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## **Rehabilitation strategies in wastewater networks as combination of operational, property and model information**

Stratégies de réhabilitation des réseaux d'égouts combinant des données d'exploitation, de propriété et de modélisation

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### **RÉSUMÉ**

La planification du renouvellement des réseaux d'alimentation en eau et des égouts représente en République Tchèque depuis plusieurs années l'une des principales activités à long terme de la compagnie des eaux. Les auteurs de la présente étude proposent une solution optimale de planification du renouvellement des réseaux d'alimentation en eau et des égouts en s'appuyant sur une synthèse des données d'exploitation et de propriété, et des résultats obtenus par un modèle de simulation. La stratégie d'évaluation repose sur le principe de l'analyse multicritères déterminée à partir de l'ensemble des indicateurs clés de performance, qui donnent la meilleure indication de l'état du réseau d'une localité donnée. La présente étude traite d'une méthode de choix des indicateurs clés de performance, de leur étendue et de leur poids ainsi que des possibilités d'une politique d'investissement optimale en fonction de la durée de vie moyenne ou de la durée de vie résiduelle des réseaux pour une longue période. Les auteurs de cette étude argumentent également qu'il est possible d'algorithmiser de manière appropriée la méthode choisie et de créer un logiciel permettant de répéter sous diverses variantes la solution de planification du renouvellement en fonction des limites des investissements annuels, de la coordination de ces investissements en rapport avec d'autres projets d'investissement d'une localité donnée et de l'établissement de priorités en ce qui concerne les investissements associés dans les réseaux d'alimentation en eau et des égouts suivant une planification des investissements pour les deux types de réseau à la fois.

### **ABSTRACT**

Planning of water and sewer network reconstructions represents in Czech Republic one of basic, long-term tasks under the competence of water utility companies. In this contribution, the authors focus on a proposal of optimum method of handling of the water and sewer infrastructure renewal plan by utilizing the combination of operational and property information with results from simulation model. The evaluation method is based on the principle of multi-criteria analysis defined on a set of key performance indicators, which give the best view on the network status for a given locality. In the contribution the authors discuss a selection of the key indicators, their ranges and weights and the possibilities of defining an optimum long term investment strategy based on obtained results. In the contribution the authors further argue that the selected approach can be transformed into a software program that would enable evaluation of distinct alternatives defined for the renewal plan with regard to annual limits of investments, coordination of proposed reconstructions with other planned investments in a given locality, and last but not least, prioritization of investments in water mains and sewers in the combined investment plan for both networks.

### **KEYWORDS**

Mike Urban, rehabilitation, sewer network, simulation model, urban drainage

## 1 INTRODUCTION

The current infrastructural challenges in many Czech water and wastewater networks are given primarily by city historic development. Water and sewer mains and connections in central areas are quite old in most cities and consequently suffer from many problems like water leaks and infiltrations, high probability of structural failures, incrustation of networks and decreasing pipe capacity. Described situation makes a long term development and rehabilitation as well as day to day operation and maintenance of these systems difficult.

The planning of water and sewer pipe reconstructions is often made on ad-hoc basis after local failures are detected. A new approach should be made available for Water Utility companies based a transparent method and utilizing available digital data resources combined with practical operational and maintenance experience once an optimal long-term strategic solution is searched for. The methods of global data processing together with simulation modelling can be then fruitfully used in response to this urban infrastructure challenge.

In connection with the Public Notice of the Czech Ministry of Agriculture from November 9, 2006, which changes the Execution Notice by the MA no. 428/2001 Coll. for the Law no. 274/2001 Coll., About Water Mains and Sewers for Public Need, new legislative requirement is released on Water Utilities in Czech Republic. The law requires creation of sewer and water main infrastructure renewal plans with five year update period and defined scope of required output data in a longer time horizon. The method of renewal plan creation is not exactly defined by the notice, however and the notice does not handle selection of strategy for planning of these reconstructions either.

The complex approach to long term sewer and water reconstruction planning should be based on integrated elaboration of technical infrastructural requirements under the context of financial and economic framework in particular company. The methods of multi-criteria analysis can be applied for defined set of key performance parameters to evaluate the state of sewer and water pipes for distinct technical viewpoints and to provide proposal for their renewal. The selection of key parameters is then the fundamental task at each Water Utility company based on data availability and local conditions. Obviously, the combination of simulation model results with infrastructural and operational information is used to define proper key performance parameters. The local condition aspects are then considered while assigning the particular importance (weight) to every parameter including other planned reconstruction measures/plans e.g. street surfaces renewal, combined water and sewer reconstructions, etc. The impact of material aging plays important role in this approach and needs to be incorporated in the method if system development in long term time frame is under concern.

DHI developed together with representatives of Water Utility (WU) companies during 2007-2008 a methodical procedure for analyzing water and sewer network status and for proposing network renewal based on combination of operational, property and modeling information. The proposed methodology was further implemented into MIKE URBAN simulation model of DHI and was used for sewer and water network reconstruction plans at several WU organizations.

## 2 APPLIED METHODOLOGY

The proposed methodology is based on a multi-criteria analysis principle. There is a set of key performance and status indicators defined for a water/wastewater network which represents the best possible insight into the infrastructure at given locality. Each indicator is structured into several classes using agreed range of values with corresponding point scores (Tab.1). The classification is performed for each network section and particular indicator. Considering the fact that individual indicators have different significance for the network and consequently for the final evaluation of a network status, each indicator is balanced with particular percentage weight before the overall evaluation is performed.

The multi-criteria analysis performs summarization of the final score of individual sewer sections for all selected indicators and their weights (Eq.1.). The appropriate score range (e.g. 1 – 1000) can be than achieved through suitable selection of ranges of classes for individual indicators and their weights. The received score then represents for the individual network section the rate of an overall section degradation and in consequence a disposition to the reconstruction. The actual inclusion of the particular section into reconstruction program for the given year is determined by agreed limit value. The selection of limit value is based on empirical knowledge and experience and is to be in harmony with the specific network status analysis in the given locality. All sections that exceed the limit value

are marked as suitable for reconstruction. The reconstruction cost is then calculated for the sections marked for reconstruction according to Methodical Guideline by Ministry of Agriculture “Methodical Guideline for Orientation Calculation Indicators of Object Cost Prices for Selected Data about Water Main and Sewer Property Records, Water Main and Sewer Development Plans, and Water Main and Sewer reconstruction financing plans” from 2007.

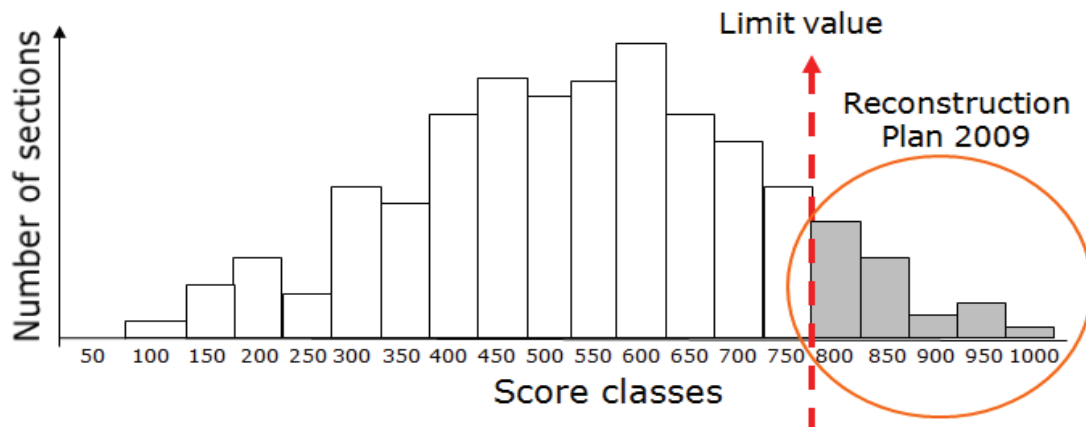


Fig. 1 Histogram of achieved score frequency for sewer network sections with limit value and reconstruction plan

A score frequency histogram (Fig. 1.) is a suitable form of representing the results of multi-criteria analysis and overall network status summary for given year. The histogram shows the distribution of the network degradation over network sections that are grouped based on their score into equidistant classes (Each column represents a sum of all sections within particular section range e.g. 100-150, etc.). Distinct general facts concerning the network state can be then recognized based on the frequency histogram such as an historical underestimated reconstruction investment or different phases of network development in a course of history of system development (Fig. 2).

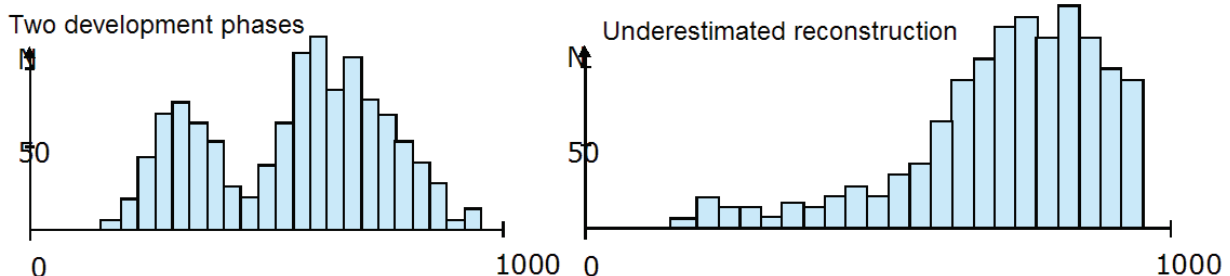


Fig. 2 Frequency histogram of sewer network sections for various network states

It is possible to perform water and/or sewer system current state analysis by described approach and to evaluate the sections proposed for reconstruction. Nevertheless, this calculation still does not provide the information regarding long term reconstruction plan over defined time period. To achieve this objective the financial reconstruction limits specified for individual years of the simulation period as well as material “aging curves” has to be considered. The annual financial limit is defined as agreed maximum planned investment in the particular water utility company. The part of the network that needs the reconstruction but cannot be included in the reconstruction plan for given year due to budget limit is then moved to the next year plan. However, the whole network will age one year in the meantime, and that will affect the values of several key indicators for subsequent year evaluation. To be able to cope with the network deterioration over time the material aging curves are used (they can be obtained from specific research analyses in the literature or from documents provided by manufacturers – Fig.3). The aging curve is used to change the value of the indicator “material” for all network sections based on overall simulation time. Obviously 30 years simulation is carried out for reconstruction plan, where the value of this indicator changes for every year of the simulation (and is set to “0” for newly reconstructed sections).

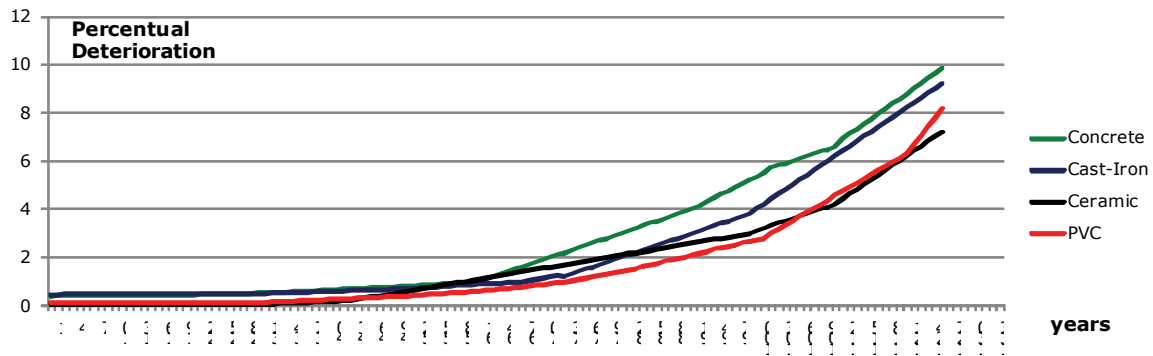


Fig. 3 Deterioration curves – water supply pipe material

A long term reconstruction plan (usually 25-30 years) can be calculated based on the described procedure and important global network characteristics can be analyzed e.g. total network age, percentage of reconstructed network, investment into the network, remaining network service life, etc. (Fig. 4). The description of these characteristics and the way of calculation is presented in next chapter. The prognosis for long term sustainable investment into the network can be optimized based on overall company strategy and goals in several reconstruction plan scenarios.

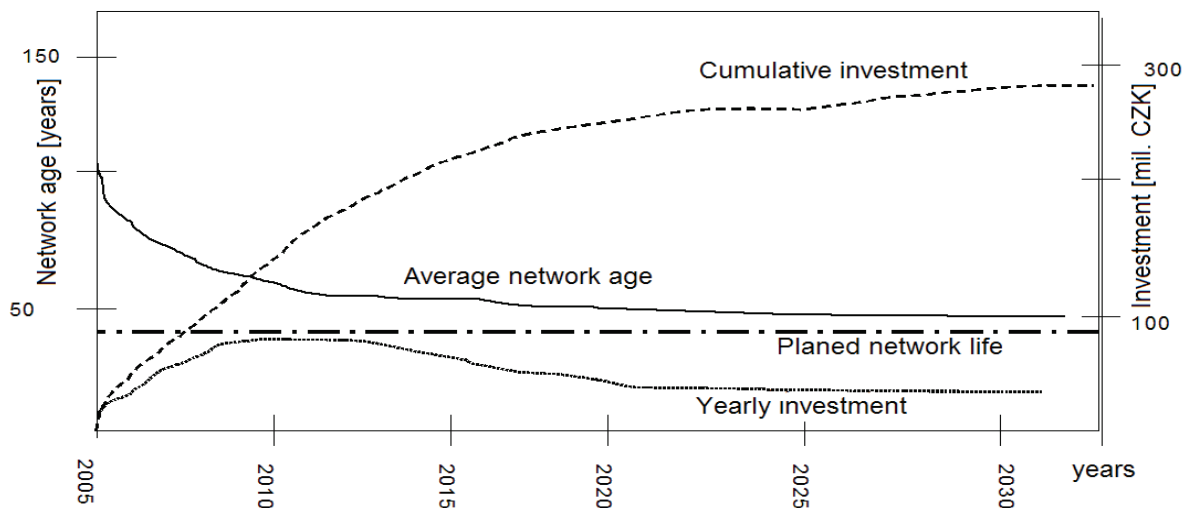


Fig. 4 Temporal development of global sewer network characteristics with regard to planned reconstructions

## 2.1 Multi-Criteria Analysis and Key Indicators for Sewer Networks

The multi-criteria analysis represents evaluation procedure for all network sections based on selected parameters (key network status indicators) in one simulation time step (typically 1 year). Selection of these key indicators is always a matter of compromise between the amount and quality of available data and agreement with practical experience of water utility specialists. Inputs from the simulation model and from GIS system are usually used in practice as source data. Missing values can be added /extrapolated based on additional surveys. As example next key indicators are presented for the evaluation of technical state and for proposal of program of reconstruction for sewer network:

- network age,
- network status according to results of camera survey,
- sewer material,
- sewer dimension,
- sewer significance from the point of view of city infrastructure,
- surcharge “capacity” characteristics of sewer network.

The development of individual classes and class ranges is then a matter of cooperative work with local

water utility specialists. An example of such distribution of classes and ranges is presented in the table (Tab. 1).

<b>Sewer age</b>	<b>Points</b>	<b>Sewer filling</b>	<b>Points</b>
> 80 years	10	> 1500%	10
60-80 years	9	1000-1500%	9
40-60 years	6	500-1000%	8
20-40 years	3	400-500%	7
< 20 years	0	300-400%	6
<b>Camera survey</b>	<b>Points</b>	200-300%	5
Static damage, necessity of immediate repair	10	150-200%	4
Static damage, repair needed ASAP	7	110-150%	3
Static damage, repair needed in middle time horizon	3	80-110%	2
Incrustation, moisture, repair need in long-term horizon	2	< 80%	0
No repairs needed at this time	0	<b>Sewer material</b>	<b>Points</b>
<b>Difficulty of repair</b>	<b>Points</b>	at life expectancy	10
freeway, railroad	10	old	7
city center	7	medium	3
main streets, important locations	5	new	0
main roads, local mass transport routes	3	<b>Sewer dimension</b>	<b>Points</b>
side streets, empty areas	0	> 800	10
		500-800	8
		300-500	4
		< 300	0

Tab. 1 Key indicator class table

The significance of particular key indicator is considered by implementing the indicator weights. The balance among distinct significance indicators is reached and the multi-criteria calculation can be performed by this means. An example of key parameters weighting is shown in the table (Tab. 2).

<b>Indicator</b>	<b>Weight</b>
sewer age	30%
sewer profile dimension	7%
camera survey	30%
sewer material	10%
sewer overload	18%
repair difficulty	5%
<b>Total</b>	<b>100%</b>

Tab. 2 Key indicator weight table

Similarly to the previous table the weights of indicators are to be defined and agreed together with local water utility specialists using the sensitivity analysis.

The final score for each section of the network is calculated based on the defined classes and selected indicator weights according to the following equation:

$$S_i = \sum_{n=1}^m (P_i^n * V^n) \quad (1)$$

Where:

$S_i$  ... score value in  $i^{\text{th}}$  network section

$P_i^n$  ... indicator “n” value for section “i”

$V^n$  ... weight of indicator “n”

The evaluation of the final score is done for all network sections during one simulation run (1 year). Next to that, there is a statistical post processing performed on multi-criteria method results to get a frequency histogram for a given reconstruction year as well as reconstruction cost for all sections over the limit value or alternatively for part of sections within the agreed reconstruction budget. Remaining sections are then moved with higher priority for subsequent year calculation. New values are set for all indicators according to material aging curves before calculation for the next year is made.

The global network characteristics are further determined to see the long term trends for particular network infrastructure (Fig.4). The “average network age” and “remaining network life” characteristics are selected and used in this work. The average network age is defined as normalized age value of all network sections.

$$T = \frac{\sum T_i * L_i}{\sum L_i} \quad (2)$$

Where:

$T$  ... average network age

$T_i$  ...  $i^{\text{th}}$  network section age

$L_i$  ...  $i^{\text{th}}$  network section length

The remaining network age is defined as a difference of the planned network life and its average age.

$$Z = P - T \quad (3)$$

Where:

$Z$  ... remaining network age expectancy

$P$  ... planned network age expectancy

$T$  ... average network age

Using above formulas the long term evaluation and analyses can be performed on sewer and water networks and the trends in the network development over period of several decades disclosed and optimized. The simulation results are transformed into annual network characteristics for each subsequent simulation year and they can be presented in a form of long term network development graph (Fig.4.)

## 2.2 Programming Environment for Network Reconstruction Plan

The method for long term reconstruction plan described in above chapters was translated into the software code and integrated as a component into DHI simulation model Mike Urban. This way large digital pool of data used for simulation model as well as for asset management system can be fruitfully utilized together with “network failure” database, CCTV results and other data storages used at water utility companies. Moreover, the GIS architecture of Mike Urban model facilitates better understanding of topological aspects and relationships between reconstruction sites during the decision making process in terms of optimal flow of investment in time and space (Fig. 5).

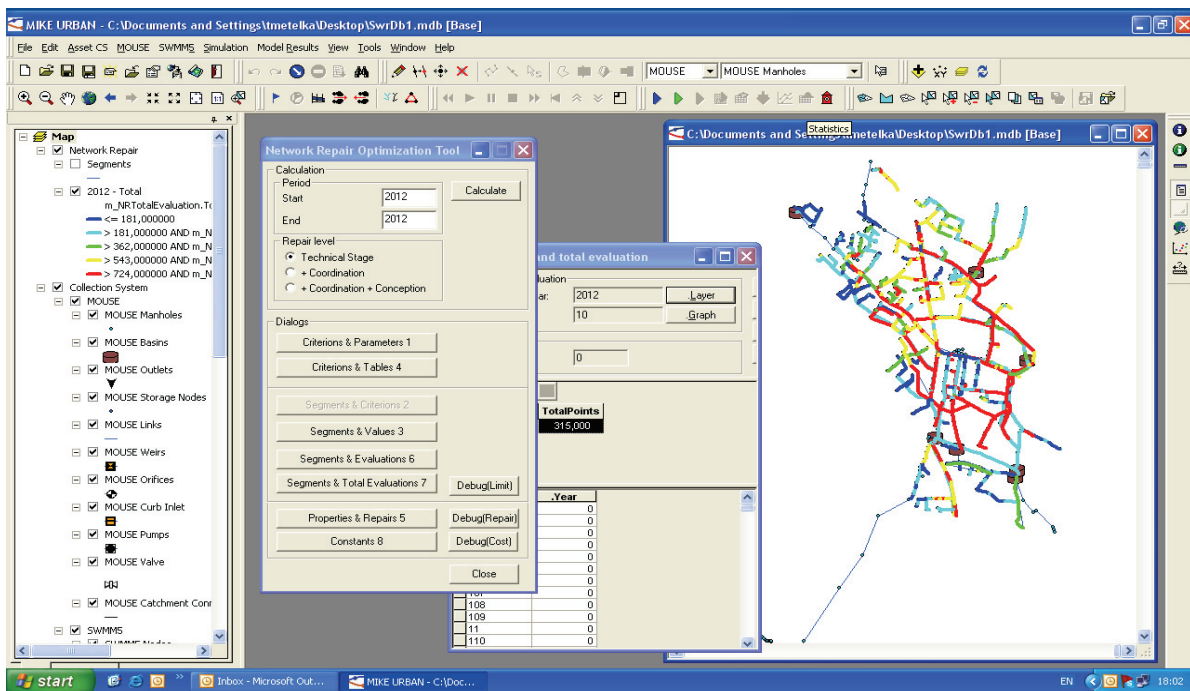


Fig. 5 Mike Urban - reconstruction planning program user environment

### 3 CASE STUDY – CITY OF FRANTISKOVY LAZNE

The described method was applied for development of long term sewer network reconstruction plan in the city of Frantiskovy Lazne as an integral part of city urban drainage master plan. Following criteria for evaluation of the sewer network were agreed with the client

- Point evaluation was grouped into frequency classes with 50 point ranges.
- Time horizon of 2012-2041 (30 years) was set for reconstruction plan.
- The reconstruction limit was set to 610 points (from maximum of 1000 possible).
- For all reconstructed sewers stone material will be used.
- Methodical guideline for calculation of sewer reconstruction costs released by Ministry of Agriculture will be used.

The results of current sewer network status evaluation are presented in the following figure (Fig. 6). (The term “sewer length” on the vertical axis means a sum of all sewer network segments that fall into a given interval by their scores.)

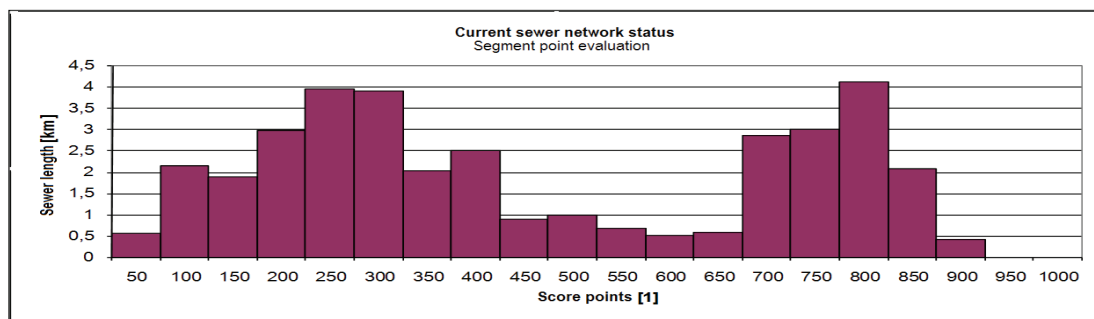


Fig. 6 Histogram of score frequencies of all sewer network segments – current status

It is clear from the graph that relatively large portion of the city sewer network is in good conditions (they are sections, which have scores between 0-450 points). On the other hand part of the sewer

network is in worse condition and therefore requires reconstruction (sections with the range of 700-1000 points). This takes approx. 12.5 km of sewers from the total evaluated length of 36.2 km that requires planned repairs.

The sewer network reconstruction plan was developed for the period of 2012 to 2041 in four scenarios, namely for yearly investments of 3 mil CZK (120 ths. EUR), 5 mil CZK (200 ths. EUR), for unlimited investment (e.g. in the form of loan from EU funds) and finally for no investment (lack of investment funds). The results of the multi-criteria analysis for 30 years simulation (2012-2041) are presented on graph (Fig. 7) showing the annual reconstruction length recommended by the method.

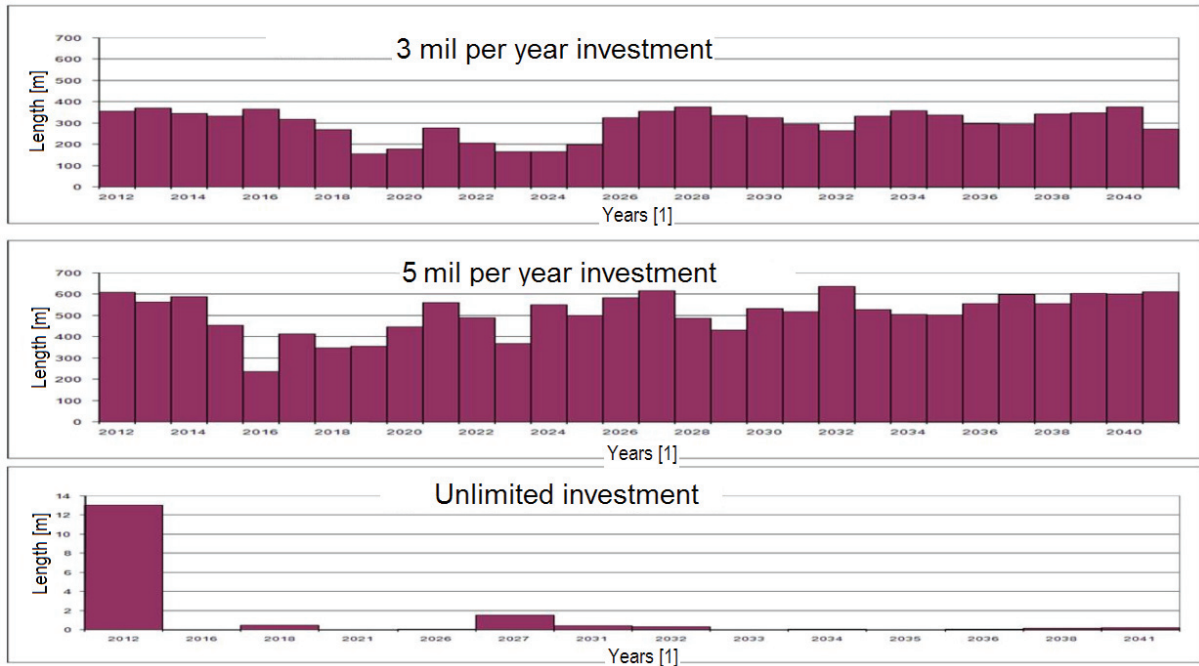


Fig. 7 Proposals of investment plan for alternative solutions of sewer network reconstruction

The selected scenarios of long term reconstruction plan further enables monitoring and evaluation of future system state after the end of simulated period (30 years), as shown on the next figure (Fig. 8).

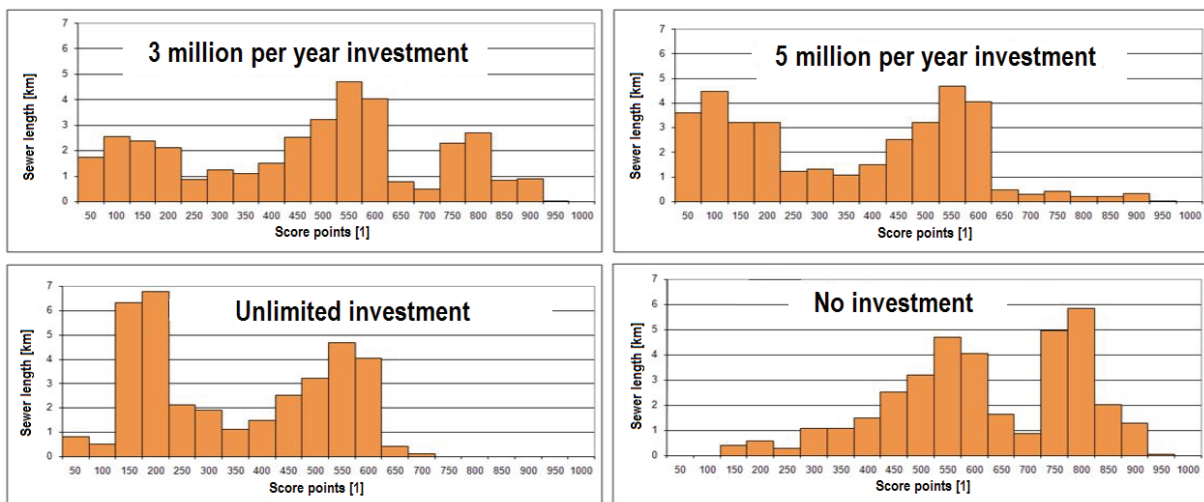


Fig. 8 Histogram of score frequencies for the year 2041 – for selected scenarios of investment

The results received can be easily transformed into table form for additional considerations and analyses e.g. list of network sections and their reconstruction time and price schedule (Tab. 3) or a summary table of investment plans for separate years (Tab. 4.)

Segment ID	DN [mm]	Material	Construction year	Street	Length [m]	reconstruction year	Price [thou. of CZK]
1238	300	Stone	1920	Nezvalova	29,93	2012	213
1239	300	Stone	1920	Nezvalova	63,40	2012	452
1246	300	Stone	1920	Chebská	22,77	2012	162
1247	300	Stone	1920	Chebská	6,95	2012	50
1256	900	Stone	1920	NZP	8,95	2012	187
1258	500	Stone	1920	ZP	13,74	2012	137
1267	300	Stone	1920	Chebská	85,49	2012	610
133	300	Stone	1920	Husova	13,57	2012	97
149	800	Stone	1920	Dlouhá	3,04	2012	53

Tab. 3 Detailed reconstruction plan of sewer network sections

Year	Reconstruction [km]	Reconstruction [%]	Price [thou. of CZK]	Cumulative price [thou. of CZK]
2012	0,39	1,08%	3 000	3 000
2013	0,41	1,12%	2 998	5 998
2014	0,37	1,03%	2 994	8 992
2015	0,37	1,03%	2 991	11 983
2016	0,40	1,11%	3 000	14 982
2017	0,27	0,74%	2 999	17 982
2018	0,22	0,62%	2 990	20 971
2019	0,19	0,52%	2 996	23 968

Tab. 4 Yearly plan of investments into sewer network reconstruction

Graphical representation of results in the form of maps brings additional view to the results of the reconstruction plan and help the structuring the reconstructions into specific phases according to the other planned city renovations. The main effects of provided results are obtained after the integration with information systems of Water Utility in the city of Frantiskovy Lazne (Fig. 9).

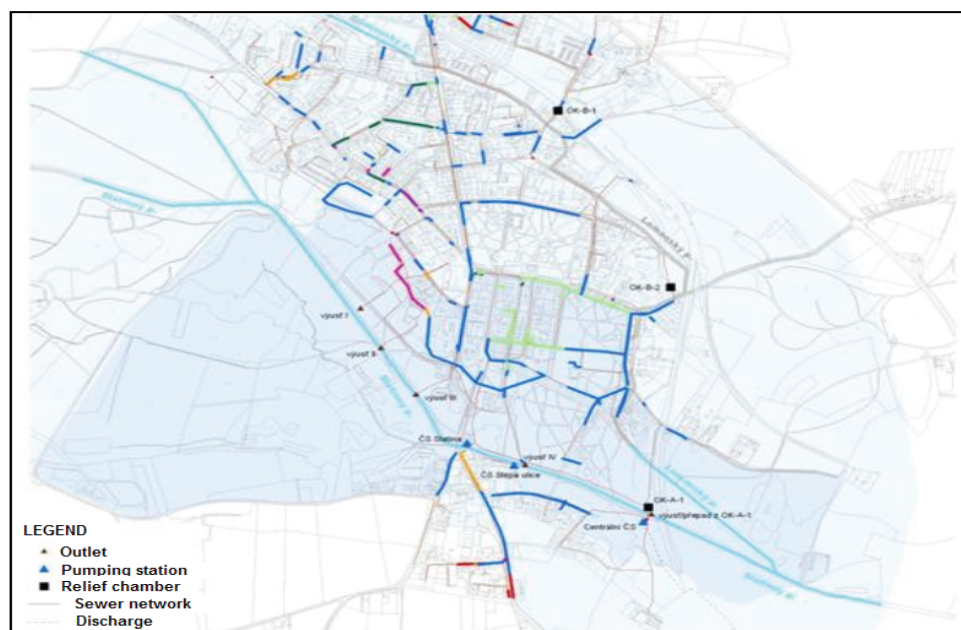


Fig. 9 Reconstruction plan – output maps

The sewer network average age characteristics were calculated in addition (see Eq.2) to the performed works for all four scenarios. The results of sewer network development prognosis are shown on the figure (Fig. 10) showing the temporal development of the overall network age for the simulation period.

It can be argued based on above prognosis that from the current average age of approx. 47 years and with no reconstruction the sewer network will age to 75 years of age, and even the average yearly investment of 3 million CZK will not be enough to completely stop the network aging process (the network will “age” 52 years in 30 years). In contrary, yearly investment of 5 million CZK seems to be a

suitable optimum for keeping a status quo, or even creating slight improvement (the network will “become younger” in 30 years it will reach resulting 39 years of age). Prognosis graph represents also a suitable decision making means in terms of planned life expectancy of a network, which Water Utility companies define in their long-term development strategies.

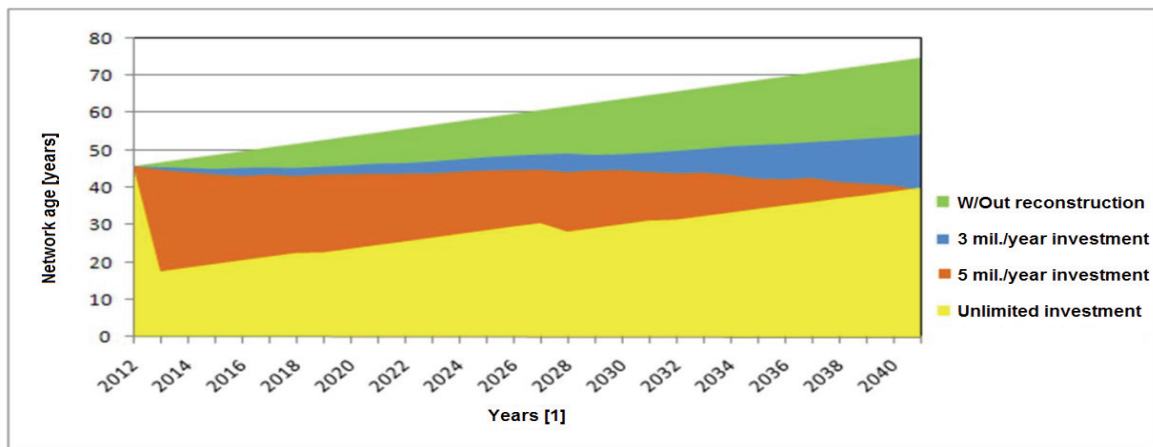


Fig. 10. Prognosis of sewer network average age development trend – for selected scenarios

## 4 CONCLUSION

Long-term planning of water and sewer network reconstructions belongs to key objectives for water utility companies. That is why the network reconstruction plans become important documents that affect not only long-term behavior of the whole system under operation but also the economic results at water utility organizations. At the same time, the development of reconstruction plan is influenced by uncertainties originating from lack of information about condition of this infrastructure. In consequence, the best available technology and know-how is to be utilized once optimal long term investment plan in terms of cost/effect is to be achieved.

The procedure based on multi-criteria analysis and applied on defined set of key network indicators seems to fit well to the objective of systematic long-term reconstruction planning. Use of information technologies in combination with operational and maintenance information and together with application of simulation modeling is a proper way of meeting the objective for long term optimization of reconstruction cost according to the authors. The method described in the paper can be used and modified according to the actual situation in any locality. It is also possible to perform parallel calculations for water and sewer networks with this method to achieve significant investment savings related to coordination of both plans in time and space. The evaluation of the network technical condition and the development of long term reconstruction plan enable longer term overview on network reconstruction needs. Presented approach makes the mutual balance between investment and operational costs possible in relation to the strategy used for network renewal in each particular water utility company.

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