First European Junior Scientist Workshop on

Applications of Operations Research
to Real Time Control of Water Resources Systems

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Experience with real time control of an Urban Drainage System

I. Introduction to the Problem

As portion of the City of Bremen combined sewer network is used as an example in this paper.
This network drains part of the city which is situated on the left side of the river Weser, in German referred to as 'Bremen links der Weser'. Graphics of the network (real state and modelized state) are attached.

The main problem in Bremen is to reduce the combined sewerage overflows into the river Weser and both small receiving streams the Krimpelflet and the Wasserlöse, which carry the overflows to the River Weser. Even a small combined sewerage overflow into either the Krimpelflet or the Wasserlöse, can lead to very negative ecological consequences.
According to the municipal law, more than 90% of the whole quantity which flows into the network should be directed into the treatment plant.
The usual solution in such a case would be to construct large retention basins, into which the peak flows during the storm event can be directed and stored for later treatment.
Unfortunately, studies and simulations have shown that according to the standard concept, the size of the retention basins would be so great that it exceeds the financial capability of the city. At the

same time, it has been noted that the in-line capacity of the Bremen network is considerable (>40 000 m^3). If it could be activated, the required on-line storage capacity would be greatly reduced. This is the basic idea that underlies the concept of real time control.
In the case of Bremen, due to the extreme flatness of the rainfall catchment areas (slope < 1/1000), pumps have been installed from the beginning to control the entire waste water transport within the network as well as into the treatment plant or into the on-line retention basins.

The approach for real time control can therefore be stated in the following way:
What should the pump control strategy be to minimize the combined sewerage overflows through activation of the in-line as well as the on-line storage capacity?

It is assumed that the on-line decision is based on receiving, at any time, all relevant data on the state of the system, with control over the pumps and other facilities.
During the seventies, the City of Bremen used a first version of an on-line survey and monitoring system, which has since been re-structured over the last three years.
Now, a computer, located at the main pumping station (called HPWL), receives every fifteen seconds and stores every five minutes, measurement data on rainfall (3), waterlevels (18), flowrates (5), pump activities (about 40), energy consumption (3).
The operator can, at any time, receive the momentary network situation -especially the in-line capacity reserves- through different graphical representations.

II. Development of a Control Strategy : Basic Requirements

The original manual control strategy over the pumps (especially in the two most important stations of Krimpel and HPWL) was originally set with establishment of the pump stations and in the course of time has been modified, more precisely simplified (principally to render the task of the operator easier). The development of this control strategy was an evolutionary process over years.
Consequently, it was believed that a scientific and rational analysis of the strategy research could lead to better results for the control of the system (ie reduced overflow quantities).

Therefore such a study started three years ago, as the German Ministry of Research and Technology (in German B.M.F.T) decided to support a joint project in which the City of Bremen and the Institute of Hydrology of the University Hannover cooperate.

The development and verification of control strategies necessitates two basic conditions:

- a sufficiently precise simulation of the network
- a good decision module.

The simulation of the network is essential to evaluate each strategy and the impact of any modifications.
ithout a sufficiently accurate simulation model, it is questionable whether any further step has any sense. In this respect, the choice of an appropriate simualtion moduke must be carefully developed, depending on the characteristics of the catchment and the limits of the modelization.
In the case of Bremen, it was necessary to use an hydrodynamic simulation model, because of the very flat slope as well as the considerable influence of the pumps over the state of the network (flow rates and water levels).
On the other hand, in order to keep the calculation time within acceptable limits, a relativly coarse description of the network must de defined.
The real network consists of several thousand reaches, which nummer was reduced to 70 reaches. The calibration phase was in this case very critical and tedious. It required a good understanding of the processes as well as of the structure and limits of the model.

In the decision module, the decision process is described. Basically, we consider two possible approaches:

- *the definition of the control strategy through optimization*
- *the definition of the control strategy through an knowledge base system (better known as expert-system).*

In the case of Bremen, we opted for the second solution.
A knowledge base system is now in operation in Bremen. Every five minutes or every minute, depending on the acutness of the situation, it receives data on the state of the network and delivers control recommendations to the operator.
One remaining problem is that the strategy rules, presently built into

the system have been derived from a system analysis and as yet are not completely tested through simulation.
Until recently, it was not possible to test the knowledge base, since no connection between the simulation model and the decision module was available. The actual connected version (simulation-expertsystem) is presented with this paper.

III) Development of Control Strategies: Proposed Methods

The aim of the research is to construct a tested rule base for the on-line control of the pumps.

Two ways will be investigated:

- *implementation of an learn algorithm*
- *analysis of the results obtained by optimization.*

In the first case, a preliminary step is to develop a standard rule base for the strategy determination, modify it 'manually' and evaluate through simulations the impacts of the modifications. This will allow the determination of the relevant decision parameters and their influences over the strategy results, which is an essential step towards an improvement of the set of rules.
As a further step, an automatic learn process will be performed. This learn process bases on so-called 'meta-rules'.
The prefix 'meta' refers to the domain of investigation and application of these rules. In the case of normal (strategy) rules, the implicit object of treatment is the network itself. In the case of meta-rules, the object of treatment is the set of strategy rules itself. The abstraction level is therefore higher, which is indicated through the terminology.
'Meta-rules' will be fired, any time a strategy research is performed. They make a diagnosis of the network state.
If the results reveal unsatisfactory, the meta-rules determine the strategy rule(s) which may be responsible for the disorders as well as the corrections that should be made.

The second way is to use an optimization module as strategy research module and analyze the results.
At the Institute of Hydrology of the University Hannover, a linear optimization model for strategy research has been developed and connected to the hydrodynamic transport simulation model EXTRAN. Some

simulations have already been performed over one event for the network of Bremen.
A representative set of events will be chosen and simulations will be made. The analysis of the strategy proposed by the optimization will lead to the formulation of a set of 'optimized' strategy rules.

References:

'Real Time Control Of Urban Drainage System; The State of The Art'; IAWPRC task group; edited by W. Schilling; Pergamon Press, April 1989

Adaptation of an Expert-System for the Real Time Control of a Sewerage Network: Case of Bremen Left Side of the Weser; A. Khelil, M. Grottker, M. Semke; Fifth International Conference on Urban Storm Drainage; July 23-27 1990, Japan. (to be published).

'Implementation of an Expert-System for Control Strategy Research; Case of Bremen'; A. Khelil; Intermediate Report of Research, Project 02-WA86470 , German Ministry for Research and Technology; April 1989 (in German).

Fig.1: The Network 'Bremen Left Side of the Weser'(Real state)

Ni : Pluviometer number i (3).
hi : Water level measurement number i (18).
qi : Flow rate measurement number i (5).
S-PW : Pumping station for sanitary water.
M-PW : Pumping station for combined water.
The most important pumping stations ones are:
HPWL : the main pumping station situated at the outlet of the entire catchment,
Krimpel station : situated at the outlet of the Krimpel catchment.
RÜB/KÜ : Combined sewerage overflow.

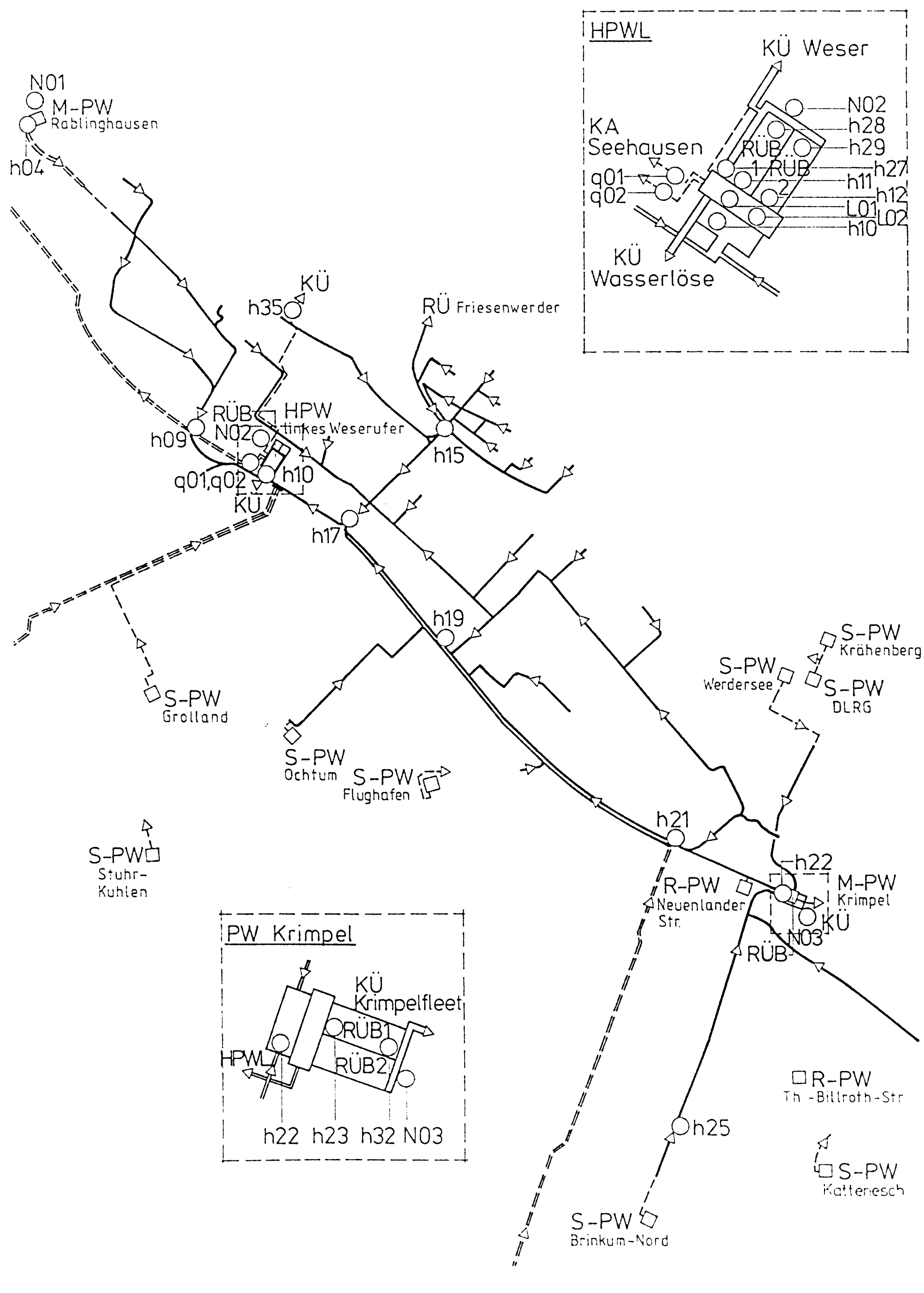
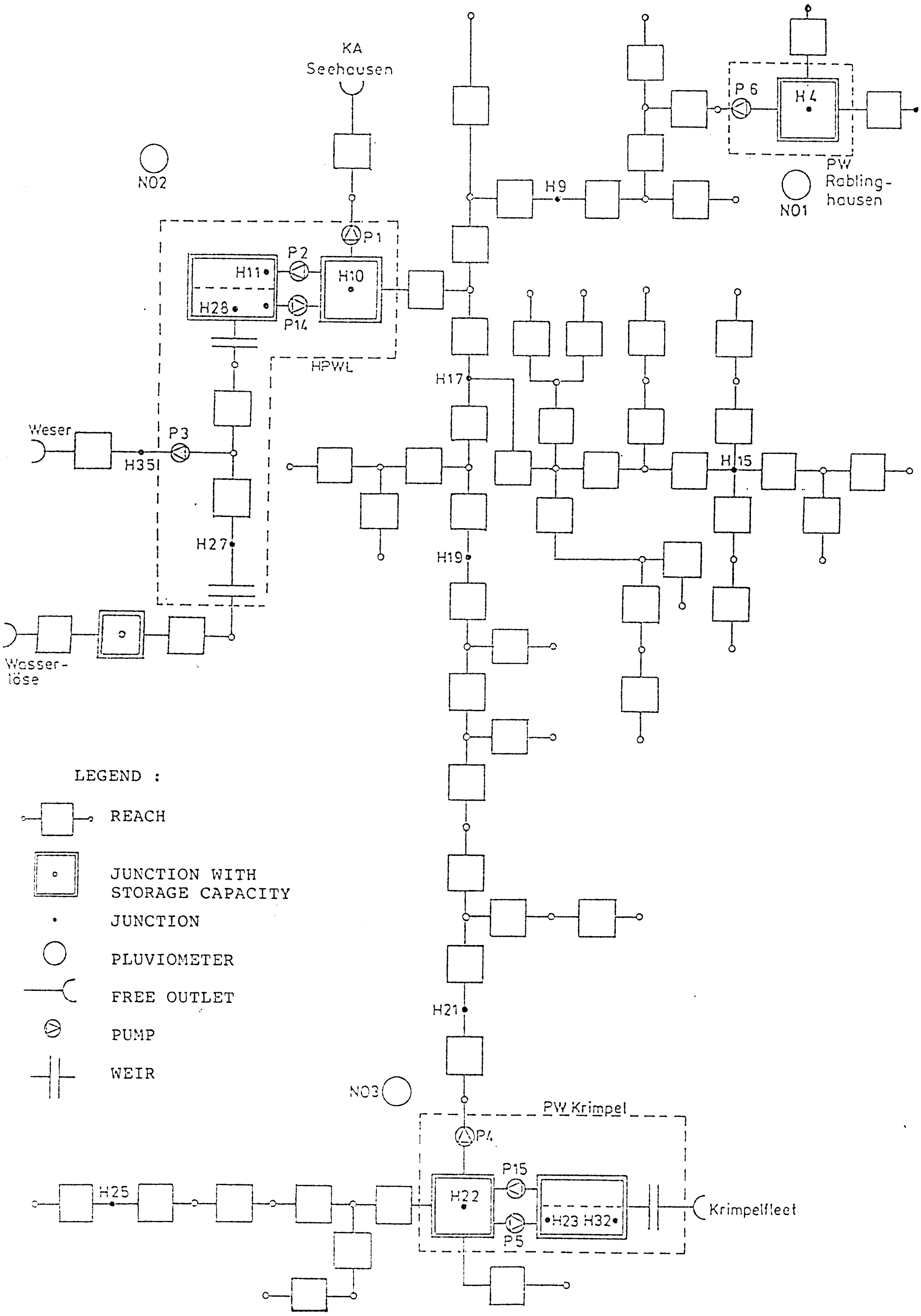


Fig.2: The Network 'Bremen Left Side of the Weser'(model description)



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REPORT OF THE FIRST SESSION.

List of the presentations:

1) Matthias Grottker: Towards Real Time Control in the Urban Drainage System of Fehraltorf /Zürich.

2) Jan Forsberg: Hydrodynamics of shallow water waves in sewers and their control in real time

3) Dietmar Gatke: Model for simulation of controlled urban drainage systems -problems and exemplary applications on activating storage in a trunk sewer.

4) Wytze Scuurmans: Hydrodynamical simulations of controller behavior.

Matthias Grottker examined the technical requirements that should be taken into account when designing a survey and monitoring system for the real time control of a drainage system.
As an example, he described the design process of the control system, that is to be installed in the catchment of Fehraltorf (Zürich) in the near future.

Following points were given special emphasis:
- the choice of the regulators,
- the choice of the measurement devices,
- the type of transmission,
- some requirements on the decision system.

In the following discussion, the majority of the questions were related to:
- the precision of the measurement
- the consistency of the measured data.

For each type of maesurement variables (rainfall intensities, water level, pipe flow) there is a choice between several devices whose

measurement principles differ to each other. The avantages and shortcomings of each measurement system are reviewed depending on the boundary conditions and objectives of the controll.
As measurement errors or defects on measurement gages can not be totally excluded, it is recommended that the control system analyze the consistency of the received data, on which basis it shall propose a control strategy.
No method exists to evaluate with certainty in the general case, the relevance of the data. As a consequence, this complicated problem can only be solved through the simultaneous use of several analysis methods based on

- a statistical treatment (probability analysis),
- a system analysis (a simulation of the processes within the catchment and the network)
- consideration about the principles of measurement.

Jan Forsberg presented a project in which will be examined how the strategy over the control gages influences the process of filling of a storage tunnel.
This storage tunnel (called the 'Snake') is planed to be built under the drainage system of the city of Stockholm. If there is a risk of discharge of combined waters into the environnemnt, the underground storage bassin will be fed by 9 gravity shafts, whose inflows shall be controlled through side weirs.
The originality of the project ist that the simulation of the weirs will not be performed as usual through a numerical model but through a physical one.
The discussion focused about the advantages and shortcomings of the physical models.
In this respect, the translation of the model results to the reality (the so called 'scaling problem') constitutes a major issue.
On the one hand, the established relationship betwenn model and reality is only valid for the chosen configuration of the network, which constitutes an handicap when compared to numerical models. On the other hand, if the physical model predicts instability, it is assured that this instability is not due to the numerical resolution of the equations system.
In this respect, this method give a new insight about the nature and the course of the phenomena.

The last two presentations dealt with numerical simulations of control gages. These gages regulate either the water level or the flow rate.

Dietmar Gattke presented an extension of the EXTRAN model.
The model itself simulates the flow processes within the canalisations by resolution of the Barre de Saint Venant equations system.
The extended model allows the simulation of gates.
The flow rates through the regulators will be calculated by means of transition functions, whose characteristics depend on the flow conditions.
The impact and efficiency of the regulation mode will be analyzed and the influences of different regulation parameters estimated.

During the following discussion, the main concern dealt with the relevance of the transition functions.
'hese functions constitute raw approximations of the real processes. Moreover, every discontinuity due to the change of flow condition, was erased through the use of weighting coefficients. It was disputed whether such a suppression of the numerical discontinuities is valid and in which extent the conclusions of the study about the characteristics of the controller depend on the simulation model.
One possibility to clarify the situation would be to compare the simulation results with some measurement data.
Another solution would be to use several simulation models and compare the results to each other.

In the last presentation, Wytze Schnurmann also considered the numerical simulation of automatic controlled regulators, to analyze the relevance of the mode of regulation.
The main difference between the two studies is their field of application, which on the other hand determines some important features of the modelization.
In the first case, the controll gages should be installed in a urban drainage network. Among others, one aim of the study is to precise, whether and in which extent, it is possible to operate a local control of the drainage network in the city of Hamburg (West Germany) by means of gates.
In the second case, the gages are operated to controll an very wide irrigation system in Jordan.

Final Objective of the study:

Development of Computer Tools to assist the Operator in the On-line Control of Urban Drainage System UDS.

The major function of a UDS is to transport the sanitary water flow into the treatment plant before it is discharged into the environnement. Normally is the UDS so dimensionned that in dry weather condition the network as well as the treatment plant meet the requirement.
During wet weather in combined sewerage system, the storm water inflow wave is so big that some perturbations can occur:
- within the network (impoundage, submersion)
- in the treatment plant (the capacity is exceeded)..

In the first case, impoundages, submersions or inoundations happen, which may cause financial damage and even endanger human beeings.
In the second case, combined sewerage overflows happen, which may cause ecological disaster.

How critical each of the aspects are, depends of the configuration the network and of the priorities of the local authorities.

In the city of Bremen, the canalisations have been rather big dimensionned so that the second point represents the key issue. During wet weather CSO can discharge in so small affluent of the river Weser, which are very sensitive to pollution chocs. Under the pression of the public opinion during the last years, the local authorities have adopted a very strict reglementation.
More than 90% of the whole sanitary water should be cleansed. The trend is to set even stricter reglementation in the next years.

In order to tackle the problem, several solutions are possible, which can be ordered into 3 main categories:
- solutions that imply a alteration of the drainage concept (installation of a separate system, reduction of storm water inflow through infiltration)...
- constructive measures ex. the construction of supplementary storage capacities (retention basin, sewer trunk).

- solutions whose purpose is to optimaly dispose of the latent capacities within the network during the rainfall event through control, in other words real time control.

Real Time Control has in Bremen a long tradition. Pumps are necessary to extract the water of the system, since the watershed is very flat (mean slope of the canalisation is smaller than 1 / 1000) and the lowest points of the drainage system are situated under the level of the treatment plant or the river.

Four years ago, the city of Bremen decided to completly update its on-line surveying and monitoring system.
At the present time, 66 parameter values are measured every 15 seconds and stored on the hard disk of the central computer on the central pump station (HPWL).

- 1 raingauge information on each combined sewerage pumping station (3 values))
- waterlevel informations (within the network, in the pump pits, on the river Weser, in the retention basins, at the overflows) (18 values)
- flow rates (the flow rate in direction of the TP from the left side and the right side of the Weser) (5 values)
- pump delivery in the separate sewerage system upstream and in the combined sewerage system downstream (37 values).

One quality measurement gauge had been installed at the pump pit of the main pumping station (BOD 3minute measurement) but the proximity of the pumps has proven to create such great perturbations specially through resuspension of solids that the measured data are of no use. The gauge must be reinstalled elsewehre.

The question is to be solved is the following:
Is it possible by using the on-line information about the state of the system collected by the surveying system to develop an optimized control strategy that would reduce the CSO quantities without producing inoundation ?
In the case of Bremen, a control strategy is defined by the set point values for the delivery of the main pumps (Station HPWL and Krimpel).

The two objectives are contradictory:

- On the one hand, the existing on-line (retention basin) and in-line (sewer trunk) storage capacity should be used to the last extent in order to store the quantity that can't be treated by the TP.
- On the other hand, security against inoundation requires that at any time sufficient storage capacity should remain free to storage a peak inflow wave that could not be transported through the system because of the limited flow capacity of the pipes.

To tackle the problem we considered two possibilities:

- to develop an optimization model
- to develop a knowledge base system (expert system).

Linear or dynamic optimization models has already been used to find out a optimized control strategy. They base upon:

- a simplified modelization of the UDS (in most case as a linear system with very few state variable)
- a search modul to minimize a cost function.

Advantages:
Providing the modelization is accurate and the cost function is relevant, the results shall be very good.
Shortcomings:
- to simplify the UDS system as well as to determine the cost function require a lot of skills.
in the first case, hydrological knowledge is required to analyse the behavior of the system. In the second case, mathematical knowledge is required to correctly evaluate the non financial costs.
The main difficulties are neverthless practical ones.

- first, in case the system be on-line implemented, it will be very difficult to explain the operator how and why the computer system make this or this recommendation. (In fact there is no why!)
- secondly, the method is relatively unflexible. For example, in case a control gauge or a measurement gauge fails during the rainfall event, the optimization theretically can not

give accurate recommendation anymore, unless a new corresponding modelization of the system already exist.
The same if some modifications in the UDS are performed. It will hardly be the case that the personal that control the UDS, itself makes the necessary modifications.

A knowledge base system is based on a strict separation between:

- the knowledge about the actual problem stored in a file as a set of fact (values of the state variables and the perturbation variables).

- the knowlege itself that is required to solve a special problem. This knowledge is stored in a file as a set of 'declarations'. These declarations are in most cases written in the form of rules, which specify when or why this or this decision is to be made.

- the treatment of this knowledge (rules + facts) stored in programs, which constitutes the shell, whose main part is the inference engine.
  During a decision process the rules that are appropriate to the situation described by the facts are found out and fired. It means their conclusions are considered true. The set point values of the control variables are a part of these conclusions.

Shortcomings:
- the notion of optimal solution is abandonned. It is replaced through the notion of good solution with all the incertainties that it implies.
- The system will only be as good as the knowledge base, which is stored in it.
- Commercial shells for the writing of the rule base are not admissible, insomuch the modul should communicate with the surveying system, whose programms are written in FORTRAN. that are In this case one should build the shell itself (respectively the inference engine) in the computer lan-

guage FORTRAN, so that any interface problems are solved.

Advantages:

- the 'logic' of the decision making is written in a file in a form that is understandable for the operator. He can any time check the file and analyse and criticise the existing rules.

- the system is very flexible, in case of failure of measurement or control gauges special rules can be started, in which control priorities may be rearranged (to meet security requirements for example).

- It is possible to make profit of the knowledge which have been gained over the years through experience at least as a basis for the further development.
  A manual exits, in which the control strategy recommendation have been written. These recommendations should normally be followed by the operators.

Both methods were tested at the Institute of Hydrology of the University Hanover. We finally gave the preference to the knowledge based system. One version was implemented on the PDP 11 computer situated at the central pump station HPWL.

In this transparency the structure of the information flow is described.

Some informations :
- How many rules ?
- How many facts ?
- How many variables are manipulated?
- How many recommendations are possible?

As already noticed, a knowledge based system can only be as good as its knowledge base. The acquisition of the knowledge constitutes therefore a key task, which unfortunatly requires a lot of

skills, time and effort.
As sources of knowledge about the behaviour of the system, we listed:

- **Analysis of the existing strategy and discussion with the staff;** elaboration of a representation of the network.

- **Exploitation of the existing measurement data;** analysis of significant events to verify whether the standard strategy is always followed (if not why, which could be the reasons) and find out the weak point.

- **Simulation of the drainage system.**
  Simulation of the drainage dystem is necessary to evaluate the influence of modifications of the rule base. Since a comparison with the measurement data should be possible, the requirements to the simulation model are high.
  A hydrological simulation was discarded because:
  - the catchment is very flat (possible backwater effects),
  - the modell has to perform a good simulation even if the pipe is under pressure.

  A hydrodynamic simulation, on the other hand, needs a lot of calculation time.

  As a compromise we decided to make hydrodynamic simulation with a simpfified description of the drainage system.
  The obtention of a simplified network description, which neverthless allows a good estimation of the respective state variable values, implies a difficult calibration phase (in-line storage capacity and flow condition within the pipes must not be distorted).

Difficulty: The original simulation model is very limited regarding the permitted control strategy. The decision module only allows local control and gives no possibility to simulate the emptying of the on-line retention bassin.

We decided to develop a extended simulation model in which the old simulation core is connected with the knowledge based system (programs implemented on PC Compaq). We have now the possibility to test through simulation any modifications of the rule bases

At the present time, we work with the extended version and try to evaluate the standard rule base as well as evaluate its modifications. Final results are expected at the end of the year.