opened to allow ships to enter and exit. During this time, the brackish (or salt) water in the chamber mixes with the fresh water. The difference in densities between the fresh and salt water creates a flow of salt water out of the chamber along the bottom and of fresh water into the chamber above the salt water. This exchange process is the primary way in which salt is transferred through the lock to the fresh side.

The final step in the lock cycle consists of closing the door on the freshwater side and allowing salt water to flow into the lock chamber until leveling is accomplished. The gate on the salt side is then opened, and the density currents replace the fresh water in the chamber with salt water. No salt is transferred to the freshwater side in this step, but there is a loss of fresh water to the saltwater side.  

E.2.2. Calculation of the Amount of Salt Intrusion

We first calculate the amount of salt passing through the lock, assuming that the lock doors are kept open long enough that the chamber becomes completely salt or fresh at the end of each half-cycle. Later, we correct for the effect of closing the doors before the mixing process is completed. The difference between the salt in the lock at the initial condition (Condition 1 in Fig E.1) and that at the end of the mixing process on the freshwater side (Condition 3 in Fig E.1) is

\[ \text{SALTin} = N \times A_w \times (h_s \times S_s - h_f \times S_f) \]  \hspace{1cm} (E2.1)

where SALTin = the amount of salt which has entered the fresh side (kg),
N = number of lock cycles,
A_w = area of the water surface in the lock chamber (m^2),
h_s = water level on the salt side (m above NAP),
h_f = water level on the fresh side (m above NAP),
S_s = salinity on the salt side (kg Cl^-/m^3),
S_f = salinity on the fresh side (kg Cl^-/m^3).

It should be noted that, while we speak of "salt" intrusion throughout this section, actual concentrations are given in terms of chloride ions rather than salt.

By some algebraic manipulation, Eq. E2.1 can be expanded and written as

\[ \text{SALTin} = 0.5 \times N \times A_w \times [(h_s + h_f)(S_s - S_f) + (h_s - h_f)(S_s + S_f)] \]  \hspace{1cm} (E2.2)

At this point, we introduce two coefficients to allow for (1) the volume of water displaced by ships in the lock, (2) the possibility that, if the locking rate is high, the lock doors may not be open long enough to allow complete displacement of salt water in the lock by fresh water,
and (3) the use of devices to reduce salt intrusion. We apply these factors to the first term in Eq. E2.2. This procedure is approximate, but examination of the available data on locks indicated that it was satisfactory for PWNN purposes. Note that the first term represents the average water volume in the lock, which is approximately the volume involved in the mixing of salt and fresh water when the gates are open.

The displacement coefficient, \( \lambda \), is the fraction of the average lock volume that is actually occupied by water (the rest of the water is displaced by ships). The number and tonnage of the ships in the lock are calculated by the Lock Operation Model. We then calculate the value of \( \lambda \) using this information and the water volume of the lock.

The exchange coefficient, \( \varepsilon \), allows (1) for the possibility that the lock doors may close before the displacement of the water in the chamber by outside water is complete, and (2) for the use of lock designs intended to reduce salt intrusion. In the literature, it is generally defined as

\[
\varepsilon = \alpha \times \frac{t}{T} \quad \text{but } \varepsilon \leq 1
\]  
(E2.3)

where \( \alpha \) = coefficient to describe the salt intrusion design,

\( t \) = time the lock doors remain open (sec),

\( T \) = time constant for the exchange process (sec).

We calculate the time that the lock gate remains open with the Lock Operation Model. The value of the time constant, \( T \), is determined in Ref. E.1 by an analysis of density currents flowing in and out of the chamber. This reference shows that

\[
T = 4.0 \times \frac{Lc}{\text{SQRT}(\Delta \rho \times g \times H/\rho_0)}
\]  
(E2.4)

where \( Lc \) = lock chamber characteristic length (water volume divided by the mean water depth at the lock sill and the lock chamber width at the sill),

\( \Delta \rho \) = difference in density between the salt and fresh water,

\( g \) = acceleration due to gravity (9.81 m/s\(^2\)),

\( H \) = mean depth of lock chamber (the average of the salt and fresh side depths),

\( \rho_0 \) = density of water (1000 kg/m\(^3\)).

When the coefficients \( \lambda \) and \( \varepsilon \) are introduced into Eq. E2.4, we obtain

\[
\text{SALT}_{\text{in}} = 0.5 \times N \times \Delta w \times [(\text{hs} + \text{hf})(\text{Ss} - \text{Sf}) \times \lambda \times \varepsilon + (\text{hs} - \text{hf})(\text{Ss} + \text{Sf})]
\]  
(E2.5)
Our model for salt intrusion through a lock, then, is defined by Eqs. E2.3, E2.4, and E2.5.

E.2.3. Calculation of Freshwater Loss

In addition to the salt intrusion through the lock, we also wish to find the net water flow through the lock (this is needed to analyze the flow through adjacent sluices) and the amount of freshwater lost through the lock. The net flow through the lock is equal to the water volume required for leveling, unless this water is returned to the salt side by pumping, in which case there is no net flow. Thus,

\[ Q_{\text{in}} = N \times A_w \times (h_s - h_f) \]  

(E2.6)

where \( Q_{\text{in}} \) = net flow of water through the lock (m³),
\( N \) = number of lock cycles,
\( A_w \) = area of the water surface in the lock chamber (m²),
\( h_s \) = water level on the salt side (m above NAP),
\( h_f \) = water level on the fresh side (m above NAP).

There is no net flow due to the flow from the lock each time the gate is opened, because this flow is alternately in one direction and then the other. However, the freshwater loss is caused by this flow out of the gate on the salt side. We calculate the freshwater loss as

\[ Q_{\text{out}} = N \times V \times \lambda \times \eta \]  

(E2.7)

where \( N \) = number of lock cycles,
\( V \) = volume of lock chamber (m³),
\( \lambda \) = ship displacement coefficient,
\( \eta \) = exchange coefficient that depends on the design and operation of the lock.

E.2.4. Calculation of Salt Remaining on the Fresh Side

While these equations define the salt entering through a lock and the freshwater lost through it, they do not tell us how much of this salt will remain on the freshwater side. There are sluices located near most locks that are required to manage the flow of water, and much of the salt that enters through the lock will soon be carried out either through a sluice or through the lock when it is operated on the next half-cycle. Often, the water level on the salt side will be higher than that on the fresh side, particularly when the tide is high. In this situation, the sluices are opened at low tide to let the fresh water out and closed at high tide to keep the salt water from entering. In PAWN, we deal with average flows over a 10-day period; thus, we average over this tidal effect.
We consider two situations—one in which the lock is at the mouth of a canal, and one in which the lock separates a large freshwater lake from the sea. In the canal case, a flow is maintained in the canal to flush out salt and pollutants, and only a relatively small volume of canal water can be influenced by the lock. Thus, if the flushing flow is changed, a new equilibrium is quickly reached, and we can assume equilibrium conditions in our analysis. (In this case, the motion of salt near the lock is governed primarily by transport rather than by diffusion.) In the lake situation, the amount of water entering through the lock is very small in comparison with that in the lake, and the incoming salt mixes slowly with that in the lake under the influence of diffusion and density currents. This results in a concentration of salt near the lock with a gradual decrease of salinity to lake level some distance from the lock. In this situation, salinity near the lock changes only slowly as the flushing flow changes, and we cannot assume equilibrium conditions in our analysis.

**E.2.4.1 Canal-Type Locks.** A diagram of the canal situation is shown in Fig E.2. A water balance for the canal is given by

\[
Q_{\text{in}} + Q_{\text{flu}} = Q_{\text{slu}} + Q_{\text{inta}}
\]  

(E2.8)

where \(Q_{\text{in}}\) = daily mean net flow entering the canal through the lock \((m^3/s)\),

\(Q_{\text{flu}}\) = daily mean flushing rate in the canal \((m^3/s)\),

\(Q_{\text{slu}}\) = daily mean discharge rate through the sluice \((m^3/s)\),

\(Q_{\text{inta}}\) = daily mean intake rate at the intake point \((m^3/s)\).

The salt balance is

\[
\text{SALT}_{\text{in}} + Q_{\text{flu}} \times \text{Scan} = \text{SALT}_{\text{out}} + Q_{\text{inta}} \times \text{Sinta}
\]  

(E2.9)

![Diagram of canal type of lock complex](image)
upstream of the pit. When we use Eq. E2.12, we can omit the quantity Qin because the salt water remains separate from the flushing water and is removed by pumps. Thus, only the flushing flow is available to carry salt out of the sluice.

In a Kreekrak lock [E.9, E.15], the salt and fresh water in the chamber are kept separate by gravity, the salt water being admitted and withdrawn through ports in the bottom, and the fresh water through ports near the surface. As salt water enters or leaves through the bottom ports, fresh water is transferred through the surface ports so that the desired water level is maintained. Salt water withdrawn from the chamber is pumped to the salt side. Fresh water may either be returned to the fresh side, if regaining it is important, or it may be used to flush the lock of any remaining salt water. Kreekrak locks are complicated and expensive to construct, and it is not possible to modify an existing lock to the Kreekrak design.

The effectiveness of Kreekrak locks in preventing salt intrusion depends on the importance of regaining fresh water. If fresh water is used to flush the lock, the salt intrusion can be as little as 1 percent of the salt contained in the chamber. For operation to regain fresh water, salt intrusion can rise to 10 percent.

We represent the Kreekrak lock in our model by eliminating the second term in Eq. E2.5 (since leveling water is returned to the fresh side), and by using a value of $\varepsilon$ of 0.01 for operation without regain and of 0.1 with regain. The amount of fresh water lost is calculated as 91 percent of the chamber volume without regain and as 35 percent of the chamber volume with regain. The quantity Qin is omitted from Eqs. E2.8 and E2.12 because there is no flow from the salt side to the fresh side in a Kreekrak lock.

E.2.6. Specific Lock Complexes

Because the geometry and flow conditions were peculiar to individual lock complexes, we examined each complex in detail before deciding how to apply our equations. In this section, we present specific details regarding each complex and describe how we applied our method. Our discussion of the locks proceeds geographically from north to south.

E.2.6.1. Delfzijl. At Delfzijl, there are two modern locks located between the Eems and the Iemskanaal. Flushing through an old lock is accomplished by opening the gates at low tide. A flushing rate of about 1 m$^3$/s is sufficient to keep the salt concentration at the nearest intake point (20 km upstream from the lock) at an acceptable level. The lock is fitted with two bubble screens. For our purposes, this is a canal-type situation, and we used Eqs. E2.5, E2.6, and E2.12 to analyze it.

E.2.6.2. Harlingen. The arrangement of the locks and sluices at Harlingen is shown in Fig. E.3. The Grote sluis and the Klein sluis are used very little, and we omitted them from our analysis. There is
Fig. E.3 -- The lock arrangement at Harlingen

sufficient flow in the canal that this lock was treated as a canal-type lock; thus, we used Eqs. E2.5, E2.6, and E2.12 to calculate salt concentration on the fresh side of the lock. The locks are equipped with two air bubble screens.

We also needed to calculate the decrease of the salt concentration between the locks at Harlingen and the freshwater intake at Franeker, 9 km upstream. We selected a diffusion coefficient of 30 m²/s after examining measurements made in the Delfshavensche Schie, a canal that has similar dimensions but that is probably more completely mixed (a value of 15 m²/s was derived from these measurements). The theoretical value for a completely mixed canal of this size is about 1 m²/s. The flow area of the canal is 123 m², and the distance to the intake is 9000 m. Using these values in Eq. E2.10, we obtained the following expression for salt concentration at the Franeker inlet:

\[ S_{int} = S_{can} + (S_f - S_{can}) \times \exp(-2.4 \times Q_{flu}) \]  

(E2.13)

E.2.6.3. Kornwerderzand and Den Oever. Measurements of chloride concentration in the Ijsselmeer show an increase in chloride concentration toward the corners where the locks at Kornwerderzand and Den Oever are located. This indicates a nonequilibrium condition, which
where \( \text{SALTin} \) = average rate at which salt enters the canal through the lock (kg/s),
\( \text{Scan} \) = salt concentration in the canal far upstream of the lock (kg/m³),
\( \text{SALTout} \) = average rate at which salt flows out through the sluice,
\( \text{Sinta} \) = salt concentration at the intake point (kg/m³).

We calculate the salt concentration at the intake point by assuming that the propagation of salt upstream from the lock is by diffusion, and can be represented by an exponential as

\[
\text{Sx} = \text{Scan} + (\text{Sf} - \text{Scan}) \times \exp[-Q_{\text{flu}} \times x/(D \times A)]
\]  
(E2.10)

where \( \text{Sx} \) = salt concentration at a distance \( x \) upstream from the lock,
\( \text{Scan} \) = salt concentration in the canal far upstream of both the lock and the intake (kg Cl⁻/m³),
\( \text{Sf} \) = salt concentration immediately inside the lock (kg Cl⁻/m³),
\( D \) = diffusion coefficient (m²/s),
\( A \) = area of canal cross section (m²).

Combining Eqs. E2.9 and E2.10 gives

\[
\text{SALTin} = Q_{\text{in}} \times \text{Sf} + Q_{\text{flu}} \times (\text{Sf} - \text{Scan}) \\
\times [1 + (Q_{\text{in}}a/Q_{\text{flu}}) \times \exp(-Q_{\text{flu}} \times x/D \times A)]
\]  
(E2.11)

This expression defines the relation between the extraction rate and the intake flow \( (Q_{\text{in}}a) \) and the salt concentration immediately inside the lock. Investigation showed that the extraction rate in the situations of interest in FAWN was always much less than the flushing rate. Thus, the last term is approximately 1, and Eq. E2.11 may be simplified to

\[
\text{SALTin} = Q_{\text{in}} \times \text{Sf} + Q_{\text{flu}} \times (\text{Sf} - \text{Scan})
\]  
(E2.12)

In the canal situation, we use this equation, combined with Eqs. E2.5 and E2.6, to determine the salt concentration inside the lock \( (S_f) \) when the flushing rate \( (Q_{\text{flu}}) \), the salinities on the salt and fresh side, and the water level difference across the lock are known.

E.2.4.2. Lake-Type Locks. Locks that have a large freshwater lake behind them are treated differently from those with a canal because the salt that comes in through the locks does not dissipate quickly. Instead, there is a region of high salinity in the neighborhood of the lock. We assume that this high salinity also exists at the entrance of the sluice, and is thus the salinity of the outflow water. The sluice
discharge carries out part of the water that enters through the lock, so that only a fraction of the entering salt actually contributes to the overall salinity of the lake.

Given the complexity of this problem, and the different arrangements of locks and sluices at various lock complexes, we felt that an analytic solution was not possible within the PAWN framework. Instead, we defined the fraction of SALTin that actually enters the lake as k. The fraction going out through the sluice is then \((1 - k)\). We next evaluated k for each lock complex on the basis of discussions with WWS personnel who had information on the individual locks. In cases where data were not available to estimate k, we had to rely on analogy with other locks.

E.2.5. Lock Design Tactics To Reduce Salt Intrusion and Freshwater Loss

The previous sections described the salt intrusion process as it occurs in a traditionally designed lock. Over the years, a large number of locks have been designed to reduce salt intrusion. We investigated several of these, but a preliminary screening process narrowed our selection to three types deemed appropriate to the locks of interest in PAWN. These lock technologies are air bubble screens, selective withdrawal systems, and the construction of "Kreekrak"-type locks.

An air bubble screen consists of a horizontal pipe lying along the sill of the lock door. Air is pumped through numerous small holes in the pipe, and the bubbles induce vertical water velocities that delay the mixing of the salt and fresh water. Reference E.1 develops a theory explaining the operation of a bubble screen and gives equations for estimating the amount of air that must be pumped. Air bubble screens may be installed on either the salt or fresh side of the lock, or on both. They are inexpensive to install and can be easily added to an existing lock. The addition of a second bubble screen does not increase the required air compressor capacity because it is only necessary to operate one screen at a time, as one gate is always closed.

Measurements carried out at the Volkerak and the Rozenburg locks [E.13,E.14] provide the following values for \(\alpha\):

- If no air bubble screens are used: \(\alpha = .6\)
- If a single bubble screen is used: \(\alpha = .4\)
- If double bubble screens are used: \(\alpha = .2\)

A selective withdrawal system makes use of the density difference between the salt and fresh water by trapping the salt water in a pit dug in the bottom of the lock. The salt water is then pumped from the pit to the salt side of the lock. This type of system can be added to existing locks. With a properly designed pit, the amount of salt that passes into the fresh water beyond the pit can be limited to about 2 percent of that which enters through the lock [E.4]. When used with selective withdrawal systems, SALTin and Sf are measured immediately
we would suspect anyhow because the amount of salt entering the lake through the locks in any 10-day period is very small compared with the salt stored in the lake. Thus, we used the lake model rather than the canal model for these locks. Measurements show that the chloride concentration on the fresh side of the locks is quite constant throughout the year (0.5 to 1.0 kg Cl⁻/m²). Consequently, we assumed that the concentration on the fresh side remains constant in calculating the amount of salt intruding through the locks (SALTin) by Eq. E2.5.

At both lock complexes, a fraction of the salt intruding through the lock is carried out of the IJsselmeer through the discharge sluices. Reference E.12 gives the relation between the coefficient k (the fraction of the entering salt that remains inside the lake) and the discharge at each complex:

<table>
<thead>
<tr>
<th>Qslu (m²/s)</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>.60</td>
</tr>
<tr>
<td>190</td>
<td>.35</td>
</tr>
<tr>
<td>285</td>
<td>.20</td>
</tr>
<tr>
<td>380</td>
<td>.10</td>
</tr>
</tbody>
</table>

For use in the lock model, we fitted these data with the following equation:

\[ k = \exp\left(-\frac{Q_{slu}}{173}\right) \quad (E2.14) \]

**E.2.6.4. Den Helder.** The lock complex at Den Helder lies between the Marsdiep (which connects the North Sea and the Waddenzee) and the Noordhollandsch Kanaal (see Fig. E.4). The Loodswezen en Marinesschutsluis and the Zeedoksliits are little used and cause no significant salt intrusion; they were omitted from our analysis. We treated the Koopvaardersschutsluis as a canal-type lock. It is provided with two air bubble screens and also has a selective withdrawal system, but this has not proved satisfactory, and we did not consider it.

We used Eq. E2.10 to get the concentration at the Anna Paulowna polder, located 7100 m upstream from the lock. The canal flow area is similar to that at Harlingen (120 m²), and we assumed the same diffusion coefficient (30 m²/s). Using these values, we found salt concentration to be

\[ S_{inta} = S_{can} + (S_f - S_{can}) \times \exp(-2.0 \times Q_{slu}) \quad (E2.15) \]

**E.2.6.5. IJmuiden.** The IJmuiden lock complex is located at the entrance to the Noordzeekanaal from the North Sea. There are four locks in the complex (see Fig. E.5), and they are bypassed by a pumping
station and sluice. We treated this complex as a canal type. The locks are large, and they are frequently used. They have been equipped with bubble screens, but these are not in use because there is sufficient flushing water available from the Markermeer to keep salt concentrations in the Noordzeekanaal at acceptable levels, and the noise from the air compressor was found to be undesirable. The Noordzeekanaal is brackish near the lock complex, and two different layers of water may be identified:

- An upper layer of about 10 m depth in which the salt concentration runs between 1 and 5 kg Cl⁻/m³ near the locks and decreases farther upstream.
- A bottom layer of 6 m depth with a concentration of 8 to 12 kg Cl⁻/m³ that does not decrease upstream.

Fig. E.4 -- The lock arrangement at Den Helder
Velocity measurements show that the flushing flow moves almost entirely through the upper layer. We defined $S_f$ as the average chloride concentration in the upper layer of the first 4 km from the lock. We assumed that the amount of salt stored in the bottom layer remains constant.

We can calculate the amount of chloride that enters these locks as

$$\text{SALT}_{\text{in}} + Q_{\text{flu}} \times S_{\text{an}} - Q_{\text{flu}} \times S_f = \text{change in stored amount} \quad \text{(E2.16)}$$

All of the terms in this equation except $\text{SALT}_{\text{in}}$ have been measured in the field for a number of two-week periods [E.17]. Thus, we can calculate $\text{SALT}_{\text{in}}$. With information on the number of locking cycles and the lock dimensions, we can next calculate the values of $\alpha$. The following values were obtained:

$\alpha = 0.6$ if no air bubble screens are used,
$\alpha = 0.5$ if air bubble screens are used.

![Diagram of lock arrangement at IJmuiden](image_url)
Field measurements show that the chloride concentration of the water that goes out the 10-m deep sluice is roughly equal to the average concentration in the top 10-m layer of water near the locks (which we have defined as Sf). This implies that $k = 1$ for these locks because

$$\text{SALTout} = Q_{slu} \times S_{slu}$$

and

$$\text{SALTout} = (1 - k) \times \text{SALTin} + Q_{slu} \times S_f$$

Thus, if $S_f = S_{slu}$ (as the measurements show), $k$ must be equal to one, and our assumption that this is a canal-type lock complex is borne out.

We were able to obtain values for the diffusion coefficient for these locks by analyzing measurements of the chloride distribution and flushing rate along the canal. We found the following values:

- Without air bubble screens: $D = 1200 \text{ m}^2/\text{s}$
- With air bubble screens: $D = 963 \text{ m}^2/\text{s}$

We used a single value of 1100 $\text{m}^2/\text{s}$ in our analysis. The canal flow area (in the upper 10 m) is 2200 $\text{m}^2$. These values were used in Eq. E2.10 to calculate the chloride concentration at any point in the canal.

We also analyzed the locks at IJmuiden assuming the use of a selective withdrawal system. Because this system removes the salty bottom layer, we expect that the existing two-layer structure will disappear, and the water will be well mixed vertically. Thus, $S_f$ will be determined as the chloride concentration averaged over the whole 16-m deep cross section near the locks. The area of this cross section is 3040 $\text{m}^2$. We used a diffusion coefficient of 350 $\text{m}^2/\text{s}$, which was measured in the Kanaal Terneuzen-Gent where dimensions are similar to the Noordzeekanaal.

E.2.6.6. Spaarndam. Figure E.6 shows the layout of the complex at Spaarndam. The lock is connected to the Noordzeekanaal by Zijkanaal C, which opens on the Noordzeekanaal about 8 km upstream from IJmuiden. (Zijkanaal B is no longer connected to the Noordzeekanaal.) Thus, in order to find the salt concentration on the salt side of the lock, we must first apply the lock model to the locks at IJmuiden and determine the distribution of salt concentration in the Noordzeekanaal.

Measurements made in the Noordzeekanaal near IJmuiden show that the salt concentration in the upper 10 m of the canal is about 1.3 times that in the upper 6 m. Because the depth of Zijkanaal C is about 6 m, we assumed that the lower concentration should be used. Thus Eq. E2.10 gives the concentration on the salt side of the Spaarndam lock as

$$S_s = (1/1.3) \times \left\{ Scan + (S_f - Scan) \times \exp \left[ Q_{slu} \times 8000/(1100 \times 2200) \right] \right\}$$
where Scan is measured far upstream of the lock, Sf is measured behind the locks at IJmuiden, and Qflu is the flow in the Noordzeekanaal.

If a selective withdrawal system is used at IJmuiden, the salt concentration at Spaarndam is obtained from Eq. E2.10 (D = 350 m²/s, A = 3040 m², x = 8000 m) as

$$S_s = 1 \times \{\text{Scan} + (\text{Sf} - \text{Scan}) \times \exp[Qflu \times 8000/(350 \times 3040)]\}$$

Fig. E.6 -- The lock arrangement at Spaarndam
Salt concentration on the fresh side of the Spaarndam was the subject of a special substudy. Because of the complex system of canals on the fresh side of this lock, we could not apply Eq. E2.12. Instead, we took the results given in Ref. E2.5, in which a network model was used to investigate flow in these canals. Using the flows obtained from this model and a diffusion coefficient based on data from the Delfshavensche Schie, but corrected for the difference in depth, we developed an expression for salt concentration at the important intake points. There are two such points, and each point was investigated in both summer and winter. We found that the expressions for salt concentration at both inlets and for both seasons were similar, and we simplified the situation by averaging to produce a single expression valid for the whole northwestern area of Rijnland:

\[ \text{Sinta} = \text{Scan} + (S_f - \text{Scan}) \times \exp(-1.0 \times Q_{flu}) \]

E.2.6.7. Rotterdam. The Parksluizen at Rotterdam consist of two older locks between the Delfshavensche Schie and the Nieuwe Maas (see Fig. E.7). Information on the diffusion coefficient and the lock characteristics was obtained from Ref. E.6, which gave a diffusion coefficient of 15 m²/s and ratio of canal length to cross-section area of 19. We used these values in Eq. E2.10 to obtain the salt concentration at the mouth of the Delfshavensche Schie as

\[ \text{Sinta} = \text{Scan} + (S_f - \text{Scan}) \times \exp(-1.3 \times Q_{flu}) \]

E.2.6.8. Volkerak. A sketch of the layout of the Volkerak complex is given in Fig. E.8. The three large locks are used by commercial traffic, while the smaller lock is for recreational vessels. At present, the Krammer is salt while the Hollandsch Diep is fresh. When the Zoommeer is completed, the water on both sides of the Volkerak complex will be fresh. Thus, the Lock Salt Model was used only on the present configuration.

The complex geometry of the Hollandsch Diep and the Haringvliet makes it hard to predict the effect that salt coming through the locks will have on the salt concentration on the fresh side of the locks. Reference E.17 finds that when the discharge through the sluices is 45 m³/s (as it was in the summer of 1977), the net amount of chloride that enters the Haringvliet is about 5 kg Cl⁻/s. Normally, there is a flow from the Hollandsch Diep to the Haringvliet and Krammer, so that some of the salt that enters the locks will be carried into the Haringvliet. We used the Lock Salt Model to estimate the salt that came through the locks in the summer of 1977 and found a value of 20 kg Cl⁻/s. This implies that when the sluice flow is 45 m³/s, the value of k is 0.25. Thus, the sluices remove about 75 percent of the salt that enters through the locks when the sluice flow is 45 m³/s.
Fig. E.8 -- The lock arrangement at Volkerak

We were told by RWS personnel who were familiar with the Volkerak locks that when the sluice flow reaches 100 m³/s, there is no significant salt intrusion. (We assumed that "no significant salt intrusion" meant 1 kg Cl⁻/s.)

Finally, we know that if there is no discharge through the sluice, all the salt will enter the Haringvliet. That is, if Q slu = 0, k = 1.

We fitted these three data points with an exponential function to obtain a general relation for k:

\[ k = \exp(-Q\text{ slu}/33.0) \]  

E.2.6.9. Philipsdam. The Philipsdam lock complex will connect the Krammer and the Zijpe, which is part of the Oosterschelde (see Fig. E.9). When completed in 1984, the complex will contain two large locks for commercial traffic and one small lock for recreational vessels. For environmental reasons, it is desired to reduce the freshwater loss to the Oosterschelde. Consequently, Kreekrak locks are being built, and
there will be no sluice for flushing. Thus, all of the salt that intrudes through these locks will go into the northern Zoommeer. We were dealing with a lake-type situation with $k = 1$. We used the Lock Salt Model to provide the Distribution Model with the amount of salt entering the Zoommeer through the Philipsdam locks. The Distribution Model then determined the total amount of salt and the salt concentration in the Zoommeer. (The lock complex at Bruinisse is discussed in Sec. E.4.)

E.2.6.10. Kreekrak. A sketch of the layout of the Kreekrak complex and its locks is given in Fig. E.10. The two Kreekrak locks are located in the Schelde-Rijn Connection, between the Oosterschelde and the Antwerpss Kanaalpand (the canal leading to Antwerp). The canal forms the salt side of the complex, with the Zoommeer on the fresh side. Thus, this is a lake-type complex. We assumed that all the salt that passes through the locks reaches the Zoommeer. The Distribution Model used the amount of salt intrusion as calculated by the Lock Salt Model to determine the salt concentration of the Zoommeer. (The lock in the Oesterdam is discussed in Sec. E.4.)
E.3. CALIBRATION CASE RESULTS

The results for the calibration cases at each lock are presented in Tables E.2 and E.3. Table E.2 includes those locks for which salt intrusion is reported as the increase in salt concentration. Table E.3 gives the results for the remaining locks. In all instances, the calibration case calculations are based on the 1976 context, and incorporate the technical and managerial tactics in use at the locks during that year.
<table>
<thead>
<tr>
<th></th>
<th>Lock (Period)</th>
<th>Flushing Rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20 30 40 50 60 80 100 120 140 160</td>
</tr>
<tr>
<td>IJmuiden(a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan-Apr/Sep-Dec</td>
<td>5.32 4.19 3.47 2.96 2.59 2.07 1.72 1.48 1.29 1.15</td>
<td></td>
</tr>
<tr>
<td>May-Aug</td>
<td>5.59 4.43 3.68 3.16 2.76 2.21 1.85 1.59 1.39 1.24</td>
<td></td>
</tr>
<tr>
<td>Spaarndam(b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr-May/Sep-Oct</td>
<td>3 5 7+ 10 12+ 15 17+ 20 25 30</td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.13 0.08 0.06 0.04 0.03 0.03 0.03 0.02 0.02 0.01</td>
<td></td>
</tr>
<tr>
<td>NZK - 4.0</td>
<td>0.37 0.24 0.17 0.13 0.10 0.09 0.07 0.06 0.05 0.04</td>
<td></td>
</tr>
<tr>
<td>Nov-Mar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.08 0.05 0.04 0.03 0.02 0.02 0.02 0.01 0.01 0.01</td>
<td></td>
</tr>
<tr>
<td>NZK - 4.0</td>
<td>0.25 0.16 0.11 0.08 0.07 0.05 0.05 0.04 0.03 0.03</td>
<td></td>
</tr>
<tr>
<td>Jun-Aug</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.01 0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.18 0.11 0.08 0.06 0.05 0.04 0.03 0.03 0.02 0.02</td>
<td></td>
</tr>
<tr>
<td>NZK - 4.0</td>
<td>0.50 0.33 0.23 0.17 0.14 0.12 0.10 0.09 0.07 0.06</td>
<td></td>
</tr>
<tr>
<td>Harlingen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr-May/Sep-Oct</td>
<td>6 7 8 9 10 11 12+ 13 14 15</td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.29 0.17 0.15 0.14 0.12 0.11 0.10 0.10 0.09 0.08</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.18 0.16 0.14 0.12 0.11 0.10 0.09 0.09 0.08 0.07</td>
<td></td>
</tr>
<tr>
<td>NZK - 4.0</td>
<td>0.21 0.18 0.16 0.14 0.13 0.12 0.11 0.10 0.09 0.08</td>
<td></td>
</tr>
<tr>
<td>Den Helder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb/Apr-May</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct-Nov</td>
<td>1.09 1.09 0.76 0.59 0.48 0.32 0.25 0.20 0.17 0.12</td>
<td></td>
</tr>
<tr>
<td>Dec-Jan/Mar</td>
<td>0.80 0.80 0.58 0.44 0.36 0.24 0.18 0.15 0.12 0.09</td>
<td></td>
</tr>
<tr>
<td>Jun-Sep</td>
<td>0.87 0.87 0.60 0.46 0.37 0.25 0.19 0.15 0.13 0.10</td>
<td></td>
</tr>
<tr>
<td>Parksluizen(c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar-Apr/Oct-Nov</td>
<td></td>
<td>2 4 5 5+ 7+ 10 12+ 15 17+ 20</td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.05 0.03 0.02 0.02 0.02 0.01 0.01 0.01 0.01 0.01</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.39 0.23 0.19 0.17 0.13 0.10 0.08 0.07 0.06 0.05</td>
<td></td>
</tr>
<tr>
<td>NZK - 3.5</td>
<td>0.47 0.47 0.39 0.36 0.28 0.21 0.17 0.16 0.13 0.11</td>
<td></td>
</tr>
<tr>
<td>NZK - 5.0</td>
<td>0.75 0.75 0.62 0.57 0.44 0.34 0.28 0.23 0.20 0.18</td>
<td></td>
</tr>
<tr>
<td>Dec-Feb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.05 0.03 0.02 0.02 0.01 0.01 0.01 0.01 0.01 0.01</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.36 0.21 0.17 0.15 0.12 0.09 0.07 0.06 0.05 0.05</td>
<td></td>
</tr>
<tr>
<td>NZK - 3.5</td>
<td>0.48 0.43 0.35 0.32 0.25 0.19 0.15 0.13 0.11 0.10</td>
<td></td>
</tr>
<tr>
<td>NZK - 5.0</td>
<td>0.67 0.67 0.56 0.51 0.39 0.30 0.25 0.21 0.18 0.16</td>
<td></td>
</tr>
<tr>
<td>May-Sep</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NZK - 0.5</td>
<td>0.05 0.03 0.02 0.02 0.02 0.01 0.01 0.01 0.01 0.01</td>
<td></td>
</tr>
<tr>
<td>NZK - 2.0</td>
<td>0.36 0.20 0.17 0.15 0.12 0.09 0.07 0.06 0.05 0.05</td>
<td></td>
</tr>
<tr>
<td>NZK - 3.5</td>
<td>0.44 0.44 0.36 0.23 0.25 0.20 0.16 0.15 0.12 0.10</td>
<td></td>
</tr>
<tr>
<td>NZK - 5.0</td>
<td>0.69 0.69 0.58 0.52 0.40 0.31 0.25 0.21 0.18 0.16</td>
<td></td>
</tr>
</tbody>
</table>
Table E.2 (continued)

<table>
<thead>
<tr>
<th>Lock (Period)</th>
<th>Flushing Rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delfzijl</td>
<td>1  2  3  4  5  10  15  20  30  40</td>
</tr>
<tr>
<td>Dec-Feb</td>
<td>0.35 0.28 0.20 0.15 0.13 0.07 0.04 0.03 0.02 0.02</td>
</tr>
<tr>
<td>Mar-May/Sep-Nov</td>
<td>1.18 0.37 0.27 0.21 0.17 0.09 0.06 0.05 0.03 0.02</td>
</tr>
<tr>
<td>Jun-Aug</td>
<td>0.41 0.17 0.12 0.10 0.06 0.04 0.03 0.02 0.01 0.01</td>
</tr>
</tbody>
</table>

(a) Flushing rates are shown opposite lock location; the + indicates rates slightly larger than the given value.
(b) Results are shown for varying salt concentrations in the Noordzeekanaal outside the lock.
(c) Results are shown for varying salt concentrations in the Nieuwe Maas outside the lock.

Table E.3

SALT INTRUSION THROUGH LOCKS (1976 CALIBRATION CASES):
AMOUNT OF SALT INTRUSION
(million kg Cl⁻/day)

<table>
<thead>
<tr>
<th>Lock (Period)</th>
<th>Flushing Rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volkerak(a)</td>
<td>5 10 15 20 25 30 35 40 45 50</td>
</tr>
<tr>
<td>Jan-Feb</td>
<td>1.21 1.04 0.90 0.77 0.65 0.57 0.49 0.42 0.36 0.31</td>
</tr>
<tr>
<td>Mar/Nov-Dec</td>
<td>1.44 1.23 1.06 0.91 0.78 0.67 0.58 0.50 0.43 0.37</td>
</tr>
<tr>
<td>Apr-May</td>
<td>1.47 1.27 1.09 0.95 0.80 0.69 0.59 0.51 0.44 0.38</td>
</tr>
<tr>
<td>Jun-Jul</td>
<td>1.62 1.29 1.19 1.03 0.88 0.76 0.65 0.56 0.48 0.41</td>
</tr>
<tr>
<td>Aug</td>
<td>1.83 1.57 1.35 1.16 1.00 0.86 0.74 0.63 0.54 0.47</td>
</tr>
<tr>
<td>Sep-Oct</td>
<td>1.68 1.45 1.24 1.07 0.92 0.79 0.68 0.58 0.50 0.43</td>
</tr>
<tr>
<td>Kornwerderzand</td>
<td>5 10 20 30 50 75 100 200 300 500</td>
</tr>
<tr>
<td>Apr-May/Sep-Oct</td>
<td>0.35 0.35 0.33 0.32 0.28 0.25 0.21 0.12 0.07 0.02</td>
</tr>
<tr>
<td>Nov-Mar</td>
<td>0.18 0.17 0.17 0.16 0.14 0.12 0.11 0.06 0.03 0.01</td>
</tr>
<tr>
<td>Jun-Aug</td>
<td>0.56 0.56 0.55 0.53 0.47 0.41 0.36 0.20 0.11 0.04</td>
</tr>
<tr>
<td>Den Gever</td>
<td>5 10 20 30 50 75 100 200 300 500</td>
</tr>
<tr>
<td>Apr-May/Sep-Oct</td>
<td>0.36 0.36 0.35 0.33 0.30 0.26 0.23 0.13 0.07 0.02</td>
</tr>
<tr>
<td>Nov-Mar</td>
<td>0.15 0.15 0.14 0.14 0.12 0.11 0.09 0.05 0.03 0.01</td>
</tr>
<tr>
<td>Jun-Aug</td>
<td>0.53 0.53 0.52 0.49 0.45 0.39 0.34 0.19 0.11 0.03</td>
</tr>
</tbody>
</table>

(a) Flushing rates are shown opposite lock location.

E.4. MISCELLANEOUS SALT INTRUSION CALCULATIONS

We did not use the lock model to calculate the salt intrusion at two lock complexes. These were small locks in the Delta area of the Netherlands, one at Bruinisse (on the Grevelingen) and the other in the future Oosterdam (on the Zoommeer).
For the lock at Bruinisse, we calculated an approximate salt intrusion by comparing the situation with that at the Volkerak recreation lock. The locks are similar in size and characteristics, the ship traffic at Bruinisse is primarily recreational, and the difference in salt concentration across both locks is the same. As a result, we felt reasonably confident that we could scale the salt intrusion results at the Volkerak recreation lock by the relative amounts of ship traffic using the two locks. The results of this process are shown in Table E.4, which shows salt intrusion at Bruinisse in the 1976 context, both with and without air bubble screens.

Table E.4

<table>
<thead>
<tr>
<th>Salt Intrusion (kg/s)</th>
<th>Without Bubble Screens</th>
<th>With Bubble Screens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>4.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Winter</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The lock in the Gasterdam will be specifically designed to reduce salt intrusion by using one of four alternative configurations [E.2]. The salt intrusion through this lock has been calculated by the RWS, assuming a particular design and number of lock cycles per day [E.15]. We recalculated this intrusion, based on additional information about the lock type and dimensions, using the same assumptions for the number of lock cycles. The results of this calculation were: salt intrusion = 55,000 kg Cl⁻/day; freshwater loss = 0.065 m³/s.

NOTES

1. This is true for all normal locks, because lock operation does not depend on the type of salt intrusion technology used. For locks with the Kreekrak system, however, level equalization time will vary with the type of cycle. As a result, the simulation had to be repeated for each technical tactic at the Kreekraksluizen and Philipsdamsluizen.

BIBLIOGRAPHY


E.6. Delft Hydraulics Laboratory, Onderzoek naar de waterbehoefte ter bestrijding van de externe verzilting van de Hoogheemraadschappen Delfland en Schieland (Study on the Water Demand in the Abatement of Chloride Intrusion in the Hoogheemraadschappen Delfland and Rijnland), R146, Delft, March 1979.


Appendix F

HIGHLANDS LOCK ANALYSIS RESULTS

All loss function curves developed in the study are presented in Figs. F.1 through F.5. These curves plot lock delay costs as a function of water consumption by the lock or canal section. Figure F.1 gives the loss functions for Maasbracht in the 1976 context. The three curves represent different fractions of the nominal traffic level. Figure F.2 shows the loss function for the nominal predicted traffic at Maasbracht in the 1985 context. Figure F.3 presents the curves for Born, also on the Julianakanaal, for both the 1976 and 1985 contexts. The composite curves for the Kanaal Wessem-Nederweert (Panheil) and the Wilhelminkanaal are shown in Fig. F.4. Finally, the curves for the three sections of the Zuid-Willemsvaart are presented in Fig. F.5.
Fig. F.1 -- Loss functions for Maasbracht at three traffic levels (1976)
Fig. F.2 - Loss function for Maasbracht (1985)
Fig. F.4 -- Lock loss functions for Wilhelminakanaal and Kanaal Wessem-Nederweert
Fig. F.5 -- Lock loss functions for Zuid-Willemsvaart
Appendix G

SHIPPING SAFETY AND ACCIDENT ANALYSIS

G.1. BACKGROUND

Chapter 7 discussed the purpose of this analysis, to develop models for estimating the probability and cost of shipping accidents in the Netherlands. With these models we could study how alternative water management policies affect shipping safety. A preliminary step in the analysis was to discuss the problem of shipping accidents with numerous Dutch authorities and to collect data and reports.

During this investigation, we discovered that the problem of accident prediction is especially complex and cannot easily be analyzed because:

- Shipping authorities have not systematically collected data.
- Accident reports are difficult to obtain.
- Accidents occur infrequently except on heavily traveled waterways.
- Local conditions are important causes of accidents.
- No one collects data for conditions when no accidents occur.

As a result, we decided to limit the initial analysis of the problem. If a preliminary investigation indicated that we could not easily obtain any useful models or results, no additional resources would be invested in the project. This appendix discusses that analysis.¹

G.2. ACCIDENT DATA

The analysis was limited to accidents on the Waal (between the German border and Gorinchem) during the years 1973 through 1976. The data set included reports of 437 such accidents (an average of about one every three days). These reports provided extensive information about each accident, including:

- Date, time, and location.
- Description of the river where the accident took place.
- Number of ships involved, and their characteristics.
- Environmental conditions.
- Type of damage.
- Potential causes, including human factors and malfunctions.

We were able to obtain daily discharge (flow) data for the Rijn at Lobith. If the weir control policy at Driel does not change, one can assume that daily Waal flows are determined by the Lobith discharges.
Although daily ship traffic data would seem to be important, it is difficult to obtain. We could only find monthly traffic data for Lobith and the locks at the Volkerak and Hartelkanaal.

G.3. ANALYSIS PROCEDURE AND RESULTS

The limited data on ship traffic restricted consideration to only monthly accident rates. We found very low correlation coefficients between accidents per month, monthly traffic volumes (at the three locations), and mean monthly flows for the Rijn. The R-squared value from multiple linear regression was also low, less than 0.10. This leads to the conclusion that either monthly data are too aggregated to be useful, or else no linear effect exists. Scatter diagrams also did not yield any relationship between monthly accident rates and the other variables.2

The analysis also considered the relationship between daily flow and the number of accidents. The results of this investigation are shown in Fig. G.1. Below a discharge rate of 3000 m³/s, the fraction of days with one or more accidents remains relatively constant at about 20 percent, except when the discharge is between 1000 and 1500 m³/s. In this interval, the fraction is 30 percent. For discharges exceeding 3000 m³/s, the fraction increases. Figure G.2 shows the distribution of days by discharge rate. From this we can see that

![Graph showing distribution of days with one or more accidents](graph.png)

Fig. G.1 -- Distribution of days with one or more accidents
discharges above 3000 m³/s occur only about 8 percent of the time in our data. Data for a more extended period might therefore change this result.

We do not know what might cause this result, particularly the lower rate at smaller flows. Again, however, the data may be insufficient, because flows below 1000 m³/s are relatively rare. The most likely cause of additional accidents at low flows would be the combination of additional ships (because of lower load factors) with a narrower and more shallow waterway. A separate analysis of the average number of accidents per day by discharge rate yielded the same pattern. Days with flows between 1000 and 1500 m³/s averaged about 0.4 accidents per day, about 40 percent higher than other flows below 3000 m³/s.

We also found other interesting results. Table G.1 shows the percentage of Waal accidents during different times of the day. Considering rates on a more detailed level than that shown, we found that they are low in the early and late hours, increase sharply after 0600, peak at 0700, drop at 1200 and 1700, and taper off sharply after 1900. The number of accidents does not vary with the seasonal shift of daylight hours. Rates vary little by day of week, except for weekends, which have far fewer accidents. These results can probably be explained by variations in the density of ship traffic during the day and week.
Table G.1

DISTRIBUTION OF ACCIDENTS OVER TIME

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Mean</th>
<th>Best Hour</th>
<th>Worst Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000-0599</td>
<td>13.1</td>
<td>0.66</td>
<td>3.50</td>
</tr>
<tr>
<td>0600-1159</td>
<td>34.8</td>
<td>4.81</td>
<td>7.44</td>
</tr>
<tr>
<td>1200-1759</td>
<td>31.3</td>
<td>3.28</td>
<td>6.56</td>
</tr>
<tr>
<td>1800-2359</td>
<td>20.8</td>
<td>1.53</td>
<td>5.25</td>
</tr>
</tbody>
</table>

Accident frequency depends strongly on location. Local irregularities and impediments to smooth traffic flow are important. These problems make navigation more difficult, and require operators to be always alert. Accidents occur often at bends, splits, anchorages, harbor entrances, waterway intersections, and the toll facilities at Lobith. Altogether, about 60 percent of all accidents occurred in open waterways; the other 40 percent happened where navigation requirements are more demanding.

Other important causes of shipping accidents were human error and environmental conditions, including visibility, wind, and currents. Table G.2 presents the percentage of accident reports that cited such factors as possible causes.

Table G.2

IMPORTANT INFLUENCES IN ACCIDENTS

<table>
<thead>
<tr>
<th>Accident Influence</th>
<th>Percent of All Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor visibility</td>
<td>19.0</td>
</tr>
<tr>
<td>Difficult currents</td>
<td>13.0</td>
</tr>
<tr>
<td>Wind conditions</td>
<td>8.0</td>
</tr>
<tr>
<td>Human error</td>
<td>80.0</td>
</tr>
<tr>
<td>Equipment malfunction</td>
<td>18.0</td>
</tr>
<tr>
<td>Inattention</td>
<td>38.0</td>
</tr>
<tr>
<td>Judgment</td>
<td>12.0</td>
</tr>
<tr>
<td>Other</td>
<td>12.0</td>
</tr>
</tbody>
</table>

The dataset had no information about the cost of damage from the accidents. These data are apparently confidential, and the insurance companies will not release them. Although some information about damage to the national infrastructure is available, it is incomplete. The accident reports gave qualitative information about the type of damage incurred, however. This information revealed that about 60 percent of the accidents had little or no damage. Although 33 percent reported severe damage, only 5 percent involved a vessel sinking.
G.4. CONCLUSIONS

The analysis results discussed above are not encouraging. There are no strong relationships between accident frequencies and variables affected by water management policies, particularly flow rates on the Waal. Instead, the results indicate that accidents are more often caused by other influences, such as waterway configuration, environmental conditions, and human error. Most of the PAWN tactics would affect only water levels and flows. These may indirectly influence accident rates, through induced changes in ship traffic levels and channel navigability, but the analysis revealed only weak effects at best.

We were additionally handicapped by the complete lack of data on accident costs. We could not integrate the analysis results into the overall project, if the results could not be expressed in monetary terms. We might do this during the impact assessment phase of PAWN, but not in either strategy design or tactic screening. In these processes, the objective functions must be expressed in monetary terms.

Considering these problems, it was not feasible to expand the accident analysis. The results indicate that the effect of PAWN tactics would be very slight, if measurable at all, and that we would be unable to predict these effects with the available information. Future development of accident models might be possible with more complete information, if the inherent problems can be overcome.

NOTES


2. The analysis did confirm the expected relationship between Lobith discharge and ship traffic on the Rijn. The data gave a relatively strong negative correlation (-0.71) between these variables.
Appendix H

PRICE AND REGULATION TACTICS

Chapter 1 discussed how PAWN classified the various types of water management tactics that could be applied in the Netherlands. These tactics were organized into four classes: (1) technical, (2) managerial, (3) price, and (4) regulation. The main body of this volume discusses the methodology and analysis for the technical and managerial tactics, but says little about the price and regulation (P/R) tactics. These tactics were left for this appendix, because they did not require any specific analysis. Instead, the DM and MSDM could calculate how they affect shipping operations by using the low water and lock delay loss functions. Outside these costs, they have no particular relevance to shipping.

Almost all of the potential P/R tactics are directed toward water users other than shipping, and thus affect shipping only indirectly. Being intended for agriculture and other sectors of the economy, they affect water consumption patterns and distribution throughout the network. These changes in distribution can be directly translated into shipping cost changes with the low water and lock delay loss functions. The DM and MSDM have done this translation in the screening and strategy design processes. There was no need to determine the direct costs to shipping for any of the P/R tactics.

This is not to say that P/R tactics cannot be applied to the shipping industry. However, because shipping does not directly consume water, water management P/R tactics for shipping would generally be directed toward improving water quality or salinity. Most shipping regulations that affect water management relate to water quality.

One can argue that tactics which involve charging for, or otherwise restricting, passage through highlands or lowlands locks should be included. These tactics would attempt to control freshwater consumption or salt intrusion at locks, by limiting the number of ships using the locks. Instead of trying to control the number of ships, however, we should try to control the number of lock cycles. This can be done with lock management tactics, which can be imposed and analyzed much more easily than the corresponding P/R tactics for ships. We have taken this approach and discussed the analysis completely in Chap. 6.

Tactics could also be used to prohibit or restrict passage on certain waterways under predetermined circumstances. Although these restrictions could be imposed, they were not considered seriously. For waterways without locks, nothing can be gained by restricting ship traffic. Ships do not consume water, and their passage will be naturally restricted by water depths and flows. For waterways with locks, management tactics at these locks will most directly and easily restrict ship traffic. Additional regulations would be unnecessary.
Although P/R tactics to control water consumption can be eliminated, tactics to control waste discharges from ships should be considered. We found, however, that such restrictions already exist on most major waterways in the network. Discharge of oil or bilge water is prohibited on the Rijn and state waters. Garbage discharge has been limited because most carriers voluntarily collect it for disposal at ports and harbors. No laws restrict discharge of toilet effluents, but they only cause problems in local areas where recreational boating and swimming are popular. For these reasons, waste discharges from ships were not considered to be an appropriate problem for further consideration.

Finally, P/R tactics could be used to control the pollution from accidental spills in collisions. These regulations could either be designed to reduce the probability of accidents or to reduce the probability of spills in accidents. In neither case are they appropriate for a water management study. Tactics to influence exclusively shipping industry safety are outside the boundaries of the problem. Such tactics are best left to shipping experts who know the costs and benefits of possible regulations and who thoroughly understand the safety problem.

This decision might have changed had we been able to develop and use a shipping accident model. However, because we could not adequately predict or explain shipping accidents, we could not realistically consider tactics that would directly affect accidents or spills caused by accidents.
Appendix I

ECONOMIC EVALUATION OF BENEFITS AND LOSSES

Assuming that water management policies can affect shipping operations, we need some means by which to evaluate the effects. In the PAWN project, we did this by assuming that policies changed the effective supply of ship transport. Such a shift in the supply curve will cause a change in overall welfare equal to the market-valued gains (or losses) to producers (carriers) and consumers (shippers) of transport services. We must consider this matter in both the long-run and short-run situations.¹

I.1. LONG-RUN ANALYSIS

A supply and demand diagram for the long-run case is shown in Fig. I.1. Assume that some change in the water system increases the production costs for all firms producing a particular commodity (e.g., ship transport). This increase will shift the supply curve for the industry, as shown by the change from $a^0S^0$ to $a^1S^1$ in the diagram.

![Diagram showing long-run gains and losses from an increase in supply costs](image)

Fig. I.1 -- Long-run gains and losses from an increase in supply costs
The demand curve for the commodity is indicated by $cD$. In the original equilibrium situation, consumers are willing to pay an amount equal to the area $cb^*a^*$ for the amount ($Q^*$) they are consuming. Because they are all charged the same price ($P^*$), with actual payments equal to $P^* b^* Q^*$, they are deriving a consumer surplus equal to the area $cb^*a^*$.

At the price $P^*$ the industry sells $Q^*$ units, receiving revenue equal to $P^* b^* Q^*$. Because production costs are only $a^* b^* Q^*$, the industry earns profits equal to $P^* b^* a^*$. The sum of consumer and producer surplus is thus the area $cb^*a^*$.

When the cost increase for the firms causes the industry supply curve to shift upward to $a^* S^*$, the market price rises to $P^1$ and sales drop to $Q^1$. This causes consumer surplus to fall to an amount equal to the area $cb^1 P^1$ and profits to fall to $P^1 b^1 a^1$. The total effect of the water system cost increase is thus valued by the market as the sum of the area $P^1 b^1 a^1$, the loss of consumer surplus, and $P^1 b^1 a^1$ minus $P^* b^* a^*$, the change in profits. If the welfare of producers and consumers is valued equally, the effects add to derive a net market-valued loss equal to the area $a^1 b^1 b^6 a^2$.

Although this long-run situation is relevant to changes in the shipping fleet, we must also consider what happens in the short run, where the supply of ships is fixed. This situation corresponds to the other shipping costs considered in the analysis.

1.2. SHORT-RUN ANALYSIS

Geometric treatment of short-run market-valued gains and losses is more difficult than treatment of long-run effects, because the supply functions are more complex. In the short run, the number and size of firms and the major items of equipment (ships) are fixed. The remaining cost items, the short-run marginal costs, are shown in Fig. I.2, where they are drawn as step functions. Assume that the fixed costs (which do not change and are not shown) include some required annual minimum of labor and other items. Then some small amount of production ($Q^{1*}$) is possible in the short run without incurring any additional costs. To provide more than that, however, requires costs of $MC^*$ per unit. Also assume that those marginal costs are constant until some capacity level ($Q^*$) is reached. No further amount can be produced in the short run at any cost.

In the most general case, a change in water availability or cost may shift the entire short-run marginal cost function--the starting point, the level of costs, and the ultimate capacity. This is indicated in Fig. I.2 by the shift from $S^*$ to $S^1$. Using the numbered areas in the figure, we can derive the market-valued gains (or losses) associated with the shift in supply. The net benefit is again the sum of the change in consumer surplus and the change in industry profits, just as before. The calculation of net benefits is shown below, where we have
omitted the fixed costs because they cancel out and do not affect the results.

\[
\text{Change in consumer surplus} = -(1 + 2)
\]

\[
\text{Change in producer profits} = (\text{Revenue} - \text{Costs})^1 - (\text{Revenue} - \text{Costs})^0
\]
\[
= (1 + 3 + 4 + 5 + 7 + 8 + 9) - (5 + 8 + 9)
\]
\[
- (3 + 4 + 5 + 6 + 7 + 8 + 9 + 10)
\]
\[
+ (9 + 10)
\]
\[
= 1 - 5 - 6 - 8
\]

\[
\text{Net benefit to society} = \text{Change in consumer surplus} + \text{Change in producer profits}
\]
\[
= -(1 + 2) + (1 - 5 - 6 - 8)
\]
\[
= -(5 + 8 - 10) - (2 + 6 + 10)
\]

The final calculation allows us to separate the net benefits into two distinct and important components. The first term \((5 + 8 - 10)\) represents the change in marginal production costs, the variable costs of shipping. The second term \((2 + 6 + 10)\) is the market-valued consumption loss, the loss associated with goods that did not get produced. For shipping, this loss equates to transport not used, thus goods not shipped after the change in supply. As such, it represents
the opportunity cost to consumers (shippers) of not receiving those goods from the original source during the given time period.

Figure I.2 shows that we can obtain a lower-bound estimate of the consumption loss from the area (6 + 10), which is given by:

\[ \text{Lower bound} = P^* \times (Q^* - Q^1) \]

This is just the amount that consumers have demonstrated a willingness to pay for transport of the goods. Similarly, an upper-bound estimate of the consumption loss would be:

\[ \text{Upper bound} = P^1 \times (Q^* - Q^1) \]

This is the amount that consumers who have left the market have refused to pay (after the introduction of the policy).

NOTES


2. For a general discussion of consumer and producer surplus, the reader should consult a standard text in microeconomics, such as Jack Hirshleifer, Price Theory and Applications, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1976.