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MODELLING CONCEPTS AND DECISION SUPPORT IN ENVIRONMENTTAL SYSTEMS

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Olgierd Hryniewicz

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The purpose of the present publication is to popularize information tools and applications of informatics in environmental engineering and environment protection that have been investigated and developed in Poland and Germany for the last few years. The papers published in this book were presented during the workshop organized by the Leibniz-Institute of Freshwater Ecology and Inland Fisheries in Berlin in February 2006. The problems described in the papers concern the mathematical modeling, development and application of computer aided decision making systems in such environmental areas as groundwater and soils, rivers and lakes, water management and regional pollution. The editors of the book hope that it will support the closer research cooperation between Poland and Germany and when this intend succeeds then also next publications of the similar kind will be published.

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CHAPTER 3

Water management and Decision support

DECISION MAKING SYSTEMS FOR COMMUNAL WATER NETWORKS AND WASTEWATER TREATMENT PLANTS*

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Abstract: *The Systems Research Institute for many years has been cooperating with the Polish communal waterworks in Rzeszow which is a middle size city with 170.000 inhabitants in the south part of Poland. The enterprice is an owner of the communal water and wastewater networks as well as of the wastewater treatment plant. To improve the management of them two computer aided decision making systems have been developed at the Institute with the financial support of the Polish Ministry for Science. In the presentation the structures, the functions and properties of the systems are described and also some results and conclusions of their implementation in the enterprise are given. The innovation of these systems consists in the usage as their basic module of the mathematical models of the object investigated, i.e. of the water-net and of the wastewater treatment plant. The object model helps to optimize the structure and the operation of the water-net and to control the technological process realized in the wastewater treatment plant. After the systems were made and introduced, many new concepts have been arisen concerning some modifications of the systems and which are now under investigation. These new directions in developing the computer aided management of communal waterworks are also presented and discussed.*

Keywords: Computer aided decisions making systems, mathematical modeling and computer simulation, water networks and wastewater treatment plants management.

1. Introduction

Polish communal waterworks have been during the last few years in a process of great transformation after the communist system of economy transformed in 1989 into the capitalistic one. This transformation process consists in introducing new technologies and performing large modernization tasks in the processes of water and wastewater treatment as well as in the development of new computer tools for better management of the waterworks. In the following we will concentrate on the second aspect of this transformation process, i.e. on the

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* The paper is a result of the research project of the Polish Ministry of Education and Science No. 3T11A01026

development of computer aided decisions making systems for improving the operational work of the operators and planers of the communal water networks and wastewater treatment plants. All consideration are illustrated with the examples concerning the real Polish waterworks in Rzeszow which has been the research partner of the Systems Research Institute for already about 13 years.

2, Mathematical modeling and simulation of water networks

A water net operation can be simulated with the following hydraulic model that enables the calculation of water flows in the pipes and of water pressure in the nodes of the water-net. The mathematical description of the model occurs with the linear and nonlinear algebraic equations which are formulated in the following.

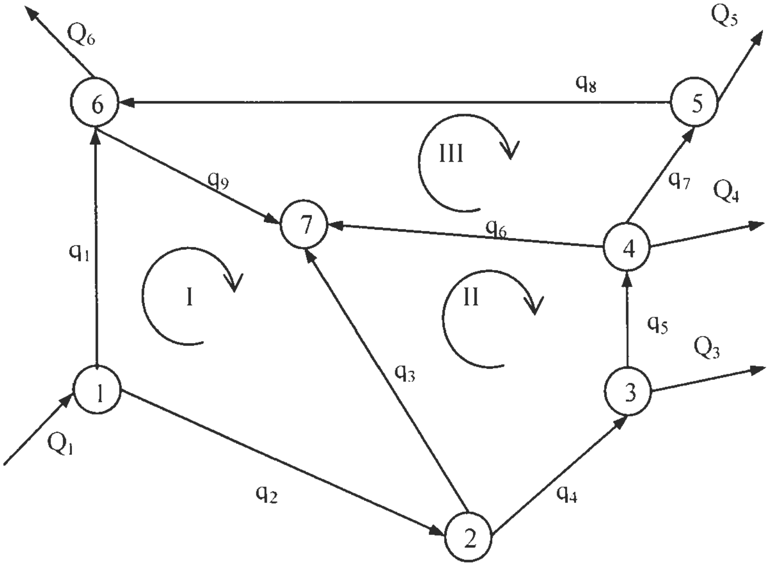

Figure 1. An exemplary diagram of a water net.

On fig. 1 an simplified example of a water net is shown with the following data: nodes number K = 7, pipes number R = 9, rings number S = 3, and *Qi* are water input or output.

The simulation task is to calculate the flows *qi* in R pipes and the pressure values Pi in K nodes what means that the number of unknowns to calculate is R + K = (K + S – 1) + K = (K – 1) + S + K. To do it the following equations are used:

Linear flow equations from the 1st *Kirchhoff law* (K equations):

Node 1: $Q1 - q1 - q2 = 0$

....

Node 7: $q3 + q6 + q9 = 0$

Nonlinear flow equations from the 2nd *Kirchhoff law* (S equations):

$$\text{Ring 1: } ht1 + ht9 - ht3 - ht2 = 0$$

……

$$\text{Ring 3: } ht6 - ht9 - ht8 - ht7 = 0$$

Linear pressure equations from the *Bernoullie equation* ((K – 1) equations):

$$\text{Node } i\text{: } Pi = Pi\text{-}1 - hti$$

where

$$h_t = \frac{\lambda l v^2}{2gD} \quad \text{and} \quad v = \frac{4q}{\pi D^2}$$

and hti means the pressure decrease in a pipe, Pi means the node pressure, λ means the friction coefficient and l, D mean the pipe length and pipe diameter.

A computer program for solving the above equations was developed at the Systems Research Institute and its main window is shown in Fig. 2.

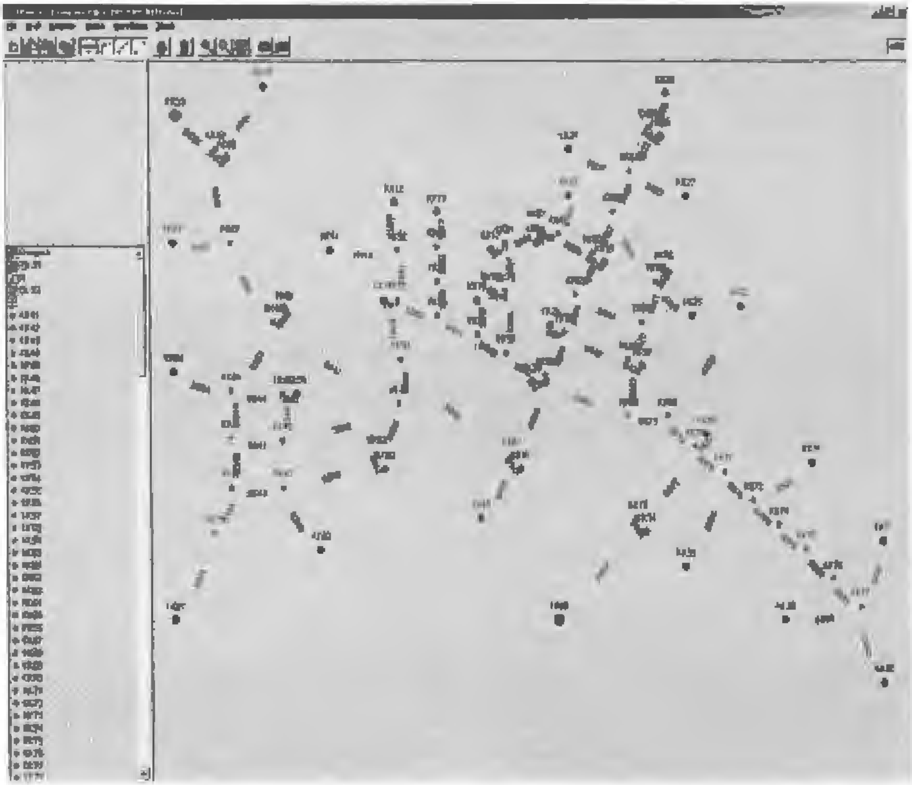

Figure 2. The main window of the computer program for performing the hydraulic calculations of a water net.

3. Water networks optimization

There are two tasks of the water net optimization: the planning and the control of the water-net. There are also two tasks of the water net planning and they are the reconstruction and development of the water-net. These optimization tasks will are explained more detailed below.

The water net **planning** means the choice of such technical parameters which fulfill some technical, technological and economical demands of the water net operator and manager. There are the following methods of planning:

- simulation
- optimization

where the optimization is divided into the one-criterial optimization and the multicriterial one.

The **simulation** way of planning is characterized by the following features:

- arbitrary choice of the values for water-net parameters
- the water net simulation occurs with the use of the hydraulic model
- arbitrary evaluation of the simulation results
- multiple repetition of simulation runs for other sets of the parameters values
- arbitrary choice of the best solution.

The above characteristic of the simulation results in the conclusion that it is much work and time consuming problem and its solutions can be very unreliable because they are chosen in a very subjective way.

The **optimization** way of planning is characterized by the following features:

- automatic choice of the water-net parameter values
- arbitrary choice of constrains for the parameters to be changed
- automatic evaluation and choice of the best solution.

This characteristic of the optimization results in the conclusion that it is fast, reliable and very handy metod in comparison with the simulation way of planning. As to the division of the optimization into two kinds of calculation they can be described as follows:

By the **one-criterial** optimization:

- the assessment of the calculation results occurs with the use of only one goal function
- the goal function can be of technical or economical art.

As a result only one optimal solution are received what is positive but very limited area of investigation is considered by the calculation what is negative.

By the **multi-criterial** optimization:

- the assessment of the calculation results occurs with the use of several goal functions
- the goal functions can be of technical **and** economical arts.

As a result many quasi-optimal solutions is received what is very positive and a very large area of investigation is considered by the calculation what is also very positive.

The water net **control** means a calculation task for securing the water demands and appropriate water pressure in the water net nodes with minimal operation costs. To do it the hourly water demands in the water net nodes must be given.

The control task can be considered as a specific kind of optimization in which several goal functions are formulated and similar optimization methods are used to make the calculation. In the following some exemplary goal functions of a real control task are shown:

- Function 1 (to minimize): Maximal difference between demanded and calculated pressure in the end nodes of the water net.
- Function 2 (to minimize): Daily consumption of energy by the water pumps operating in the water net.
- Function 3 (to minimize): Maximal number of turnings on / turnings off of the water pumps.
- Function 4 (to minimize): Maximal pumping pressure of the water pumps.
- Function 5 (to maximize): Minimal water velocity in the water net pipes.
- Function 6 (to maximize): Total water exchange in the retention reservoirs including into the water net.

As a result of the calculation some scenarios of the water pump runs and filling and emptying of the retention reservoirs for given water demand distributions in the end nodes of the water net are received.

4. Computer aided management of water networks

Under consideration of different activities realized by the management of communal waterworks and calculation possibilities offered by modern information tools a concept of a computer aided decisions making system for the water net operator has been developed at the Systems Research Institute which is shown in Fig. 3.

The main elements of this computer system are as follows:

- Branch Data Base
- numerical map of the water net

- monitoring system
- hydraulic model with optimization algorithms included.

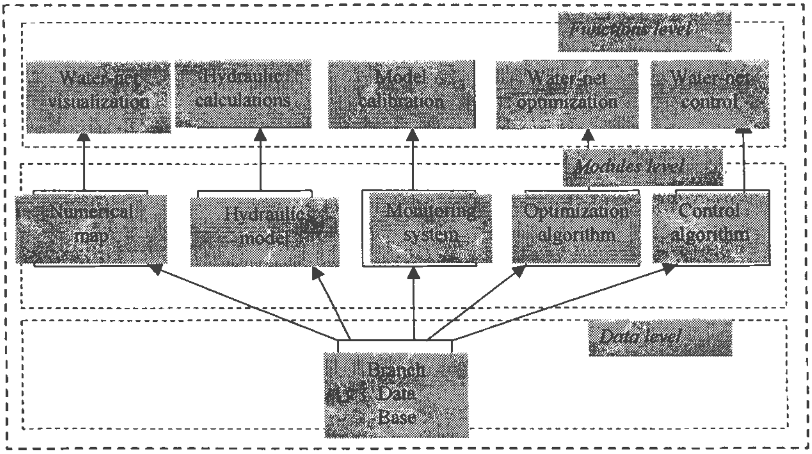

Figure 3. Structure of a computer aided decisions making system planned for waterworks.

The main functions realized by the computer system are:

- visualization of the water-net
- simulation of the water network running
- optimization of the water network parameters
- control of pumps running and of filling and empting of water reservoirs.

The Branch Data Base (BDB) is a source of technical, technological and operational information of the water net for all programs included into the system. By developing the BDB the typical objects of communal water net and their attributes had to be defined.

These objects are:

- water net pipe
- water net node which can be of the following kind:
  - water source like pumps station and retention reservoir
  - end user node what means the water consumer
  - montage node
  - measuring node
- water-net equipment like pumps, gate valves, reducing valves and check valves.

The object attributes are:

- for a water net pipe: length, diameter, material art, age

- for a water net node: water pressure, water consumption, geographic coordinates
- for a pump: type, characteristic, producer
- for a retention reservoir: geometric dimensions
- for a gate valve, reducing valve and check valve: running state and characteristic.

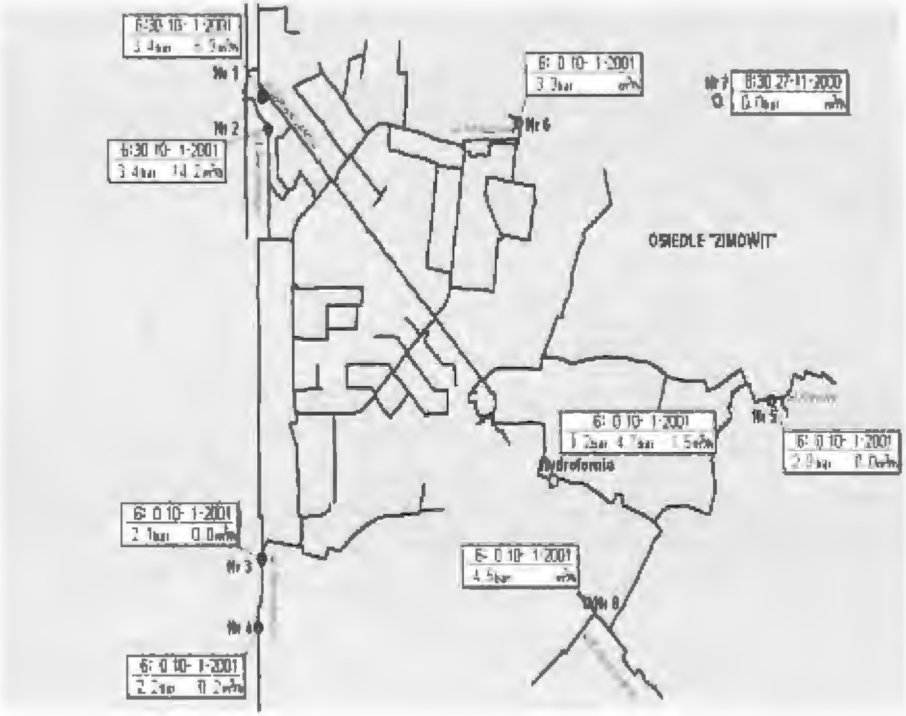

Figure 4. Diagram of an exemplary monitoring system.

The numerical map serves as a generator of the water net graph and is for the visualization of the water net on the computer screen. This generator can produce three kinds of the water net graph which are following:

- complex graph which means the real and full structure of the water net
- simplified graph which means the water net structure without nodes with small water flows less than a value given
- mixed graph which means a chosen part of the water net in complex form and the remaining part of the water net in simplified form.

The monitoring system installed on the water net is for collecting and recording measurements data such as water pressure in the water net nodes and the water flows in the water net pipes which are then used for the calibration and verification of the water net hydraulic model. By developing a monitoring system for the communal water net the following tasks have to be considered and solved:

- optimal choice of the measurement points on the water net what means that the points number shall be minimal and the information quantity received in these points shall be maximal
- choice of a data transmission system whereby the following main transmission systems are: telemetry, mobile telephony and radio
- definition of the data transfer conditions which can be continuous or periodical
- choice of a computer program for data recording and visualization.

An exemplary monitoring system developed for the waterworks in the Polish city Rzeszow is shown in Fig. 4. It consists of nine measurements points and the data transmission occurs by the mobile telephony system.

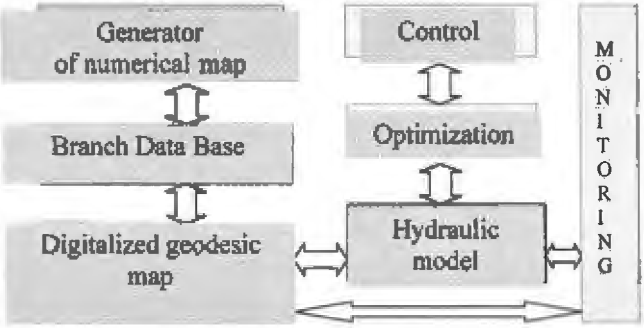

Figure 5. Practical realization of a computer aided decision making system for the water net in Rzeszow.

Basing on the concept of the computer aided decisions making system planned for communal waterworks (see Fig. 3) and taking into consideration demands and limits recognized in the real waterworks in Rzeszow a simplified computer system to support the operational work at the water net has been developed. This system is shown in Fig. 5.

The main functions realized by the system are:

- water-net visualization using the graphical and descriptive data of the water net geodesic map
- water net monitoring
- generation of the water net graphs for hydraulic calculations
- water net simulation with the hydraulic model

- water net optimization with the use of an one-criterial algorithm for minimizing the pressure deviations in the end nodes
- generation of scenarios for the water-net control.

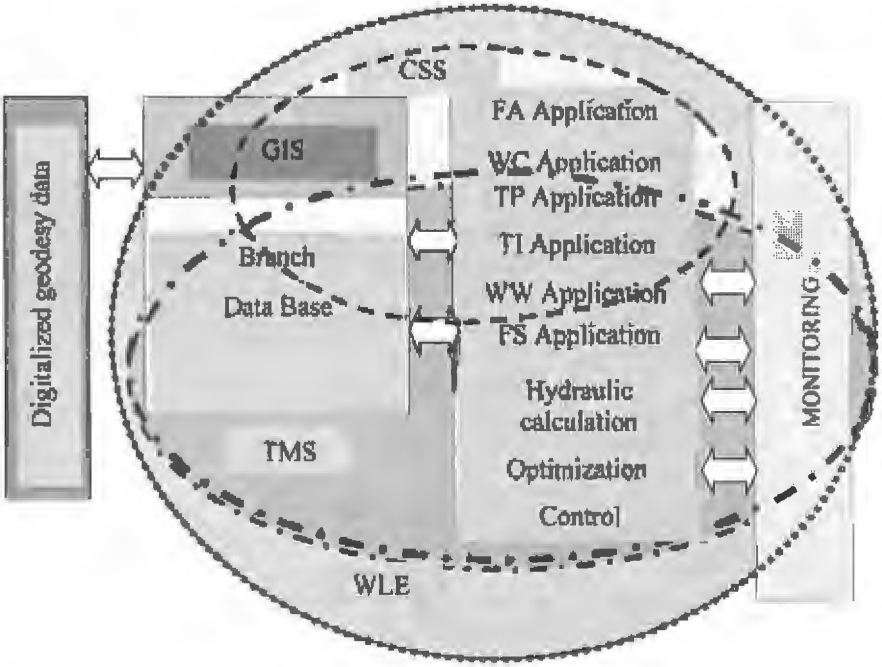

Figure 6. Concept of extension of the computer aided decisions making system for the water net in Rzeszow.

After this system had already been developed and introduced into the practice some new ideas arose as a result of the experience gained. They concerned the possibilities of the extension of the system by some new functions. The developed version of the computer system realizes only technical functions concerning the water net operation and it does not take into consideration the financial nor administrative functions which must be also realized by the waterworks management. These technical and non-technical functions use in the practice the same or similar data recorded in the Branch Data Base and there are many relations between these tow kinds of functions. This observation resulted in the idea to add some new applications to these already existed ones.

The possible additional programs which could and should be included into the system structure are as follows:

- Application FA for realizing the Financial and Accounts service what means recording the water consumers

- Application WC for recording the Water Consumption by the water consumers
- Application TI for realizing the Technical Inspection service what means the water net repairs and extension works
- Application TP for issuing the Technical Plans of the water net repairs and extension works
- Application WW for the Water and Wastewater management, i.e. recording the water and wastewater production
- Application FS for supporting the Failures Service

The concept of the extended computer aided decisions making system for the water net operation is shown in Fig. 6. In the structure of this system some separated sub-systems can be isolated which would be responsible for different areas of the waterworks management. These separated sub-systems of the whole computer, their applications or tools for realizing the specific sub-system functions and the results of the sub-system activity are following:

1. Technical Management Sub-system (TMS):
   - Tools: monitoring system, hydraulic models, optimization and control algorithms, application FS
   - Results of functioning: efficient water net operation, professional planning of repairs and extension tasks
2. Client Service System of (CSS):
   - Tools: applications TP, TI, WC
   - Result of functioning: efficient and progressive client service concerning the generation of the technical plans, carrying out the technical inspections and water selling
3. Water Losses Elimination System of (WLE):
   - Tools: analysis of data from the CSS and TMS systems
   - Result of functioning: help by the identification and elimination of the critical water net parts which generate large water losses.

5. Mathematical modeling and simulation of wastewater treatment plants

Besides the computer system for operating the water nets also a system for computer aided management of wastewater treatment plants has been developed under close cooperation with the waterworks in Rzeszow. The system is intended to support the operation of mechanical and biological wastewater treatment processes.

The mechanical treatment means the sedimentation of fest mineral and organic particles contained in the wastewater and the biological treatment means the decomposition of organic, nitric and phosphoric wastewater compounds under activity of several kinds of bacteria creating the activated sludge in the sewage.

The main control parameters of the biological wastewater plants are oxygen concentration in the tanks with the activated sludge and the activated sludge recirculation rate. In modern wastewater plants with full biological treatment of the wastewater also the wastewater recirculation rate is considered as the additional control parameter.

Usually the technological process control consists in stabilization of values of the control parameters which is quiet effective by steady-state conditions of the process and especially of the raw sewage inflow to the plant. If these conditions are not fulfilled and the raw sewage parameters are changing fast and in large range then computer aided decisions making systems are needed and useful to improve the operation of the treatment process.

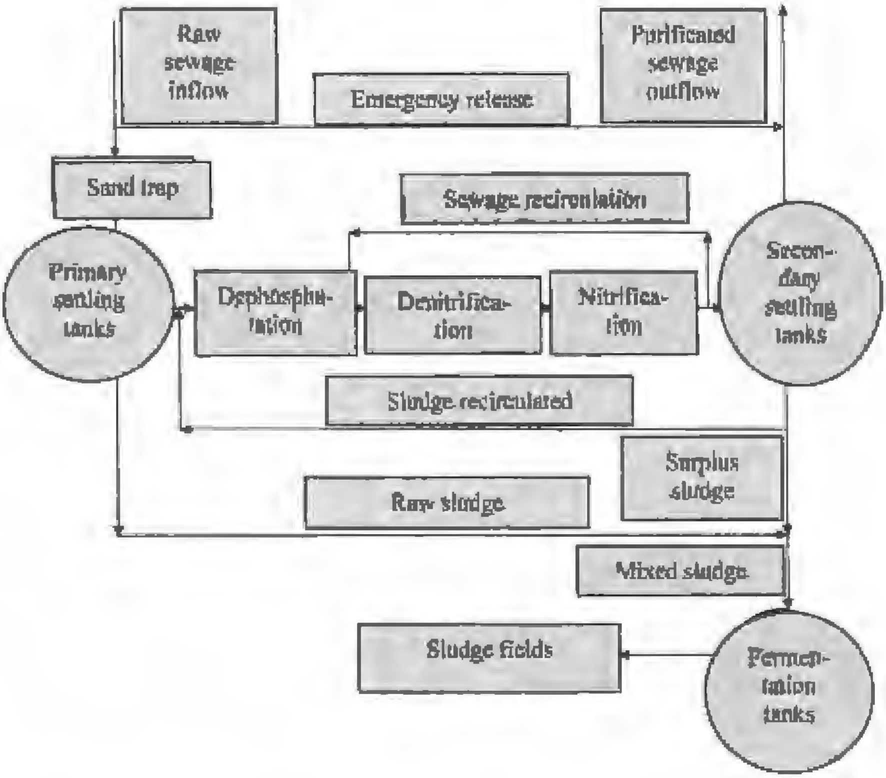

Figure 7. A typical wastewater plant structure with activated sludge.

A typical wastewater treatment plant is shown in Fig. 7. It consists of the following elements:

- Sand trap – it realizes the mechanical treatment by the sedimentation of big mineral particles
- Primary settling tank – it realizes the mechanical treatment by the sedimentation of fest and organic undissolved compounds and by mixing of dissolved compounds
- Activated sludge chambers – it realizes the biological treatment in form of hydrolysis, nitrification, denitrification and dephosphatation processes
- Secondary settling tank – it realizes the mechanical treatment by the wastewater clarifying in the form of activated sludge sedimentation.
- Recirculation systems which are the internal sewage and external sludge recirculation.

The computer system for the wastewater treatment plants operates on the basis of different mathematical models developed for the whole process and for its separated parts. One kind of these models are **hydraulic models** which are used for the identification of the active volumes of the primary and secondary settling tanks and of the sludge chambers of the plant.

These models are described with the following flow equation:

$$\frac{\mathrm{d}\,c(t)}{\mathrm{d}\,t} = \frac{Q(t)}{V}(c_{we}(t) - c(t))$$

where V is the active volume, c is the marker concentration, t denotes time, Q is the sewage flow and c_{we} are the marker concentration in inflow.

To solve this flow equation with the variable parameter $Q(t)$ it shall be transformed into the equations with constant parameters and this new equation form is:

$$V\frac{\mathrm{d}\,c(\varsigma)}{\mathrm{d}\,\varsigma} = c_{we}(\varsigma) - c(\varsigma)$$

The analytical solution of the transformed flow equation is:

$$c(\varsigma) = C\,\mathrm{e}^{\frac{-\varsigma}{V}} + \frac{1}{V}\int_{\varsigma_o}^{\varsigma} \mathrm{e}^{-\frac{\varsigma-\tau}{V}} c_{we}(\tau)\,\mathrm{d}\,\tau$$

and its discrete form is:

$$c_n = ac_{n-1} + bc_{we\,n-1}$$

Under consideration of some measurements errors by measuring the marker concentration in the sewage in form:

$$y_n = c_n + \varepsilon_n$$

the following linear equation of the hydraulic model with 2 parameters results:

$$y_n = ay_{n-1} + bc_{wen-1} + \varepsilon_n - a\varepsilon_{n-1}$$

If some new replacements will be formulated in the following forms:

$$z_n = y_n - c_{wen-1} \qquad u_n = y_{n-1} - c_{wen-1} \qquad v_n = \varepsilon_n - a\varepsilon_{n-1}$$

then the new form of the model with only 1 parameter will result in the following linear equation:

$$z_n = au_n + v_n$$

This last linear equation can be also written in the following nonlinear form with 1 parameter V:

$$z_n = \mathrm{e}^{-\frac{\Delta_n}{V}} u_n + v_n$$

The converting formulas to calculate the active volume V from the linear model parameters a and b are as folows:

$$a = \mathrm{e}^{-\frac{\Delta_n}{V}} \qquad b = 1 - \mathrm{e}^{-\frac{\Delta_n}{V}} = 1 - a$$

$$V_a = -\frac{\Delta_n}{\ln a} \qquad V_b = -\frac{\Delta_n}{\ln(1-b)}$$

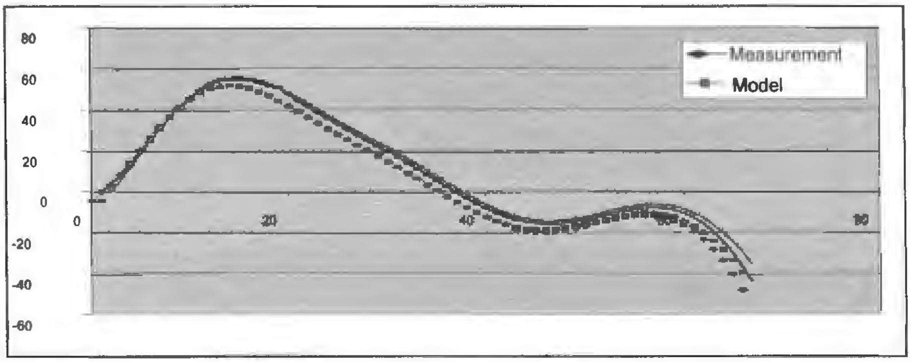

Figure 8. Model of the primary settling tanks.

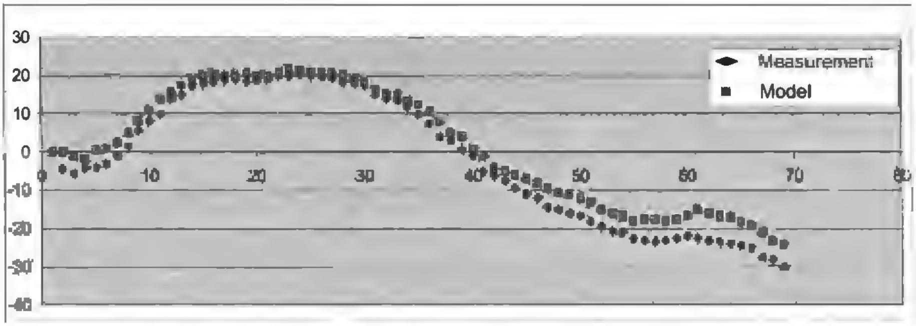

Figure 9. Model of the activated sludge chambers.

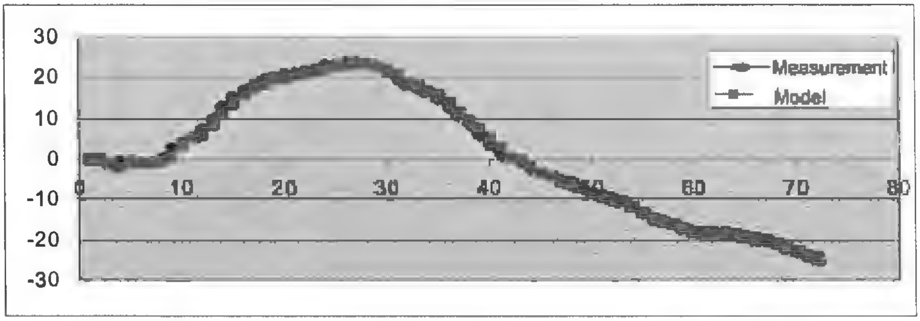

Figure 10. Model of the clarification zone of the secondary settling tanks.

Table 1. Identification results of the primary settling tanks.

Method	**Values of *a* & *b* parameters**					
	a/σ_a	b/σ_b	$a+b$	V_a	V_b	V_g
Kalman	0,73 (±0,04)	0,24 (±0,03)	0,97	4.675	5.427	7.820
Clarke	0,80 (±0,04)	0,16 (±0,03)	0,96	6.701	8.444	
Maximum likelihood	0,76 (±0,04)	0,22 (±0,04)	0,97	5.327	6.049	

Table 2. Identification results of the activated sludge chambers.

Method	**Values of *a* & *b* parameters**					
	a/σ_a	b/σ_b	$a+b$	V_a	V_b	V_g
Kalman	0,98 (±0,02)	0,04 (±0,02)	1,02	182.790	96.673	13.500
Clarke	0,55 (±0,08)	0,34 (±0,073)	0,89	6.164	8.378	
Maximum likelihood	0,97 (±0,03)	0,04 (±0,03)	1,01	131.005	82.725	

Table 3. Identification results of the clarification zone of the secondary settling tanks.

Method	**Values of *a* & *b* parameters**					
	a/σ_a	b/σ_b	$a+b$	V_a	V_b	V_g
Kalman	0,76 (±0,02)	0,22 (±0,01)	0,98	5.087	5.491	11.060
Clarke	0,76 (±0,03)	0,22 (±0,03)	0,98	5.048	5.500	
Maximum likelihood	0,76 (±0,02)	0,22 (±0,02)	0,98	5.071	5.494	

Table 4. Active volumes of all tanks identified.

Method	**Primary settling tanks**	**Activated sludge chambers**	**Secondary settling tanks**	
			Clarification zone	Sedimentation zone
Linear Regression (LR)	5.676	11.246	4.723	6.303
Nonlinear Regression (NR)	6.283	12.087	4.612	6.514
Geometrical volume	7.820	13.500	11.060	
[%] (LR)	73	83	100	
[%] (NR)	80	90	101	

The above three kinds of hydraulic models have been identified using several least squares methods such as Kalman, Clark, maximum likelihood, linear and non-linear regression methods.

Especially detailed the most complicated linear model with 2 parameters was investigated and some results of these investigations are shown on Figures 8, 9, 10 and in Tables 1, 2, 3. Unfortunately these results are not satisfactory although the models fit good to the data what can be seen on the figures. The models generate very differentiated active volume values V_a and V_b which shall be equal and also these values are in many cases bigger than the geometrical volume V_g what is not acceptable. This eliminates these models from farther investigations.

The best results of identification have been achieved with the simplest method of linear regression and with the use of the simplest model description in form of linear equation with only 1 parameter. These results are shown in Table 4. The active volumes calculated are smaller than geometrical ones what is the main criterion of their rightness. On the other side this essential inequality between the active and the geometrical volumes of the wastewater plant tanks shows the importance of their identification and the incorrectness of acting when the appropriate identification process is not performed.

The second kind of the models which were developed as the integral elements of the computer system supporting the decisions of the treatment process operator was the **physical model** of the treatment plant. It describes the main systems of the object, i.e. the primary and secondary settling tanks, activated sludge chambers and the external recirculation of the activated sludge, as well as the main processes occurring there, i.e. the sewage mixing and wastes sedimentation in the settling tanks and the reduction of organic and nitric wastes in the sludge chambers.

To formulate the physical model the wastewater fractions must be defined which are depending on the characteristic of the sewage investigated. The following wastewater fractions have been distinguished:

- organic fractions:
  - undissolved and slowly reduceable fractions x_S
  - undissolved and unreduceable fractions x_I
  - dissolved and fast reduceable fractions s_S
  - dissolved and unreduceable fractions s_I
- Nitric fractions:
  - Nitrogen fractions N_{og}
  - Ammonia fractions s_{NH}
  - Nitrites & Nitrates fractions s_{NO}
  - organic dissolved and fast reduceable Nitrogen fractions s_{ND}
  - undissolved organic and slowly reduceable Nitrogen fractions x_{ND}

- other fractions:
  - mineral suspension x_{min}
  - Heterotrophic bacteria x_H
  - Autotrophic bacteria x_A
  - organic undissolved bacterial fractions x_P
  - dissolved Oxygen s_O
  - alkalinity s_{alk}.

The next steps of the physical model formulation consist in separated description of all systems taking part in the wastewater treatment process.

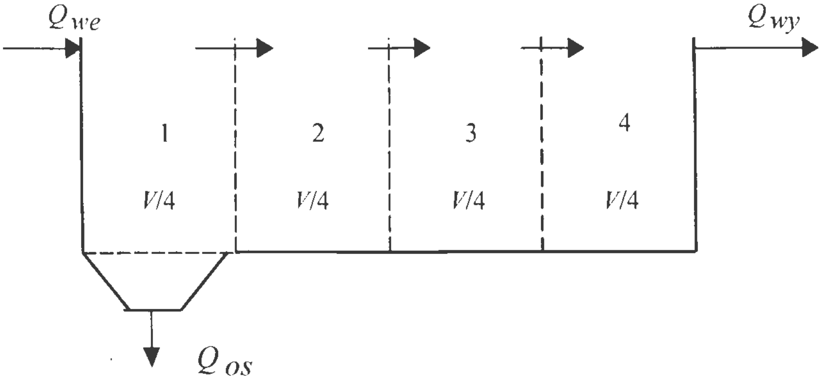

Figure 11. Model structure of the primary settling tanks.

At first the **primary settling tank** is modelled in form of compartment model consisting of four chambers (see Fig. 11). The model equations are following:

$$\frac{V}{4}\frac{\mathrm{d}s_1}{\mathrm{d}t} = Q_{we}(s_{we} - s_1) \qquad \text{for chamber 1}$$

$$\frac{V}{4}\frac{\mathrm{d}s_i}{\mathrm{d}t} = Q_{wy}(s_{i-1} - s_i) \qquad \text{for chambers i = 2, 3, 4}$$

$$\frac{V}{4}\frac{\mathrm{d}x_1}{\mathrm{d}t} = Q_{we}(x_{we} - x_1) - \frac{V}{4}Ax_1^B \qquad \text{for chamber 1}$$

$$\frac{V}{4}\frac{\mathrm{d}x_i}{\mathrm{d}t} = Q_{wy}(x_{i-1} - x_i) - \frac{V}{4}Ax_i^B \qquad \text{for chambers i = 2, 3, 4}$$

for $Q_{wy} = Q_{we} - Q_{os}$ and $k = Ax^B$. In these equations V is the active volume of the tank, s denotes a dissolved fraction and x denotes an undissolved fraction in the sewage.

Then the **secondary settling tank** is modeled also in form of compartment model but consisting in this case of 12 layers (see Fig. 12).

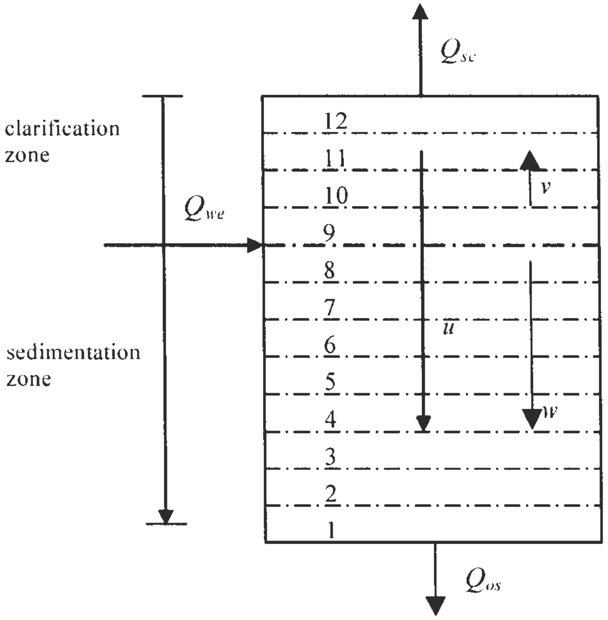

Figure 12. Model of the secondary settling tanks.

The model equations are as follows:

$v_s = -v$ for layers 9–12

$v_s = w$ for layers 1–8

$v_x = -v + u$ for layers 9–12

$v_x = w + u$ for layers 1–8

where $u(x) = u_0\, e^{-bx}$, and:

$$\frac{V_s}{8}\frac{\mathrm{d}s_8}{\mathrm{d}t} = Q_{we}s_{we} - Q_{os}s_8 \qquad \text{for layer 8}$$

$$\frac{V_s}{8}\frac{\mathrm{d}s_i}{\mathrm{d}t} = Q_{os}(s_{i+1} - s_i) \qquad \text{for layers } i = 7, 6, \ldots, 1$$

$$\frac{V_c}{8}\frac{\mathrm{d}s_9}{\mathrm{d}t} = Q_{we}s_{we} - Q_{sc}s_9 \qquad \text{for layer 9}$$

$$\frac{V_c}{8}\frac{\mathrm{d}s_i}{\mathrm{d}t} = Q_{sc}(s_{i-1} - s_i) \qquad \text{for layers } i = 10, 11, 12$$

$$\frac{V_s}{8}\frac{\mathrm{d}x_8}{\mathrm{d}t} = Q_{we}x_{we} - A(w_8 + u_8)x_8 \qquad \text{for layer 8}$$

$$\frac{V_s}{8}\frac{\mathrm{d}x_i}{\mathrm{d}t} = A((w_{i+1} + u_{i+1})x_{i+1} - (w_i + u_i)x_i) \qquad \text{for layers } i = 7, 6, \ldots, 2$$

$$\frac{V_s}{8}\frac{\mathrm{d}x_1}{\mathrm{d}t} = A((w_2 + u_2)x_2 - w_1x_1) \qquad \text{for layer 1}$$

$$\frac{V_c}{8}\frac{\mathrm{d}x_9}{\mathrm{d}t} = Q_{we}x_{we} - (u_9 - v_9)x_9 \qquad \text{for layer 9}$$

$$\frac{V_c}{8}\frac{\mathrm{d}x_i}{\mathrm{d}t} = A((u_{i-1} - v_{i-1})x_{i-1} - (u_i - v_i)x_i) \qquad \text{for layers } i = 10, 11$$

$$\frac{V_c}{8}\frac{\mathrm{d}x_{12}}{\mathrm{d}t} = A((u_{11} - v_{11})x_{11} - v_{12}x_{12}) \qquad \text{for layer 12}$$

where s denotes a dissolved fraction, x denotes an undissolved fraction, A is the tank section and V_s and V_c are the active volumes of the layers in the clarification or sedimentation zone.

The next and already final step of working out the physical model is modelling the **activated sludge chamber**. This model is formulated also as a compartment model like the models of settling tanks and it consists of four compartments like the primary settling tank model (see Fig. 13).

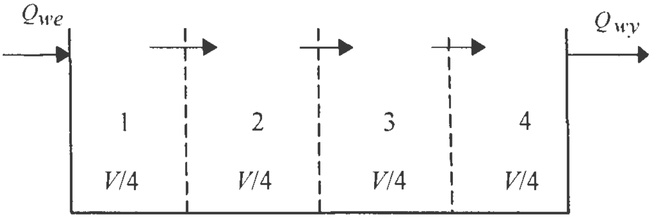

Figure 13. Model structure of the activated sludge chamber.

The model is described with the following equations (for $Q_{wy} = Q_{we} = Q$):

$$\frac{V}{4}\frac{\mathrm{d}z}{\mathrm{d}t} = Q(z_{we} - z) - \frac{V}{4}k_z$$

$$k_z = \sum_{i=1}^{k} r_{zi} = \sum_{i=1}^{k} \gamma_{zi}v_i$$

where the equation parameters are: V - active volume of the chamber, Q - wastewater flow, z - waste fraction s or x, k_z - concentration change velocity of fraction z, K - number of processes with fraction z included, r_{zi} - concentration change velocity of fraction z in process i, v_i - process i velocity, γ_{zi} - transformation coefficient of fraction z in process i.

The essential problem while developing the model of activated sludge chamber is definition of the processes occurring in the chamber and of their velocities. The following variables were then defined:

- aerobic growth of bacteria x_H caused by the Ammonia assimilation:

$$v_1 = \mu_H \frac{s_S}{K_S + s_S} \frac{s_O}{K_{OH} + s_O} \frac{s_{NH}}{K_{NH} + s_{NH}} x_H$$

- aerobic growth of bacteria x_H caused by the Nitrites and Nitrates assimilation and restrained by the Ammonia:

$$v_2 = \mu_H \frac{s_S}{K_S + s_S} \frac{s_O}{K_{OH} + s_O} \frac{s_{NO}}{K_{NO} + s_{NO}} \frac{K_{NH}}{K_{NH} + s_{NH}} x_H$$

- anoxic growth of bacteria x_H caused by the Ammonia, Nitrites and Nitrates assimilation and restrained by the Oxygen:

$$v_3 = \mu_H \frac{s_S}{K_S + s_S} \frac{s_{NH}}{K_{NH} + s_{NH}} \frac{s_{NO}}{K_{NO} + s_{NO}} \frac{K_{OH}}{K_{OH} + s_O} x_H$$

- anoxic growth of bacteria x_H caused by the Nitrites and Nitrates assimilation and restrained by the Ammonia and Oxygen:

$$v_4 = \mu_H \frac{s_S}{K_S + s_S} \frac{s_{NO}}{K_{NO} + s_{NO}} \frac{K_{NH}}{K_{NH} + s_{NH}} \frac{K_{OH}}{K_{OH} + s_O} x_H \eta_H$$

- aerobic growth of bacteria x_A caused by the Ammonia assimilation:

$$v_5 = \mu_A \frac{s_O}{K_{OA} + s_O} \frac{s_{NH}}{K_{NA} + s_{NH}} x_A$$

- atrophy of heterotrophic bacteria x_H:

$$v_6 = b_H x_H$$

- atrophy of autotrophic bacteria x_A:

$$v_7 = b_A x_A$$

- ammonification of the organic dissolved fast reduceable Nitrogen s_{ND} under influence of the bacteria x_H:

$$v_8 = b_a s_{ND} x_H$$

- hydrolysis of the undissolved and slowly reduceable organic compounds x_S into the fast reduceable ones s_S :

$$v_9 = b_h \frac{x_S / x_H}{K_x + x_S / x_H} \left(\frac{s_O}{K_{OH} + s_O} + \eta_h \frac{K_{NO}}{K_{NO} + s_{NO}} \frac{K_{OH}}{K_{OH} + s_O} \right) x_H$$

- hydrolysis of the undissolved slowly reduceable organic Nitrogen x_{ND} into the fast reduceable one s_{ND} :

$$v_{10} = \frac{x_{ND}}{x_S} v_9$$

where μ_H, μ_A are maximal velocities of the bacteria growth, K_S, K_{NH}, K_{OH}, K_{NO}, K_{OA}, K_{NA}, K_X are saturation coefficients, $\eta_H, \eta_h \leq 1$ are process velocity inhibiting coefficients and b_H, b_A, b_h, b_a are velocity coefficients.

The second essential problem we face during formulation of the model of activated sludge chamber is the definition of the concentration change velocities for the waste fractions defined before. The following formulas have been developed for the investigated wastewater treatment process:

- fraction x_S : related processes are the atrophy of x_H and x_A (causing the growth of x_S) and the hydrolysis of x_S (causing the reduction of x_S); the concentration change velocity of x_S is:

$$k_{x_S} = (1 - f_P)(v_6 + v_7) - v_9$$

- fraction x_{ND} : related processes are the atrophy of x_H and x_A (causing the growth of x_{ND}) and the hydrolysis of x_{ND} (causing the reduction of x_{ND}); the concentration change velocity of x_{ND} is:

$$k_{x_{ND}} = (i_{XB} - f_P i_{XP})(v_6 + v_7) - v_{10}$$

- fraction s_S : related processes are the aerobic and anoxic growth of x_H by the assimilation of s_{NH} and s_{NO} (causing the reduction of s_S) and the hydrolysis of x_S (causing the growth of s_S); the concentration change velocity of s_S is:

$$k_{s_S} = -\frac{1}{Y_H^{NH}}(v_1 + v_3) - \frac{1}{Y_H^{NO}}(v_2 + v_4) - v_9$$

- fraction s_{ND} : related processes are the ammonification of s_{ND} (causing the reduction of s_{ND}) and the hydrolysis of x_{ND} (causing the growth of s_{ND}); the concentration change velocity of s_{ND} is:

$$k_{s_{ND}} = -v_8 + v_{10}$$

- fraction s_{NH} : related processes are the aerobic and anoxic growth of x_H and the aerobic growth of x_A by the assimilation of s_{NH} (causing the reduction of s_{NH}) and the ammonification of s_{ND} (causing the growth of s_{NH}); the concentration change velocity of s_{NH} is:

$$k_{s_{NH}} = -i_{XB}(v_1 + v_3) + v_8$$

- fraction s_{NO} : related processes are the aerobic and anoxic growth of x_H by the assimilation of s_{NO} (causing the reduction of s_{NO}) and the aerobic growth of x_A by the assimilation of s_{NH} (causing the growth of s_{NO}); the concentration change velocity of s_{NO} is:

$$k_{s_{NO}} = -i_{XB}v_2 - \frac{1 - Y_H^{NH}}{a_1 Y_H^{NH}} v_3 - \left(\frac{1 - Y_H^{NO}}{a_1 Y_H^{NO}} + i_{XB}\right) v_4 + \frac{1}{Y_A} v_5$$

- fraction s_{alk} : related processes are the aerobic and anoxic growth of x_H by the assimilation of s_{NH} (causing the reduction of s_{alk}) and by the assimilation of s_{NO} (causing the growth of s_{alk}) and the aerobic growth of x_A by the assimilation of s_{NH} (causing the reduction of s_{alk}) and the ammonification of s_{ND} (causing the growth of s_{alk}); the concentration change velocity of s_{alk} is:

$$k_{s_{alk}} = a_2 i_{XB}(-v_1 + v_2) - \left(a_2 i_{XB} - \frac{1 - Y_H^{NH}}{a_3 Y_H^{NH}}\right) v_3 +$$

$$+ \left(a_2 i_{XB} + \frac{1 - Y_H^{NO}}{a_3 Y_H^{NO}}\right) v_4 - (a_4 + a_2 i_{XB}) v_5 + a_2 v_8$$

- fraction x_H : related processes are the aerobic and anoxic growth of x_H by the assimilation of s_{NH} and s_{NO} and the atrophy of x_H (causing the reduction of x_H); the concentration change velocity of x_H is:

$$k_{x_H} = v_1 + v_2 + v_3 + v_4 - v_6$$

- fraction x_A : related processes are the aerobic growth of x_A by the assimilation of s_{NH} and the atrophy of x_A (causing the reduction of x_A); the concentration change velocity of x_A is:

$$k_{x_A} = v_5 - v_7$$

- fraction x_P : related process is the atrophy of x_H and x_A (causing the growth of x_P); the concentration change velocity of x_P is:

$$k_{x_P} = f_P(v_6 + v_7)$$

- fraction s_O : related processes are the aerobic growth of x_H by the assimilation of s_{NH} and s_{NO} and the aerobic growth of x_A by the assimilation of s_{NH} (causing the reduction of s_O); the concentration change velocity of s_O is:

$$k_{s_O} = -\frac{1-Y_H^{NH}}{Y_H^{NH}}v_1 - \frac{1-a_5 i_{XB} - Y_H^{NO}}{Y_H^{NO}}v_2 - \frac{a_5 - Y_A}{Y_A}v_5$$

where f_P is the suspension concentration in the biomass, i_{XP}, i_{XB} are the Nitrogen concentrations in the biomass, Y_H^{NH}, Y_H^{NO}, Y_A are coefficients of the bacteria growth efficiency and a_1, a_2, a_3, a_4, a_5 are weight coefficients.

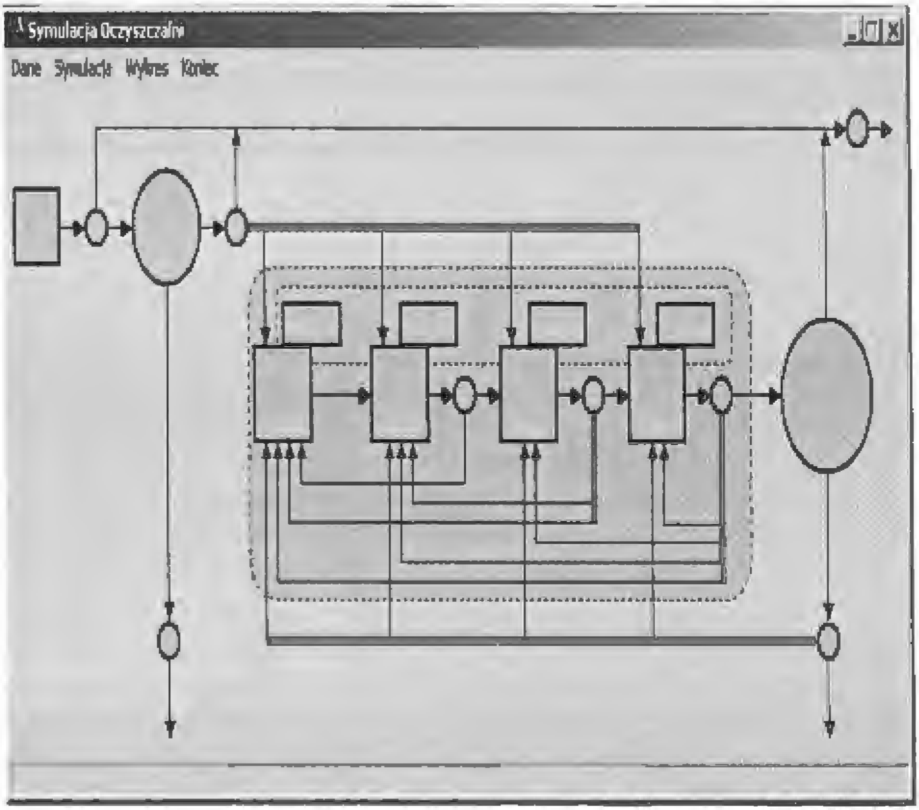

Figure 14. Wastewater treatment plant simulation program.

For the physical model formulated above a computer program has been developed as a tool for simulating the whole technological process of the wastewater treatment (see Fig. 14). Using the real data from the wastewater treatment plant in Rzeszow the calibration of the model has been done and its results are shown in Tables 5, 6 and 7.

One can see from the Tables that the model fits well to the data what demonstrates a good quality of the model. There is only one problem that arose by calculating the model: a very long time of an individual simulation run. This observation was unexpected and very discouraging for it meant that the model was not suitable for doing optimization runs which usually need many simulation runs. This meant also the impossibility of using the model to control the wastewater treatment process because for generation of a control scenario some optimization algorithms must be used and this results either in the necessity of realizing many simulation runs.

The conclusion was then that the physical model developed suits well for carrying out separated simulation runs of the wastewater plant but when the optimization or control of the process have to be done then other kinds of the models must be worked out. This resulted in the idea of developing for the wastewater treatment plants some simpler and faster models than the physical model which could be then used for the operational purposes.

Table 5. Calibration of the primary settling tank model.

Model parameters			
Calculated values		**Literature values**	
A [g/m^{3}d]	B	A [g/m^{3}d]	B
$1.2\cdot 10^{-6}$	3.76	$1.232\cdot 10^{-6}$	4.05

Process parameters (daily values)				
Parameter	**Unit**	**Measurements**	**Model**	**Error [%]**
x_{og}	g /m^3	163	162	0,6
x_{min}	g /m^3	60	47	21,6
BOD	g O$_2$/m^3	186	188	1
COD	g O$_2$/m^3	448	451	0,7
s_{NH}	g N/m^3	29,3	26,3	10
N_{og}	g N/m^3	39,3	32,0	18,6
s_{alk}	val/m^3	8,3	7,9	4,8

Table 6. Calibration of the activated sludge chambers model.

Parameter	**Unit**	**Measurements**	**Model**	**Error [%]**
x_{og}	g /m^3	3.815	3.890	2
x_{min}	g /m^3	1.144	1.322	15,6
BOD	g O$_2$/m^3	18	18,3	1,7
COD	g O$_2$/m^3	53	53,6	1
s_{NH}	g N/m^3	26,3	24,2	8
N_{og}	g N/m^3	32,1	26,1	18,7
s_{alk}	val/m^3	7,9	7,7	2,5

Table 7. Calibration of the secondary settling tank model.

Model parameters			
Calculated values		**Literature values**	
u_0 [m/d]	b [m^3/g]	u_0 [m/d]	b [m^3/g]
187,2	6,23 10^{-4}	187,2	6,23 10^{-4}

Process parameters (daily values)

Parameter	**Unit**	**Measurements**	**Model**	**Error [%]**
x_{og}	g /m^3	19	19	0
x_{min}	g /m^3	14	7	50
BOD	g O$_2$/m^3	19	23	21
COD	g O$_2$/m^3	55	81	47
s_{NH}	g N/m^3	24,9	24,2	2,8
N_{og}	g N/m^3	28,1	26,9	4
s_{alk}	val/m^3	8,1	7,7	5
x_{og-r}	g /m^3	5.719	6.090	6,5

6. Operational models of wastewater treatment plants for forecasting and control

The new kinds of the wastewater plant models, **the operational models,** have been developed in form of the time series and of neuronal nets. These two mathematical descriptions were used for working out the model to forecast the raw sewage inflow to the wastewater plant. The time series model is as follows:

$$y_n = a_1 y_{n-1} + a_2 y_{n-2} + \dots + a_R y_{n-R} + v_n$$

where R denotes the model order, a_i is the model parameter and v_n is the measurement error. The optimal model received is of the 5th order.

The neuronal models are of two arts: they consist of three layers with five neurons on the 1st layer, with one neuron on the third layer and with different number of neurons on the hidden layer. These five input neurons are the equivalent of five terms on the right side of the autoregressive equation which describes the time series model.

The modelling approach was realized on the basis of real data collected in the wastewater treatment plant investigated and it consisted in two steps: of the modelling step on which the model coefficients were calculated and the testing step on which the quality of the model was validated. The results of the modelling are shown in Figures 14 and 15. One can see that both kinds of models fit well to the data and there are practically no differences in the quality of fitting between the time series model and the neuronal one.

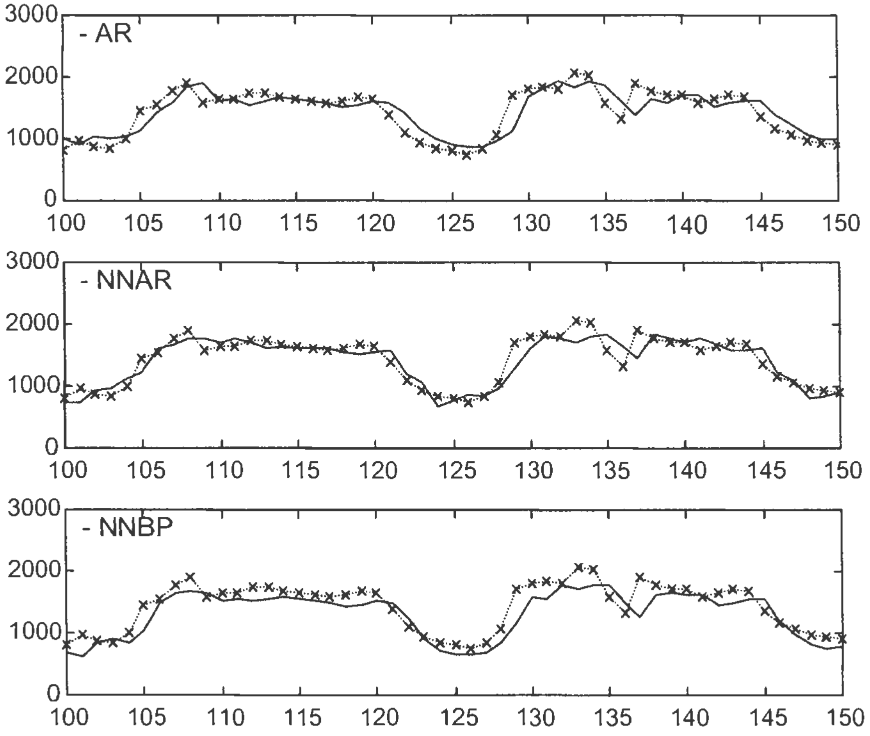

Figure 15. Autoregressive model of 5th order (*upper diagram*) and two neuronal models (*lower diagrams*) (*modelling step*).

A model for controlling the wastewater plant has been developed in form of nonlinear neuronal net. It consists of three layers with logistic transfer function between the input and hidden layer. Two neurons are located on the output layer and they are the Oxygen concentration in the activated sludge chambers of the plant and the flow intensity of the activated sludge recalculated. These variables mean the controls of the whole wastewater treatment process.

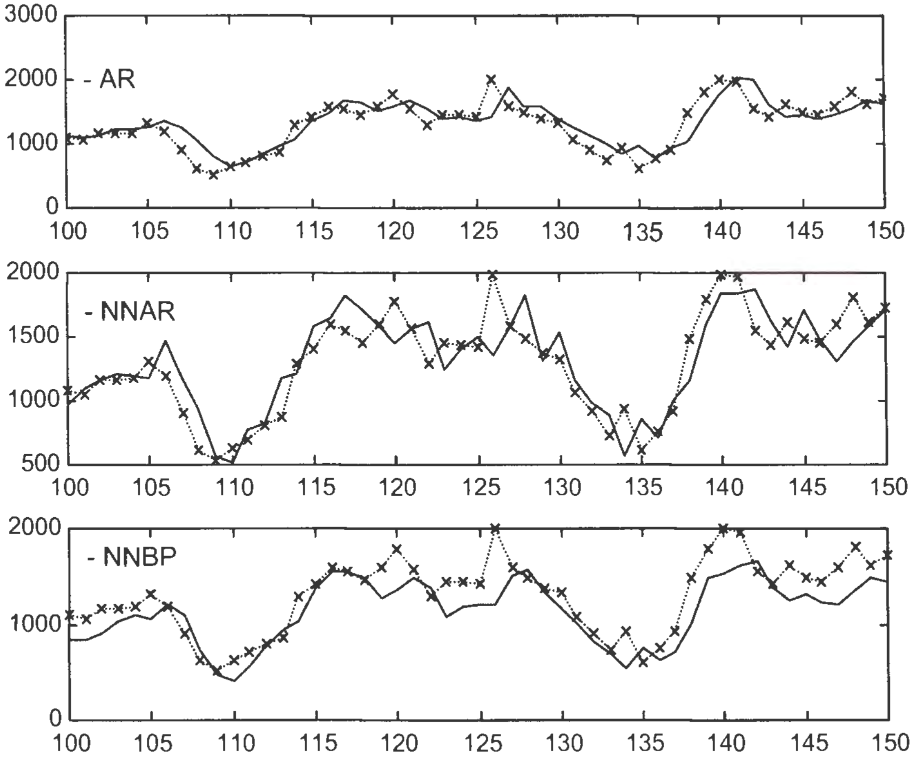

Figure 16. Autoregressive model of 5th order (*upper diagram*) and 2 neuronal models (*lower diagrams*) (*testing step*).

There are 16 neurons on the input layer which mean the following wastewater fractions:

- Raw sewage parameters in time *t* (4 inputs): *BOD*, ammonia and suspension concentrations and the sewage inflow intensity;
- Sewage parameters of the activated sludge chambers in times *t* and (*t*+*T*) (4 inputs): activated sludge concentration and activated sludge settling ability;

- Purified sewage parameters in times *t* and (*t*+*T*) (6 inputs): *BOD*, ammonia and suspension concentrations;
- Recirculated sludge parameters in times *t* and (*t*+*T*) (2 inputs): activated sludge concentration.

The results of working out the neuronal control model are shown in Fig. 17. One can see there that the model output fits well to the real data on the modeling step of the identification approach and the controls generated by the model approximate quite well the data on the validation step of the calculation.

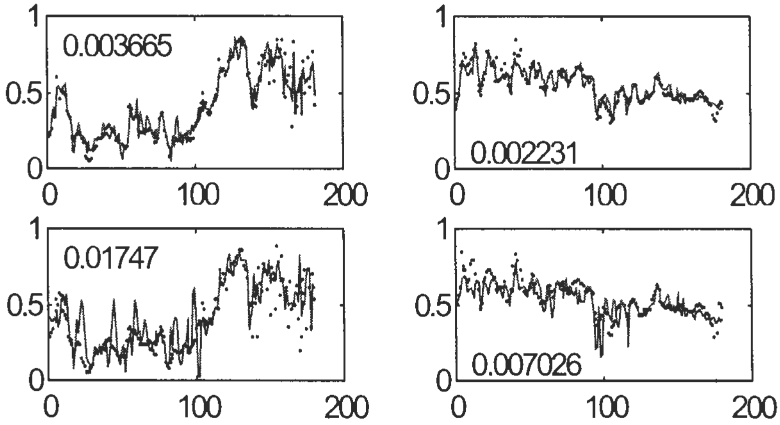

Figure 17. Control model results: modelling and testing results on the upper and lower diagrams; Oxygen concentration and the flow intensity of the activated sludge recirculated on left and right diagrams.

7. Computer aided management of wastewater treatment plants

After the different mathematical models for the wastewater treatment plant under investigation have been developed then all elements of a possible computer aided decisions making system for wastewater plants were already ready. A concept of such system is shown on Fig. 18. Its structure is similar to the computer system worked out for water nets. It consists of many models realizing different tasks resulted by running the process of wastewater treatment, of a monitoring system for collecting the measurement data, and of the Branch Data Base in which all technical and technological data of the process are recorded.

The operation of this computer system occurs as follows:

- on-line measurement of the main parameters of the process
- recording of the data collected in the Branch Data Base

- forecasting the raw sewage inflow and of the wastes concentration with the neuronal operational models
- generation of the process control parameters by the neuronal control model
- verification of the controls generated by simulation runs with the physical and/or neuronal model of the process.

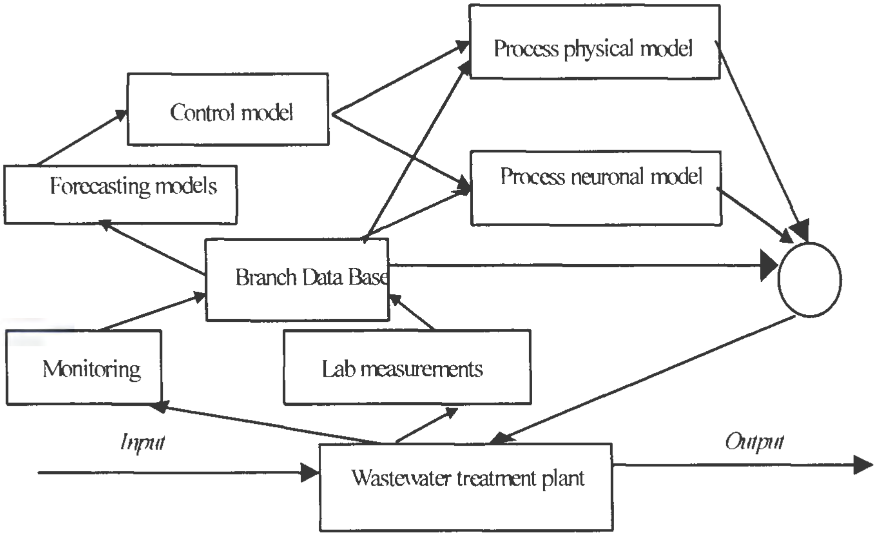

Figure 18. Concept of a computer aided decisions making system for the wastewater treatment plant in Rzeszow.

The innovative feature of this computer system is the application of many different mathematical models for performing different operation tasks such as forecasting, control and simulation. These models are then divided into classes: the operational models which are rather simple in description and fast in calculation, and the physical models which are complex in description and slow but exact in calculation. In this way the calculation results received with the operational models can be verified with the physical ones what shall guarantee the good quality of the technological decisions generated by the system.

8. Concept of information systems for communal waterworks

In the paper the concepts of two computer aided decisions making systems for operational running the communal water networks and wastewater treatment plants are presented. The models of these objects are the essential elements of these systems and they have been worked out and tested in Polish waterworks. After these systems had been designed and some operational experience had been collected an idea of developing a complex computer system to support the management of the whole water and wastewater system in a city arose.

This computer system would consist of the modules related to the water take out stations, the water distribution network, the wastewater transport network and the wastewater treatment plant which are the subsystems of the whole communal water and wastewater system and are connected each other in form of a linearly ordered set. The structure of such system designed is shown in Fig. 19.

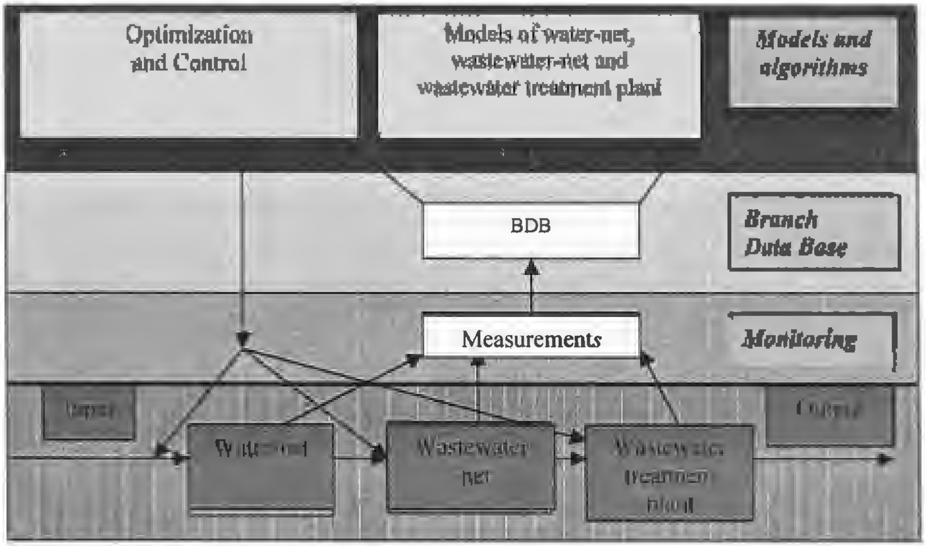

Figure 19. Concept of a complex computer aided decisions making system for communal waterworks.

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Jan Studzinski, Olgierd Hryniewicz (Editors)

MODELLING CONCEPTS AND DECISION SUPPORT IN ENYIRONMENTAL SYSTEMS

This book presents the papers that describe the most interesting results of the research that have been obtained during the last few years in the area of environmental engineering and environment protection at the Systems Research Institute of the Polish Academy of Sciences in Warsaw and the Leibniz-Institute of Freshwater Ecology and Inland Fisheries in Berlin (IGB). The papers were presented during the First Joint Workshop organized at the IGB in February 2006. They deal with mathematical modeling, development and application of computer aided decision making systems in the areas of the environmental engineering concerning groundwater and soil, rivers and lakes, water management and regional pollution.

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