Urban Drainage Master Planning - long term behavior analysis

T.Metelka & A.Mucha
Hydroprojekt a.s., Czech Republic

E.Zeman & R.Kuby
Hydroinform a.s, Czech Republic

L.G.Gustaffson
UHC, Sweden

O.Mark
Danish Hydraulic Institute, Denmark

ABSTRACT: The urban drainage pilot project has been executed during 1997 aiming in the proving the simulation technology to be feasible for the master plan of the capital city of Prague. Three simplification model levels were defined and evaluated each answering particular questions concerning the system functionality. The extreme events as well as long-term (up to twenty years) effects have been analysed in a scope of the system sensitivity analysis. Final alleviation schemes have been proposed and evaluated using a set of system parameters and key numbers. The execution of the pilot project proved the feasibility of a proposed approach and methodology bringing new quality information, which can not be achieved using the traditional method of master planning.

1 INTRODUCTION

The capital city of Prague is the largest city in the Czech Republic. The city population is at present estimated to be more than 1,320 million inhabitants living in an area of approximately 400 square kilometres. The city is located on both sides of the Vltava river close to the confluence with the Elbe river.

1.1 *Pilot project objectives in frame of Prague Urban Drainage Master Plan*

The Magistrate of Prague is fully aware of the necessity to execute a new urban drainage master plan as well as of present evaluation possibilities. During the year 1996, the tender for a master plan preliminary study was released with the principal aim to generate the overall methodology, workflow and to estimate data availability for a new master plan. Hydroprojekt won the tender together with Hydroinform and UHC companies. The study was submitted in late 1996 to create the fundamental framework for the master planning with the use of mathematical modelling approach. In principal, four major milestones were proposed in the study as follows: integral approach, simulation approach, digital approach and continual update approach. As far as the work schedule is concerned, the idea of ”working verticals” was introduced allowing the separation of work activities. Following a Swiss experience, the idea of ”situation report” execution was implemented as a very first step in the master planning.

Proposed methodology for the master plan of the capital city of Prague defines an ambitious goal, which needed practical verification. In early 1997, the Magistrate contracted the above mentioned companies to prove a proposed methodology in a pilot project study area. The pilot project results were submitted to the contractor in December 1997.

2 PILOT CATCHMENT DESCRIPTION

The contractor of the project selected the pilot catchment. All principal requirements derived from master plan methodology were respected, namely the presence of a receiving water and CSO’s, combined sewer system, presence of rural areas suitable for the urbanization, diversity of the catchment types and source data availability.

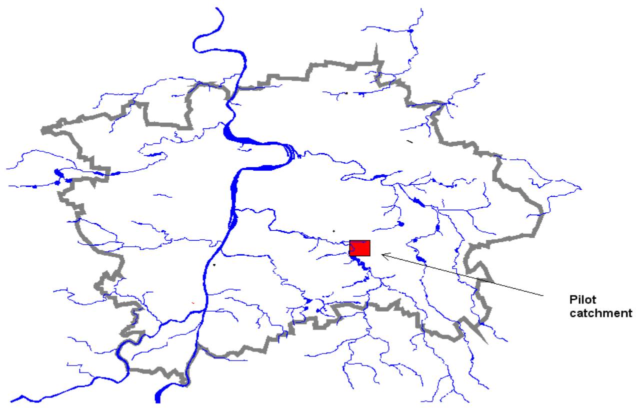

Figure 1: Pilot catchment location in Prague

The Hostivar district was selected for the execution of the pilot study, see Figure 1. This catchment is located in an eastern part of the city. The total size of the area is 1027 ha with the population around 10000 inhabitants. In general, the catchment is gently sloped north/south towards the valley of the Botic creek, one of the important tributaries of the Vltava river. Close to the creek, the morphology of the terrain changes to a steep slope. At present, three combined sewer overflows are under operation in the sewer network diverting the excess of rainfall water into Botic. Mean discharge in the Botic creek is estimated around 230 l/s. Environmentally protected Botic creek meanders are located in the area of the pilot catchment with important diversity of habitats. The Hostivar dam is located at the upstream catchment border.

In particular, the presence of a local technical problem was indicated by a contractor in the pilot catchment. This fact put additional weight on the selection of this area. Basically, repeated flooding of number of cellars used to occur in the past due to a bottleneck in a part of the main trunk sewer. To cope with this drawback the upstream CSO K83 was designed. Most of rainfall water was diverted to the creek causing the high pollution of the environmentally protected area. The contractor also required that this local problem has to be analysed and evaluated in a frame of a pilot project execution.

3 APPROACH USED

Referring to the above mentioned facts the pilot project has been aimed at approving the ideas implemented in the Preliminary study for the master plan of the capital city of Prague. In principal, basic approach foundations are built on the simulation modelling technique. The use of the "virtual reality system" of the natural processes is believed to have the important advantages in the master planning of the urban drainage systems. The fundamental advantages of this approach are summarised in the next four paragraphs.

3.1 *Integration of processes*

The rainfall - runoff, the transport of a media and pollution, the treatment in WWTP and receiving waters represent in general the chain of most important natural processes which have to be considered once master planning of the urban drainage is to be executed. Moreover, these processes, being mutually interrelated, need integrating into one logical system. Once this request is met the profound evaluation of system causality can be accomplished.

3.2 *Long-term simulation*

The analysis of system behaviour is strongly dependent on the evaluation time scale. When evaluating one single rainfall runoff event the clear answer "what-if" can be found out. On the other hand no clear information can be obtained concerning the probability of the occurrence or return period of the selected event. From the point of view of master planning this type of information is requested. That is why it is necessary to carry out and statistically evaluate the long-term simulation of processes to get relation between cause and consequences.

3.3 *Digital elaboration*

The request for a digital elaboration of the master plan is partly related to the proposed simulation approach and its data consumption requirements. In addition, there are also other types of information needed for the successful execution of the master plan, which can be stored and maintained in a digital form. This approach is aimed at the increasing data consistency of the final product. This way, the simplified management of the distinct master plan information can be achieved.

3.4 *Continuity of Master Plan*

All three above proposed fundamentals form a basis for the continual update of the master plan in a course of time. Once the urban drainage master plan is handled in digital "virtual reality" form it can be maintained and refreshed according to the actual changes in the real system. This topic has got also its financial value. Although the investment to the very first master plan can be relatively costly, all its further updates of master plan are expected to be much cheaper then those based on the ”classical approach”.

4 APPLIED METHODOLOGY

The master planning activities represent in principal, a global analysis of the overall behaviour of the system resulting in the identification of the malfunctioning sites rather then in detailed evaluation of these local sites. This fact is reflected in the preliminary study. Two phases of the master plan are proposed in the study e.g. a conceptual and a detailed phase. The financial and time consumption aspects compose the couple of main reasons for that division. From this perspective, only the first phase is understood as a master plan, although the subsequent detailed phase can follow immediately at several distinct sites. The results from the second phase are then to be used to update the master plan in a particular location. The pilot project has been primarily directed to the verification of a first master plan phase. However, the contractor asked also for the second phase execution in the indicated malfunctioning site of the pilot catchment.

4.1 *Situation reports*

The proposed approach for the urban drainage master planning is strongly dependent on the data availability, consistency, accuracy and transferability. This issue can highly influence the whole work schedule of the master plan. Referring to the importance of the data sources the concept of so called ”situation reports” has been proposed. The situation reports consist of all the collecte
d data relevant to a particular urban drainage topic as follows:

- Catchment situation report
- Surface absorption situation report
- Inflow/Infiltration situation report
- Sewer network situation report
- Waste water treatment situation report
- Receiving water situation report

In addition, the situation report includes also possible operational and maintenance data. An example version of situation reports has been generated for the pilot project in a digital form.

4.2 *Monitoring*

Monitoring activities constitute an integral part of the proposed methodology. The calibration and verification of deterministic and conceptual models selected for the master plan represent an important part of the formulation procedure. A relatively comprehensive monitoring set-up has been defined on a pilot catchment by realising the importance of the project task. Altogether, 6 ADS flowmeters, 5 water level meters, 2 water quality samplers and additional equipment (control structures) have been installed in predefined locations of the catchment in accordance with the defined schematization levels, see Figure 2. The monitoring campaign has been conducted for six months (April 97 - September 97) by the Prague Waste Water Board (PKVT). Measured data was collected, processed and submitted on a monthly basis. Then the data was transferred into a prescribed digital format.

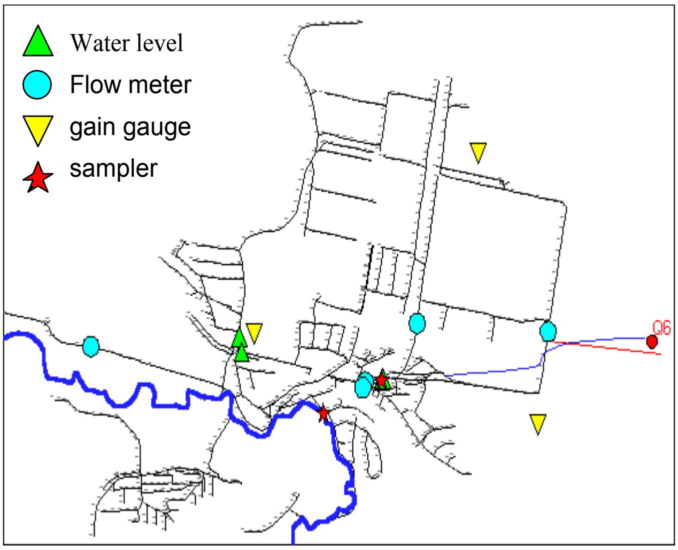

Figure 2: Set up of the monitoring campaign on the pilot catchment

4.3 *Work flow*

The management of the project working activities has been considered as a crucial point in the master plan execution. During the project, a number of parallel or chain procedures are to be carried out for the successful completion of results. In a frame of a proposed methodology, the idea of ”information matrix structure” has been verified.

The information matrix represents the description of the practical organisation work schedule. This matrix describes the overall data flow, information and work in time and space. Information verticals represent certain independent domains possibly supported by a particular technological tool. Information horizontals then represent data exchange bridges and results of the defined level of schematization.

4.4 *Model formulation*

The results of the pilot project should give the answer to a number of various general questions. On one side the overall long-term water balance information is requested, on another side, return period, excedence and frequency of events are to be evaluated. Moreover, the behaviour of extreme events has to be verified. In order to satisfy all these requirements, three levels of the model schematization have been proposed each focused to a particular direction of exploring the system. Besides that, the effectiveness of work and present modelling possibilities played a role in the proposed levelling of the pilot project. The MOUSE and MIKE11 software packages from DHI have been selected for the practical modelling activities fulfilling most of the evaluation requirements. Each model level uses own scale of topological schematization, own calculation time scale, own focus on the system parameters or key numbers and consequently own way of evaluation of the results. Nevertheless, it should be stated that described model levels could not be in principal isolated because of the overall solution consistency. Further schematization levels were proposed and elaborated in a frame of the pilot project.

A. *Lumped model schematization*

The lumped model schematization is focused on the evaluation of the long-term water balance of the pilot catchment. The sewer system is simplified to the main trunk sewer CXIIb, see Figure 3.

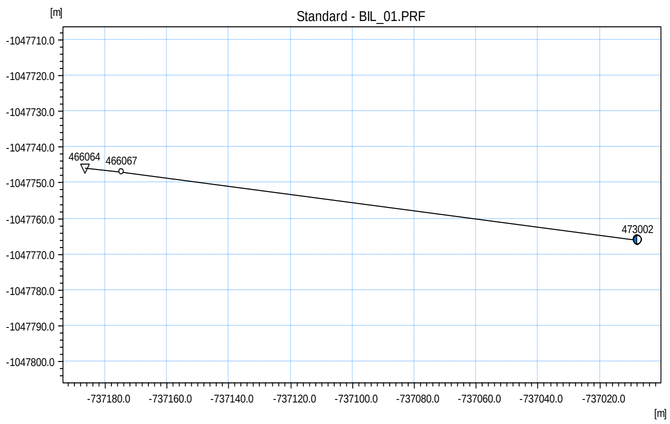

Figure 3: Lumped model schematization

The conceptual NAM module is applied to simulate the long-term behaviour of the upstream catchment. The system is loaded by 20 years of historical rainfall time series. The frequency distribution curve, the excedence curve, the water volume key numbers (total annual outflow, FRC - fast runoff component flow, SRC - slow runoff component flow, dilution ratio, average discharges etc.) belong to focused parameters and key numbers in this model level.

B. *Distributed model schematization*

The distributed model schematization is focused primarily on the CSO's long-term functionality in relation to the receiving waters, see Figure 4. In addition, evaluation of the inflow / infiltration in a number of subcatchments is carried out. A historical "mean" year rainfall record loads the system. The system is simplified into the skeleton of main sewers (270 manholes) complemented by 8 NAM upstream subcatchments. Besides the above mentioned system parameters, the total annual volumes, duration time, Number of events and maximum discharge for all CSO's belong to focused parameters and key numbers in this model level.

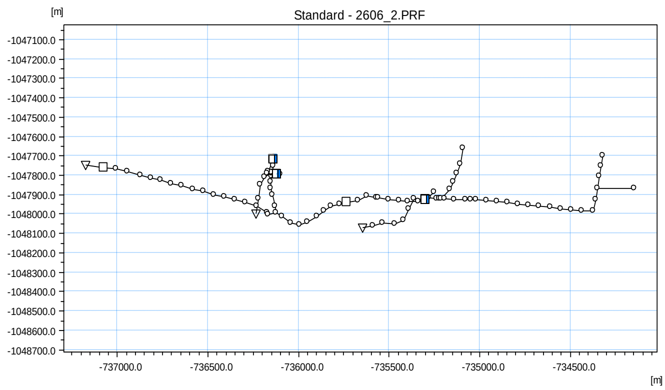

Figure 4: Distributed model schematization

The system capacity analysis is also carried out at this model level. The subset of 20 rainfalls is selected from the 20 years historical time series based on the maximum effect (max. discharge, maximum volume) generated in a defined location of the lumped model system. This way a selected rainfall set is then used as a load in the distributed model for the extreme event analysis. The evaluation is then carried out in a form of return periods of key variables (capacity flow, pressurised flow, surface flooding) in a particular sewer section.

C. *Detailed model schematization*

The detailed model schematization shown in Figure 5 is focused on the evaluation of the single

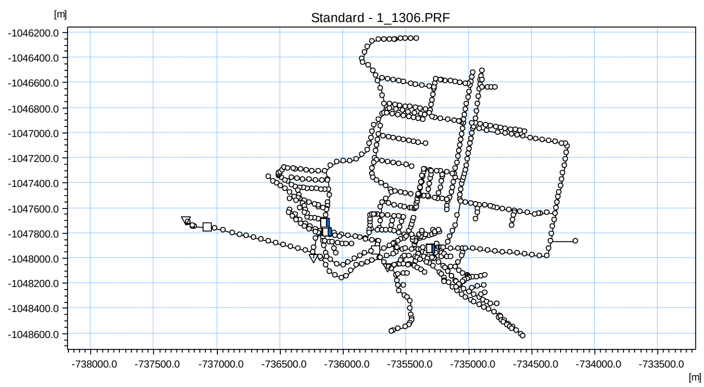

Figure 5: Detailed model schematization

extreme rainfall events. The complete sewer system of the pilot catchment (740 manholes) is used for the simulation. The concept of NAM is again applied for 150 subcatchments. The model is loaded by one synthetic rain event generated from 20 years historical rainfall record using the Dorsch Consult method. The maximum rainfall effect has been focused at a selected location of the sewer system using the variation of the time scale (finally reaching 60 minutes rain). Selected rain ”DC60” has been then used for the ”dimensionless” mutual comparison of all defined alternatives.

4.5 *Evaluation strategy*

The evaluation strategy applied to the pilot catchment is based on the aim to reduce the amount of waste water and/or to control its flow throughout the drainage system to the waste water treatment plant and to the receiving waters. This reduction can be applied on current parts of the system, the main usefulness of this approach is expected in planning of future urbanised areas. The next four categories are defined where reduction and/or transformation of waste water can be searched for and achieved.

- category A: reduction of the fast runoff flow component (inflow)
- category B: reduction of the slow runoff flow component (infiltration)
- category C: increase of transport and/or storage capacity of the system
- category D: change of the functionality of the system.

The above described categories form a set of alternative solutions as described later in this paper. The sensitivity analysis has been worked out first to deal with the potential benefit of separate alternatives constituting then a base for the definition of final alleviation schemes.

5 MODEL VALIDATION PROCEDURES

The calibration and verification procedures were applied at all three levels of the pilot catchment model after models were formulated. High fluctuations of a spatial rainfall distribution were detected during the monitoring campaign. This fact was considering while triggering the model coefficients. The comprehensive analysis of the monitoring data records covered an important part of these activities. While calibrating models, some discrepancies in measured data were also disclosed and analysed, Figure 6.

The calibration of the eight months data record has been carried out on NAM and PILOT modules of MOUSE software package for the long-term simulation purposes in lumped and distributed levels of the model.

The estimated coefficients were then applied on the detailed model level where a detailed surface description has been elaborated. The presence of a pumping station in the catchment (irregularly pumping household sewage from a detached district to the pilot catchment) caused an additional effort during the calibration phase.

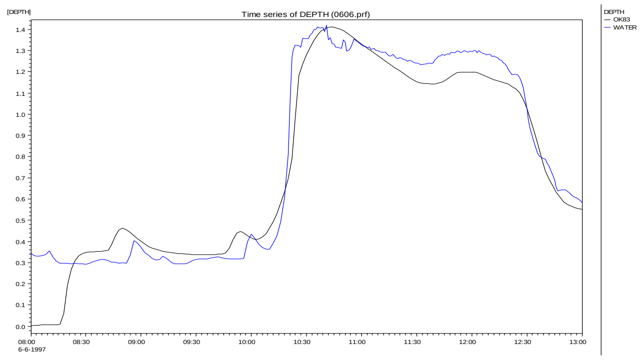

Figure 6: Single event Q calibration

A single event calibration of the water quality MOUSE TRAP module has been carried out in parallel.

6 EVALUATION OF THE PILOT CATCHMENT

The evaluation of the system behaviour, its potential reserves and weak points fall into the area of the practical master plan aims. The future concept of urban drainage can then be elaborated based on this analysis in relation to the future urbanistic views, actual legislation and environmental policy. The system evaluation procedure is defined in a couple of subsequent steps

* The sensitivity analysis of the system parameters
* Alleviation schemes definition and evaluation.

6.1 *Sensitivity Analysis*

The sensitivity analysis procedure can be defined as a set of activities focused on the inspection of the sensitivity of system parameters and key numbers in consequence of defined changes in rainfall runoff process. Above listed categories A-D are used as a frame for the definition of a analysed set of alternatives directed to the reduction and/or transformation of waste water. The results of this analysis show the effect of each single measure for the pilot catchment urban drainage and consequently a relative drainage potential of the catchment. Further separate alternatives were defined for the sensitivity analysis of the pilot catchment.

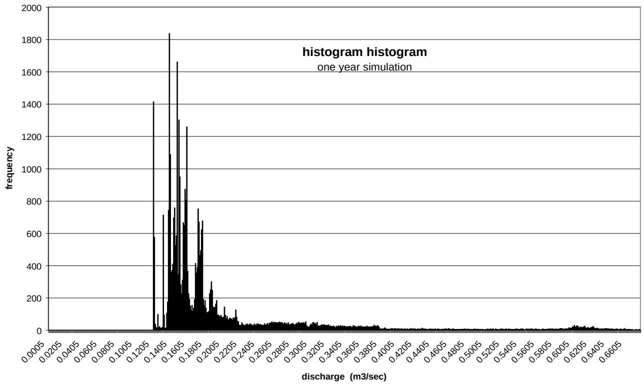

Figure 8: An example of the frequency distribution curve for one year simulation - time step 1 hour

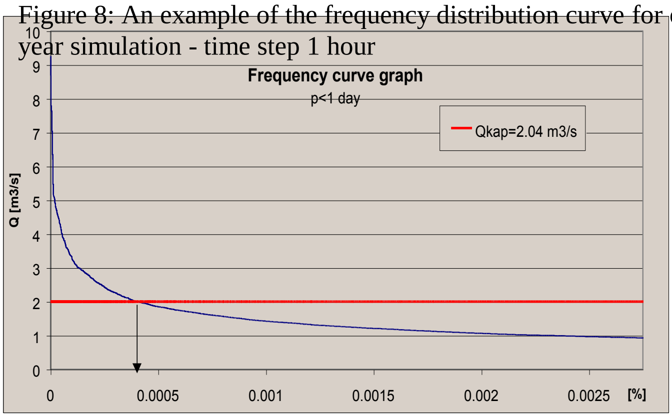

Figure 7: The long-term system capacity evaluation with 1-day subset from the whole curve

A1. The implementation of infiltration structures directed to the reduction of FRC
A2. The implementation of changes in the size of impermeable areas
B1. The reconstruction of pipe section directed to the reduction of infiltration
C1. The increase of the storage in the catchments
C2. The implementation of the local storage capacity in sewer structures
C3. The increase of storage capacity in main trunk sewers
D1. The removal of the local capacity failures

From these, twelve alternatives have then been defined and evaluated together with the current state ”base line variant” on the pilot catchment. The catchment key numbers and other catchment parameters were then evaluated for each alternative. The evaluation possibilities give the consultant a power to inspect the system from various perspectives.

6.2 *Key numbers and catchment parameters*

The evaluation of the long-term effects is referred as a very time consuming post-processing task, Figure 7. During this phase of the project, special post-processing tools has been designed to serve this task.

The effort in transforming the output data records to the statistical curves resulted in the generation of the frequency distribution and cumulative frequency curves, Figure 8. The one-year and twenty years data sets were evaluated this way in all relevant alternatives. It resulted in the fundamental information about the long-term behaviour of the system in a particular location, see Figure 9.

SUBCATCHMENT NAME		Q1	Q5
real area of the catchment	[ha]	328,7	128,2
total area of FRC	[ha]	54	25
total area of SRC	[ha]	560	200
% FRC		10,2	9,4
% SRC		39,1	36,1
% FF		50,7	54,5
total FRC outflow volume	[m3]	442000	151000
total SRC outflow volume	[m3]	1690000	597000
total FF outflow volume	[m3]	2190000	874000
total outflow volume	[m3]	4324000	1604000
extent of dilution KD=Vtot/Vff	[1]	1,97	1,83
average discharge Qsrc	[m3/s]	53,5	18,3
average discharge Qfrc	[m3/s]	14,0	4,8
average discharge Qff	[m3/s]	69,5	27.7
pipeline length[m]	[m]	26355	3420
Infiltration load	[m2]	64,1	169,3

The CSO’s long term functionality has been analysed by comparing the total volume, duration, maximum discharge and number of events for all three CSO’s and all relevant alternatives (see table bellow).

CSO’s functionality *1 year simulation*	**OK 83**	**OK81**	**OK80**	**units**
total overflow volume	60150	1360	3000	[m3]
total duration of overflows	23	11	11	[hours]
total number of overflows	27	11	11	[1]
overflow maximum discharge	3.68	0.12	0.27	[m3/s]

The extreme events return period analyses have been carried out on twenty selected extreme rainfall events from the historical data record. By evaluating the number of events exceeding defined criteria (e.g. capacity flow, top of the sewer, level above surface) the pipe capacity return period map has been generated. In principal, the system exhibited good capacity behaviour with almost no pressurised flow except a couple of locations where 1-2 years return period has been detected, see Figure 10.

The final example of the evaluation techniques has been focused on one synthetic rainfall event effect (Dorsch Consult - 60 minutes). By comparing the results from different locations detailed information has been retrieved concerning the

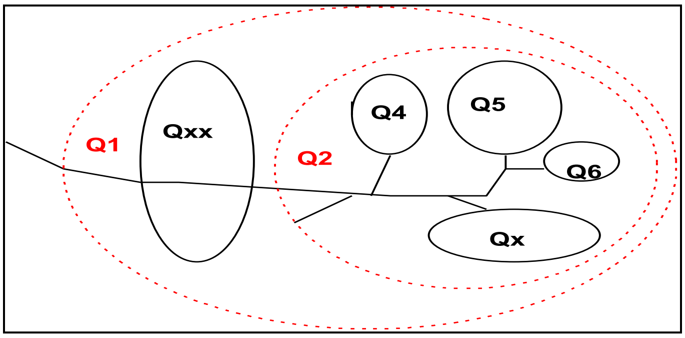

Figure 9: Sketch of the distributed model level schematization

propagation of the flood in a detailed sewer system. An example is showing the flow hydrographs upstream of the CSO 83, over the crest and behind it.

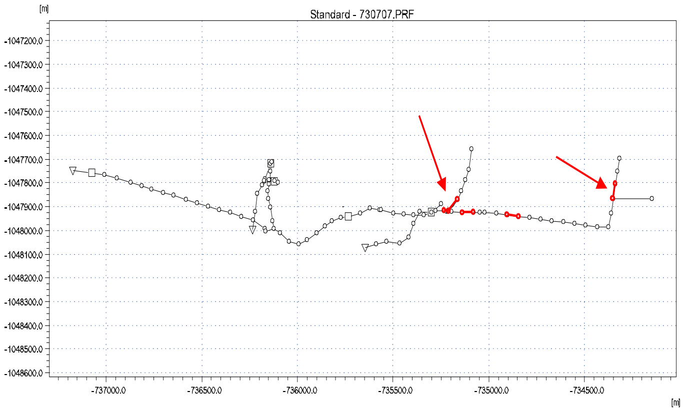

Figure 10: The capacity problems detected on a pilot catchment

The sensitivity analysis phase of the evaluation of pilot catchment showed up the following findings.

1. The infiltration of the SRC is estimated in the whole pilot area to be 35%.
2. The implementation of the infiltration structures has almost no effect on the reduction of wastewater.
3. The highest infiltration load has been detected on a subcatchment Q5 of the pilot catchment.
4. No principal capacity problems are detected in the system (most probably due to CSO83).
5. The operation of CSO83 reduces 1/5 of the total incoming flow and has a fundamental influence on the whole functionality of the system.

6.3 *Final scenarios*

A set of final alleviation schemes has been proposed and evaluated after the completion of the system sensitivity analysis. The main concern of all the schemes has been primarily focused on the improvement of the functionality of CSO83. The reason for this requirement has been disclosed after the discussion with operation and maintenance staff of the sewer system. The old throttling line is located downstream of CSO83. The bottleneck effect caused by this line generated a flooding of cellars in this area.

Three final alleviation schemes were introduced all focusing on the improvement of the flow regime in the vicinity of the CSO83 - scheme A: the deep tunnel, scheme B: reconnection of the sewer and scheme C: the retention basin. All three schemes are evaluated based on the key numbers and catchment parameters as described above. The urbanisation of a particular area and expected future reconnection of the pumping area to other trunk sewer were also introduced in the model to analyse effects of future changes in the area.

The deep tunnel scheme is based on the construction of a new by-pass tunnel with an egg profile of 1400/2200 mm and mean slope of 0,25%. The length of the tunnel is 640 meters. The tunnel entrance is designed as a 9-meter deep drop manhole.

The reconnection of the sewer scheme is based on the utilisation of the natural possibility to reconnect the sewer system from the Q4 subcatchment downstream the bottleneck site of the main trunk sewer. This way a reduction to the problematic area is to be achieved. The length of the sewer is 780 meters, the slope 4.7‰ and the sewer diameter is 800 mm.

The retention basin scheme is based on the construction of the retention basin upstream of the CSO83 to reduce and transform the flood peaks.

The ground plan size of the basin takes 1210 m2, the length 8.0 m, the bottom slope 3‰. Expected retention volume is estimated to be 3500 m3. In addition, the throttling line diameter enlargement from 500 to 800mm has been proposed. For all three schemes the capacity behaviour, the long term functionality and CSO functionality have been explored on a distributed model level using the above described key numbers and catchment parameters.

By evaluating the excedence curves for the final schemes the following changes in flows for specified frequencies are estimated (see the table).

	P=0,005	P=0,01	P=0,02
present state [m3/s]	0,627	0,611	0,58
tunnel [m3/s]	1,45	1,36	1,2
retention basin [m3/s]	1,88	1,39	1,02

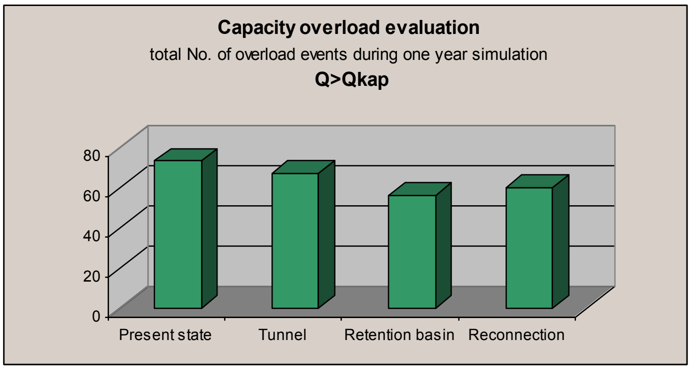

Figure 11: The twenty extreme event evaluation for final schemes

Based on the evaluation of the final alleviation schemes it can be stated that the scheme C, the retention basin, is the most promising solution in the pilot catchment. The main advantage is the reduction of the peak flows resulting in the reduction of the number of overflows at CSO83 from 27 to 3 during the average year without a negative effect downstream of the main trunk sewer. This scheme has been finally proposed to the contractor.

6.4 *Conclusions*

The integrated approach used for the Pilot Project incorporated all available input data, maps and situation reports with the information on catchment, surface absorption, inflow/infiltration, sewer network, waste water treatment and receiving water. A relatively comprehensive six-month monitoring set-up has been defined on a pilot catchment by realising the importance of the project task. Applied mathematical models enabled the authors to indicate overloading of combine sewers. In order to satisfy all requirements, three level model schematizations (lumped model, distributed model, detailed model) have been proposed each focused on a particular direction of exploring the system. The results of sensitivity analysis showed the effect of each single measure for urban drainage of the pilot catchment. A set of final alleviation schemes has been proposed and evaluated. All three final schemes (the deep tunnel , the reconnection of the sewer, the retention basin) were evaluated based on the key numbers and catchment parameters.

It has been proven that the proposed master planning approach is a feasible method and brings new quality results to live, which can not be achieved using the traditional way of master planning. Although the methodology used puts additional requirements on the management of the project, the knowledge of a working team and the technology and equipment used provided the contractor with ”a virtual copy" of the real system that can be continuously used and updated in a future.

REFERENCES:

Abbott, M, B (1991) "Hydroinformatics: Information technology and the aquatic environment". The Avebury technical, Alderschot, UK and Brookfield, USA, 1991.

Deakin, R (1994) "Data to information GIS and decision support for coastal engineering". Proceedings of International User-group Meeting - Computer Aided Analysis and Operation in sewage Transport and Treatment Technology, Gottenburg, Sweden, 1994

Fabri, A.G (1992) "Spatial Data Analysis in Raster-based GIS: An Introduction to geometric Characterization". in Introduction to GIS edited by C.R.Valenzuela, ITC, 1992.

Maksimovic, C, Prodanovic, D, Elgy,J, Fuch.L (1994) ”GIS (or GIM) in water projects - Tools or toys". Hydroinformatics ‘94 Delft, 1994, Balkema, Rotterdam, 1994

Gustafsson, A.M. (1994), ”Key Numbers for Infiltration/Inflow in Sewer Systems", 7th European Junior Scientist Workshop on Integrated Urban Storm Runoff, Èernice Castle - Bechynì - Czech Republic, 1994.

Almeida, M. and Schilling W.(1994), ”Real time control in small urban drainage systems", 7th European Junior Scientist Workshop on Integrated Urban Storm Runoff, Èernice Castle - Bechynì - Czech Republic, 1994.

Zeman E. at al. (1994), ”Simulation of Dynamic Pollution Impact on Rivers Using a Combined Modelling Approach", Proceedings of International User-group Meeting - Computer Aided Analysis and Operation in sewage Transport and Treatment Technology, Gottenburg, Sweden, 1994.

Kuba P., Kuby R., Metelka T., Mucha A., Zeman E. ”Parallel design of sewer networks: a case study in Kolin”, IMUG 1995, Blackpool, UK

Kuba P., Metelka T., Pliska Z.: ”Impacts of the hydroinformatics technology on the way of master planning”, Proceedings of The 2nd International Conference on Hydroinformatics, Zurich, Switzerland, 1996

Metelka T., Mucha A., Pryl K., Kuby R., Gustafsson L.G.: ”Urban Drainage Master Plan of the Capital City of Prague - Preliminary Study”, Proceedings of 2nd DHI User Conference, Helsingor, Denmark, 1997