Environment Protection Engineering

Vol. 32 2006 No. 2

DANIEL SŁYŚ*

SIMULATION MODEL OF GRAVITATION-PUMP STORAGE RESERVOIR

The paper continues theoretical analyses of the operation of innovative solutions of storage reservoirs employed in gravitational and pumping systems. A hydraulic and mathematical model of storage reservoir was built and used in order to develop a model and software programs for the simulation of a storage reservoir operation in rainwater and combined sewage systems. It permits a study of hydraulic processes as well as the most significant design parameters of storage reservoirs of this type.

1. INTRODUCTION

The problems of hydraulic overload of sewage systems and control of wastewater flow rate are particularly interesting in terms of efficient operation of wastewater treatment facilities and the purity of water in reservoirs. That objective is commonly achieved by a widespread use of reservoirs or tanks for periodic storage of surge flows of rainwater or combined drainage and for averaging the wastewater composition. The interest in such an equipment is accompanied by a significant development of research on new designs that broaden the field of their economically viable applications [1]–[3]. Presently the engineers in design bureaus have at their disposal multi-chamber reservoir solutions with much higher cubature effectiveness compared to single-chamber version, operating in gravitational, gravitation-vacuum as well as gravitation-pump systems of accumulation chambers.

In the development of a new, effective equipment and the methods of wastewater drainage and neutralization in sewage systems, modern research methods are indispensable. The fundamentals of the theory and design of copyrighted solutions of storage reservoirs operating in gravitation-pump systems enabled the model for simulating the operation of *GPW* type reservoir in a sewage network to be constructed.

* Rzeszów University of Technology, ul. Wincentego Pola 2, 35-959 Rzeszów, Poland, phone: (+48 17) 865 1427, fax: +(48 17) 865 1175, e-mail: daniels@prz.rzeszow.pl, http://www.prz.rzeszow.pl/reservoirs/

2. MODEL FOR SIMULATION OF RESERVOIR OPERATION IN RAINWATER AND COMBINED SEWAGE SYSTEMS

A hydraulic and mathematical model of storage reservoir of *GPW* type and the mode of its operation in the rainwater and combined sewage systems has been described in detail, among others, in [4]–[6]. Therefore, in this paper, we present merely the diagram of a hydraulic system of reservoir (figure 1).

The mathematical model of storage reservoir operation in a sewage system consists of differential equations and systems of equations defining variations in filling the reservoir chambers with wastewater during the process of its accumulation. That model takes into account the characteristic variation intervals of the functions representing the rate of wastewater supply through sewage network, as well as the effect of various times of rain duration *Td* versus the calculated flow generation time *Tp* on the hydrogram shape and the wastewater flow rates in the sewage system.

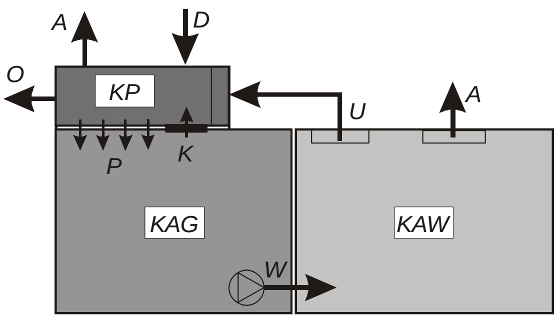

Fig. 1. Diagram of hydraulic system of gravitation-pump reservoir of *GPW* type
A – emergency overfall, *D* – reservoir inflow channel, *K* – reflux valve,
KAG – gravitational accumulation chamber, *KAW* – upper pump accumulation chamber,
KP – through-flow chamber, *P* – interchamber overfall,
U – bottom sink of wastewater from *KAW* to *KP*,
W – pumping system transporting wastewater from *KAG* to *KAW*

The attempts undertaken to solve analytically the mathematical model developed have shown that for a clear majority of the relationships, numerical methods of solving differential equations and systems of equations ought to be applied. For this purpose, the procedures of solving the regular differential problems on the basis of numerical methods of a higher order were reviewed and chosen [7].

Approximate solutions of differential equations and systems of equations are calculated based on the Runge–Kutta method of the fourth order, also called a predictor, together with the control of the error value on the basis of Adams' correction formula, also called a corrector. In figure 2, there is given the calculation algorithm that solves numerically differential equations and systems of equations in the mathematical model of reservoir in simulation software programs.

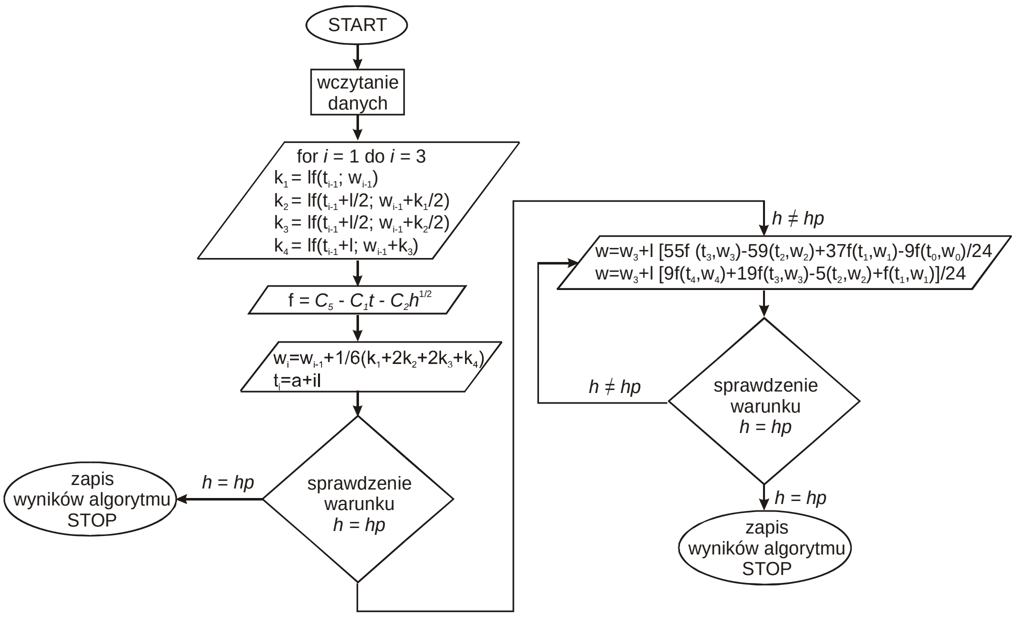

Fig. 2. Example of algorithm for the numerical solving of differential equations and systems of equations by the predictor–corrector method used in *WEGA* software programs

Because of the differences in mathematical formulas defining storage reservoir operation at various times of rain duration *Td*, three independent simulation programs are to be utilized in the process of reservoir operation. They are as follows:

WEGA 1 – software program simulates the storage reservoir operation at the time *Td* of rain duration, equal to the time *Tp* that is appropriate to sewage network designing;

WEGA 2 – software program simulates the storage reservoir operation at time *Td* of rain duration longer than the time *Tp* appropriate to sewage network designing;

WEGA 3 – software program simulates the storage reservoir operation at the time *Td* of rain duration shorter than the time *Tp* appropriate to sewage network designing.

When the algorithms are designed and programs run the following assumptions and operating conditions have been defined for *WEGA* simulation programs:

1. Wastewater inflows to the storage reservoir according to the wastewater inflow hydrograms assumed and, e.g., for $Td = Tp$ the hydrogram shape is triangular, while those for $Td < Tp$ and $Td > Tp$ are trapezoidal.

2. The rain characteristics are given by the method of boundary intensities which does not take into account the space-time variability of precipitation rate and/or its displacement over a drainage area.

3. Based of the method of boundary intensities, the programs calculate momentary rates of wastewater inflow to reservoir as a sequence of linear elementary functions.

4. The frequency of rains in the area of storage reservoir corresponds to the frequency of the rains appropriate for sewage network calculation.

5. Storage reservoir chambers have a fixed area of horizontal cross-section (from its bottom up to the maximum filling level).

6. The changes in filling the reservoir chambers with wastewater are represented by equations and equation systems for wastewater balance for respective phases of its operation, taking into account the variability in wastewater inflow over time.

7. The wastewater outflow from the reservoir varies over the time of its operation cycle and is a function of the through-flow chamber filling.

8. In the model of reservoir operation, the retention and the wastewater surges phenomenon in the inflow channel of storage reservoir are not taken into account.

9. The time *Tp*, appropriate to the sewage system design, is the sum of the times of wastewater flow, channel retention and local concentration.

10. Wastewater pumps are characterized by the flexibility of their efficiency and are switched on and off once in the entire cycle of the reservoir operation.

11. Variation of filling in the reservoir accumulation chambers does not affect the delivery of a pumping system.

12. Gravitational accumulation chamber has a limited horizontal area and a limited maximum filling.

13. The upper accumulation chamber has a limited area of the horizontal projection and an unlimited height of the maximum filling.

14. The through-flow chamber of the reservoir has a limited area of the horizontal projection and an unlimited height of the maximum filling.

15. Wastewater pumps allow the wastewater in gravitational accumulation chambers to be kept on the preset levels.

16. Filling of the upper accumulation chamber begins at the moment of reaching the wastewater level in the *KAG* accumulation chamber preset above the level of inter-chamber overfall edge.

17. In the simulation model, the phases of emergency operation of the storage reservoir are not taken into account.

18. The wastewater pumping system is switched off at the moment the wastewater inflow and outflow rates in the reservoir are equal, $QA = QO$.

19. Wastewater begins to outflow from the upper accumulation chamber to the through-flow chamber of the storage reservoir at the moment the wastewater level in the through-flow chamber reaches the preset filling level *hu*.

20. The wastewater sink is a hydraulically non-submerged opening.

21. The intensity of a pressure outflow of wastewater from the upper accumulation chamber is adjustable which allows stabilizing the intensities of wastewater outflow from the storage reservoir.

22. When wastewater outflows from the upper accumulation chamber, the sink level *hup*, set in the through-flow chamber, makes the wastewater flow from through-flow chamber, to accumulation chamber impossible.

23. The level of opening h_k of the reflux valve is set below the edge of the inter-chamber overfall.

In the *WEGA* simulation programs, the sequence of the stages in the reservoir operation is taken into account. The program performs an analysis of the preset parameters, boundary conditions and calculation parameters during operation. Once the specific boundary conditions preset for individual phases of reservoir operation have been met, its operation stages are sequentially switched. These conditions can be itemized as follows: characteristic wastewater levels in the storage reservoir as well as the times and intensities of the wastewater inflow and outflow.

The characteristic parameters of reservoir operation phases include: *hp*, *ho*, h_k, *hu*, *hup*, *Hpwg*, *Td*, *Tp*, *QA*.

The calculation of reservoir operation parameters is done based on the input data from the calculation-program. They are as follows:

b – inter-chamber overfall edge length, m;
c – frequency of rain occurrence, once per *c* year(s);
fo – cross-sectional area of the outflow channel opening, m²;
f_k – cross-sectional area of the reflux valve opening, m^2;
F_{KAG} – horizontal surface of the gravitational accumulation chamber, m^2;
F_{KAW} – horizontal surface of upper pump accumulation chamber, m^2;
F_{KP} – horizontal surface of through-flow chamber, m^2;
Fz – reduced surface of the drainage area, ha;
H – mean annual rainfall, mm;
h_k – level of reflux valve actuation, m;
ho – level of pumping unit start and operation, m;
hp – height of inter-chamber overfall edge elevation, m;
Hpwg – starting level of gravitational wastewater outflow from upper accumulation chamber, m;
Hu – level of wastewater sink activation, m;
Hup – level of wastewater sink opening, m;
N – number of samples;
$QW_{\max}$ – maximum intensity of wastewater outflow from the sink of the upper accumulation chamber, m^3/s;
Td – rain duration time, min;
Tp – wastewater flow time, min;
μ_k – flow-rate coefficient at reflux valve opening;
μ_u – flow-rate coefficient at wastewater sink opening;
μ – flow-rate coefficient at reservoir outflow opening;
μ_1 – flow-rate coefficient at non-submerged interchamber overfall;

μ_2 – flow-rate coefficient at non-submerged interchamber overfall for a non-submerged layer of overflowing wastewater;

μ_3 – flow rate coefficient at submerged interchamber overfall for a submerged layer of overflowing wastewater.

The *WEGA* software programs calculate the rate of wastewater outflow *QO* from the storage reservoir and the rate of wastewater inflow *QA* to it at variable filling times $t_i = a + il$ in individual chambers of the reservoir.

The calculation results of numerical *WEGA* simulation programs are stored in separate files, i.e.:

- filling of chambers: $h(t)$, $Hp(t)$, $Hpw(t)$;
- time of the accumulation process, t_{pr};
- rates of wastewater outflow from the reservoir $QO(t)$;

as well as in the files of parameter values calculated in individual differential equations and equation systems defining the unitary hydraulic processes, i.e.:

- in the through-flow chamber *KP:* $h_1(t)$, $h_2(t)$,..., $h_n(t)$;
- in gravitational accumulation chamber *KAG:* $Hp_1(t)$, $Hp_2(t)$,..., $Hp_n(t)$;
- in upper pump accumulation chamber *KAW*: $Hpw_1(t)$, $Hpw_2(t)$,..., $Hpw_n(t)$;
- times of hydraulic processes: t_{pr1}, t_{pr2},..., t_{prn};
- intensities of wastewater outflow from the reservoir: $QO_1(t)$, $QO_2(t)$,..., $QO_n(t)$.

Additionally the *WEGA* programs define the time and rate of wastewater inflow to and outflow from the reservoir at the moment of its filling completion and achieving the maximum storage capacity.

The adopted notation of program operation results permits analysis, both in the whole range of wastewater accumulation process and in individual phases of storage reservoir operation. The parameters defined as a result of the program operation allow the selection of the rain time *Tdm* appropriate to reservoir designing as well as the essential reservoir storage capacity $Vzb_{\max}$.

The *WEGA* simulation programs enable a study of the wastewater accumulation in gravitation-pump reservoirs with upper accumulation chamber of the *GPW*, *GPWS* and *GPWP* types in the filling phases of reservoir chamber.

Such a simulation range, common to the reservoirs of this type, provides a potential for calculations of the essential operation parameters universal for all solutions such as:

- filling the reservoir chambers with wastewater within the range of reservoir filling processes: *h*, *Hp*, *Hpw*;
- maximum filling in chambers: $h_{\max}$, $Hp_{\max}$, $Hpw_{\max}$;
- rate of wastewater outflow from reservoir within the range of reservoir filling *QO*;
- duration times of storage reservoir filling t_{pr};
- times and rates of wastewater inflow and outflow at the moment of reservoir filling completion (full accumulation).

3. CONCLUSIONS

Making use of modern research methods based on computer simulation of real physical and chemical processes enables a dynamic development of many branches of science, including environmental engineering. This article presents the assumptions for the simulation model of a gravitation-pump reservoir designed in order to relieve hydraulically the sewage networks and wastewater treatment stations. Computational parameters of simulation programs are characterized and the method of their calculation as well as the obtained results are presented.

The objective of the simulation studies was to show the effect of the factors tested during induced variations on the behaviour of the resulting parameters of the hydraulic processes and design parameters of the reservoirs of this type. The computation procedure developed enables studying hydraulic processes on firm basis in the successive phases of the reservoir operation while taking into account the curvilinear character of the functions describing the filling variations in all chambers of the reservoir at the same time.

The results of the simulation study, to be presented in further publications, confirmed a significant contribution of the programs to the development of the design and the methods of dimensioning the storage reservoirs operated in gravitation-pump systems.

ACKNOWLEDGEMENT

This publication has been realized within the framework of the research project of the State Committee for Scientific Research No. 4T07E 083 26.

REFERENCES

[1] DZIOPAK J., *Analiza teoretyczna i modelowanie wielokomorowych zbiorników kanalizacyjnych*, Monografia 125, Politechnika Krakowska, Kraków, 1992.
[2] DZIOPAK J., KISIEL A., *Badanie wpływu sposobu retencjonowania ścieków w wielokomorowych zbiornikach grawitacyjno-podciśnieniowych na efektywność działania systemów kanalizacyjnych*, Projekt badawczy KBN nr 7 TO7G 003.09, Politechnika Częstochowska, Częstochowa 1998, Sprawozdanie z realizacji badań.
[3] DZIOPAK J., NEVEROVA-DZIOPAK E., SŁYŚ D., *Analiza wpływu grawitacyjno-pompowych zbiorników wielokomorowych na efektywność działania systemów kanalizacyjnych i ochronę wód powierzchniowych*, Politechnika Rzeszowska, Rzeszów, 2004, wniosek o finansowanie projektu badawczego.
[4] SŁYŚ D., *Model wielokomorowego zbiornika grawitacyjno-pompowego z górną komorą akumulacyjną*, Zeszyty Naukowe Politechniki Rzeszowskiej Nr 204, Rzeszów, 2003.
[5] SŁYŚ D., *Równania modelowe bilansu ścieków w zbiorniku grawitacyjno-pompowym z górną komorą akumulacyjną w fazach jego napełniania*, III konferencja naukowo-techniczna *Nowe materiały i urządzenia w wodociągach i kanalizacji*, Politechnika Świętokrzyska, Kielce, 2003.
[6] SŁYŚ D., *Modelowanie zbiorników grawitacyjno-pompowych*, rozprawa doktorska, Akademia Górniczo-Hutnicza, Kraków, 2004.

[7] PROSNAK W., *Wprowadzenie do numerycznej mechaniki płynów*, Polska Akademia Nauk, Wrocław, 1993.

MODEL SYMULACYJNY RETENCYJNEGO ZBIORNIKA GRAWITACYJNO-POMPOWEGO

W wyniku prac badawczych, których celem było opracowanie podstaw naukowych nowej grupy rozwiązań funkcjonujących w grawitacyjno-pompowych układach komór akumulacyjnych, otrzymano model hydrauliczny oraz model matematyczny działania zbiornika grawitacyjno-pompowego typu *GPW.* Na podstawie tych dokonań opracowano model w postaci programów komputerowych *WEGA* służący do symulacji numerycznych funkcjonowania zbiornika na sieci kanalizacji deszczowej i ogólnospławnej. W artykule przedstawiono założenia, parametry i sposób działania modelu symulacyjnego oraz uzyskane wyniki.