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TOMASZ CICHOŃ*, JADWIGA KRÓLIKOWSKA**

THE IMPACT OF SOME EXTERNAL FACTORS ON THE METROLOGICAL PROPERTIES OF A WATER METER

WPŁYW WYBRANYCH CZYNNIKÓW ZEWNĘTRZNYCH NA WŁAŚCIWOŚCI METROLOGICZNE WODOMIERZA

A b s t r a c t

The paper refers to the study of water meters and the impact of some external factors on the variability of water meters metrological parameters during their operation period. The study was conducted in three groups, depending on cause and the moment of dismounting – before expiry of operation period, at the end of operation period and to metrological expertise. In this paper, are presented results of measuring errors investigations, which show variability of errors during operation time. In the group of water meters with exceeded errors, analyses were conducted on the damage types and the factors affecting the deterioration of metrological accuracy. Research is aimed to define the conditions required in order to maintain the metrological accuracy during operation period.

Keywords: water meter, measuring error, water meter damages

S t r e s z c z e n i e

W artykule opisano badania wodomierzy oraz wpływ niektórych czynników zewnętrznych na zmienność parametrów metrologicznych wodomierzy w czasie ich eksploatacji. Badania były prowadzone w trzech grupach w zależności od czasu i powodu demontażu – przed upływem okresu eksploatacji, na koniec okresu eksploatacji oraz w ramach ekspertyz metrologicznych. W artykule przedstawiono wyniki badań błędów metrologicznych, które wykazują zmienność błędów wskazań wodomierzy w czasie ich eksploatacji. Wśród wodomierzy z przekroczonymi błędami pomiarowymi przeprowadzono analizę typów występujących usterek oraz czynników mających wpływ na pogorszenie własności metrologicznych. Badania zmierzają do określenia warunków pozwalających utrzymać poprawność metrologiczną przez cały okres eksploatacji.

Słowa kluczowe: wodomierz, błędy pomiarowe, uszkodzenia wodomierzy

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1. Introduction

Water meter tasks include: measurement of a physical value, processing the obtained information and making it available to the observer at certain working conditions and according to the preset requirements. The basic future of a water meter is its usable quality, i.e. metrological characteristics, which can be determined both during its selection and then throughout the life cycle. Optimizing a water metering and selling system, which comprises water meters placed in series, the operator tries to minimize the number of damaged water meters (k) within the system ($k \to 0$).

Indeed, the selection of water meters proceeds along the rules, which are specified in the regulations, but they are not precisely defined with explicit mathematical methods; this issue has been the subject of many studies and publications [1–7].

The meter, as a measuring instrument, is subjected to legal metrological control procedures. In order to obtain a correct, and above all, a legal basis for water charges, all water meters installed at the consumers should present valid certificates [8–11].

The main regulations featuring the rules of instrument admission for a commercial use and its inspection are regulated by the Polish Act on Measures Law (i.e. Journal of Laws 2004.243.2441 with later amendments). The Act tries to impose uniform measurement units and measurement accuracy for the physical values. It establishes measurement administration bodies as competent bodies to rule on matters regarding measurements within the Polish Republic. The Act comprises delegations to the implementing regulations defining the detailed requirements. The Regulation of the Minister of the Economy describes the requirements that have to be met by water meters and a detailed scope of tests performed during legal metrological control of these measuring instruments. During the next certification, a checking procedure determines water meter errors for at least three flow rates, specific to each meter. Each time, at the certification stand, the amount of water that actually flowed through the meter is compared with the amount indicated by the counter [12–15].

2. Characteristics of the Krakow's water supply metering system

The Krakow water supply system has been selected as a pilot system for the monitoring of metering instruments and their performance. The system consists of more than 54,000 water meters installed at connections to water consumers. Water meters with a diameter of 20 mm constitute by far the largest number (over 75%) of all water meters in use. They are installed mainly in single family houses and small apartment buildings. Other dimensions are used for measurements in multi-family buildings, industrial facilities and for water wholesale services to neighbouring municipalities [16].

Currently, single-jet meters, next to industrial screw water meters, are the most popular types of used water meters. The Krakow waterworks (MPWiK) also use a new kind of a water meter – a displacement water meter. This type of meter is used mostly for diameters ranging from 20 mm to 40 mm, and currently, only this type water meters are purchased because of its high metrological class. Also, water meters with an ultrasonic measuring system and an electromagnetic transducer have been tested in Krakow.

Collection and transmission of data on the water meter conditions is an integral part of a water supply metering system. The readings from water meters registers, that are managed by the Krakow MPWiK, are done either in a traditional way (by a collector), or by using remote reading of registers. Traditional data collection involves a visual inspection of a water meter by a collector; the reading is then registered in a log book. In case of water companies/suppliers, it means that each register has to be made available for a service person to see and read the value indicated on the odometer. On the other hand, for each recipient, it usually means that a controller of each medium needs access to each meter installed at the property, or has the readings provided by the owner.

The basic system of water meters readings have been carried out in 90-day cycles. This way, nearly 50,000 of water consumers were held accountable. A remote reading system is based on water meters with radio pads which are read by collectors. They are equipped with portable computers and periodically visit the area around the city collecting data readouts. The Krakow MPWiK has also begun tests of automatic (unattended) reading systems. A pilot system of fixed readings was implemented in the area, where radio communicates are read from pads by a stationary set. Such a kit equipped with a passive radio antenna was installed on the roof of a tall building. Another option is a system in which each water meter is equipped with a unit for data transmission via the GSM network using a GPRS data packet.

3. Water maters failures

From a reliability point of view, water meters were divided into two categories: damaged (meter does not work) and meters which lost metering accuracy (meter works with errors that exceed acceptable values). Thus, the study of water meters was carried out for three data groups:

a) meters dismantled before its certification has expired,
b) meters dismantled just before its certification expires,
c) meters dismantled for inspection (the readings questioned by recipients).

The water meters came from the Krakow water supply metering system as well as from other metering systems, mainly from Southern Poland. The reasons for removing the water meter before its certification has expired included:

- damages and failures reported by the collectors or water recipients,
- metering accuracy questioned (based on the consecutive readings),
- others e.g. closure of the intake point.

It was found that most of 976 water meters tested, after their dismantling before the expiration day, had their mechanism locked; such cases constituted for 54.3% of the collected data. Another cases included counter breakdowns or a water meter burn out. Figure 1 presents the percentage of remaining water meters for which it was impossible to measure the errors of indications, broken down by cause. The data set is dominated by water meters with a flooded counter. This is a common problem for meters mounted in a men hole, when a counter is not hermetically sealed. If there is water in the men hole, a counter gets flooded, and consequently, corrosion of a steel counter axle blocks a drive. Failure of a counter results in lack of digit movements due to bearings wear off, or gears release (wear of gear teeth).

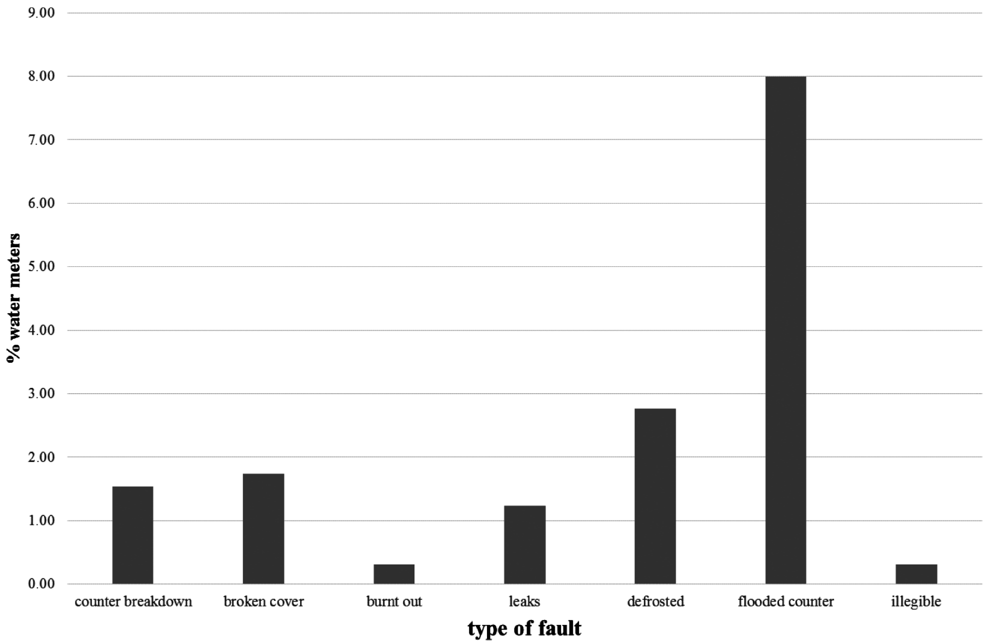

Fig. 1. Classification of water meters for which readings errors cannot be measured (broken down by a cause) [16]

A water leakage from a water meter may result from an excessive water pressure in the network or defective seal materials. The phrase "a defrosted water meter" means that damages

occurred as a result of water freezing inside the water meter. They include a water leakage from the water meter as well as other damages typical to disruption of housing or other components while ice melting. A partial deformation of a counter, or even a unit burn out, was observed as a result of an intense heating of a water meter in winter. Another reason for melting of a measuring chamber was a failure on the mains, after which the hot water from the tank "backed up" to the meter.

A percentage distribution of damaged water meters, grouped according to their service life, is shown in the Fig. 2. Analysis of all damages observed at water meters dismantled during the operation brings up the question whether the units, dismantled before their expiration day, were running. Therefore, over a thousand of such water meters were additionally studied. The study proceeded in two directions, at first, the measuring errors were determined and then analysis of causes of failures was carried out.

The survey of measurement errors of water meters after their service life and before the expiration day was carried out for almost all units (1,138 from 1,150 dismantled). The remaining 12 units were damaged in such a way that measurements of reading errors were not possible; they were simply broken. A range of measurement errors found in the examined water meters at nominal or continuous and intermediate flows were plotted in Fig. 3.

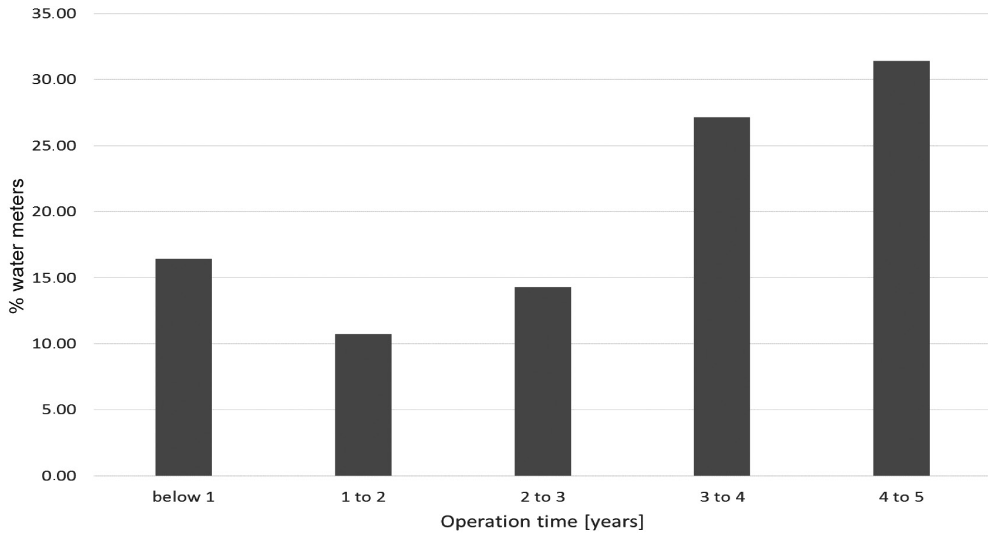

Fig. 2. Operation time of the damaged water meters [16]

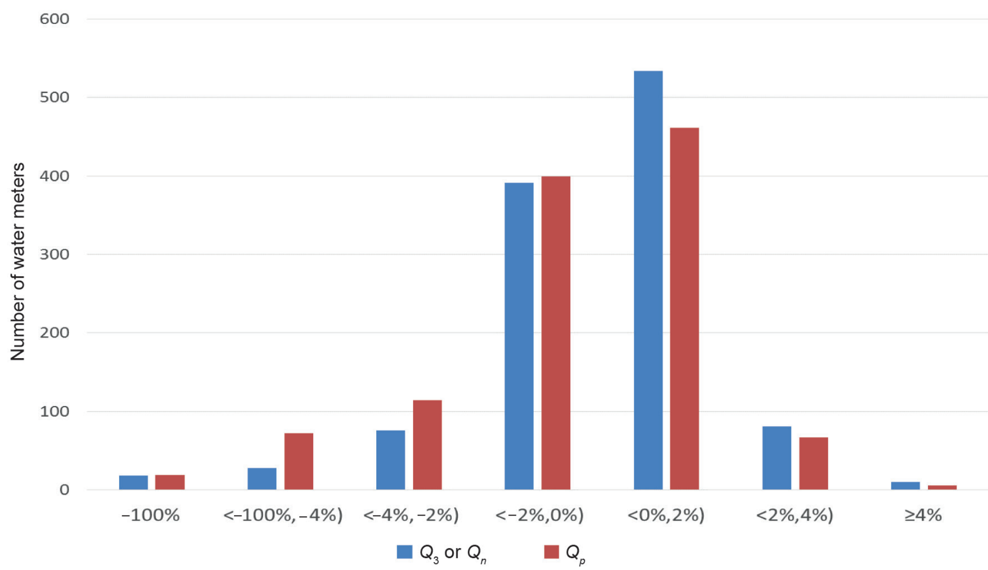

Fig. 3. Water meters and their measuring errors at nominal (Q_n) or continuous ($Q3$) and intermediate flows (Q_p) [16]

It can be noted that there is a group of water meters, which shows significant negative absolute errors or does not measure flow at all (errors greater than –4% and –100%). The maximum permissible positive errors (4%) were not exceeded in any water meter owned by the Krakow MPWiK. All units tested during metrological examinations had been certified, which proves that, during legalization, measurement errors of all water meters stayed close to 0%. Thus, analysing the changes of measurement errors it should be noted that if there is a change of metrology it is usually a shift toward negative values, which means that the measured flow is lower than the actual flow. In such situations, there is a considerable risk of generation of apparent water losses.

The cause/effect analysis of deviations associated with the operation of the water meters was combined with analysis of such features as: water quality, working pressure in the system and a previous history of water meter operation.

The largest number of cases, when measurement errors were exceeded, was found in the area supplied with water from Dobczyce Lake, as well as in areas where this water is mixed with water from other sources; the size of the zone is partially responsible for such situation. Analysing a content of sediment found inside the water meters, it may be concluded that corrosive water is also responsible for a higher number of damaged water meters; water from the Raba river up to year 2004 had elevated corrosive properties (the Langelier index <–0.4, as calculated according to the Polish standards PN-72/C-IL 04609). The situation improved after 2004 once water had been stabilized using milk of lime, and then in 2006, when the coagulant was changed from a low-alkaline PAX-16 to a high-alkaline coagulant, which resulted in elimination of a corrosion problem in water from the Raba Water Treatment Plant (WTP); since that time water has been much less corrosive.

The water meters analysed in this study have been in operation since 2008, i.e. shortly after the change of coagulants. Despite the improvement, water pipe corrosion initiated in the water system supplied by the Raba WTP before 2004, resulted in later problems associated with an increased number of corrosion products (such as iron oxides and hydroxides). Due to their ferromagnetic properties, they may adhere to inner surfaces of the water meter increasing the failure rate. In other areas, (the water systems supplied by the Rudawa, Dłubnia and Bielany WTP) water throughout the operation time was not corrosive, and therefore, adhesion of corrosion products was much lower in water meters. Also, other factors, such as the network age, pipe material, actual investments as well as current failures may have had impact on this situation. They were not analysed in detail, but you cannot rule out their influence on the measuring properties of the units.

Figure 4 shows the number of damaged water meters divided according to operating water pressure categories. The analysis shows that most water meters, which lost metrological properties during operation, worked within the pressure range of 4 to 5 bar. This is the most common pressure in the Krakow water mains. The damaged water meters were also observed in other categories with both lower and higher pressures.

Therefore, it may be concluded that water pressure has no direct impact on a failure rate of water meters in the Krakow's water supply metering system. However, it cannot be definitely excluded that such effect would be observed in other metering systems.

Some failures can be caused by an excessive wear out of water meters. For a long time of centrally controlled economy, the water works had great difficulties with a purchase of new water meters. A number of waterworks specialises in the regeneration and repair of water meters. Sometimes, even today, one can come across the notion that that every meter can be regenerated and certified again. Among the dismantled water meters they were also units produced in the eighties of the last century, which have worked through four or more certification periods. To investigate the relation between an operation time and a loss of metrological functions all damaged water meters with a diameter of 20 mm were selected, since these units made the largest group of 252 water meters. The study was confined only to one diameter to get a meaningful comparison for water meters of similar design and capacity. The results of the analysis are shown in Fig. 5.

The analysis showed that 32% of water meters had finals readings up to 500 m^3, while for more than 68% the readings were 500 m^3. The calculated median of readings for the meters with a diameter of 20 mm after the certification is 740 m^3. It leads to the conclusion that

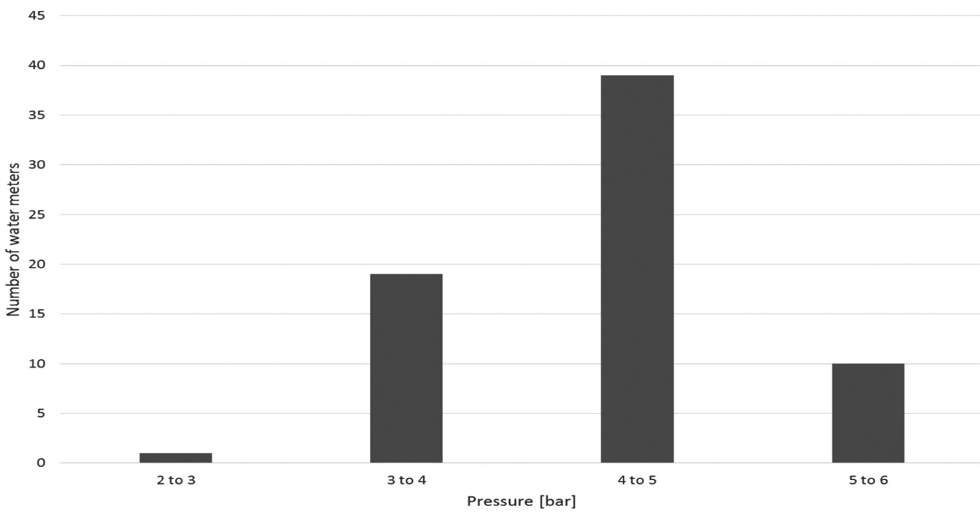

Fig. 4. Number of damaged water meters according to operating water pressures [16]

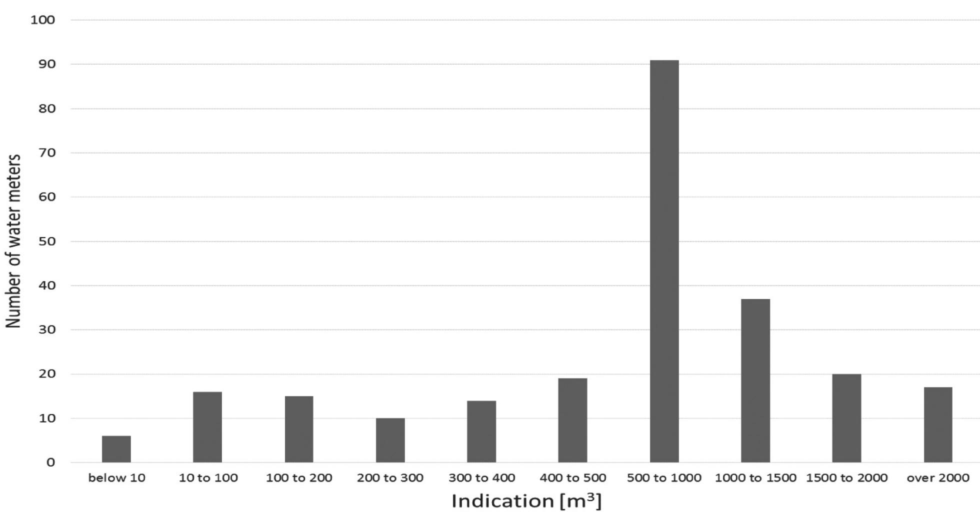

Fig. 5. Distribution of damaged water meters according to the final readings [16]

“mileage” of a water meter has an impact on the loss of metrological properties; the higher the readings, the higher the likelihood that the metrological properties get worse.

Since a number of water meters have been blocked by sediment pieces, torn off pipes, or other solids, the authors analysed whether there is a relationship between such accidents and failures that occurred on pipelines next to these units. In order to verify this fact, the group of blocked water meters was selected that were spotted in the last quarter of 2013; the group comprised 199 water meters. Taking into account the quarterly system for meter readings collection, this group of water meters was compared with the water supply network failures that had occurred in the third quarter of 2013. The detailed analysis revealed that water supply system failures were previously observed in the immediate vicinity of the 28 water meters. Other cases may have been caused by various dynamic conditions within the system such as e.g. switching changes or pressure changes. An increased number of failures are found also in old pipes in the city centre.

4. Summary

The basic principle of water meter management is to comply with the validity of the certification mark for all operating units. Therefore, they have to be gradually replaced before the expiration date. The studies confirmed that it has been a right approach, which has to be followed not only due to formal requirements, but also due to considerable risks of apparent water losses.

It is necessary to gradually accumulate the data base on failures of the water meters “in service”, as they age. The optimum situation would be if the company had its own certification stand, which runs regular tests for different types of water meters.

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JERZY CIEPLIŃSKI*

SINGLE SBR REACTOR'S ENERGY USAGE IN COMPARISON WITH TOTAL ENERGY CONSUMPTION OF MEDIUM WASTEWATER TREATMENT PLANT

PORÓWNANIE ZUŻYCIA ENERGII PRZEZ POJEDYNCZY REAKTOR TYPU SBR W ODNIESIENIU DO CAŁKOWITEGO ZUŻYCIA ENERGII PRZEZ OCZYSZCZALNIE ŚCIEKÓW ŚREDNIEJ WIELKOŚCI

A b s t r a c t

The paper analyses the share of single SBR in total energy consumption of studied wastewater treatment plant. The analysis is based on a two sets of data: measurements, gathered by automated measuring installation and data archived manually by plant's operator. Energy consumption was also analysed with reference to archive data of daily flows.

Keywords: energy consumption, wastewater treatment plant, SBR

S t r e s z c z e n i e

W artykule zestawiono zużycie energii elektrycznej pojedyńczego reaktora typu SBR w odniesieniu do całkowitego zużycia energii przez badaną oczyszczalnię ścieków. Porównania dokonano w oparciu o dwa zestawy danych: pomiary, zgromadzone przez automatyczną instalacje pomiarową oraz dane eksploatacyjne archiwizowane przez operatora oczyszczalni. Analizę zużycia energii odniesiono również do zarejestrowanych przepływów dobowych przez oczyszczalnię.

Słowa kluczowe: zużycie energii, oczyszczalnia ścieków, SBR

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1. Introduction

In recent decades, more and more efforts are undertaken in order to increase energy efficiency in industry and everyday life. This trend will continue despite potential changes in political, ideological, economical and cultural trends. The reason is simple – higher efficiency is profitable. Part of the human nature is minimizing costs and maximizing profits, therefore, searches for improvements will continue. However, not all branches of industry are equally improving their efficiency. In Poland, the problem of energy efficiency, in small and medium wastewater treatment plants, is still not well examined in comparison to bigger facilities, or other countries [1]. Overall the situation is improving due to newer and more efficient equipment, but there is little coordinated effort in that area. Intentional optimization cannot be performed without solid data on current situation. Such data can be obtained by creating measuring grid similar to installation installed in the studied treatment plant. Built measuring grid is fully operational, although it is a pilot installation. Gathered data supplemented with plant`s archive were used to investigate the amount of energy used by single SBR in comparison to plant's total energy consumption and daily flow.

2. Basic information

2.1. Plant's description

The studied plant is located near Kraków. The plant consists of two independent technological lines, 2 SBRs and 1 sludge stabilization chamber each. The plant's capacity is 1250 m^3/d and PE 14 950. However, due to incomplete municipal sewerage, real daily flows usually are below 700 m^3/d. That is why usually only 2 reactors are operational, and if there is need to treat higher amount of sewage, one of the two remaining reactors is actuated. Sometimes the 3rd reactor is activated intentionally by the operator to avoid period of inactivity that is too long. With only two reactors operational, the plant's capacity is: 720 m^3/d and 7300 PE. Plant's main devices list (1.5 kW of power and above) [2]:

- sludge truck's discharge station 3.5 kW,
- vertical sieve 1.5 kW,
- stage 1 pumping station 4.7 kW (1+1 in reserve, working interchangeably),
- grit & grease removal 4.0 kW,
- retention tanks' blowers 5.5 kW (1+1 in reserve, working interchangeably),
- stage 2 pumping station 7.5 kW (1+1 in reserve, working interchangeably),
- 2 x 2 SBRs (no 1.2 – older tech-line, no 3.4 – newer tech-line):
  - 2 x 3 blowers 30.0 kW each (2x 2+1 in reserve, working interchangeably),
  - 2 x 2 excess sludge pumps 5.5 kW each (1 pump per reactor),
  - 2 x 2 internal turbines 11.0/7.5 kW (2 gears) (1 turbine per reactor),
- 2 x 1 sludge stabilization chamber (1 chamber per 2 reactors):
  - 2 x 1 blower 11.0 kW each (1 blower per chamber),
  - 2 x 1 internal turbines 5.5 kW (1 turbine per chamber),
- stabilized sludge pump 2.2 kW,

– centrifuge (sludge dewatering) 17.2 kW,
– dewatered sludge auger 1.5 kW.

During the studied period, WWTP operated flawlessly and easily met the administrative requirements [3, 4].

2.2. Measuring grid's description

Measuring grid consists of (main elements only):
- 1 central unit (notebook) with specialized software,
- 1 signal converter,
- 5 automated energy counters.

The software installed on the central unit controls work of the installation. Notebook functions also as data archive. Signal converter translates data from meters to a form that is acceptable by the computer. Automated counters measure the total energy used by selected devices in 5 minutes intervals (current settings). Counters are installed on the following devices:
- Blowers (D4, D5, D6),
- SBR internal mixing-aerating turbine (Tr4),
- Excess sludge pump (P11).

To measure energy usage of one reactor, an installation of meters on all devices directly connected with this reactor is needed. This means SBR internal turbine, excess sludge pump, and oxygen source. Because of reliability reasons, all three blowers are connected into one oxygen supply system for both reactors [5]. All other devices are not directly connected with reactor's work. For example, stage 2 pumping station supplies all 4 reactors, and without very specific data, unfortunately not recorded by WWTP's systems, it is impossible to define how much energy was used to supply reactor no 4 with sewage. During the measuring period, SBR4 worked only with blower no 5, however, due to long-term character of measurements, the change of blower is highly probable. Secondly, the installation is scheduled to be expanded at least on the SBR3, also supplied by blowers no 4, 5 and 6, therefore all 3 blowers must had been equipped with meters.

Installation was launched and calibrated in April 2015. Since then, it worked stable with one exception, there are no records from 26 May 6:40 to 1 June 00:00. After launch, even before identifying the problem of missing data, the installation was scheduled for potential recalibration after two-three months of measurements. It was accepted that, after 60–90 days period, it will become clear if current measurement settings are sufficient. Observed lack of records added one more variable that needs to be assessed before scheduled recalibration. Several reasons probably responsible for this data gap are being investigated, however, for the time being, nothing has been confirmed yet. Fortunately rest of the data is valid and can be analysed.

3. Data

Data analysed in this paper came from two sources: automated measurements provided by measuring grid and plant's journal of the exploitation provided by WWTP's operator. Data recorded by installation had been registered with 5 minutes intervals. Data archived by plant's operator have daily intervals, except Saturdays, Sundays and statutory holidays. After consultation with the WWTP operator, in regard to average daily flows and total energy consumption, it became clear that extrapolation of missing data with simple arithmetic average will be sufficient. Extrapolated flows and energy consumption are bit lower than recorded ones; however, during weekends, no additional wastewater is delivered by sludge trucks, hence smaller results are plausible. Please note that these averages were based on data received from an effluent meter, therefore, the total flow within studied period wasn`t extrapolated. Only missing daily flows are a result of extrapolation. The exact same situation was with WWTPs total energy consumption. All vital data used for analyses are presented in Table 1.

Table 1

SBR4 energy consumption compared to WWTP's total energy usage

Date/Active SBRs	SBR4 total energy consumption [kW]	WWTP total energy consumption [kW]	SBR4 % of WWTP's total energy consumption	Daily flow [m^3/d]
30–04/2	430	*1185*	36.26%	268
01–05/2	430	*1185*	36.26%	268
02–05/2	383	*1185*	32.31%	268
03–05/2	355	*1185*	29.98%	268
04–05/2	368	1380	26.65%	405
05–05/2	405	1200	33.72%	406
06–05/2	389	1440	27.00%	624
07–05/2	390	1320	29.52%	470
08–05/2	441	*1240*	35.59%	358
09–05/2	454	*1240*	36.62%	358
10–05/2	427	*1240*	34.46%	358
11–05/3	424	1620	26.18%	467
12–05/3	425	1020	41.67%	504
13–05/3	441	1380	31.94%	409
14–05/3	432	1380	31.29%	405
15–05/3	444	*1280*	34.68%	272
16–05/3	464	*1280*	36.22%	272
17–05/3	414	*1280*	32.37%	272
18–05/3	427	1140	37.45%	405

tab. 1

19–05/3	432	1200	36.00%	406
20–05/3	439	1260	34.86%	572
21–05/3	416	1260	33.00%	576
22–05/3	410	*1220*	33.57%	328
23–05/3	370	*1220*	30.36%	328
24–05/3	380	*1220*	31.18%	328
25–05/3	344	1200	28.64%	489
Sum:	10 733	32 760	–	10 080
Average:	413	1260	32.76%	388

Presented data are part of long-term experiment. These data covers the first 26 days of operation of fully calibrated measuring grid. Therefore, all conclusions are true only to these 26 days. All other observed regularities, or anomalies will have to be confirmed by next sets of data. However, almost a month of observations reveals potential directions on which further researches should focus.

For the first 10 days of studied period, only two SBRs were active (whole newer tech-line). On the eleventh day of May, reactor no 1 was reactivated, after 8 days, SBR1 was turned off again, but SBR2 was reactivated instead. Dates of switching on or off the reactors are marked in Table 1 by bolding. Data extrapolated is in *italics*.

4. Analysis

4.1. Dependence between total energy consumption and daily flow

According to previous researches [6], there is a direct connection between average daily flow and total energy consumption. Creating a chart identifying a nature of relation between daily flows and energy usage helps in verification of data correctness. As can be seen in the Fig. 1, such dependency exists and is consistent with the assumptions.

However, few inconsistencies may be observed. Given the cyclical nature of the work of SBRs, some drops in the energy consumption, similar to one observed at 4–5th May, are acceptable. On the other hand, sudden spike and drop, observed on 11–12th May, is unusual. One of the possible explanations for this spike is reactivation of SBR1, therefore, reactivation of whole 2nd technological-line. If this was the case similar spike should be observed on 18–19th May when SBR1 was turned off, and SBR2 was turned on. There was an increase in energy consumption during switching SBR 1 and 2 as well, however, not as drastic as during reactivation of the SBR1 (only 60 kW increase in comparison to 380 kW). It may be also only a simple human error, made during writing down value from meter. For now, there is not enough data to decide if this spike was a one-time anomaly, and what caused it.

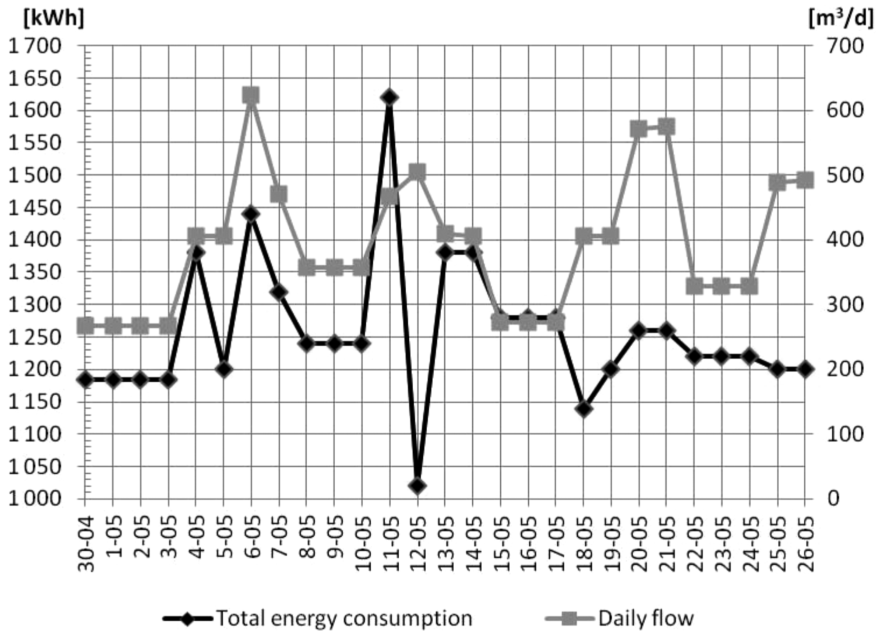

Fig. 1. Comparison of daily flow and plant's total daily energy consumption

This case will be re-investigated after gathering more data in the following months. During the studied period, average daily flow was 388 m^3/d, and excluding data from 11 and 12th May, the average total energy consumption was 1255 kWh. Max flow was recorded on 6.05 (624 m^3/d) followed by highest total energy consumption (1440 kWh). Recorded minimal flow was on the 4, 14, 18th May (405 m^3/d) however, smallest total energy consumption was recorded 12.05 (1020 kWh).

Despite minor inconsistencies, similarity of the chart in the Fig 1 to other examples confirms correctness of WWTP data archive. This allowed further analyses.

4.2. Relation between total energy consumption and daily flow

Despite visible dependency between total daily energy usage and daily flow, the relation itself is not as strong as was expected. Correlation coefficient was calculated in order to determine the degree of dependency between energy consumption and daily flow. As expected, there was a weak positive correlation between daily total energy consumption and daily flow ($R = 0.2775$). Distribution of points on the Fig. 2 is consistent with R value. The relation hardly can be called linear. However, at the time being, there is not enough data to make final statement about exact nature of this dependency, also due to a small amount of data, the calculated correlation coefficient should be treated only as a guide value for the further researches.

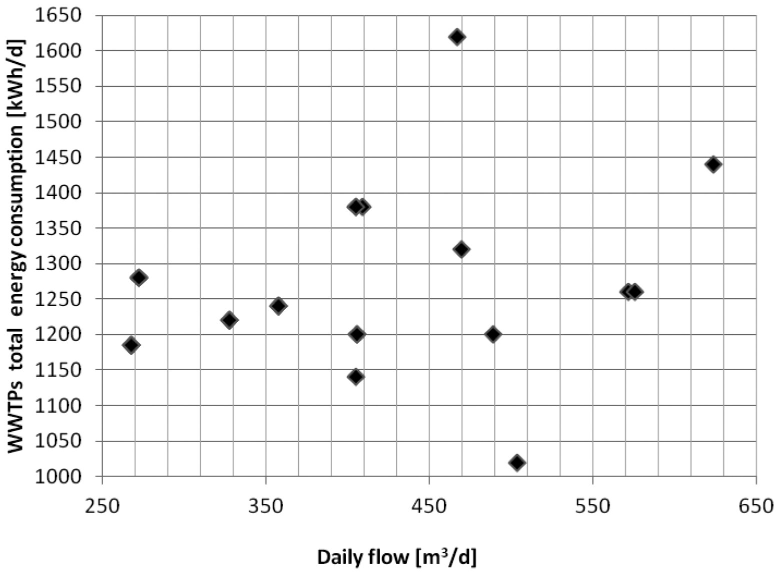

Fig. 2. Correlation of daily flow and plant's total daily energy consumption

4.3. Dependence between SBR4 energy consumption and daily flow

Second analysis made was similar to the first, but only energy consumption of SBR4 was taken into account. Results of comparison of SBR4 energy usage and daily flows are shown in the Fig. 3.

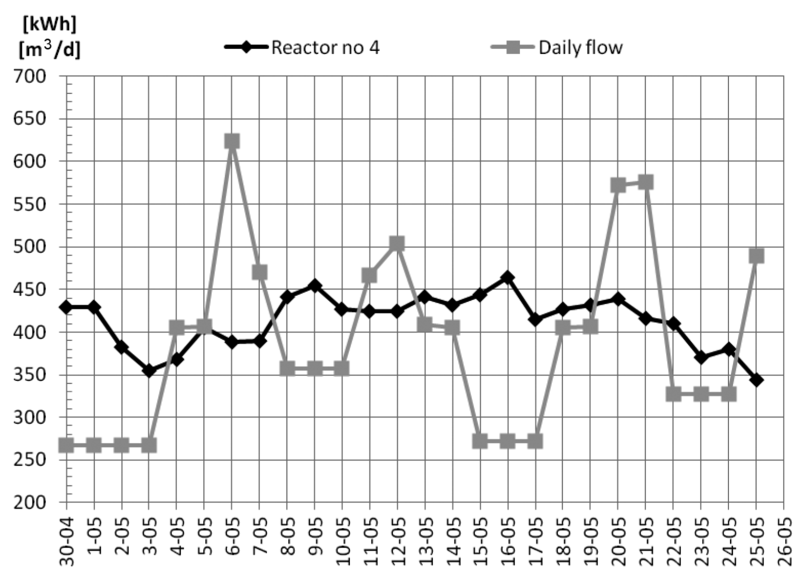

Fig. 3. Comparison of daily flow and reactor no 4 daily energy consumption

On the first look, the chart of the SBR4 changes less dynamically than of the total energy consumption (TEC) and looks also less correlated with daily flows. Nevertheless, changes in reactor no 4 energy usage are also connected with changes of the daily flows. Delay visible in the graph comes from the small inertia of treatment processes in WWTP with SBRs. Increases and decreases are of course smaller than for whole WWTP, but follow the same pattern. There is a second factor influencing energy consumption of single reactor – sewage distribution between SBRs. Reactors are rarely evenly loaded, hence energy consumption's dependence on daily flow may not be as obvious for single reactor as for the whole facility. Average daily energy consumption for SBR4 during studied period was 413 kWh. Maximum 464 kWh, recorded on 16.05 – day with the smallest daily flow. Lowest energy consumption (EC) was recorded on 25.05 with flow 101 m^3/d higher than the average, but not the highest. As mentioned before, inertia of the treatment processes and unequal load of the reactors reflects in SBR4 min-max energy consumption occurrence.

4.4. Relation between SBR4 energy consumption and daily flow

Unfortunately, there are no records on daily flow distribution between active SBRs, therefore, proper correlation coefficient cannot be calculated. It is only possible to check the relation between energy consumption of SBR no4 and total daily flow. Taking into account distribution of points on the Fig. 4 and very small dependency observed in the Fig. 3 it becomes quite obvious that, in May, there were no relation between the amount of energy

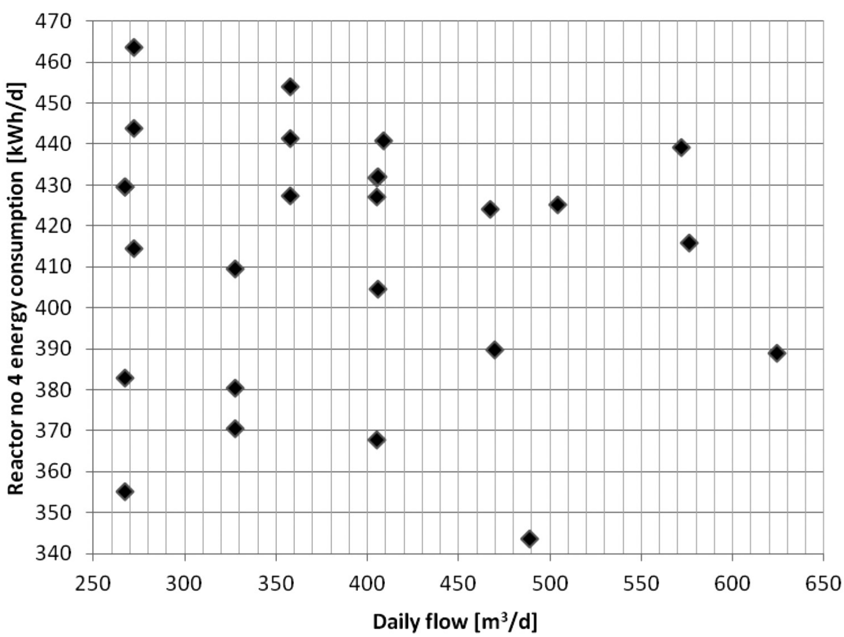

Fig. 4. Correlation of daily flow and reactor no 4 daily energy consumption

used by reactor no4 and daily flow. It is an indication that sewage distribution between active reactors is more important than total daily flow in case of WWTPs subsystems energy consumption. It is quite reasonable to assume that, if 2 or 3 SBRs are active, sewage will not be distributed equally between them, therefore, the amount of energy used should be distributed unequally between reactors. However, these are just preliminary reports and all noticed tendencies will be investigated further.

4.5. SBR4 share in total energy consumption

The final analysis – comparison of SBR4 EC with TEC is presented in the Fig. 3. Due to wide range of values a bar-diagram was the best option.

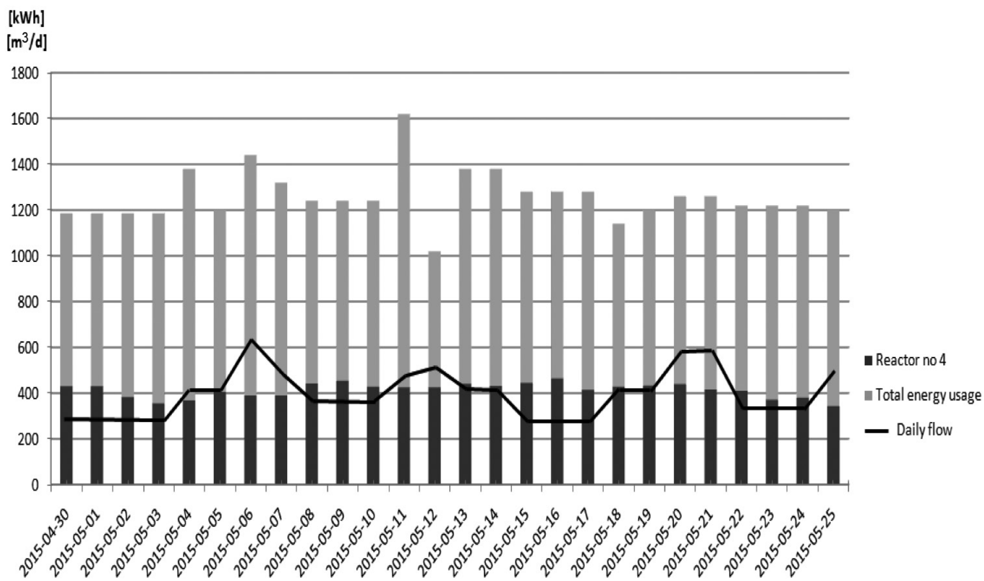

Fig. 5. Reactor no 4 participation in total energy consumption, with outlined daily flows

SBR4 Energy usage was rather stable and close to its average, TEC was more diverse, although SBR4 share in TEC was roughly the same during studied period. It ranged from 26.65% to 37.45% (values from 11 and 12th May were excluded). Average participation of studied SBR in total energy consumption is illustrated in the Fig. 4. During 26 days of measurements SBR4 was using ~ 32.76% of total energy used by WWTP.

This value is not surprising. What is surprising, however, it is that this value is not affected by activation of 3rd SBR. Average participation between 30.04 and 10.05 is 32.40 % (only two reactors were active during that period). Looking only on that short period of time, it could be assumed that twin reactor no 3 should have had similar participation, about 30 %. Using previous assumptions, it could be theorized that bioreactors share in total energy consumption is around 60% and after activation of 3rd reactor each, of them should use ~20%

of plant's TEC. Yet nothing like that has happened. Average SBR4 participation in TEC from 11 to 18th May was ~33.40% and after switching reactors no1 and no2 from 19–25th May it was ~32.53%. All averages were gathered in Table 2 for greater transparency.

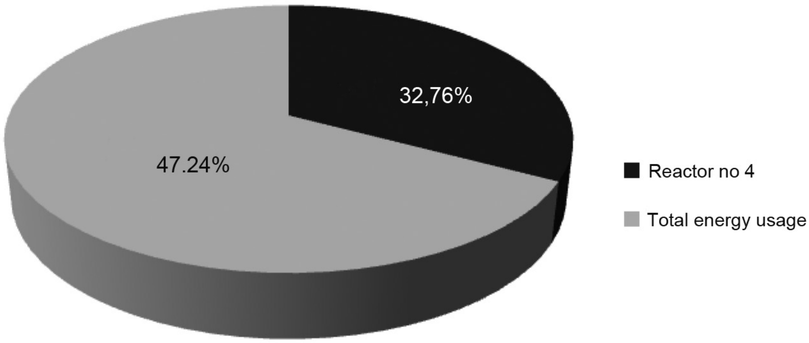

Fig. 6. Reactor no 4 average participation in total energy consumption during the analysed period

Table 2

Average SBR4 share n Total Energy Consumption in different periods of time

Period of time	Active SBRs	Average SBR4 participation in TEC [%]
30.04–10.05	2	32.40
11.05–18.05	3	33.44
19.05–25.05	3	32.53
11.05–25.05	3	33.03
30.04–25.05	2–3	32.76

There was almost no difference between participation of SBR4 in TEC, whether there were two or three reactors active. Such results are unexpected and surprising. It was expected that share of single reactor will go down after activation of 3rd SBR. For the time being, these results are the most intriguing, but more data must be gathered before making any assumptions.

5. Conclusions

Impact of daily flows on WWTP's total energy consumptions had been observed and was consistent with previous researches. This allows to assume that data gathered by plant's operator are correct.

There were no major malfunctions or long-time blackouts during the studied period. However, a data gap occurred between 26.05 and 01.06. Potential reasons for this lack of data are being investigated.

Daily flows had an influence on single reactor's energy consumption, although it is noticeably weaker than the impact on the whole WWTP.

The collected data is of reasonable quality, but there is still room for improvement. It will require bigger involvement of the plant's crew in collecting data, but it is possible.

Contrary to expectation, SBR4 average share in total energy consumption stayed almost the same during whole studied period of time. It was expected that, after activation of 3rd reactor, each individual share should decrease a little bit, but no change was observed. This result is surprising and must be investigated when more data will be available.

All presented results and conclusions are preliminary and will be verified with next sets of data. These are long-term measurements, and some recalibrations of measuring grid may be required.

Despite few unexpected results, it is safe to assume that, after months of construction and initial calibration of the installation, it works as was expected.

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ALGAE BIOMASS AS A CO-SUBSTRATE IN METHANE DIGESTION OF SEWAGE SLUDGE

WYKORZYSTANIE BIOMASY GLONÓW JAKO KOSUBSTRATU W PROCESIE FERMENTACJI METANOWEJ OSADÓW ŚCIEKOWYCH

A b s t r a c t

The article discusses problems related to intensification of anaerobic digestion of sewage sludge. The authors have analysed the principal indicators of a methane digestion process, focusing mainly on biogas production. The most commonly used methods of sludge disintegration were reviewed. Additionally, the methods of algae biomass processing for biofuels and a methanogenic potential of the biomass were presented. The article presents the literature review to identify the possibilities of energy profit caused by using algae in anaerobic digestion of sewage sludge.

Keywords: wastewater treatment plant, anaerobic digestion, sewage sludge, algae, co-fermentation

S t r e s z c z e n i e

W artykule omówiono problemy związane z intensyfikacją procesu fermentacji beztlenowej osadów ściekowych. Autorzy przeanalizowali główne wskaźniki procesu fermentacji metanowej, skupiając się głównie na produkcji biogazu. Zostały zweryfikowane najczęściej stosowane metody dezintegracji. Dodatkowo zaprezentowano metodę przetwarzania biomasy glonów na biopaliwa, w tym potencjał metanogenny biomasy. Niniejszy artykuł stanowi przegląd literatury i na tej podstawie podjęto próbę określenia możliwości zysku energetycznego wynikającego z wykorzystania glonów w procesie fermentacji osadów ściekowych.

Słowa kluczowe: oczyszczalnia ścieków, fermentacja beztlenowa, osady ściekowe, glony, kofermentacja

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1. Introduction

A decrease of energy use and maximisation of its production through utilisation of various types of renewable energy sources has become an important aspect of the global energy management. It is worth noting that the regulations set out by the European Union imply a growing interest in energy gained from the carbon compounds stored in cells of living organisms (i.e. energy generation from biomass). For a long time, various studies on some unconventional physical, chemical and biological methods have been carried out to intensify energy production from biomass [37].

The main goal of wastewater treatment plants is to protect the water environment from excessive pollution loads. During the wastewater treatment process, an organic fraction is separated from wastewater and transferred to the sludge, which is a by-product of mechanical-biological processes. There are three types of sludge produced at a wastewater treatment plant [8]:
- primary sludge – after a mechanical treatment,
- secondary sludge (or excess sludge) – after the biological treatment,
- tertiary sludge – precipitated in chemical processes.

Table 1

Sewage sludge production (tons of dry solids (DS)/year) in different countries of the Baltic Sea region, as submitted to the European commission, and its predicted growth [27]

Country	2005/2006 [tons of DS/year]	2010 [tons of DS/year]	2020 [tons of DS/year]
Belarus	50 000	50 000	70 000
Denmark	140 021	140 000	140 000
Estonia	n/a	33 000	33 000
Finland	147 000	155 000	155 000
Germany	2 059 351	2 000 000	2 000 000
Latvia	23 942	25 000	50 000
Lithuania	71 252	80 000	80 000
Poland	523 674	520 000	950 000
Russia	180 000	180 000	200 000
Sweden	210 000	250 000	250 000
Total	**3 405 240**	**3 433 000**	**3 928 000**

Sludge produced during treatment of municipal wastewater at new wastewater treatment plants amounts to 0.5–2% of the wastewater volume [45]. Table 1 shows the amount of sewage sludge produced by individual countries of the Baltic Sea region. It is estimated that the production of sludge would continue to grow in some countries, which translates into a global increase [27]. Therefore, a special attention should be paid to a sewage sludge digestion as a source of biogas of a high calorific value, which can satisfy the wastewater treatment plant energy needs.

2. Methane digestion of sewage sludge

Methane digestion is the most popular method of sludge stabilisation. It utilises a biochemical decomposition of organic compounds at different oxidation stages to methane and carbon dioxide using microorganisms (bacteria). A proper balance between the substrate and bacteria, mainly methanogenic ones, is the important condition for a good degradation of organic matter in sludge and wastewater. Table 2 shows the key parameters of a mesophilic anaerobic digestion. Decomposition of organic compounds can be divided into four main phases [10]:

- phase I – hydrolysis,
- phase II – acidogenesis,
- phase III – acetogenesis,
- phase IV – methanogenesis.

Table 2

Parameters of mesophilic anaerobic digestion [29]

Parameters	Optimal value	Range
Temperature [°C]	30–35	20–40
pH	6,8–7,4	6,4–7,8
Redox potential [mV]	– 520 do –530	–490 do –550
Volatile organic acids [$mgCH_3COOH/dm^3$]	50–500	>2000
Alkalinity [$mgCaCO_3/dm^3$]	1500–3000	1000–5000

Table 3

Sludge chemical composition (average values) [19]

Compounds	[%]		
	Raw primary sludge	Raw activated sludge	Digested sludge (mixed)
Volatile solids (VS)	60–80	60–75	45–60
Inorganic (fixed) solids	20–40	25–40	40–55
Proteins	20–30	30–40	15–20
Fats	6–35	5–12	3–20
Cellulose	5–15	5–15	5–15

Chemical composition of organic compounds, which are broken down by microorganisms under anaerobic conditions, determines the amount and the type of the end product. A caloric biogas is produced as a result of a methane fermentation of organic compounds. It is a blend of different constituents mixed in different proportions. At the optimum conditions, the biogas contains 60–70% of methane, 29–39% of carbon dioxide and 0.1–0.7% of hydrogen sulphide [22]; its content depends essentially on the nature of the substrate decomposed in the digester, i.e. sludge (Table 3). The best gas quality (the highest methane content) comes from decomposition of proteins, while a highest gas volume is obtained from fat digestion [34]. The gas yield in a digestion process is associated with a treatment process at the wastewater treatment plant [1]; from 0.75 to 1.12 m^3 of biogas can be produced from 1 kg of volatile solids [30].

Disintegration of thickened sludge before its anaerobic digestion is considered to be an interesting option that could improve the efficiency of a methane digestion. Disintegration causes a breakdown of sludge flocs (microbial cells) leading to the release of intracellular fluids to a liquid phase. This way, they become more accessible for further biological wastewater treatment and sludge processing [8]. Implementation of sludge disintegration ahead of anaerobic digesters (WKF) results in a higher biogas yield, and a higher loss of organic matter in the digested sludge are observed, in comparison with conventional systems.

Table 4

Disintegration methods

<table>
<tr><th colspan="2">Mechanical</th><th colspan="3">Others</th></tr>
<tr><td rowspan="3">Mills</td><td>Ball mills</td><td rowspan="4">Physical</td><td rowspan="2">Thermal</td><td>Drying</td></tr>
<tr><td>Pulveriser</td><td>Freezing/defrosting</td></tr>
<tr><td>Vibrating ball mill</td><td>Osmotic</td><td>Decompression</td></tr>
<tr><td rowspan="3">Homogenizer</td><td>High pressure homogenizer</td><td>Electric</td><td>Highly efficient impulse technique</td></tr>
<tr><td>Ultrasound homogenizer</td><td rowspan="3">Chemical</td><td colspan="2">Osmotic shock</td></tr>
<tr><td>Scissor homogenizer</td><td colspan="2">Disintegration with detergents</td></tr>
<tr><td rowspan="3">Press</td><td>Ball press</td><td colspan="2">Disintegration with acids</td></tr>
<tr><td>Stream press</td><td rowspan="3">Biological</td><td colspan="2">Enzymatic decomposition</td></tr>
<tr><td>Vibration press</td><td colspan="2">Hydrolysis</td></tr>
<tr><td>Centrifuge</td><td>Hydrolytic centrifuge</td><td colspan="2">Bacteriophages</td></tr>
</table>

Only excess sludge is subjected to disintegration due to a higher rate of biogas production. Primary sludge, produced during a mechanical wastewater treatment, has a different structure. It comprises mainly of easily settling solids that contain a large amount of pathogenic organisms and quickly decompose. On the other hand, excess sludge subjected to an aerobic biological decomposition with no readily available carbon source, is resistant to any kind of treatment [9, 17].

Disintegration of the sewage sludge can be carried out using different techniques. Depending on the nature of a disintegrating agent, the disintegration methods can be divided into four basic groups (Table 4) [11]:

- mechanical,
- thermal,
- chemical,
- biological.

The most promising sludge disintegration methods include mechanical methods, mostly the ultrasound method, which has recently become available and widely used [8].

Co-fermentation, which combines at least two types of organic matter in anaerobic digestion, is another method used to intensify a biogas production from sewage sludge. As a result, a higher gas yield or a higher efficiency of a digestion process is observed [5]. Recently, a wide range of plant biomass has been used as a popular co-substrate in order to intensify a fermentation process.

3. Co-digestion of sewage sludge and algae biomass

Algae are simple, autotrophic (microalgae) or multicellular (macroalgae) organisms. They are found in fresh and brackish water, both cold and warm [15]. In order to grow, they need mostly light, carbon dioxide, water and mineral salts [44]. Each species has a different morphology and properties. The size of the organisms depends on the species and ranges from microscopic microalgae to macroalgae that can have several tens of meters [20]. Algae absorb CO_2 (2 kg CO_2/kg of DS) [23] and this way reduce its emission to the atmosphere [2]. Their cells are rich in such elements as carbon nitrogen, phosphorus, iron, cobalt and tin, which have a stimulating effect on anaerobic digestion. Water, as the main component of the algal biomass, amounts to approx. 75–90% of their wet weight. Algae contain also a significant amount of mineral salts and carbohydrates (30–50%), which make up the bulk of their dry matter (approx. 60%); proteins represent approx. 7–15% of algae dry matter [18].

Table 5

Methane volumes produced during anaerobic digestion of different substrates (30 days of mesophilic digestion) [21, 25]

Substrate	Methane volume [m^3/kg DS]
Municipal waste	0,20–0,53
Sewage sludge	**0,25–0,75**
Fruits and vegetables	0,42
Jatropha oil	0,42
Pig manure	0,34
Corn and straw silage	0,31
Microalgae	**0,26**
Organic waste reach in lignin	0,20

Another important feature of these organisms is their ability to acquire nutrients. Therefore, algae can be grown on wastewater, and this way, two beneficial effects are combined: treatment of wastewater and production of biomass for energy purposes [38]. Various types of biofuels can be produced from algae (Fig. 1). A biodiesel production yield obtained from these organisms was 15–300 times higher than using oil from traditional crops [46]. In addition, algae biomass can help to solve the problem of competition between crops grown for consumption and energy production; the algal biomass can be seen as one of the most promising fuels for the future (Table 5) [42].

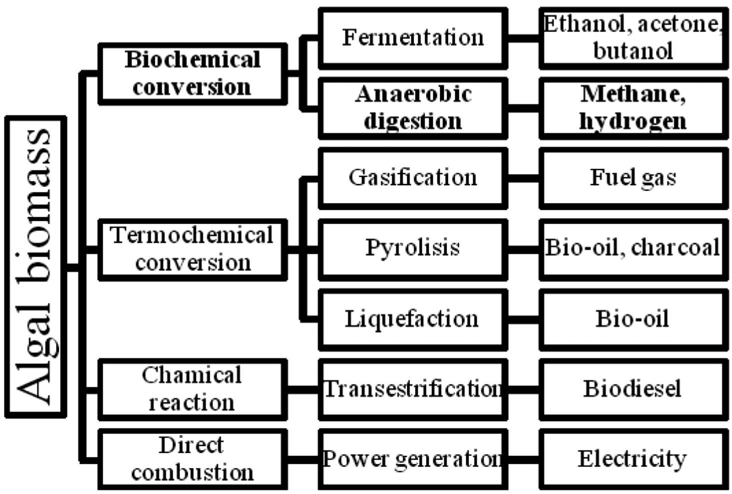

Fig. 1. Algal biomass conversion processes [26]

Table 6 shows the volumes of methane produced from the various algae species. It has been shown that the methane production from algae biomass can exceed by 2 to 20 times a production yield from conventional crops. These organisms can double their biomass during a day [3]. Additionally, small and insignificant amount of lignin present in the organisms is more easily degradable if compared to regular plants, so primary treatment of biomass before its digestion is not required. Therefore, use of algae as a co-substrate in methanogenesis may enhance the process efficiency and increase the volume of biogas produced from sewage sludge [31].

The carbon to nitrogen ratio (C N) is an important indicator of a methane digestion, which defines to what extend carbon and nitrogen are available in the feed. For example, for popular plants, the average C/N ratio is 36, while for algae 10.2 [26]. A low C/N ratio enables a nitrogen release and then its accumulation in the form of ammonium ions (NH_4^+). On the other hand, the high level of ammonium ions during the digestion process leads to a pH increase, which becomes toxic for the bacteria carrying on the digestion process [6]. Therefore, while using algae as a co-substrate supporting a sewage sludge digestion, a particular attention should be paid to the right selection of species (are relatively high C/N ratio) and a proper sludge composition (a high carbon content) [31].

Table 6

Methane production from different algae species [26]

Species	C/N	Temperature [°C]	Methane volume [m^3/kgVS.]	HRT
Scenedesmus spp. *Chlorella* spp., mixed, harvested from natural lagoon	–	35	0.31	30
*Scenedesmus*spp., *Chlorella* spp., mixed, harvested from natural lagoon	–	50	0.32	30
Spirulina maxima	4.2	35	0.31	20
Nondefined mixed culture dominated by *Chlorella*	–	34	0.35	14
			0.44	25
			0.60 (biogas containing 40–65% methane)	45
Nondefined mixed culture dominated by *Chlorella*	–	41	0.28–0.35	14
			0.39–047 (biogas containing 40–65% methane	25
Scendesmus spp. and *Chlorella* spp.	6.7	35	0.10–0.14	10
Non-axenic culture of *Scendesmusobliquus*	–	33	0.21	30
Non-axenic culture of *Phaeodactylumtricomutum*	–	33	0.35	30
Non-axenic culture of *Scendesmusobliquus*	–	33	0.13	22
		54	0.17	
Non-axenic culture of *Phaeodactylumtricomutum*	–	33	0.27	22
		54	0.29	
Chlorella vulgaris	6	35	0.24	28
Chlorella vulgaris	6	35	0.147	16
Arthrospira platensis	–	38	0.293	32
Chlamydomonasreinhardtii	–	38	0.387	32
Chlorella kessleri	–	38	0.218	32
Dunaliellasalina	–	38	0.323	32
Euglena gracilis	–	38	0.325	32
Scendesmusobliquus	–	38	0.178	32
Microcystis sp. from Taihu lake	6	35	0.201	30
Microcystis sp. from Taihu lake	–	35	0.14	30
Unknown species	–	30	929–1294 ml of biogas	28
Chlorella vulgaris	–	37	0.286	49
Dunaliellatertiolecta	–	37	0.024	49

Since sewage sludge has a relatively high carbon content and includes various types of active microorganisms, it should produce, in combination with the algal biomass, biogas of a satisfactory volume and quality in anaerobic digestion. The presence of sludge improves algae digestion [43]. Several studies have been carried out on this combined biomass. Golueke and Oswald in their paper [16] showed that the biodegradation rate for algae biomass was up to 60–70% lower than for sludge. They also pointed out at some of the process constraints due to high pH, ammonia toxicity or algal cells resistance. Therefore, while estimating the fermentation process potential, one has to focus mainly on a cell composition. The change in the cell content can change the fermentation efficiency. The content of proteins, fats and carbohydrates depends on the algae species and environmental conditions. However, fats play the most important role in anaerobic digestion, so the more fat is in the biomass, the more effective the fermentation process becomes. Morandi and Briand [32] reported that fermentation of green algae resulted in methane production of 0.2 $m^3 \cdot kg^{-1}$, while fermentation of kelp by Chynoweth [7] produced 0.39–0.41 m^3 of methane per kg. Microalgae also have a high potential. Singh and Gu [36] showed that the biogas produced from microalgae contains 55–75% of methane, so it is more caloric then other plant substrates. Studies on the *Macrocystis pyrifera* and *Durvillea Antarctica* species demonstrated that biogas production from algae in a two stage anaerobic digestion system reaches 180.4 ml/g dry weight of algae and the methane concentration in the biogas is approximately 65% [24]. The test was also conducted on a mixture of these species of algae in a 1:1 by weight. Observed lower production of biogas, but the methane content was comparable [39]. In the world studied the use of such algal species as: *Macrocystis pylifera*, *Sargassum*, *Laminaria*, *Ascophyllum*, *Ulva*, *Cladphora*, *Chaetomorpha*, *Gracilaria* for compost and biogas production [13].

Samson and Leduy [35] found that the addition of primary sludge (50% of VS) increases by 2.1 times efficiency of digestion of *Spirulina maxima* blooms. In turn, Cecchi et al. [5] studied the co-digestion of sewage sludge and macroalgae in mesophilic conditions. Studies have shown that the addition of macroalgae in an amount of about 30% by dry weight resulted in methane production comparable to the one observed for sludge digestion. Dębowski [14], in his experiments, inoculated samples of algae (mixed species) from the Vistula Lagoon with 200cm^3 of digested sludge. The average biogas production yield was 420.95 ± 0.95cm^3/g VS at a methane content of 71.37 ± 0.4949%.

Mahdy et al. [28] examined the mesophilic digestion of *Chlorella vulgaris* species with sludge (after thermal disintegration). In the samples, co-substrates were mixed in algae to sludge percentage ratio of 75/25, 50/50 and 25/75.The results show (Table 7) that, after 25 days of digestion, more biogas was produced from mixed samples than from sludge samples. The highest gas volume, 225.1 ml/1g COD, was observed in samples containing 75% of algae and 25% of sludge. Also Costa et al. [12] observed an increase of methane production by 26% while studying *Ulva* and *Gracilaria* species in combination with sludge in mesophilic conditions.

Also Wang and Park [41] analysed sludge with two algae species – *Micractinium* and *Chlorella*. The samples were mixed at an algae to sludge percentage ratio of 21/79. Table 8 shows the results after 20 days of anaerobic digestion at 35°C. As it can be seen, once algae were added to sewage sludge the digestion efficiency increased and more biogas was produced.

Table 7

Biogas and methane volumes produced during methane digestion of *Chlorella* species [28]

Chlorellavulgaris	Excess sludge	Biogas volume [ml/1g COD]	CH_4 [ml/1g COD]
100%	0	266.7	180.0
75%	25%	225.1	155.3
50%	50%	208.5	135.2
25%	75%	157.8	115.0
0	100%	80	136.1

Table 8

Biogas and methane volumes produced during methane digestion of *Micractinium* and *Chlorella* species [41]

Substrate	Biogas volume [dm^3/kg VS.]	CH_4 [dm^3/kg VS.]
Chlorella	415	230
Micractinium	378	209
Chlorella + sewage sludge	431	253
Micractinium + sewage sludge	418	236
Sewage sludge	391	243

Olsson et al. [33], in their studies, also confirmed the ability of algae to improve the efficiency of a sludge methane digestion in mesophilic conditions. However, they also proved that the presence of algae in thermophilic conditions has an adverse effect on biogas production. The same conclusions were reported by Caporgno et al. [4] in the studies on *Isochrystis galbana* and *Selenastrum capricornutum* species; using these specimens as a co-substrate in thermophilic conditions the authors observed a drop of a biogas production by 40.5% and 31.7%, compared to the digested sludge samples.

The authors started respiration studies on excess sludge from a municipal wastewater treatment plant and selected fresh water algae in the laboratory of the Cracow University of Technology. During the initial stage of the research, different types of algae were identified and selected. The samples include the algae from the group of green algae (Fig. 2) – *Spirogyra*, *Oedogonium*, *Tabellaria*, *Mougeotia* and *Pleurotenium*. Then, between January and April 2015, a 3 series of runs on excess sludge were conducted. The objective of the study was to determine to what extend the sludge under goes biochemical decomposition. It was found that a biogas production ranged from 0.46 to 0.66 m^3/kg VS (60–70% CH_4) at the mesophilic conditions. These measurements will serve as an introduction to further research on co-digestion of sewage sludge and algae biomass.

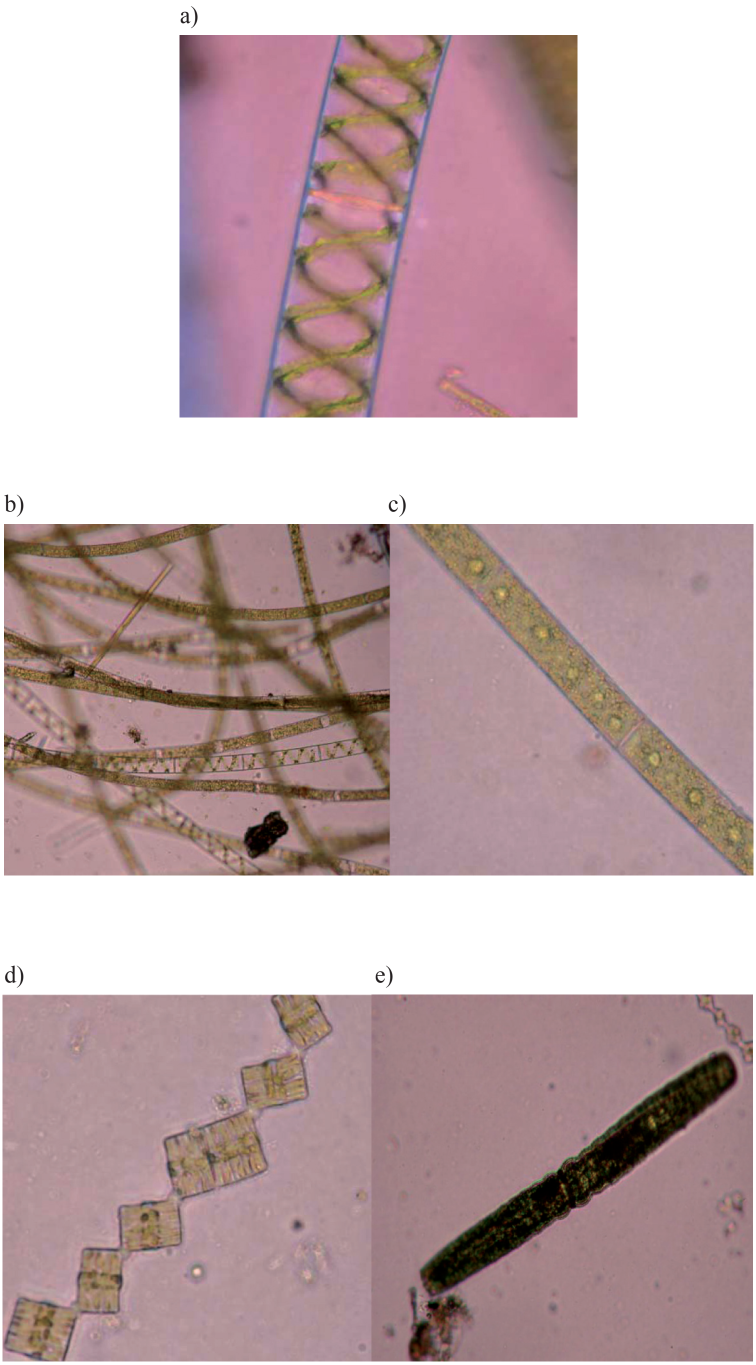

Fig. 2. Microscopic photos of algae by T. Woźniakiewicz: a) *Spirogyra*, b) *Oedogonium*, c) *Mougeotia*, d) *Tabellaria*, e) *Pleurotenium*

4. Conclusions

1. The literature review confirmed a need for new renewable sources of energy. Energy from organic biomass can be one of future carbon sources.
2. Algae and sewage sludge can serve as a convenient source for energy production. A rapid growth of algae and their ability to absorb nutrients are very advantageous features, and therefore, algae can serve for both energy production and wastewater treatment. Since the amount of sewage sludge (organic matter) produced during a wastewater treatment process will increase, in perspective, the need for sensible use of such organic matter becomes urgent.
3. Co-digestion of sludge and algae biomass is one of the methods used for intensification of an anaerobic sludge digestion, apart from sludge disintegration. The analysis of the literature data suggests that the use of algae as a co-substrate in a sewage sludge digestion increases a biogas yield and then improves the efficiency of an anaerobic digestion in mesophilic conditions.

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APPLICATION OF ZEOLITES FOR THE ADSORPTIVE BIOGAS DESULFURIZATION

ZASTOSOWANIE ZEOLITÓW DO ADSORPCYJNEGO ODSIARCZANIA BIOGAZU

Abstract

The article presents the issue of adsorptive removal of hydrogen sulphide from biogas using zeolite. Based on literature data, comparing performance of the biogas desulphurisation process for various mineral adsorbents, eg. activated carbon, zeolites and metal oxides, was carried out. The efficiency of biogas desulphurisation by adsorption on zeolites is significantly lower than for the activated carbons. Therefore, this article presents opportunities for improving efficiency desulphurization by modifying the structure of adsorbents.

Keywords: zeolites, biogas desulphurisation, activated carbon, biogas, adsorbents

Streszczenie

W artykule omówiono zagadnienie adsorpcyjnego usuwania siarkowodoru z biogazu za pomocą zeolitów. Na podstawie danych literaturowych dokonano porównania wydajności procesu odsiarczania biogazu dla różnych mineralnych adsorbentów, np. węgla aktywnego, zeolitów i tlenków metali. Efektywność odsiarczania biogazu w wyniku adsorpcji na zeolitach jest zdecydowanie niższa niż dla węgli aktywnych. Dlatego też w niniejszym artykule przedstawiono możliwości zwiększenia skuteczności odsiarczania poprzez modyfikację struktury adsorbentów.

Słowa kluczowe: zeolity, biogazu odsiarczanie, węgiel aktywny, biogaz, adsorbenty

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1. Introduction

Demand for energy increases with the development of civilization. The depletion of traditional energy resources, mainly fossil fuels, such as coal, oil and natural gas takes place. It is well known that the use of conventional energy sources promotes environmental pollution, mainly by greenhouse gases. These issues make renewable energy sources increasingly important. Renewable energy sources are a group of non-fossil sources that arise spontaneously in recurring natural processes of nature. They don't have a negative impact on the environment [1].

Biogas is produced from processing of biomass under anaerobic conditions. Biomass is one of the main renewable energy sources. Chemically, biogas consists mainly of methane and carbon dioxide, but its chemical composition depends largely on the type of the raw materials from which it is derived [1]. Hernándes et al. [2] demonstrated that the landfill biogas from Pianezza MSW contains, among others, methane, carbon dioxide, water vapour, but also a substantial amount of hydrogen sulphide, mercaptans, aromatic hydrocarbons, halogenorganic and organofluorine compounds and siloxanes. While biogas, which was obtained from the sludge from wastewater treatment plants is free from halogenorganic or organofluorine compounds [3]. The most desirable component of biogas is methane, while the other gaseous substances are considered to be impurities. This is due to the fact that they do not improve the energy potential of biogas, and in addition, are corrosive. In order to increase the possibility of biogas application, its purification or treatment to natural gas quality is carried out. The essence of this process is to remove all gaseous impurities by appropriate techniques, such as adsorption.

Removal of hydrogen sulphide from biogas is called desulfurization [4, 5]. There are several methods for biogas desulphurisation, which can be divided into biological oxidation and catalytic oxidation, wet method, adsorption techniques, and a method using bog iron ore [6]. As hydrogen sulphide adsorbents coal, mineral, and mineral-carbon adsorbents are used. Zeolites are classified as mineral adsorbents.

2. Synthesis and modifying the structure of zeolites

Zeolites are crystalline aluminosilicates of alkali metals or alkaline earth metals. They are characterised by a regular and homogeneous structure of the pores (diameter of 2–10 Å), which are filled with water. This water is called zeolitic water, which evaporates when zeolite is heated. There are two groups of zeolites – natural and synthetic, that have a structure similar to natural. Chemically, aluminosilicates are a crystalline lattice consisting of SiO_4 tetrahedra and AlO_4^- (aluminate oxyanions), which are interconnected vertices. The negative charge derived from AlO_4^- ions is compensated by cations of sodium, potassium, magnesium, calcium, strontium and barium. Type of cation depends on the type of zeolite. Among the synthetic zeolites, the A, X and Y zeolite types are mainly singled out, but some of them have counterparts in nature. The chemical composition of zeolites can be expressed by the formula $Me_nO \cdot Al_2O_3 \cdot x\ SiO_2 \cdot y\ H_2O$ where Me is an alkali metal cation, n is its valence and x, y are integer numbers [7].

Synthetic zeolites are prepared by two hydrothermal methods [8, 9]. The first method is based on the crystallization of the alkali aluminosilicate hydrogel of suitable composition. As the raw material sodium aluminate (aluminosilicate support material), and sodium silicate, amorphous silica and water glass as raw materials silicon carrier are used. The second method consists of recrystallization of natural aluminosilicate. In this case, the most commonly used raw materials are minerals of the kaolinite group.

The structure and chemical properties of zeolites meant that they are widely used also in the areas of environmentally-friendly methods [10]. The zeolites are used as pollutants adsorbents, detergent components and catalysts. For example, they are used to remove radionuclides from the wastewater of the nuclear industry, also to remove ammonia from the wastewater and to remove heavy metal ions (As, Pb, Cu, Zn, Cr, Cd, Ni and others) from water and wastewater [11–28]. Zeolites are also used in catalytic oxidation processes of sulphur compounds – gases from flue gas cleaning [13].

The zeolites are used as adsorbents of which structure is modified to increase their adsorption capacity, increase their capacity ion exchange, increase capacity and to obtain the more selective material (inside the zeolite crystals only those molecules whose critical diameter is no greater than the diameter of the windows can be adsorbed). The modification can be carried out by chemical and thermal treatment. Chemical modification of zeolite surface consists in the substitution of the cations Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+} by macromolecular compounds or d-block metal cations. Introduction of metals into the zeolite structure can be done by ion exchange, necking pores or prior adsorption of polar molecules [16, 17, 29, 30].

3. Desulfurization of biogas using zeolites

Studies on zeolites [2, 29, 31] shows that zeolites have low efficacy of adsorption of hydrogen sulphide as compared to other adsorbents. Sisani et al. [31] compared the concentration of hydrogen sulphide adsorbed on several commercial adsorbents, such as activated carbons (RGM1, RBAA1 Ultra DS and RB1), ATZ zeolite, aluminium oxide Galipur S and sepiolite. The results of what the authors have obtained are shown in Fig. 1. The highest efficiency of adsorption at 30°C was obtained using the activated carbons (C_{ads} amounted to 27.15 mg/g), whereas in the case of zeolite and sepiolite, the concentration of the adsorbed H_2S does not exceed 0.1 mg/g.

Hernández and co-workers [2] compared the efficiency of biogas desulphurisation process using copper and chromium salts-impregnated activated carbon (RGM-3), zeolite 13X, molecular sieves Sylobead 522 and Sylobead 534 and two metal oxides, which commercial names are ST and Sulfcatch ECN. Desulphurisation efficiency, which the authors obtained, is shown on Figure 2. In this case, the highest efficiency was obtained for the adsorption of activated carbon, but in the presence of steam, efficiency is significantly decreased. Zeolite 13X has proven to be far more effective than metal oxide Sulfcatch ECN and studied molecular sieves.

Micoli et al. [32] conducted biogas desulphurisation and as adsorbents, they used modified by ion exchange (Ex) and impregnated (Im) with copper and zinc ions zeolite and also impregnated with solutions of KOH, NaOH and Na_2CO_3 activated carbons (AC). The results are shown in Fig. 3.

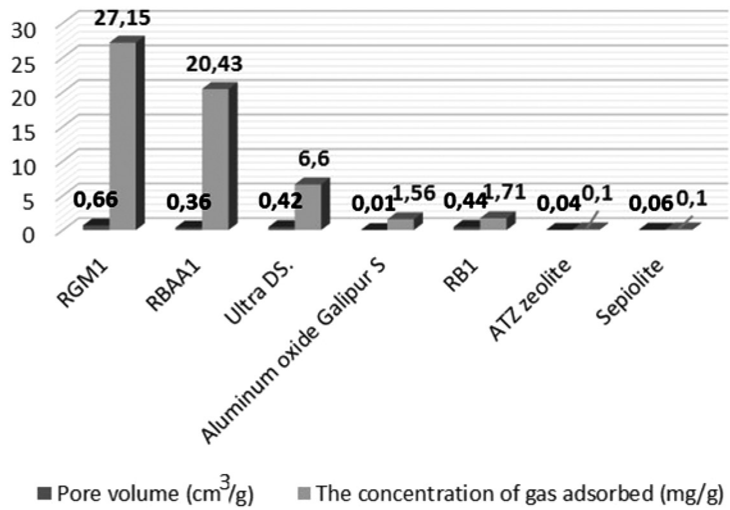

Fig. 1. Comparison of properties of some hydrogen sulphide adsorbents [31]

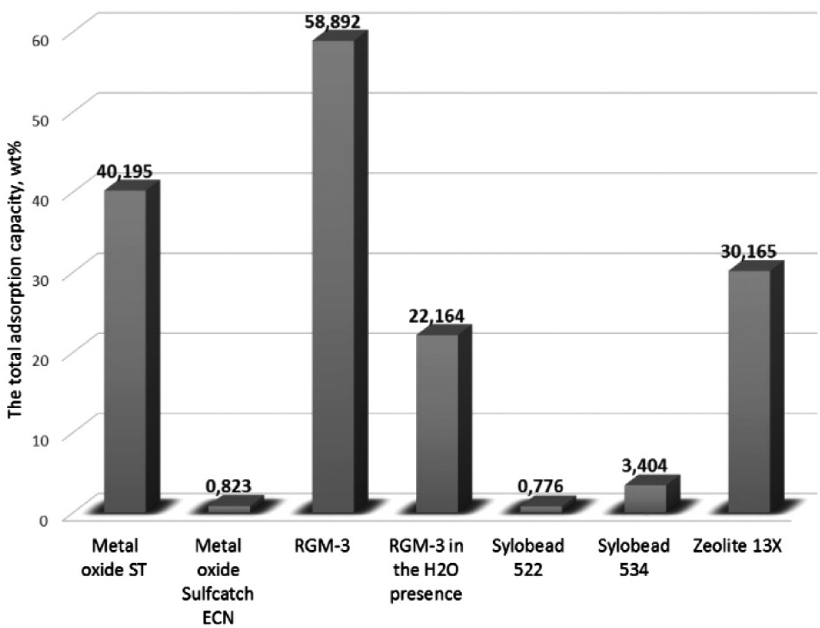

Fig. 2. The effectiveness of biogas desulphurisation for a variety of commercial adsorbents [2]

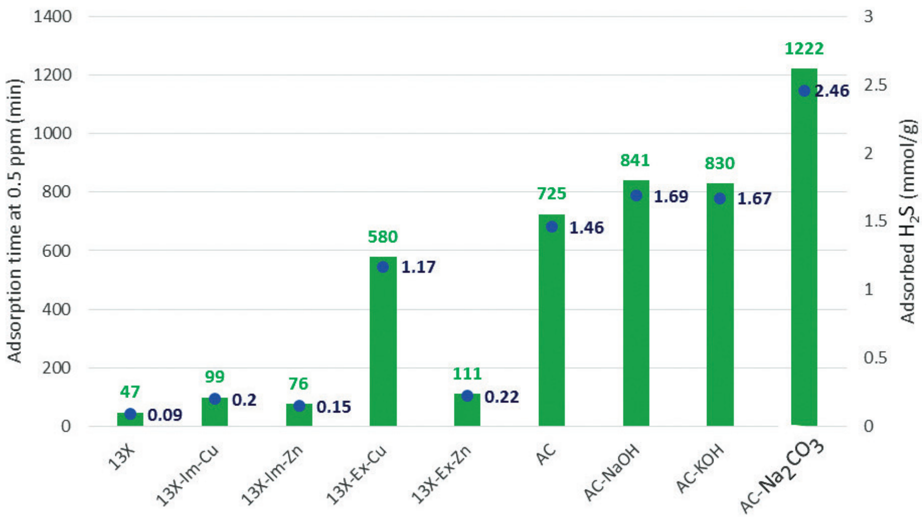

Fig. 3. The operating time (the H_2S concentration of 0.5 ppm), and the adsorption efficiency of the tested adsorbents – activated carbon and zeolite [32]

In the case of zeolites, all modified and impregnated samples achieved better results (two times longer operating time of the adsorbent – 300 min.) than the parent zeolite sample. The most effective was the one that was modified by ion exchange with copper ions zeolite, whose operation time was significantly longer than the others and was over 600 minutes at the H_2S concentration of 0.5 ppm. However, much better results were obtained with activated carbons. The best was impregnated by Na_2CO_3 solution activated carbon whose work time was longer than the others and was more than 1,400 min. and additionally, absorbed greater amounts of H_2S. Micoli and colleagues studies [32] confirmed the better efficacy of carbonaceous adsorbents with respect to the zeolites. The authors also confirmed the thesis that modifying of zeolites increases the desulphurisation efficiency.

4. Conclusion

Zeolites have been used as adsorbents because of their chemical structure and properties. They are characterised by the selectivity of adsorption associated with particle size and with their polarity. These adsorbents are capable of selective adsorption of polar molecules, such as water and hydrogen sulphide. Unfortunately, in the case of hydrogen sulphide, the adsorption efficiency is not satisfactory. Frequently, the effectiveness of adsorption on zeolites is much lower than on activated carbon. In order to increase the efficiency of adsorption on zeolites, the modification of their structure is carried out. This modifications cause a change in pore size. Depending on the used modifier ions, enlargement or reduction of the pore diameter occurs. In the first case, the molecule of larger size, e.g. n-paraffin hydrocarbons, are adsorbed. In the second case, only small polar molecules (such as water, hydrogen sulphide) are adsorbed. In order to increase the efficiency of biogas desulphurisation using zeolites, modification of their structure in the direction of reducing the pore diameter must be carried out.

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TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ENVIRONMENTAL ENGINEERING | ŚRODOWISKO

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PIOTR REZKA, WOJCIECH BALCERZAK, MAŁGORZATA KRYŁÓW*

OCCURRENCE OF SYNTHETIC AND NATURAL ESTROGENIC HORMONES IN THE AQUATIC ENVIRONMENT

WYSTĘPOWANIE SYNTETYCZNYCH I NATURALNYCH ESTROGENÓW W ŚRODOWISKU WODNYM

A b s t r a c t

The article is part of a series of publications discussing prevalence of pharmaceuticals in the aquatic environment. The aim of this study is to describe the problem of the presence of hormonal tablets ingredient 17α-ethinylestradiol and its three natural analogues in wastewater and the environment. Basic information on the substances in question and the concentrations in which these compounds can negatively affect aquatic organisms are provided. In the paper, the authors review the literature data on the presence of estrogenic hormones in wastewater, surface water and groundwater. Penetration through aquifers can lead to accumulation of these compounds in the sediments, which is reflected in the literature.

Keywords: 17α-ethinylestradiol, wastewater, surface water, sediments

S t r e s z c z e n i e

Artykuł jest częścią serii publikacji obejmujących zagadnienia występowania farmaceutyków w środowisku wodnym. Celem artykułu jest opis problemu obecności składnika tabletek hormonalnych 17α-etynyloestradiolu i jego trzech naturalnych odpowiedników w ściekach i środowisku. Przedstawiono podstawowe informacje dotyczące rozpatrywanych substancji oraz stężenia, w jakich te związki mogą negatywnie wpływać na organizmy wodne. Dokonano przeglądu literatury dotyczącej występowania estrogenów w ściekach, wodach powierzchniowych i podziemnych. Podczas przenikania przez warstwy wodonośne może dojść do akumulowania się tych związków w osadach dennych, co znajduje potwierdzenie w literaturze.

Słowa kluczowe: 17α-etynyloestradiol, ścieki, wody powierzchniowe, osady denne

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1. Introduction

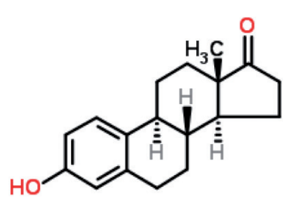
The issue of endangering health and life through contact with water containing even trace amounts of pharmaceuticals is becoming a growing problem for humans and animals. However, the presence of certain groups of pharmaceuticals is more or less controversial than other drugs. And by no means does it depend on the range of concentrations in which these substances are present in the environment, but rather on their impact on aquatic organisms and humans. Despite the high levels at which they occur in the environment, the presence of anti-inflammatory drugs [27] induces less excitement than the presence of hormonal substances. This is primarily due to the fact that the hormonal agents (in particular estrogens) have an extremely adverse effect on living organisms, including fish at a very low concentration of 0.1 ng/l [12]. They affect the feminization of fish [14, 15, 19] inhabiting ponds and rivers, which is a major threat to local ecosystems. These changes are most commonly associated with synthetic hormonal agents, in particular 17α-ethinylestradiol, but also have the effect of natural estrogens such as estrone, estradiol and estriol. All of these compounds are classified as endocrine disrupting compounds (EDC), which interfere with the endocrine system by affecting the synthesis, transport, metabolism and excretion of hormones from the body [17].

2. Characteristic of natural and synthetic estrogens

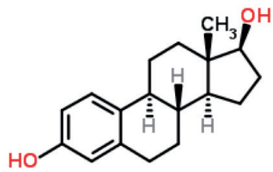
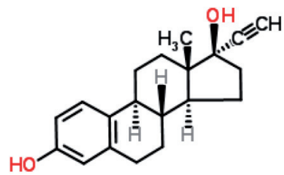
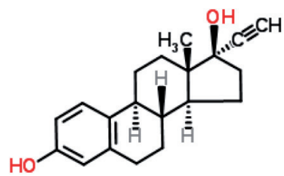
Estrogens are hormone compounds, affecting a range of functions and characteristics of an organism. The natural estrogens include estrone (E1), estradiol (E2) and estriol (E3), while the most common synthetic estrogen is 17α-ethinylestradiol (EE2), a derivative of estradiol. EE2, as a replacement for the natural hormones, is an ingredient in most two-component birth control pills, whose main objective is the inhibition of ovulation. In developed countries, hormonal contraception is one of the most popular methods of protecting against unwanted pregnancy. Table 1 shows the basic information relating to the compounds and Chemical Abstracts Service (CAS) numbers.

Table 1

Characteristics of selected estrogens and their predicted no–effect concentrations (PNEC) [4, 28]

Compound	Formula	Structure	CAS	PNEC [ng/l]
Estrone (E1)	$C_{18}H_{22}O_2$		53–16–7	6

Tab. 1

Estradiol (E2)	$C_{18}H_{24}O_2$		50–28–2	2
Estriol (E3)	$C_{18}H_{24}O_3$		50–27–1	60
17α–Ethinyl-estradiol (EE2)	$C_{20}H_{24}O_2$		57–63–6	0,1

3. Occurrence in the environment

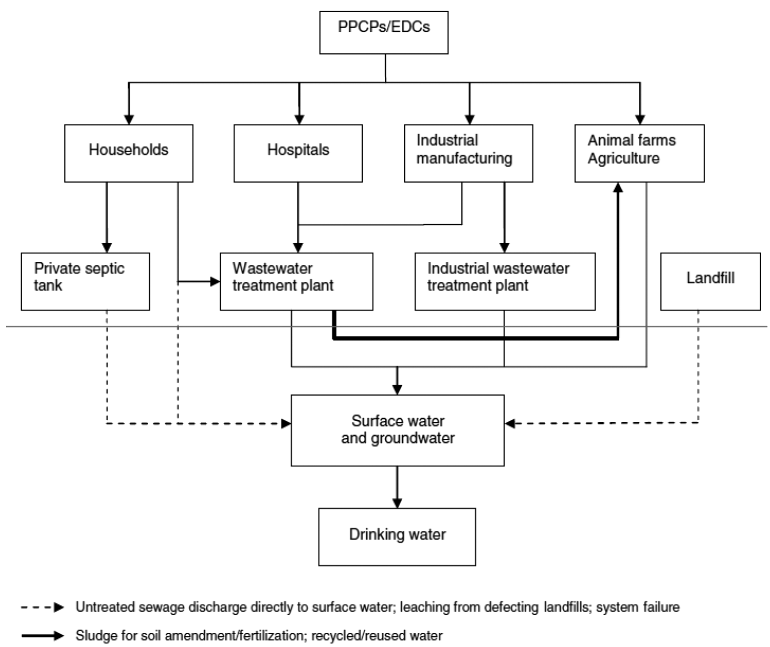


Fig. 1. Sources of endocrine disrupting compounds (EDC), pharmaceuticals and personal care

Potential sources of natural and synthetic hormones are shown in Fig. 1. Every human (especially women) excretes estrogens from the body, even without taking hormonal drugs. For this reason, hormones are expected to be present primarily in wastewater from households, which are transported through the sewer system to the wastewater treatment plant (WWTP). Estrogens, as compounds highly dangerous to the environment, should be degraded and eliminated in wastewater treatment processes with the highest possible efficiency in order to protect aquatic organisms from their harmful influence. Due to the inconstant and complex composition of sewage containing organic substances, wastewater treatment is not an easy task and high effectiveness of their elimination is not always obtained, as confirmed by research carried out in South Africa [23]. Despite up to several tens of percent effectiveness of removal of E1 (72 ± 12%), E2 (78 ± 12%) and EE2 (90 ± 3%) [23], sewage containing from 1 ng/l (EE2) to 107 ng/l (E2) estrogens were released into a river. Comparison of the contents of examined hormones in the river above and below WWTP showed a distinct increase in levels of these compounds (in the case of estradiol – 28 ng/l above and 66 ng/l below the sewage treatment), for which the WWTP is directly responsible [23]. Table 2 shows confirmed estrogen levels in wastewater, surface water and groundwater, with sources of literature.

Table 2

Concentrations in ng/l (min–max or mean) of detected hormones in WWTP influent, WWTP effluent, surface and groundwater

Compound	Influent	Effluent	Surface water	Groundwater
Estrone (E1)	1–670[1] 47–376[8] 2.4–670[11] 10–170[22] 49[25] 5–160[32]	25–42[8] 1–96[11] 36–70[21] 1–80[22] 4.3–12[25] 5–30[32]	1.4–5.74[2] 7–52[3] 22.4–66.2[6] 2.3–77.5[7] 0.45–2.98[13] 0.64–55.3[20] 0.3–5[21] 1.2–10[26] 0.08–78.7[29] 0.5[30] 1–1.45[31] 2.8–321[33] 14–180[35]	1.6–3.5[21] 0.7[30]
Estradiol (E2)	3–3000[1] 31–74[8] 2.4–150[11] 2–50[22] 72–190[24] 20[25]	31–51[8] 0.2–30[11] 9.2–180[21] 1–7[22] 0.4–1.3[25]	1.1–5.39[2] 4.8–48[3] 10–150[5] 1.4–33.9[6] 2.3–10.2[7] 0.28–1.78[13] 21.2[20] 0.31–1.2[21] 1–175[26] 2.3–7.72[29] 0.2[30] 4.41–9.96[31] 3.7–74.4[33] 1–134[35]	0.21–1.6[21] 0.4[30]

Tab. 2

Estriol (E3)	17–1000[1] 74–234[8] 23–660[11] 125–800[22] 90–830[24]	46–175[8] 0.43–275[11] 25–590[21] 270–590[24]	2.15–5.2[2] 10–480[5] 12.4–73.6[6] 2.14–4.37[13] 46.4[20] 0.1–1.9[21] 1.02–1.65[31] 2.3–47.85[33] 4–94[35]	0.16[21]
17α–Ethinylestradiol (EE2)	2–400[1] 0.4–14.4[11] 1–3[22] 70–180[24] 1[25]	0.3–4.1[11] 1.3[21] 1–2[22] 30–180[24] 0.2–0,47[25]	11.7–14[2] 4.3–51[3] 10–280[5] 7.53–27.4[6] 4.3–28.6[7] 0.28–2.67[13] 0.4–24.4[20] 0.33[21] 0.8–34[26] 0.11–53.4[29] 1.4[30] 6.03–10.2[31] 0.52–101.9[33] 7–24[35]	0.94–3[21] 1.2[30]

The presence of estrogens in surface waters is of concern not only because of penetration of these compounds into groundwater, but also as to their accumulation in bottom sediments. Table 3 shows the concentration levels of estrogen in the sediments calculated as a dry mass. These reports confirm an accumulation of natural and synthetic hormones in the sediments in concentrations up to several tens of ng/g dry mass of sediment. It should be noted that, in many cases, the concentration of these highly exceed the PNEC, which means the possible risk of harmful effects on aquatic organisms.

Table 3

Concentrations in ng/g of dry weight (min–max or max) of estrogens in sediments

Compound	Estrone	Estradiol	Estriol	17α-Ethinylestradiol
Level of hormones	0.71–50.75[9] 0.3–1.28[16] 0.4–3.3[18] 0.98–21.6[20] 4.61–11.22[34] 3–10.8[35]	0.87–40.96[9] 0.18–1.58[16] 0.03–1.2[18] 9.7[20] 3.71[34] 1.2[35]	1.26[16] 7.29[20] 1–7.6[35]	133.64[9] 9.26[20] 2–41[26] 2.48[34] 5.1[35]

4. Conclusions

Estrogenic hormones are commonly found in water in quantities greater than the predicted no-effect concentrations showing no impact on living organisms. Despite the use of advanced mechanical and biological methods of wastewater treatment, hormonal substances penetrate into the environment adversely affecting the organisms living in rivers and reservoirs to which treated wastewater is discharged. The progressive feminization of fish and the risk of the harmful effects of eating such fish by humans requires a critical approach to elimination of estrogens in WWTP. Due to the development of consciousness of young people, in particular women, gradual change of approach to contraception and easy access to this form of pregnancy prevention, we should expect a systematic increase in levels of presence of estrogens in wastewater.

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3-Ś/2015

MONIKA SZLAPA, MAGDALENA TUTRO*

USE OF NUMERICAL MODELS TO FORECAST THE PHENOMENA'S DYNAMICS IN A STORAGE RESERVOIRS

WYKORZYSTANIE MODELI NUMERYCZNYCH DO PROGNOZOWANIA DYNAMIKI ZJAWISK ZACHODZĄCYCH NA ZBIORNIKACH RETENCYJNYCH

A b s t r a c t

This article deals with applying numerical finite element models to forecast the phenomena's dynamics in retention reservoirs. Due to the fact of diversity and the dynamism of these phenomena on storage reservoirs, it is important to predict them for a good management of these objects. Historical observations can be a good source of clues for proceeding in a specific case. It is not directly used to all the possibilities. It is important to use a tool, which can estimate probable scenarios. Thanks to the use of simulation programs, it is possible both to predict physical and chemical processes, and to use the solutions to forecasts and research plans.

Keywords: numerical modelling, retention, storage reservoir, hydrodynamic, water quality

S t r e s z c z e n i e

W artykule omówiono zastosowanie modeli numerycznych bazujących na metodzie elementów skończonych do symulacji dynamiki zjawisk na zbiornikach retencyjnych. Ze względu na różnorodność zjawisk, wzajemne powiązania i złożoność dynamiki ich przemian, istotna z punktu widzenia zarządzania akwenem jest ich predykcja. Obserwacje historyczne są niezbędnym źródłem informacji, ale mają ograniczony zakres. Nie można ich wprost przełożyć na całe spektrum zjawisk, ich źródeł i konsekwencji. Ważne jest wykorzystanie właściwych narzędzi, które umożliwiają symulacje dynamiki dla prawdopodobnych scenariuszy. W przypadku akwenów istotna jest ocena zmian fizycznych i jakościowych.

Słowa kluczowe: modelowanie numeryczne, retencja, zbiornik retencyjny, hydrodynamika, jakość wody

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1. Introduction

In Poland, retention reservoirs built on rivers perform several economic functions. Most of these lakes are located in the upper basin of the Vistula and Oder rivers. Some of the reservoirs that are filled with water all the time perform multiple tasks at once like: water supply, flood flow protection and electricity generation. These reservoirs are multifunctional or at least bifunctional. This conjuncture may cause problems because of the first two functions which contradict each other are flood protection and power generation. For the first one, the best solution is maintaining the water surface on the low level, but for the second one conversely – the highest possible level of water is desirable. Most often, the maximal flood reserve isn't maintained because of the profits from the power plant and the water level is lowered only to prepare the reservoir to capture the flood wave. In that kind of situation, the basis is to know how long it takes for emptying or filling in the given values of inflow and outflow. Moreover, the information on when the lake emptying should start and how big outflow should be set is useful.

The second challenge, concerning the reservoir structure and morphology, is deposition of the sediment in the bottom of the lake. On the one hand, the problem can be the reduction of the total water body volume, but on the other, it could have an impact on chemical and biological processes, and ultimately, it may have an effect on the water quality. Therefore, the significant information is: where the particles are deposited; which conditions are appropriate to transport, re-transport and activate them; as well as the information about chemical substances being released. Similar problems could appear when the pollutions are dissolved in water. The propagation of this kind of contamination gets much faster and reaches larger zones. In addition, when the water supply inlet is situated within a lake, the danger is doubled: threat for the environment and for humans. A very important task is the possibility of prediction the way and time of pollution propagation as well as the potential places of accumulation, which can be the source of the eutrophic processes. When the water surface isn't frozen (most time of the year), it is easier to observe the flow dynamics and the transport process. When the lake is ice covered, it is almost impossible. Therefore, all of the mentioned phenomena are very weakly recognised in those conditions.

Correct resolving of the mentioned problems, and providing good ecological potential in a long period of time, requires the support of management of reservoirs using appropriate means to simulate the dynamics of these reservoirs for different scenarios involving: inflow conditions, as well as climate and other changes related to water quality and biology.

2. Background

The proper management of the water storage reservoir requires a broad and detailed knowledge about phenomena diversity and water dynamics. Prediction of the retention reservoir behaviour in a variety of scenarios is a fundamental problem, and also, very difficult one. Modern numerical techniques may be helpful in that matter. Numerical models shall be used for the description of the phenomena dynamics.

This work is based on two methodical and numerical aspects:

1. Approximation of the flow area and its description using the finite element method (FEM). FEM is known and commonly used in many engineering issues related to the simulation of non-stationary processes, such as: tension structures, thermal conductivity or fluids flow. FEM allows for correct mapping of the velocity field of the water surface with variable spatial accuracy dependant on topographic complexity of the water body.
2. Using two-dimensional (planar) equations of unsteady flow. They are approximated to FEM use for describing complex dynamic phenomena like tracing water and sediment transport or other similar fluid dynamics issues. Two-dimensional models – provided right boundary conditions setting, especially at the dam outflow – are appropriate for dynamic simulations of water storage reservoirs. They were successfully used for identifying open and closed dynamic structures within a water body [3].

Numerical models, used in this paper, are included in the SMS package. The Surface-water Modelling Solution (SMS) is a comprehensive simulation environment for hydrodynamic modelling [1]. It allows engineers and scientists to visualise, analyse and understand results of performed simulations easier. The numerical models supported by SMS are able to compute a variety of parameters applicable to surface water modelling. Primary applications of the models include calculation of the water surface elevations and flow velocities for steady-state and dynamic conditions. Other applications include the modelling of: rivers behaviour, contaminate transport, sediment transport, rural & urban flooding, estuarine, coastal circulation, inlet and wave modelling.

A great advantage of SMS is flexible modelling approaches. This simulation environment allows for building conceptual models by using GIS familiar objects like points, arcs and polygons. The conceptual models are high-level and do not rely on meshes and grids. They only need definition of parameters such as bathymetric data, flow rates, boundary conditions or water surface elevations. Moreover, SMS also includes tools that help building computational meshes and grids including their automatic generation and optimization. SMS also provides tools for result analysis and visualisation. This makes results understanding easier and allows involved people to focus on the merits of their problem. Thanks to SMS`s support for many computational models, it gives a possibility of cross-comparison of the simulation results obtained with different models [1, 8].

The models used in this paper are AdH [2,15], RMA [4,10] and PTM [6]. All of them belong to the group of two-dimensional depth averaged (also known as "2.5-dimensional") finite element method modelling tools.

The basic input parameters for this model are:

1. Bed shape (bathymetry).
2. Bed friction parameters (they may be expressed as the roughness coefficients or as the equivalent bed roughness height).
3. Initial water surface level.
4. Water parameters (density, viscosity – the later may be depth dependent).
5. Inflows and outflows (constant, time dependent or surface level dependent).

The models support many other case-specific initial conditions and parameters, for example: wind conditions, atmospheric pressure changes, Coriolis Effect or fixed ceilings (e.g. bridges).

Depending on the performed simulations, appropriate additional parameters must be defined:

- sub-glacial flow – the parameters of the ice cover (its range, density, thickness and roughness) – AdH;
- sediment transport – the parameters of – the particles of the sediment – PTM;
- pollution dissolved in water – the parameters of substances – RMA4.

The main result of the simulation is a two-dimensional planar field of the average horizontal velocity of water. Vertical movement and most of other vertically dependant phenomena are not taken into account [16].

3. Characteristic of the objects of research

The area of research is three retention reservoirs located in southern Poland: Dobczyce, Tresna and Porąbka (Fig. 1). All of these multifunctional lakes have a mountain character and have been made by constructing a dam in a river valley.

The Dobczyce reservoir is situated in Lesser Poland Voivodeship. The lake was created by building a dam on the 60th km of the Raba River, which is one of Vistula river tributaries. The surface of the catchment area is 768 km^2. The knowledge about pollution propagation in this reservoir is as significant as a function of the Dobczyce Lake itself: the lake is the

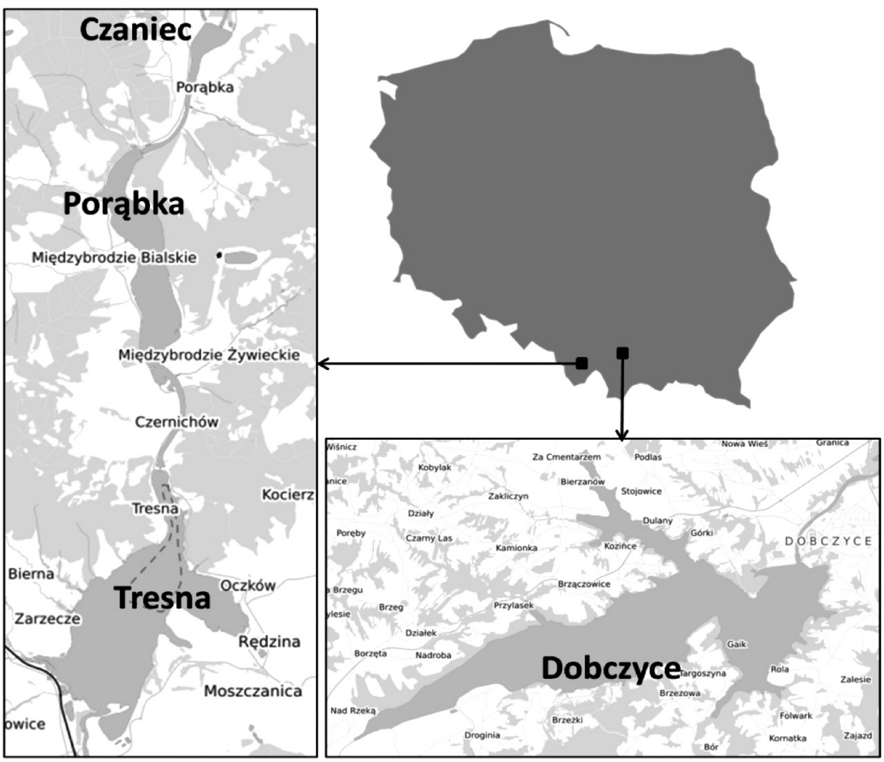

Fig. 1. Geographical location of the reservoirs [I]

primary water source for the nearby city of Cracow. Therefore, the water quality issue is the priority and presently all the lake area is under protection. However, the recreation aspect is discussed now. It is certain that some kind of recreation will be allowed there in the future. Thus, the potential sources of pollution and its contamination propagation should be under control.

The other reservoirs – Tresna and Porąbka are two of three of the Soła Cascade reservoirs located on the Soła River in Silesian Voivodeship. Soła is a right hand tributary of the Vistula River. Soła Cascade is a system of three reservoirs, of which one of the main functions is to provide drinking water for Silesia, Bielsko-Biała, Oświęcim and Kęty, and to provide water to factories and fish farms. The reservoirs are also used to produce hydroelectric power and to mitigate exceptional floods. Reservoirs can reduce the maximum flood flows from 1469 m^3/s to the 650 m^3/s.

The Tresna reservoir is a mid-size retention reservoir and is the first of three reservoirs forming the Soła Cascade. It is also called the Żywieckie Lake. It has one main inflow – the river – and one outflow located by the dam. The dam is located on the 40th km of the river. Surface of the catchment area is 1 030.0 km^2.

The Porąbka reservoir, the second one in the system, is also called the Międzybrodzkie Lake. It`s the oldest reservoir in the system (build in 1936). The dam is located on the 32.3$^{rd}$ km of the Soła River. Surface of the catchment area is 1 082.0 $km^2$. The reservoir is long but not very wide. The Porąbka`s reservoir has two hydroelectric power plants. The first one is located on the dam. The second one is located on the eastern shore. This is the second biggest pumped-storage hydroelectricity in Poland.

4. Results

This chapter outlines some representative results of the performed simulations of the phenomena, which take place on the storage lake – Dobczyce. The basis for estimation of all the processes related with the water flow is the two dimensional velocity fields. The map (Fig. 2) shows the direction and magnitude of the velocity vector. The simplest simulation needs information about: the lake bathymetry, inflow discharge, outflow discharge or water surface level and bottom roughness. These parameters can be constant or time varying (excluding the bottom roughness – the parameters describing a material are always set as constant value for the whole simulation). Additional parameters, which can be taken into account, are the factors connected with the environment. The first one is the wind direction and velocity, which in nature is time variable. This effect can have a big impact on the water flow velocity and direction in reservoirs. The simulation result can also include local surface sources of water. By this option, it is possible to take into account local evaporating or rainfall in a given part of the lake. The figure below presents water velocity field for the Dobczyce Lake obtained by AdH simulation model included in SMS package.

The next challenge, especially for the lake with a water supply function, is water quality. Firstly, it can be directly effect of contamination, which enters the water. Secondly, the danger can be caused by substances, which are affected by chemical processes in the appropriate conditions. For example, the eutrophic process is a common phenomenon in small water

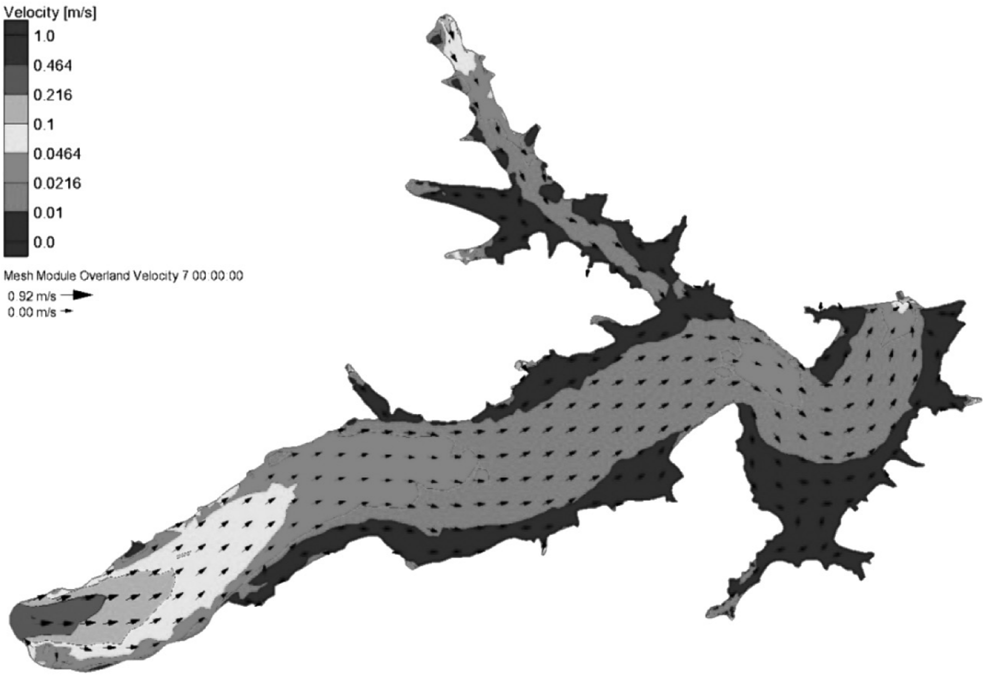

Fig. 2. The planar velocity field for water surface level of 272.6 m a.s.l. and high water flow ($500 m^3/s$) in the Dobczyce Lake

movement places like hollows. Those zones are easy to recognise in situ or can be identify within the solution calculated in AdH, RMA2 [4] or another hydrodynamic model. The situation is more complicated when considering the paths of the dissolved contaminants particles. In this case, there are a lot of variables, which control the processes advection and diffusion in water environment. Beside the parameters describing water dynamics, it is necessary to include data representing the pollution character. The first step is to give some information about the moment when contamination enters and specify the place in reservoir area as well as time duration of potential slick. Next point is to describe the pollutant itself by the following factors: concentration of a given constituent, turbulent mixing coefficient and first order decay coefficient of a given pollutant.

The simulation presented in Fig. 3 was performed under an assumption of rapid leakage of constituents that have the eddy diffusivity parameter ($0.05 m^2/s$) [5, 9, 13] suitable for “industrial” constituents like for example mineral oils. They origin from the zone where industrial-originated contamination may eventually appear: a haven located near the end of the Wolnica bay in the Dobczyce Lake. The presented results contain seven days long simulation and include wind impact taken from real life data of one march week where the most frequent were the southern and western winds.

The total mass of the leaked pollutant is assumed to be ten tons. In this case, it enters the lake during only three-hour event. It results in 926 g/s mass load. The end of the leakage marks the “zero” moment. Figure 3 presents the propagation of contamination that appeared in place where Wolnica bay connects with the main part of the Dobczyce reservoir. In the beginning, the pollution only disappears in place near place of its sources. Next, after reaching the main basin, the substance unexpectedly is turned back in western part of the lake in direction of Raba inflow. The result, where the polluted substance flows in the direction where the dam outflow is located, would be more expected. However, such a result shows that the wind conditions may be the reason of dynamic situation of flow direction in the water reservoir. During that time, the contamination is dissolved in water. In the part of Fig. 3, which represents the situation after 8 days, it is easy to see that the stain of substance changes direction once again. After 12 days, significantly lower concentration of contamination fill the middle part of the lake and follow east to the dam.

The results of this kind of calculation give information about the potential way of the contamination in the given conditions. It may also show the concentration of pollution in each point as well as present the process of decay of the given substance in time and space. This data may be used in the prediction and analysis of the risk to strategic points on the reservoir, like water supply inlet. That kind of calculation works on two levels. The first one is a hydrodynamic base calculated by RMA2 including important parameters like: inflow, outflow, wind impact etc. The second layer is RMA4 [10] model, which is based on the RMA2 solution. In this step, all data about constituents are being set to characterise potential behaviour of each of the substances in the water environment with specific terms.

The ice cover, appearing on the storage reservoir in the winter, may impact water quality. The simulation results confirm that the ice covering the reservoirs has a significant impact on the water dynamic. Ice cover reduces water velocity, which creates stagnant areas. In addition, the ice cover has a significant impact on reducing water mixing in a storage reservoir [7, 11, 14].

Fig. 4 shows the velocity maps generated by the model for main inflow of 5m^3/s and 25 m^3/s for two scenarios. The map on the left shows the flow velocity field in the reservoir Porąbka, when the water surface is free from ice. Next is a map that presents the scenario when the reservoir is covered with a 0.1 m thick layer of ice. To emphasize the significant impact of the ice cover thickness, the map on the right shows the simulation results for 0,5m ice cover thickness.

It can be seen that increasing the ice thickness damps the flow velocity. Side currents and whirlpools, that are present for the free surface scenario, tend to disappear when the ice cover is introduced.

A similar situation is presented in Fig. 5. In this case, the flow velocity map was prepared for the Tresna reservoir. As in the previous case, the flow velocity map presents solutions for 0.1 m and 0.5 m values of ice cover thickness. But, in this case, simulations were prepared for 25 m^3/s and 50 m^3/s main inflows.

Also, in this example, the velocity field differences are visible. They are smaller in comparison to the Porąbka Lake. The most significant differences in flow velocity fields are visible in the south region of reservoir. It is a place where main inflow flows into the reservoir.

In both cases (Porąbka and Tresna reservoirs) more visible difference concern simulation for lower velocity of the main inflow. In this case, the impact of the roughness coefficient is less significant. In addition, comparing the simulation solutions for the Porąbka and Tresna reservoirs, greater changes are noticeable in the Porąbka reservoir. The Porąbka reservoir

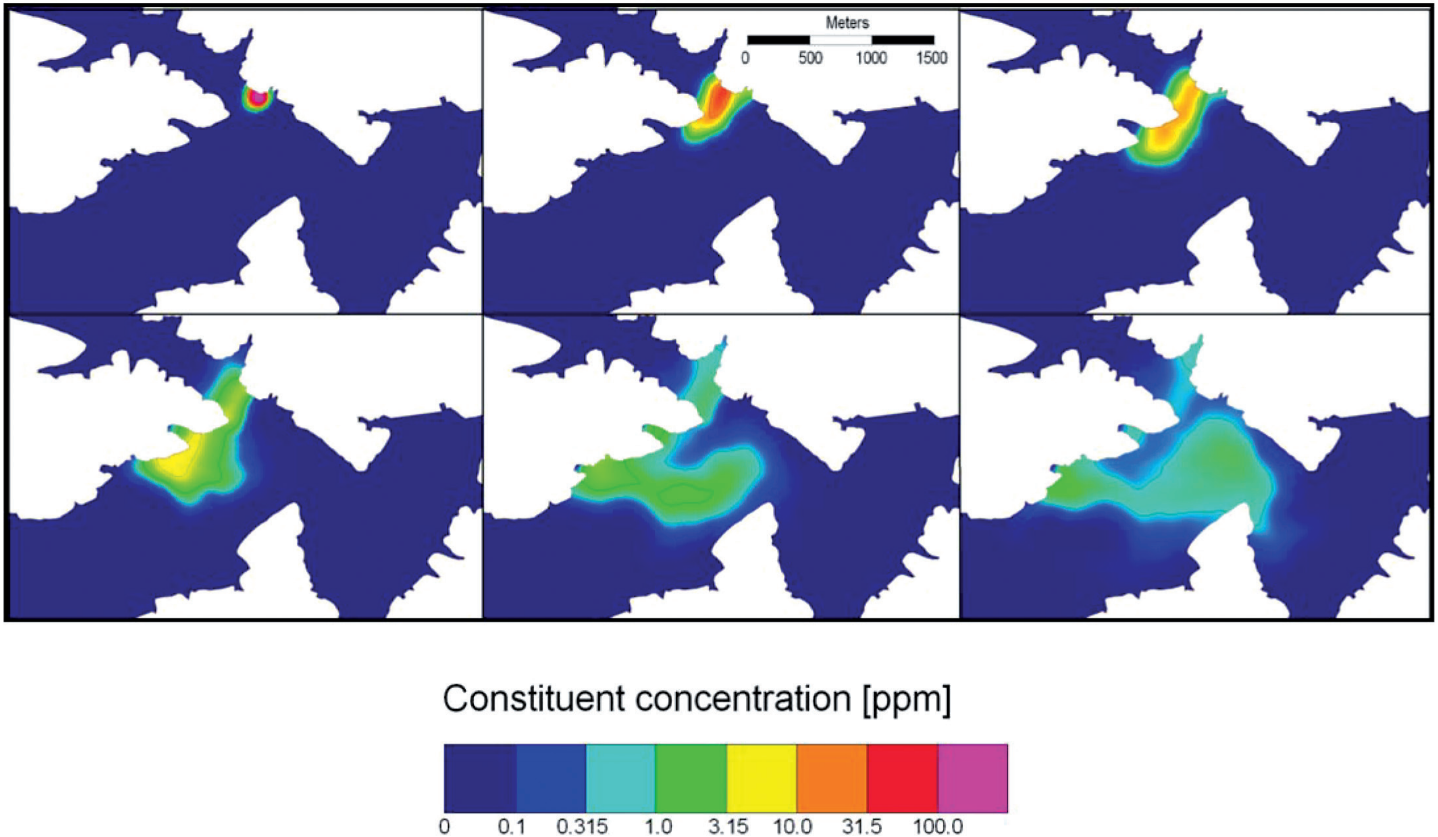

Fig. 3. Process of transporting simulated 3-hour leakage from position the haven after 5h (upper left), 1d (upper middle), 2d (upper left), 4d (lower right), 8d (lower middle) and 12d (lower right) after the “zero” moment

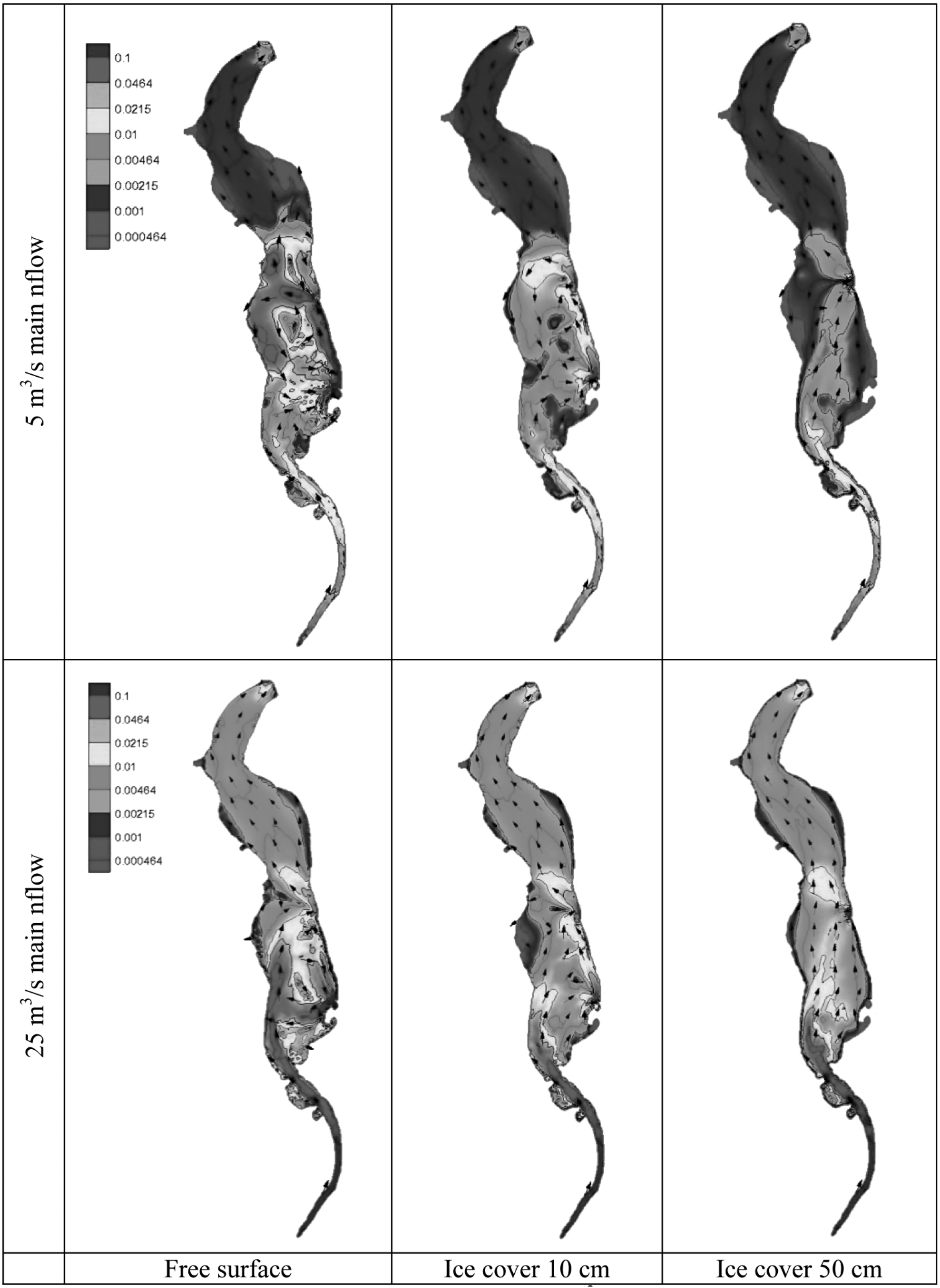

Fig. 4. Flow velocity map comparison for 5 and 25 m^3/s main inflow for a different scenarios (with different thicknesses of ice)

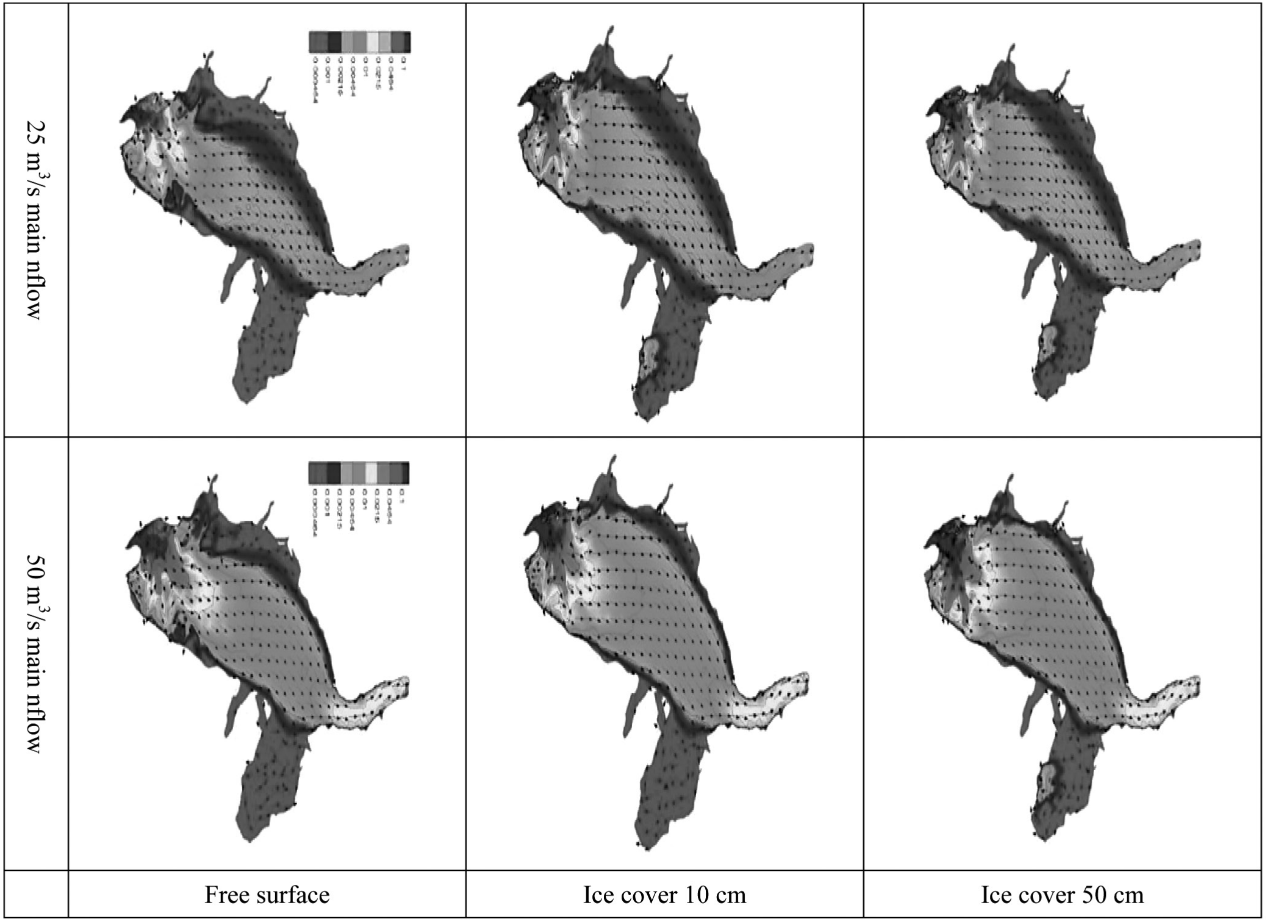

Fig. 5. Flow velocity map comparison for 25 and 50 m^3/s main inflow for a different scenarios (with different thicknesses of ice)

depth is much less than in the second reservoir. It is the next factor affecting the dynamics of the flow water under the ice cover.

Summing up the impact of ice cover for hydrodynamics situation in storage reservoir is significant. It changes flow velocity and its direction. The presence of the ice layer causes lake stagnant areas. The currents tend to straighten and whirlpools tend to disappear. Identifying the sub-ice stagnant zones is important because of water quality.

The next challenge, especially for the retention reservoir with flood protection function, is water surface elevation control. The appropriate water surface elevation is determined by the current hydro-meteorological situation. Control of the reservoir operation in flood conditions is a difficult task. It requires keeping a water level that allows to capture a flood wave. This is the reason why it is necessary to know how long it takes for drying and filling the reservoir.

Fig. 6 presents the process of drying and wetting the Tresna reservoir at the rate of 40 m^3/s and 200 m^3/s for two different water surface levels: 342 and 337.8 m a.s.l. Two figures at the top present the process of drying the storage reservoir for 10 m^3/s inflow (left) and 50 m^3/s outflow (right). Water level goes down from 342 m a.s.l. to 337.8 m a.s.l. Next water level goes up from 337.8 to 342 m a.s.l. for the same flow rate. This whole process takes almost 600 hours of the model time. The first 24 hours have been added to let the model find a stable operating point, while the remaining time present the all cycle of drying and wetting.

A similar situation was presented on the figures at bottom of the table. The difference is that the inflow value is 10 m^3/s and the outflow value is 210 m^3/s for drying process. And for the wetting process, inflow is 210 m^3/s and outflow is 10 m^3/s. This time, the whole process takes 200 hours of the model time where the first 24 hours was added to find a stable solution.

The possibility of modelling of storage reservoir wetting and drying process is very helpful. It allows modelling of different scenarios in short time. It gives the knowledge about parts of the lake that was dried and the location of stagnant areas and in next step which area was flooded and how long this process takes.

Fig. 7 shows intermediate steps in the wetting process for:

- water levels from 337.8 to 339 m a.s.l. (first figure);
- water levels from 337.8 to 341 m a.s.l. (second figure).

Inflow value is 50m^3/s outflow value is 10m^3/s. Total flow value is small and it is 40m^3/s. The wetting process is slow and takes 65 hours so almost 3 days for first figure and 183 hours so more than 7 days in case of the second figure. Water level difference is respectively 1.2 and 3.2 meters.

The similar situation is presented in Fig. 8. It shows wetting of the bed at the same water levels as before (339 and 341 m a.s.l.) at the flow rate of 200 m^3/s (210 m^3/s inflow and 10 m^3/s outflow). In this case raising the water level about 1.2 meters takes 14 hours and analogously raising about 3.2 meters takes 37 hours. The wetting process is much faster in this case than in the previous case. In addition this situation can predict the results of flood wave entrance into the reservoir.

The process of drying storage reservoir is presented on Fig. 9. It shows fast drying intermediate steps for:

- water level from 342 to 339 m a.s.l. (figure on the left);
- water level from 342 to 341 m a.s.l. (figure on the right).

Flow value difference is significant and it is 200m^3/s. Inflow value is 10 m^3/s and outflow value is 210 m^3/s. In the first case, the drying process takes 70 hours and water level difference is 3 meters. In the second case, it lasts 24 hours and the water level difference is 1 meter. In the both cases, the water level drops very fast. This case can reflect the situation when there is a need to quickly empty a reservoir. It happens when a flood wave is coming to the lake. The storage reservoir task is to catch a flood wave, in order to protect a threatened area. The simulation solutions give knowledge about the drying time, which helps elaborate the procedure in similar situation.

The other problem, in case of reservoirs, is the movement of the sediment, which can cause many problems. First aspect is the displacement of the bottom sediment, which is the reason for deepening and shallowing, especially in the places where rivers enter the lake. The water is able to grab the particles of the sediment from the bottom of the lake or river (if the water speed is high enough to grab the particles with given characteristic feature: like size and mass), transport it to another part where floating forces are not so big. The sediment can be deposited, but in other condition, it can be removed once again. It is possible to estimate these

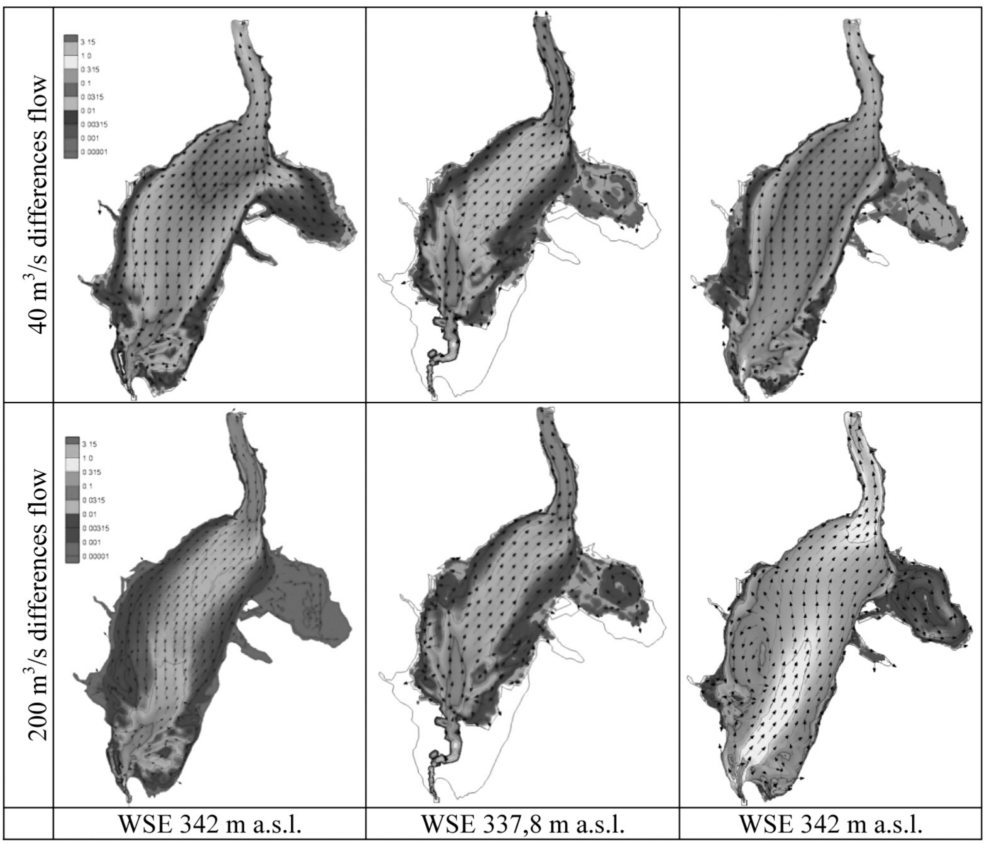

Fig. 6. Unitary flow maps for transient water level from 342 m a.s.l. through 337,8 m a.s.l. and again to 342 m a.s.l. for two different flow

phenomena by the modelling program called PTM [12]. Simulations made in this model give information about the potential places prone to erosion as well as sedimentation. Another solution, available in PTM, is tracking the way of particles introduced to the reservoir. It can be done by choosing the places of sediment source and set basic information about the particles. Fig. 10 presents simple solution of bed displacement for constant inflow of water

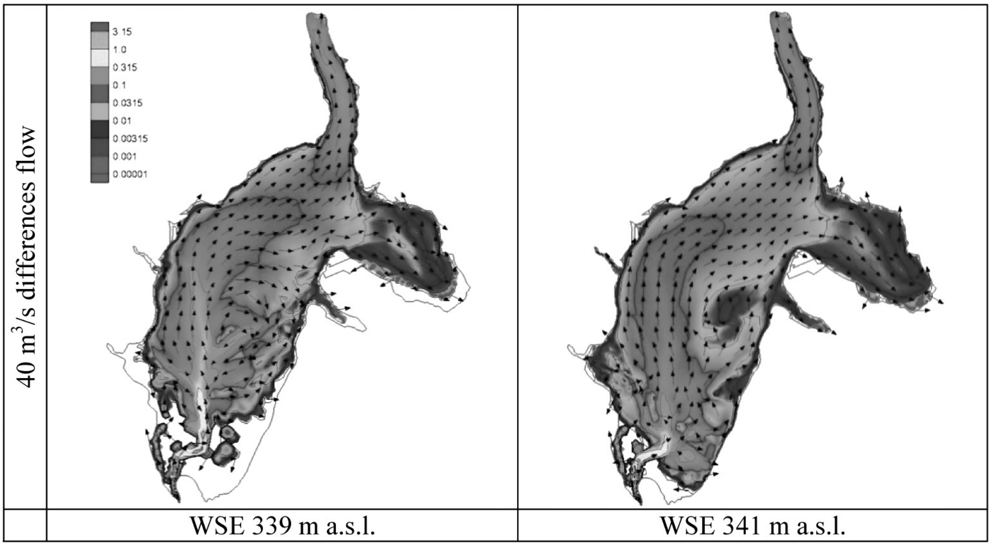

Fig. 7. Unitary flow maps for two different water level for case when the reservoir is slowly wetting

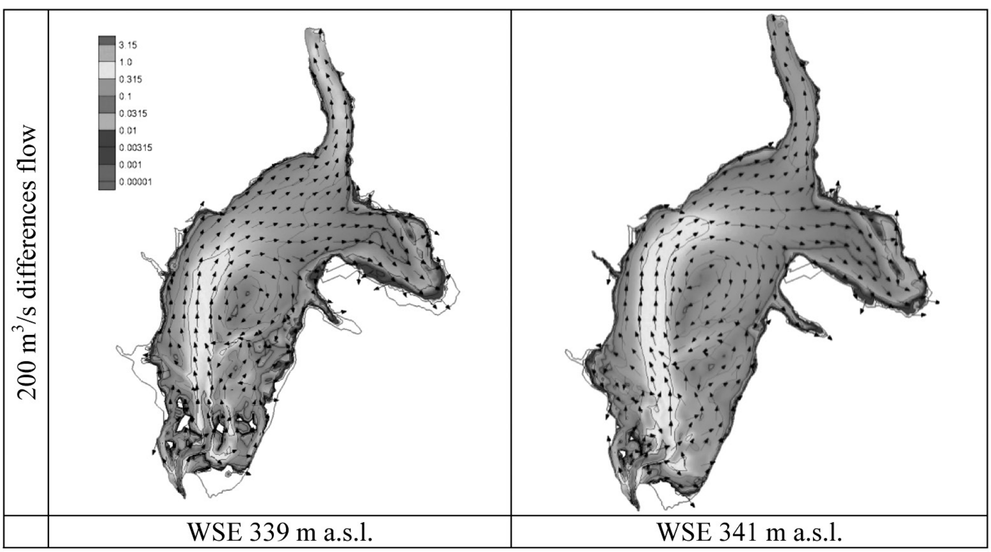

Fig. 8. Unitary flow maps for two different water level for case when the reservoir is fast wetting

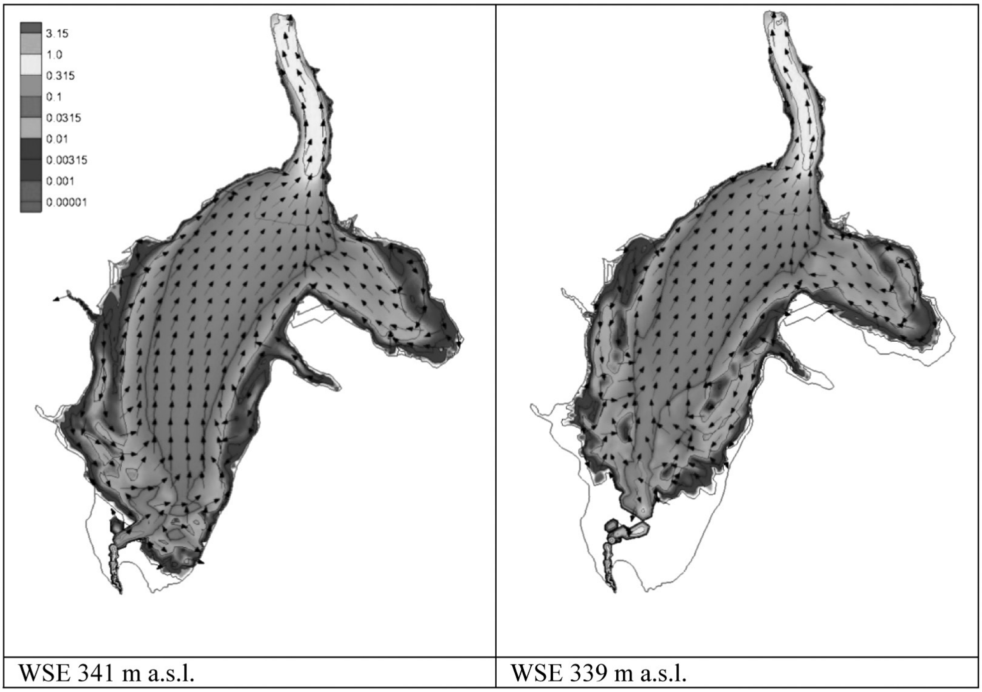

Fig. 9. Unitary flow maps for two different water levels for the case when the reservoir is drying for 200 m^3/s differences flow

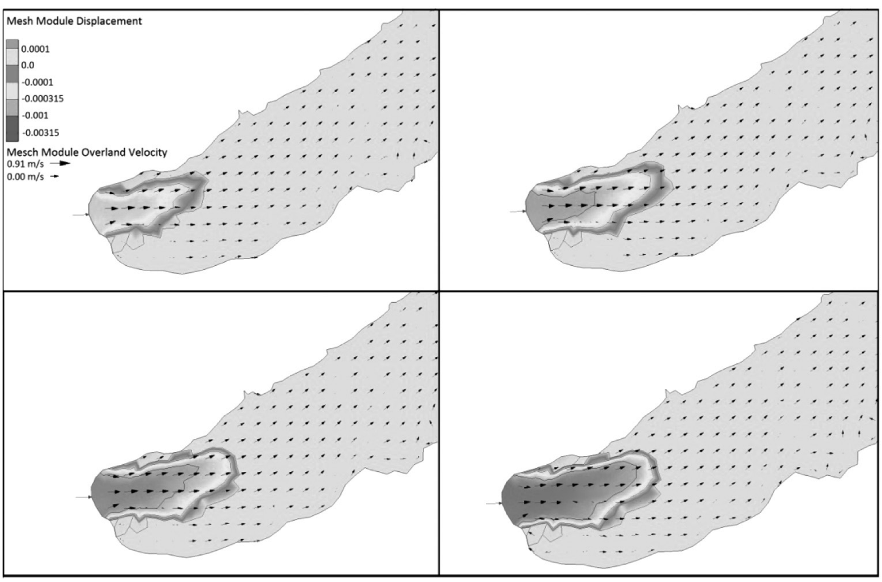

Fig. 10. Process of displacement of the bed in the first part of the Dobczyce Lake after 2d constant inflow (upper left) after 3d (upper right), 4d (lower left), 5d (lower right)

with a discharge of about 500m^3/s for five days. It is necessary to mention that this model is in a phase of testing by the authors and the presented result is only an example of its possibilities.

5. Conclusions

The obtained results indicate that, by using the numerical models, it is possible to forecast dynamic phenomena in storage reservoirs and can this be used as a clue to planning in both standard and exceptional operating conditions of the reservoirs. The above-mentioned simulation possibilities can help to choose the appropriate solutions for of the physical and quality problems as: pollution propagation, sediment accumulation and transport, flood flow capture preparation, ice cover impact on the water dynamic and water quality.

The numerical solutions are stable and physically justified. The simulation solutions can't be treated like an exact answer for the real problems. It can be only a clue for a good management the reservoir. It is obvious that field research is always recommended and it gives the best view of the situation. However, in large-scale research, as it take place on the water reservoirs, it's often hard, expensive and sometimes even unenforceable. In those cases, only a well-known simulation solution area may outline real the situation.

Nowadays, the aspect of water quality is the priority issue. Because of a large human population, more attention should be put to guarantee basic needs. This problem can't be solved only by using traditional approach. Using the modern simulation techniques is necessary and inevitable. The presented solutions are only a simple example, which focuses on individual problems. It is worth to pay attention to the fact that the simulation environment gives a wide possibility spectrum as the solution of complex problems that contain a group of single phenomena. For example, the observation of the sediment transport, in case of the drying of a reservoir, and finding the dependence between both, it is almost impossible to research in site.

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ANDRZEJ WOLAK, PIOTR PRZECHERSKI*

UNMANNED FLOATING RESEARCH VEHICLE FOR BATHYMETRIC MEASUREMENTS

BEZZAŁOGOWA PLATFORMA POMIAROWA SŁUŻĄCA DO BADAŃ BATYMETRYCZNYCH

A b s t r a c t

Unmanned water vehicles have been routinely used for marine purposes. This technology has emerged only recently for inland waters. It is used for two main purposes: bottom area scanning, in order to create maps of bottoms of rivers and lakes, artificial or natural. This information is needed for water engineering development and rehabilitation projects, and for flood protection planning. The other use is for the determination of flow velocities in rivers and lakes, which is needed for the determination of hydraulic properties of rivers, also necessary for flood protection. For the first purpose, an original vehicle is shortly described (UPP-1E), for the other, a Commercial-Off-The-Shelf solution is presented (RiverSurveyor of SonTek).

Keywords: water reservoirs, sediment accumulation measurements, unmanned surface vehicles, echosounder

S t r e s z c z e n i e

Bezzałogowe platformy pomiarowe powszechnie stosowane są do badań na akwenach morskich. Na wodach śródlądowych technologia ta pojawiła się dopiero niedawno. Zastosowanie platform pomiarowych na akwenach śródlądowych służy do dwóch głównych celów, tj. pomiarów batymetrycznych jezior i rzek (pomiary te potrzebne są dla utrzymania obiektów w należytym stanie technicznym) oraz ustalenia prędkości przepływu wody w rzekach (pomiary te są niezbędne do określenia właściwości hydraulicznych oraz zwiększenia ochrony przeciwpowodziowej). Do tworzenia map batymetrycznych w artykule opisano platformę UPP-1E do wykonywania ustalania prędkości przepływu wody opisano urządzenie RiverSurveyor.

Słowa kluczowe: zbiorniki wodne, pomiary zalądowiania, bezzałogowe urządzenie pomiarowe, echosonda

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1. Introduction

Unmanned floating vehicles have been used for marine purposes for a long time. The first remotely controlled boat was a Nikola Tesla's invention from 1898 (end of XIX century!). The first one that was actually used was the British HMS Agamenmon of 1921 – an old warship, used for targeting practice, remotely controlled.

Since then, especially after the Second World War, unmanned floating vehicles are routinely used for marine practice. They were not used for inland waters, however. Until recently, there was not much a small craft could accomplish there, be it a drone or a manned boat. This has changed, however.

One of the main issues concerning flood protection is the information about the actual volume of water stored in large retention reservoirs. Those reservoirs offer the cheapest and the most effective tool against floods. The other tools – like dikes, small "dry" reservoirs and polders are important as well, but nothing can be compared to a vast water retention reservoir – concerning overall impact and the relative cost [1].

However, the overall volume of a reservoir can decrease with time. This happens mainly because of sediment accumulation, and that alluvia is "eating-up" a useful volume of stored water. That is a rather slow process, which may speed up considerably during flood events. Therefore, it is important to know the current volume of sediments accumulated in the reservoir, firstly, to be able to calculate useful volume of the reservoir storage capacity (which is needed for flood protection planning and other purposes), and secondly, for assessment of future reservoir operation.

Another related issue is the changing of river beds due to sediment accumulation and erosion. This can lead to dramatic changes in river cross-section geometry, thus alternating its hydraulics and making flood events much more likely and severe. Knowledge of the actual geometry of the river beds, especially for river segments inside towns and cities, is also very important for flood protection and planning.

For the above-mentioned issues, an unmanned floating vehicle can be a good research platform.

2. Measurements of the bed layout of large water retention reservoir

The first problem may be, sometimes, with not the best data concerning the reservoir volume gathered during its planning. For its initial volume assessment, classic geodesics methods were usually used. These methods give, because of their very nature, a comparatively small number of measured points (compared to a vast number which can possibly be obtained using an automated device floating on the flat surface of a future reservoir). This may lead to serious inaccuracies, as shown in the Fig. 1.

As it can be seen in the above picture, increasing the number of measured points directly leads to the increase of accuracy of valley shape determination, which in turn, almost always leads to an increase of the assessed volume of water stored in the reservoir. In other words – measurements using an automatic vehicle floating on the surface of water reservoirs almost always increase the recorded volume of water, which may be used for various reservoir

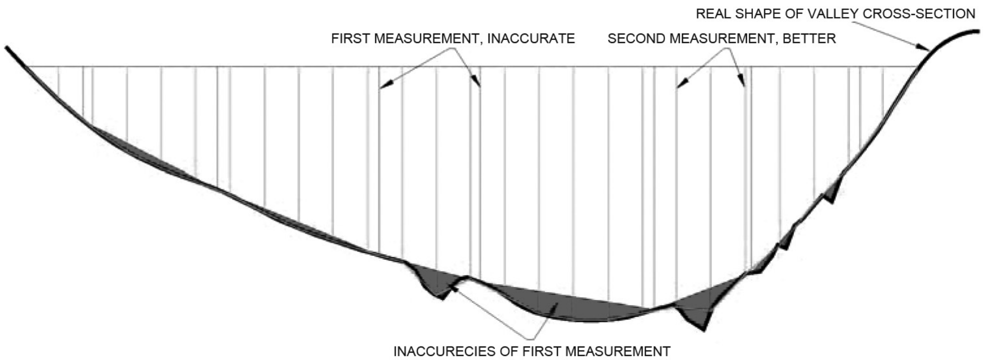

Fig. 1. Results of inaccurate measurements in valley layout and reservoir volume determination. Inaccurate initial measurements (red lines), better (denser) measurements (green lines). Errors in valley shape determination are shaded in red

purposes, including flood protection. This "extra" volume was there, of course, but it was usually not known to exist. In practice, this can be a quite meaningful number – given the fact, that the initial valley geometry has been measured with meagre (as for contemporary standards) resolution (see Fig. 1 above). It can be from a few, up to 20 percent of the overall, actual reservoir volume.

Usually, the measurements of the layout of the bed of a water reservoir are done using a device called "echosounder", mounted on a boat. The device emits sound into the water and measures time between emission and echo reception, thus allowing for distance calculation. It is attached to a boat and, together with a GPS receiver (this only for plane, or for XY, location), it is used to record actual water depth at a given position. To be able to do meaningful research, however, a lot of measurement points are required (hundreds of thousands or even more for medium-sized water reservoirs). The process is usually partially automated, but nevertheless, it is arduous, extremely time consuming and can be dangerous.

3. Our invention

To overcome the above-mentioned problems, we have developed an unmanned surface water vehicle (called UPP-1E), which is able to do that work much easier and faster. The vessel is a fully integrated device, consisting of the following subsystems (see schematics in Fig. 2):

- Measuring subsystem: high-class echosounder consisting of the central unit (signal reception and formatting) and dual frequency heads (transducers). This device is a NaviSound 215 of Teledyne-Reson.
- GPS receiver – Garmin 18x unit. Signal from that unit is directly fed into the central unit of the echosounder for combining with the depth data and then transmitted further – into central computer.

- Steering/propulsion and control system. Consisting of the central computer (with provisions for expanding into redundant double system in the future), and the switchboards (including associated firmware), electric motor and propeller. The power supply for all the systems is provided by a set of high energy density batteries (5 items, 12VDC) allowing for at least 6 hours of continuous work. Communication with the shore station is done using a GSM-based modem, allowing for almost blanket and stable signal coverage in almost all of Europe.
- Auxiliary systems. For now, it is a surveillance/hazard avoidance camera, mounted on a small mast on the fore part of the boat. Adding a forward looking, short distance hazard avoidance radar is planned in the near future (funds allowing).

The use of two measurements frequencies allows us to do two tasks at the same time: the first frequency (200 kHz) is used for first-contact measurement; this is what usually is understood as "real lake bed" depth. This sound frequency reflects off first obstacles near lake bed, be that sand, stones or vegetation. The other frequency (50 Hz) is a penetrating one, and can be used for direct deposit layer width determination. This must be carefully calibrated before any meaningful results can be presented.

A simple schematic of the system is presented on Fig 1, below:

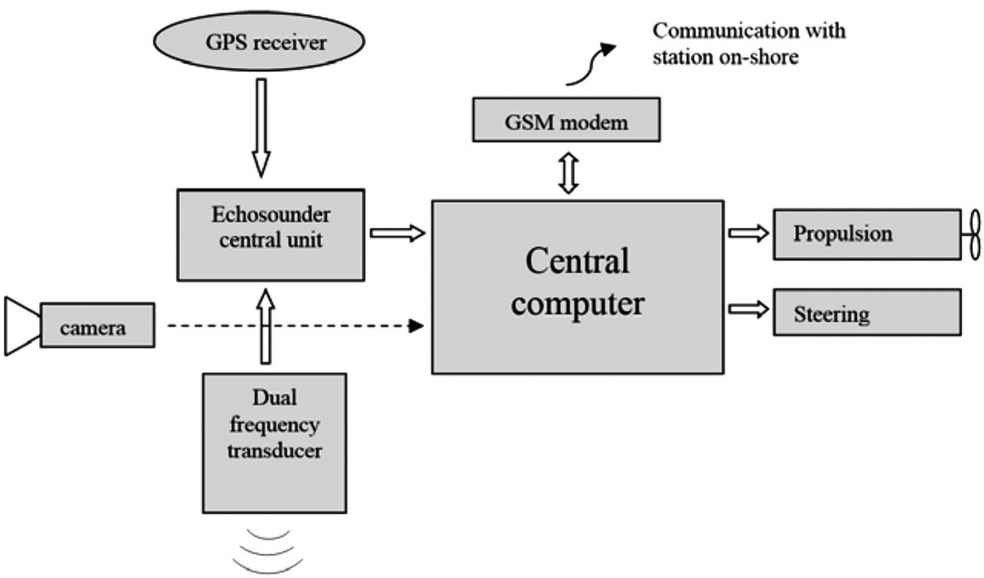

Fig. 2. Base schematics of the UPP-1E vehicle. The UPP-1E vehicle is pictured below

In the Fig. 3 the whole vessel can be seen. It is 200 cm long (not counting the rudder) and 80 cm wide (including impact dampeners – grey tube around the hull). Its projected draft shall be no more than 10 cm. The echosounder compartment is between the camera and the tall mast (first white cover). The other compartment is for batteries/propulsion (see Fig. 7).

Fig. 4 shows the details of the steering mechanism. A removable rudder will be utilized to allow for rapid replacement in case of expected rapid wear-and-tear.

Fig. 3. General view of UPP-1E vehicle. Source Delta Prototypes

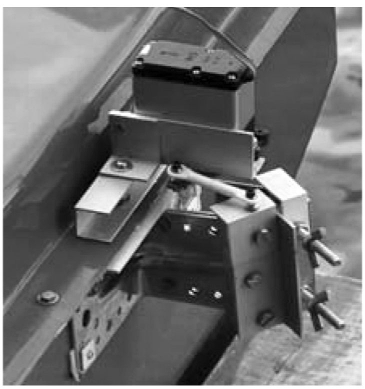

Fig. 4. Steering mechanism

Fig. 5. Propeller, diameter of 9 cm

Fig. 6. Control software screen shot

Fig. 7. Batteries compartment

On Fig. 5 the propeller is shown, just under the main hull. It is going to be the most exposed part of the entire vehicle. We expect it to be replaced fairly often (more than 6 times in a season). As for now, a 9 cm diameter is used. After initial trials, we may change it for a slightly bigger one.

On the last picture (Fig. 7), the batteries compartment can be seen. As for now, only five units are used (for testing purposes). For real-world use, there is space provided for 15 more. Our aim is to be able to have at least 8 hours of continuous operation. The maximum speed of the vehicle is set to be about 2 m per second, but for nominal measurement conditions, it shall be no more than approx. 1 m per second (as the echosounder gives up to 5 pings a second, it should be more than enough for most of applications).

The UPP-1E vehicle is meant to be able to replace the large boats (like UŚKA) as bathymetric (meaning like depth measurements) platforms. Our vessel shall be much cheaper to procure, easier to maintain and be able to do much more research, even in adverse conditions. There shall be no crew on water, much longer measurement passes are possible, the draft will be minimal.

There is, however, a problem with boat stability. Larger vessels, as a rule, offer a much more stable platform against waves than the smaller ones. For echosounder measurements, it is a difficult problem. If the sound beam emitted from the transducer is skewed (as happens when a wave rolls a boat), the resulting water depth value is bad – much bigger (30% or even more relative to the "true" value).

The UŚKA vessel is 8 meters long, 2.5 meters wide with draft of 40 cm. It is possible to record bathymetric measurements (using stabilized transducer firmly attached to her side) for up to approx. 20 cm of wave heights. Achieving the same feat with a much smaller boat is a challenge. To overcome this, we are proposing a three part solution:

1. Software. Using white noise statistical function, some impact of wave rolls can be eliminated during post-processing of the obtained data.
2. Passive wave dampening. This will be done by using two additional hulls, attached to the sides of the main one, forming a trimaran configuration. The auxiliary hulls will be much smaller, but nevertheless, shall offer some stabilization.
3. Active wave dampening. A device (under development) to actively dampen the rolling of the boat.

The anti-roll system – active and passive, integrated with steering and propulsion system – is currently under development and preparation for obtaining a Patent protection.

The entire system (even in its current configuration) is meant to be as rugged as possible. We are currently testing it to see what can be improved to be able to do work even in the most adverse conditions. Trying to assess the progress of a new technology, National Aeronautics and Space Administration (NASA) Technology Readiness Level can be utilized. Using this scale UPP-1E vehicle in its current shape is on the TRL 6 – "Prototype demonstration in relevant environment" [4].

The vehicle is still under development (working prototype 1E), but it can easily be used in its current state, albeit with some limitations (mostly concerning surface wave impact dampening, man-machine interface and firmware issues).

4. Example of use

The UPP-1E vehicle was used for determination of the layout for the planned development project (called Mała Wenecja) on Dunajec River in the city of Nowy Sącz. The river in this particular location is rather dangerous to cross, water velocity may be well above 3 m/s. There was no easy way to get the shape of the river bed there, as the use of classic geodesics method allowed to obtain only a few measurements.

However, using the UPP-1E vehicle, it was possible to get +200 measurements. A bottom map has then been made, greatly easing the design process of the future development.

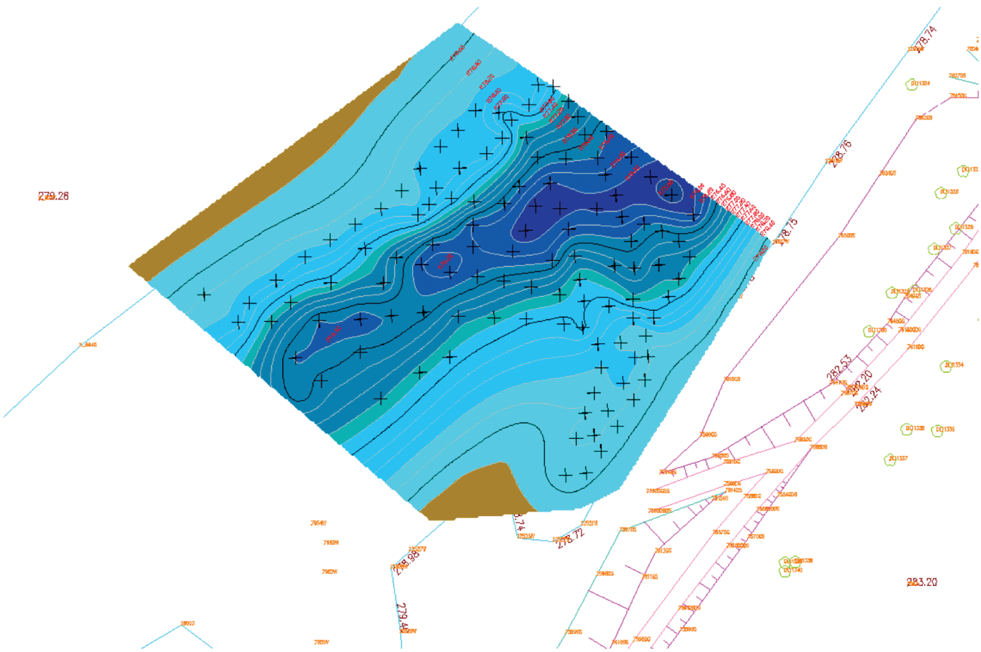

Fig. 8. River bed model for Mała Wenecja development project, Dunajec river

5. Conclusion and the way forward

The UPP-1E vessel is meant to be able to replace large boats as bathymetric (depth measurements) platforms. This vessel shall be much cheaper to procure, easier to maintain and able to perform much more research, even in adverse conditions. There shall be no crew on water, much longer measurement passes are possible, the draft will be minimal.

There is, however, a problem with boat stability. Larger vessels, as a rule, offer a much more stable platform against waves then smaller ones. It is a difficult problem for echosounder measurements. If the sound beam emitted from the transducer is skewed (as happens when a wave rolls a boat) the resulting water depth value is incorrect – much higher (30% or even more then the "true" value).

Ultimately, to overcome this, we are proposing a three-part solution:

1. Software. Using a white noise statistical function, some impact of high wave can be eliminated during post processing of the obtained data.
2. Passive wave dampening. This will be done by using two additional hulls, attached to the sides of the main one, forming a trimaran configuration. The auxiliary hulls will be much smaller, but nevertheless, shall offer some stabilization.
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The entire system (even in its current configuration) is meant to be as rugged as possible. We are currently testing it to see what can be improved for the product to be able to work in the most adverse conditions. Trying to assess the progress of this new technology, National Aeronautics and Space Administration (NASA) Technology Readiness Level can be utilized. Using this scale, UPP-1E vessel in its current shape is on the TRL 6 – "Prototype demonstration in relevant environment" [4].

The vessel is still under development (working prototype 1E), but it can easily be used in its current state, albeit with some limitations (mostly concerning surface wave impact dampening, man-machine interface and firmware issues). After it is completed, it can be a game-changer for the industry.

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